# Probing the Tropical Firebox: International Atmospheric Science

*Five thousand scientists and technicians from 72 countries—aided by a thousand land stations, 40 ships, 12 aircraft, and 6 satellites—were engaged in a coordinated research effort, spread over 20 million square miles. . . . It has been compared to the voyage of the* Beagle *as a scientific expedition of global ambitions, and to the D-Day landing on Normandy's beaches as an operation of great logistical complexity.*—H. Guyford Stever, director, National Science Foundation

What is described as an international scientific experiment of record size took place in and over the eastern Atlantic Ocean during the summer of 1974. Known as the Atlantic Tropical Experiment of the Global Atmospheric Research Program (GATE, for short) and sanctioned by the World Meteorological Organization and the International Council of Scientific Unions, it was an attempt to understand the workings of the tropical atmosphere. Employing a remarkable diversity of instruments and techniques, the experiment was a logistical and operational success to a degree that surprised many scientist-participants and that has considerably added to meteorology's credentials in the arena of big science. As an international success, GATE signals the increasing awareness among both scientists and governments that the next major step in understanding meteorological phenomena and improving weather forecasts must be a global one. And preliminary results ranging from new information on the life cycle of tropical rain clouds to observations of large-scale atmospheric waves suggest that the experiment will prove scientifically fruitful as well.

The tropics have always been something of an enigma to meteorologists. Not only are there comparatively few observations over this part of the globe, especially over the tropical oceans, but in addition the weather patterns are unlike those of the middle latitudes. The main airflows, the tropical easterlies, blow more gently than the westerly currents at higher latitudes, and the weather is dominated by extremes of wind and rain rather than of temperature. These extremes manifest themselves in disturbances that range from short-lived rainsqualls to the downpour of the tropical monsoon and the fury of the hurricane. Tropical regions receive half of the sunshine that strikes the earth, generating heat that is pumped aloft by convection within tropical rain clouds to warm the upper atmosphere. For this reason the tropics, and in particular the towering cumulonimbus clouds that reach heights of 14 kilometers, have often been described as the firebox of the atmospheric heat engine.

Not surprisingly, the central focus of the Atlantic Tropical Experiment was to understand what governs the formation of tropical rain clouds and how they interact with circulation patterns. The hope, ultimately, is to find a reliable measure of the atmospheric heating the clouds produce and hence to get a handle on one of the processes that drive the global weather system.

An additional impetus for GATE was the need to improve the numerical models of the atmosphere used in forecasting. These models, often global in scope because of the difficulty of using artificial boundaries on any lesser scale, are very much at the center of the Global Atmospheric Research Plan—of which GATE is the first major effort. Unfortunately, individual clouds or even groups of clouds are too small to be explicitly included in global models with any conceivable computers, and so parametric means of representing their cumulative effects must be used. Present methods are relatively crude, and hence GATE planners went to considerable lengths to try to observe both cloud systems and large-scale weather phenomena; the working assumption is that some large-scale weather features control the occurrence and properties of convective clouds in the tropics and hence can be used to estimate their cumulative effects in the models, thus improving forecasts.

Whether or not GATE will simplify the modelers' problems it is simply too early to say. (During the planning stages, some enthusiasts claimed that GATE was an essential and direct step toward 10-day weather forecasts, a goal now acknowledged to be much more elusive and possibly unattainable.) And some meteorologists point out that the eastern Atlantic, where the experiment was centered, is far from typical of the tropics as a whole. Nonetheless, GATE participants are convinced that the wealth of data collected in the experiment will help them to understand cloud processes and other tropical phenomena in a way never possible before.

Much of the scientific excitement over GATE data stems from the variety of observing platforms and instruments, some entirely new, that were used. Most prior observations over the tropical oceans were restricted to isolated shipboard, balloon, or

