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Role of Commercial Aircraft in Global Monitoring Systems

New wide-bodied jets provide a unique opportunity for obtaining atmospheric and meteorological data.

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Introduction

The atmosphere contains a wide variety of trace gases and inorganic and organic materials that originate from both natural and anthropogenic sources. Several recent reports have pointed out the need for global monitoring of these atmospheric constitutents (*1, 2*). Because concern is recent and the cost of even a modest program could run into tens of millions of dollars, as yet there has been no systematic attempt to monitor the atmosphere on a global basis. Plans are presently being formulated to increase the number of ground-based monitoring stations (*3*) and to explore the possibility of using jet aircraft (*4*) and satellites (*5*) equipped with various spectroscopic devices to monitor atmospheric constituents which may prove harmful to man. Each of these techniques has certain unique advantages (as well as disadvantages) and, in the future, one method may prove sufficient. However, the present and foreseeable need is for cross correlation of high-quality data obtained by ground-based, satellite, and aircraft monitoring systems. Although efforts are being made to explore the development of both ground-based and satellite techniques, monitoring through aviation has largely been the undisputed domain of a small fleet of specially instrumented research aircraft. Because of the growing need for atmospheric monitoring, the limited number of research aircraft available, and the high cost of maintaining these aircraft, it is important that we take a fresh look at the potential of commercial aviation in global monitoring.

The wide-bodied jets such as the Boeing 747, the Douglas DC-10, and the Lockheed L-1011 represent a new trend in aircraft systems. These airplanes are equipped with inertial navigation systems and central air data computers coupled to advanced data storage systems which provide for direct digital readout of latitude, longitude, and altitude. This effectively eliminates the need for pilot participation in correlating onboard measurements with position, which has been a major limiting factor in developing commercial aircraft monitoring systems. Previously such sophisticated electronic equipment had only been available on specially instrumented reconnaissance aircraft.

With the introduction of compact automated monitoring equipment, these aircraft could supply much of the atmospheric baseline and tropical meteorological data now needed. The purpose of this article is to examine this possibility.

Aircraft Platforms

Although the role of commercial aviation in global monitoring has not been fully explored, several important programs involving jet aircraft have been in progress for some time. For example, in the aircraft report program (*6*) meteorological reports from aircraft in flight are relayed through airline communications facilities and government air traffic control centers for transmission over domestic and international weather communication networks. Also, the velocity gust height program (*7*) of the National Aeronautics and Space Administration and the airlines provides for recording the effects of various forces on an aircraft during flight and comparing performance with design criteria. Both of these programs illustrate what can be accomplished with the proper stimulus.

Research aircraft dedicated to atmospheric measurements of various types are also being utilized, and over the years have contributed to our understanding of atmospheric phenomena. However, the cost of operating and maintaining these aircraft is high (*8*), and their use has therefore been limited. Because of soaring operating costs, the future availability of additional research aircraft does not look encouraging. For example, there has been a substantial reduction in the size of the RB-57F fleet available for high-altitude measurements (*9*).

Presently there are about 3000 commercial jets aloft during any one week (*10*). Many are short-haul jets and fly at altitudes between 6 and 9 kilometers; however, an increasing number are of the long-haul variety with a range up to 9600 km at cruise altitudes between 9 and 12.5 km. This discussion will be limited to the 747's and DC-10's which have recently been added to the long-haul passenger and cargo fleet. This fleet is being augmented by L-1011's, which are now going into service.

The concept of using commercial aircraft as platforms from which to conduct atmospheric research is not new and has been proposed by a number of researchers over the past decade

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(*11*). The potential in this concept has excited the imagination of many people who realize the significant increase in knowledge of atmospheric processes which could be gained at a minimum cost. There are, however, a number of technical reasons why this approach was not adopted before now, the most important being (i) the need for interaction with the pilot to obtain accurate position information for data correlation; (ii) the load factor (weight of equipment plus an observer); (iii) interference with airline schedules; (iv) reliability problems with equipment; and (v) the difficulty of integrating an adequate data handling capacity with aircraft systems. In the succeeding sections I will try to show that in the main these reasons are no longer valid and there is no immutable technological impediment to the implementation of an aircraft monitoring program.

New Wide-Bodied Aircraft

The introduction of the 747 into commercial service in 1970 was described as a major advance in passenger comfort. However, many people are not aware that this aircraft, the DC-10's, and the forthcoming L-1011's represent a significant advance in avionics because they are in essence sophisticated airborne electronic sensing platforms. These aircraft are capable of routinely measuring atmospheric parameters at rates and with accuracies equaling those currently available only on specially instrumented reconnaissance aircraft. At present there are approximately 222 Boeing 747's and Douglas DC-10's in service (*12*). Several hundred more 747's, DC-10's, and L-1011's will be introduced into commercial service within the next 5 years (*13*).

A reevaluation of the suitability of commercial aircraft as sensing platforms in terms of present technology and the large payload capability of wide-bodied aircraft such as the 747 presents a startlingly different picture from that of a decade ago. The 747's have a gross average flying weight of 350,000 kilograms and can carry payloads of over 81,500 kilograms. Flying a 113-kg instrument package (including recording instruments) should not represent a significant weight problem (*14*). All 747's flying transoceanic routes are equipped with inertial navigation systems, which provide the pilot with a direct digital readout of the position of the aircraft in latitude and longitude coordinates every 600 milliseconds. The inertial navigation system continuously computes not only position but also ground speed, wind velocity, heading, drift angle, and several other parameters related to navigation. These data, as well as other aircraft performance and atmospheric data, are then digitized and fed to a new type of flight recorder which is significantly different from the old metal foil type still in use on many aircraft. The new unit, although crashproof, uses Mylar tape and has the capacity to store 64 twelve-bit words per second for 25 hours (*15*). The tape is actually in the form of an endless loop and so new data are continually stored and erased after 25 hours. The flight recorder weighs only 3.6 kg and several can be "stacked" to record as many as 500 twelve-bit words per second. At the end of 25 hours the data can be transferred by high-speed dump (15 minutes) onto a portable auxiliary tape unit, which plugs into the flight recorder. The latter feature is important because it eliminates the necessity of physically removing the recorder tape from the aircraft.

Available Route Structure

The goal is not, of course, to instrument every available aircraft but only a selected few whose route structure will provide the most comprehensive picture of important atmospheric constituents. It is estimated that only about ten long-range aircraft would be required to obtain significant global data. Figure 1 shows a schematic of the routes presently being flown by 747's (*16*). It should be noted that many of the flights in the higher northern latitudes, especially during the winter months, will take place mainly in the lower stratosphere. Such flights through the tropopause and lower stratosphere should be an invaluable source of both atmospheric and meteorological data (*17*).

In order to facilitate data retrieval and instrument calibration or exchange, a small instrumentation laboratory would have to be set up at several key airports, such as Kennedy International Airport in New York and International Airport in Los Angeles. This would cover the majority of the specially instrumented aircraft. Other arrangements would have to be made for aircraft with important routes which were not serviced at New York or Los Angeles.

Type of Information Needed

While a critical evaluation of the possible harmful effects of trace constituents in the atmosphere is beyond the scope of this article, it should be understood that a realistic assessment of those constituents harmful to man can only be made if their cycles and behavior are fully understood. Unfortunately they are not, and there is a considerable lack of knowledge in many areas of atmospheric chemistry. As a result, in most instances we are forced to use existing climatic conditions as a base from which to investigate atmospheric phenomena. An immediate effort should be made to obtain baseline data on atmospheric constituents in the following broad groups:

1) Atmospheric aerosols, which can have a significant effect on the global radiation budget (*18*) and, hence, should be identified. Information is needed on the size distribution, concentration, chemical composition, formation processes, and spatial and temporal distribution of background aerosols (*2*).

2) Gases involved in transformations to particles (that is, sulfur dioxide, hydrogen sulfide, ammonia, organic sulfur compounds, and hydrocarbons) and gases that may reduce stratospheric ozone (such as the oxides of nitrogen).

3) Trace substances such as the halogens, the chlorinated hydrocarbons used in pesticides, and the carbon-halogen compounds which may be toxic to portions of the biosphere. Data on the generation and transport of these substances are needed.

Instrumentation Philosophy

The correct instrumentation philosophy is crucial to the success of any comprehensive sampling progam involving aircraft. What has been described up to now is a technological reality. Sophisticated aircraft are flying global routes on a daily basis. However, unless instruments are available to sample the atmosphere, these platforms will not be utilized. The problem, then, is to obtain instrumentation that can be readily integrated into existing aircraft systems. At this point it might be prudent to consider how the airlines tackled a similar instrumentation problem. In 1929, in order to establish common communication facilities, the airlines formed a company called Aeronautical Radio Incorporated (ARINC). Through ARINC, the airlines subsequently assumed the responsibility for preparing their own avionics specifications in order to develop reliable systems, with equipment that could be interchanged between different types of aircraft, and to reduce the cost of communications and navigation equipment. The company provides a single detailed specification for each piece of aircraft electrical equipment, such as the ARINC No. 576 expandable flight data acquisition and recording system. Although ARINC does not design equipment for the manufacturer, it carefully details the airline requirements. Each aircraft is equipped with standardized instrument cases called air transport radio (ATR) racks; and most aircraft electronic instrumentation is designed to fit these racks. Some of the newer instruments are self-interrogating and provide both visual and recorder outputs indicating a failure mode. In practice, the defective instrument is removed from the rack and replaced with an overhauled unit, and aircraft downtime is thereby kept to a minimum.

The requirements for monitoring equipment are similar enough to those for aircraft instruments in general to warrant applying the ARINC approach in developing instrumentation for atmospheric monitoring from commercial aircraft. The following design criteria might be required:

1) All monitoring equipment should be designed to fit a standard ATR rack.

2) The equipment should be self-calibrating and self-interrogating and provide both a visual and a recorder output indicating a failure mode.