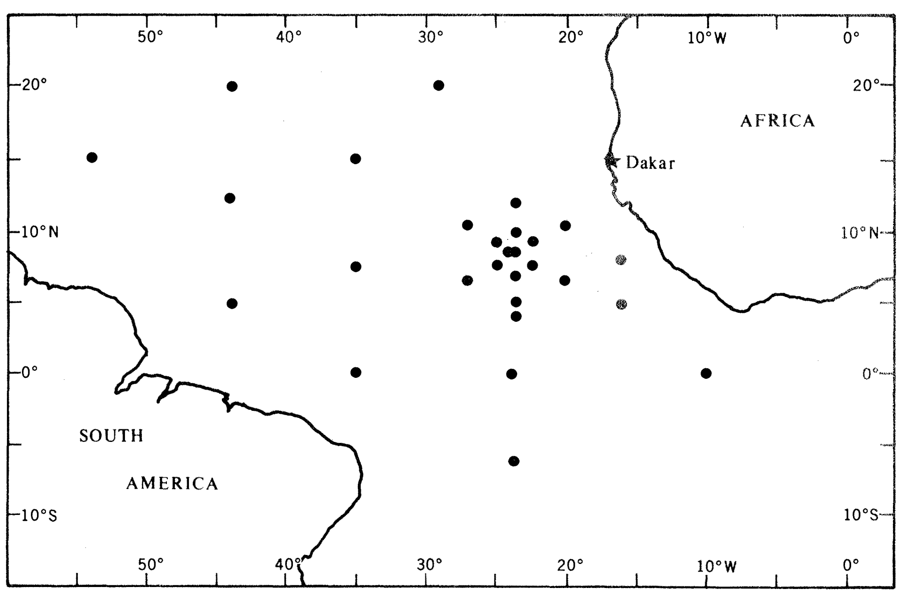


Fig. 1. Approximate positions of a widespread array of ships, including some roving ships, employed in the Atlantic Tropical Experiment. Meteorological stations on land widened the area surveyed still further. The most intensive observations were made over or near the central ship array of two nested hexagons, supplemented during the last portion of the experiment by a small cluster of ships inside the inner hexagon. Aircraft were based in Dakar but made flights covering much of the eastern Atlantic. Thus atmospheric phenomena could be observed simultaneously on scales from tens to thousands of kilometers.

aircraft measurements that could not pin down the time history and spatial variation of cloud systems. In addition to a fleet of aircraft and an enormous network of ships (Fig. 1), GATE employed the first geosynchronous meteorological satellite. Ship-based radars were used to detect precipitation, tethered balloons were raised and lowered to sound the lowest kilometer of atmosphere, and both old and new types of upper-air balloon probes were put in service. Also used were a novel acoustic device for probing the lower atmosphere from shipboard, radiation sensors, and a variety of oceanographic instruments for mapping water temperature and currents.

The synchronous satellite, the National Oceanic and Atmospheric Administration's SMS-1, was positioned over the tropical Atlantic and went into operation 15 June 1974, the day the experiment began. It produced visible and infrared photographs every half hour for the 100-day experimental period. A ground terminal installed at GATE headquarters in Dakar, Senegal, made the photographs

# Global Weather Experiment: The Petrodollar Connection

One of the most sensitive matters in planning international scientific endeavors is the question of who will pay for what. At meetings such as the just concluded Congress of the World Meteorological Organization (WMO) in Geneva, the budget debate is always a cliff-hanger, with richer and poorer nations typically ranged against each other. Twenty and even 10 years ago, the prevailing if unofficial attitude of delegates from many nations seemed to be that the United States would pay for whatever new proposal they were espousing. It is a sign of the times that what is now heard in similar contexts is "the Shah of Iran will pay."

That the petrodollar connection is more than wishful thinking is evidenced by tentative plans made public at the WMO meeting. At issue is a global meteorological experiment that has been under discussion for 10 years. The experiment, scheduled for 1978–1979, is designed to make the first comprehensive observations of the whole world's weather and to test components for a global observing system capable of extending forecasts both in time and to areas such as the tropics and much of the Southern Hemisphere, which now go without. The scope of the experiment is unprecedented: it is to include five geostationary satellites, four polar orbiters, and a host of other special observing equipment, in addition to the existing meteorological network. Time for developing and testing these new devices is running short, however, and there remain many potential sources of technical problems. Neither the Soviet Union, Japan, nor the European consortium, all of whom plan geostationary satellites, has ever launched one, and the U.S. polar orbiter entry, an ambitious two-satellite system called Tiros-N, is not scheduled to fly until 1978.

Still more troubling to many atmospheric scientists has been the slow pace of international negotiations regarding proposed balloon and buoy systems for observing the upper atmosphere and the oceans. Now it appears that Iran, in partnership with France, will provide one of the major items—balloons that circumnavigate the Southern Hemisphere at a constant altitude and relay information to satellites. Because of the Shah's interest in bringing high technology to Iran, more than just money is involved; a condition of the impending arrangement is said to be that the balloon system be manufactured in Iran with French technical help. For its part, France will provide the electronic hardware for interrogating the balloons and handling the data, hardware that is to be carried on the U.S. Tiros-N satellite. (Tiros will also carry British microwave equipment that constitutes a new generation of atmospheric sounders.)

The French-Iranian balloon system is to be technologically sophisticated and yet simple. The constant-level balloons, evolved from the earlier U.S. "Ghost" and French "Eole" balloon designs, will carry transmitting equipment only; each balloon's location will be determined by the satellite from doppler shifts in the transmitted signals. The data from hundreds of balloon tracks, meteorologists hope, will provide a composite measure of upper air flows. When these data are combined with satellite observations of temperature profiles and cloud formations, the result should be a more complete picture of world weather.

In the tropics, however, more detailed wind measurements are needed for accurate forecasts. To obtain these measurements a system of high-flying carrier balloons ("Mother Ghost") which would drop radiosonde probes on command is being developed by the United States as its major contribution to the global experiment. Balloons drifting at an altitude of 24 km would carry 100 sondes apiece and would be deployed so as to cover the entire tropical belt. Sondes would be released and interrogated by satellite.

A third major observing system—ocean buoys—is to be built in bits and pieces with buoys being contributed by many countries, especially Canada and the United Kingdom. The buoys, some moored and others drifting freely, will record atmospheric pressure and sea surface temperature. Some will also monitor conditions in the uppermost layer of the ocean to look for longer-term climatic shifts in the atmosphere-ocean system.

Formal government commitments for the global weather experiment will not be made until February 1976, but more than 50 countries have expressed interest in participating. Meanwhile planning has proceeded under the aegis of the Joint Organizing Committee, a body of 12 scientists (including two from the Soviet Union and two from the United States) appointed jointly by the WMO and the International Council of Scientific Unions. At the WMO congress planning money for the experiment, and the Global Atmospheric Research Program of which it is a part, were given highest priority in an otherwise stringent budget.

Some American meteorologists believe that too much emphasis is being placed on global and long-range forecasts as compared to more effective near-term warnings of localized phenomena, such as this afternoon's chances of rain. Others counter that to improve local forecasting significantly will require a better understanding of global phenomena. But scientific merits aside, there is little doubt that the international cooperation inherent in a global weather experiment is itself a tangible by-product of and a significant source of political support for the program.

Both scientific interest in and political support for the Global Atmospheric Research Program appear to have gained as a result of the success of last summer's international Atlantic tropical experiment (see accompanying story). Thus it appears that after a decade of hopes, a half-dozen international meetings, and a shelf-load of reports—and thanks in part to the emergence of Iran as a technologically ambitious power—a global meteorological experiment is finally becoming a reality.—A.L.H.

directly available to scientists planning the day-to-day course of operations. The infrared images also provided the first systematic look at the development of cloud clusters during nighttime hours.

Nearly all of the observing systems worked well, participants report, in spite of the unplanned absence of several ships, the failure of some ground stations on the African continent, and problems with a new U.S. upper-air balloon probe. The failures of the land and ship stations were significant because they gave rise to gaps in the sampling network for large-scale phenomena which were only partially compensated for by other observations. The upper-air probes—balloon sondes tracked by navigational radio signals that they receive and retransmit rather than by the more traditional method of ship-based radars—worked well in themselves, but their radio signals tended to fade in and out, resulting in noisy and incomplete data, especially for winds. Sondes launched by U.S.S.R. ships were tracked by radar, a more reliable (if more expensive) system, so that not all of the upper-air data were of poor quality. And intercomparison of information from the two systems will at least allow evaluation of U.S. data. (Sondes of both types were launched every 3 hours for much of the experiment.) Despite the perhaps predictable problems of a new and previously untried system, many U.S. meteorologists count the radio-tracked sondes a success and expect them to be widely used in the future.

Aircraft data from GATE promise to be of remarkable quality, not only because of improved instruments on many planes but also because of the way in which aircraft were employed during the experiment. A mission selection team composed of scientists from five nations met every afternoon in Dakar to plan the next day's flights. The result was a carefully thought-out strategy, often involving five or six aircraft flying the same pattern at the same time at altitudes from 150 to 14,000 meters.

Planning depended to a large extent on forecasts of the weather disturbances in the experimental area, forecasts which had never before been attempted for the GATE area. But by comparing satellite photos and conventional weather maps, meteorologists in Dakar headed by Robert Burpee of NOAA's National Hurricane Center in Miami were able to give a good idea of the chances of rainstorms over the central ship array. Although cloud clusters as indicated on the satellite photos tended to die out and re-form somewhere else, rather than propagate in a steady fashion, a distinct pattern did emerge. An east-west zone of cloudiness, often called the intertropical convergence zone, was observed

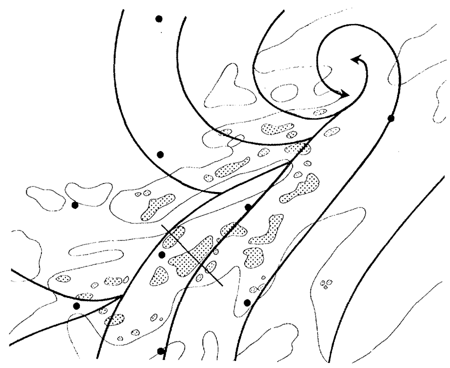

Fig. 2. Example of a band of rain clouds forming along the inflow to an atmospheric vortex. Heavy lines show winds at the sea surface; shaded areas indicate precipitation (rain clouds) seen by radar; thin lines are high-altitude clouds observed by satellite. Large dots mark ship positions, and straight line shows aircraft sampling track. [Source: A. K. Betts, Colorado State University, and D. R. Rodenhuis, University of Maryland]

to shift its position to the north roughly every 3 to 5 days, corresponding to the low-pressure region or trough of a westward-moving, large-scale atmospheric wave about 2500 kilometers in wavelength. Thus the wave, in effect, modulated the cloud activity, often bringing it northward over the central ship array in a predictable fashion.

Once an aircraft pattern or patterns had been decided upon, the procedure was for a mission scientist and his airborne alternate (positions that rotated among a group of about 20 meteorologists from several countries) to draw up detailed flight plans the evening before the mission. Rising early the next morning to check the satellite photos and (by radiophone) ship-based radar images, they would pick a tentative target area; detailed planning of mission locations before takeoff was not feasible because many cloud formations had lifetimes of only 3 to 6 hours. For the meteorologists who flew in the planes, a mission meant leaving Dakar early in the morning, flying west for 2 or 3 hours to reach the experimental area, taking data for about 4 hours, and being debriefed after the return flight. The airborne mission scientist, flying in the lead plane, often made last-minute shifts in the flight plans to focus on the desired cloud formations—a process that required on-the-spot integration of visual observations and radar information and logistical juggling of up to half a dozen planes of varying capabilities and crews that spoke different languages.

Flight patterns were coordinated with tethered balloon operations on the ships. And accuracy was maintained by routinely having all planes fly past a specially constructed tower near Dakar to calibrate instruments. Many of the scientists involved in the aircraft program lost weight as the exhaustive summer dragged on, but they acquired a remarkable quantity of wind, radiation, humidity, and temperature observations encompassing a wide range of atmospheric phenomena (more than 300 aircraft missions were flown). In combination with ship, satellite, and balloon information, the result is what many meteorologists call "the best data set we've ever had."

The degree of coordination necessary to bring off the experiment is all the more remarkable, considering the international character of GATE. At the headquarters in Dakar, for example, it was not uncommon to hear instructions being radioed from the control room in Russian, French, German, and English. Coordination proceeded on several levels. After some hesitation, U.S. and U.S.S.R. radio technicians stood joint watches. Scientists in the aircraft program routinely flew joint missions, and there was some exchange of shipboard scientists. Overall responsibility for the experiment, held by a Tropical Experiment Board representing the 13 countries that made major contributions of money and equipment to GATE, was vested for day-to-day operations in the hands of Joachim Kuettner of the United States and Yuri Tarbeev of the Soviet Union. A larger number of countries participated indirectly, through weather stations or GATE operations on their territory. The working conditions were smooth enough, according to U.S. participants, so that it was possible to criticize a poorly thought-out operations plan or even to rearrange the ship array without causing an international incident.

The international character of the experiment is also evident in its budget, which for the field phase of GATE was estimated at $50 million. The bulk of this, in money and in equipment, was provided by the United States and the Soviet Union (roughly $21 million and $15.5 million, respectively), but with major contributions by other developed nations and the host country Senegal and tangible help by the rest of the 13-nation group.* The final cost of GATE will be higher, with estimated funding of about $27 million over the next 4 years for data-processing and research in the United States alone. Data are to be archived in Moscow and Asheville, North Carolina, with four additional data centers around the world to be used for special topics.

A preliminary look at the return on this investment was to be had at a recent meet-

*Brazil, Canada, Finland, France, Federal Republic of Germany, German Democratic Republic, Mexico, Netherlands, Portugal, Senegal, the Soviet Union, United Kingdom, and the United States.

ing of the American Meteorological Society devoted to tropical meteorology, despite the fact that most GATE data are still being reduced in computers in this country and abroad. Six years ago this meeting (which is held every other year) was dominated by papers that dealt with aircraft systems and other operational aspects of meteorology and was devoted primarily to hurricanes. Now, largely because of the GATE effort, theoretical papers and discussions of observations constitute the bulk of the program, reflecting the growing importance of tropical meteorology and the increasing focus on the nature of convection and cloud systems as one of the central problems in atmospheric science.

One of the early findings of GATE concerns the organization of rain clouds in the eastern Atlantic. Very few isolated cumulus clouds were seen. According to a report on convection studies in GATE by Alan Betts of Colorado State University and David Rodenhuis of the University of Maryland, clouds in weather disturbances tend to be grouped in one of several distinct patterns, of which the most common is roughly linear bands. The bands often appear to form along the inflow to small vortices or convergence centers, perhaps several hundred kilometers in diameter (Fig. 2). A second common cloud pattern forms within other vortices of similar size. Before GATE the only visible indicators of these "mesoscale" patterns of weather disturbances were cloud clusters seen on satellite photos, but the details were essentially unknown. The cloud clusters are now known to be high cirrus clouds that form above weather disturbances and that may persist long after the rain clouds themselves have dissipated. And it is the organization of active rain clouds as revealed by GATE radar and aircraft that are under intensive study as the essential features of atmospheric convection in this part of the tropics.

Many of the characteristics of the rain clouds, such as their vertical structure, also appear to hold some surprises. Clouds in the GATE area formed at many altitudes (in numerical models it has always been assumed that cloud bases formed at a given level in the atmosphere), and many did not reach the heights often associated with tropical cumulus until the latter part of the summer. The strength of weather disturbances also intensified during the experiment. These findings may be evidence, some meteorologists believe, that the tropical atmosphere is gradually altered over the course of the summer as its moisture content increases; convection then intensifies and clouds grow taller, warming higher and higher levels of the atmosphere.

What happens in the layer of air between the cloud bases and the sea surface is also attracting a lot of interest in GATE. Observations taken every 4 seconds with tethered ballon systems and data from other instruments have provided unique data on this layer. Up to five packages of instruments were suspended from the balloons, which could be raised and lowered to obtain a profile of temperature and other quantities in the subcloud air.

According to Michael Garstang and his colleagues at the University of Virginia, the subcloud layer is profoundly altered by the passage of a cloud. Warm moist air is taken up in the cloud to "fuel" the convection and is replaced with cooler, drier air from higher in the atmosphere, thus effectively causing the cloud to stop growing after a period of time. Both the warm, moist "roots" of the clouds and the downdrafts of drier air sometimes extend all the way to the sea surface. And the resultant mixing process, Garstang believes, may explain such things as cloud spacing and lifetimes. This picture of events, admittedly preliminary, postulates an unsteady, continually changing subcloud layer during disturbed weather conditions, in marked contrast to the condition that prevails in fair weather. Since numerical models of the atmosphere now incorporate assumptions based on fair weather conditions, many meteorologists believe the GATE data will almost certainly lead to revisions.

On a larger scale, GATE documented the existence of atmospheric waves in the tropics. As proved useful in forecasting during field operations, weather disturbances appear to develop near the low-pressure portion of the wave, an indication of the hoped-for interaction between large and mesoscale phenomena.

Radiative effects of clouds and of atmospheric dust received attention too. Measurements were made from above by satellite and from below by ships and aircraft in an attempt to explore the relationship between radiation and convection. Dust storms on the African Sahara, for example, regularly move out over the tropical Atlantic, forming a layer of particulate matter reaching as high as 10 kilometers and at times extending all the way across the Atlantic. Very few clouds formed in the dust area, which was to the north of the central ship array, raising the question of whether the dust was suppressing convection. Opinions have been expressed on both sides of this issue, which is expected to be resolved as the data become fully available.

Oceanographic experiments were very much part of GATE, but the most striking oceanic phenomenon observed appears to have little direct connection with weather phenomena. What was observed by Walter Düing of the University of Miami and others was a rapid meandering of the equatorial undercurrent, which is an intense eastward-flowing stream about 100 meters below the sea surface at the equator. The current shifted north and south about 1° of latitude on either side of the equator with an apparent period of 16 days, and oceanographers are now speculating on the cause of the phenomenon.

The GATE program includes some 130 principal scientists in the United States and, by one estimate, perhaps an equal number in the rest of the world. Although the U.S. portion of the program is run by several federal agencies with NOAA as the lead agency, participants have considerable praise for the degree to which university scientists have been included in planning, operations, and research. In an effort to continue this involvement, NOAA has been making 4- and 5-year commitments of GATE research funds to university and government research groups, subject, according to James Rasmussen of the GATE Project Office, to the availability of funds. This has not entirely alleviated fears on the part of some meteorologists that GATE funds will be diverted to newer projects before the data are adequately explored and exploited. But, overall, GATE has been an impressive example of cooperative big science at its best, an auspicious first step for the Global Atmospheric Research Program.—ALLEN L. HAMMOND