3) The equipment must meet or exceed specifications (DO-138) set by the Radio Technical Commission for Aeronautics (*19*) for design of aircraft electrical equipment, and the requirements of the Federal Aviation Administration.

Such standardization would provide for the future expansion of a monitoring system. As new and more sensitive instruments are developed and the measurement of different constituents is required, the system can be adapted with comparative ease.

It would be incorrect to leave the impression that all the techniques for detecting the trace constituents described above are available at the required sensitivities and that it is only a matter of repackaging these instruments in order to begin monitoring. While some instruments are available now for monitoring ozone, ammonia, and the oxides of nitrogen, others are just getting into the ranges necessary for upper tropospheric and lower stratospheric measurements. Although much work remains to be done in this area, a significant effort is now being mounted by government and industry (*20*). The chemiluminescence technique, involving the emission of light during gas-phase chemical reactions at room temperature, now provides a simple and unique method for measuring ozone and nitric oxide (*21*). There are also chemiluminescent reactions that may permit the measurement of various atmospheric constituents such as sulfur dioxide, carbon monoxide, carbon disulfide, and hydrogen sulfide. The use of tunable diode lasers appears to have a significant potential for atmospheric monitoring because the variable wavelength range permits ideal matching to the strong infrared absorption lines of most of the molecular pollutant gases (*22*). The Department of Transportation, through its climatic impact assessment program, is sponsoring several important instrument development programs (*23*). The Environmental Protection Agency, along with

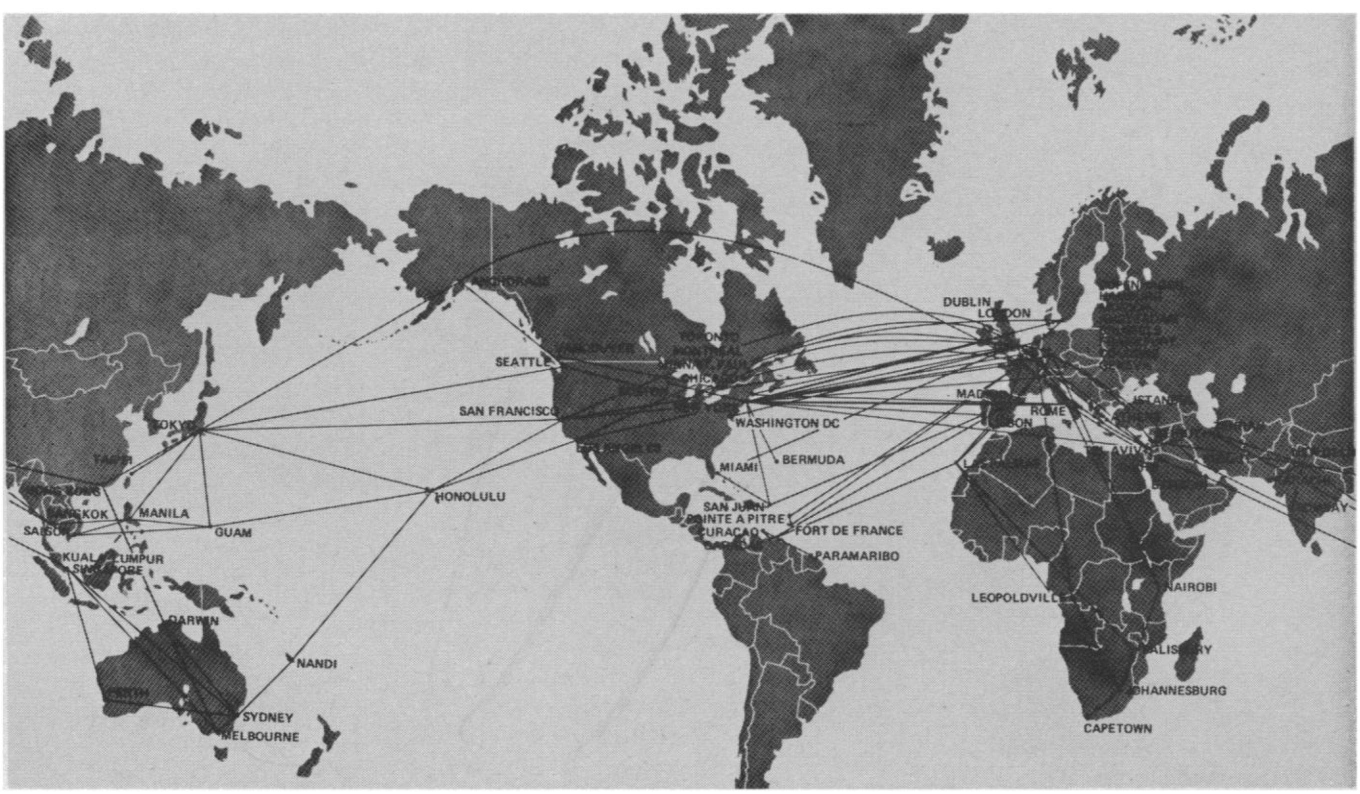

Fig. 1. Major 747 international service routes as of the summer of 1972.

other government and nongovernment groups and private companies, is also making significant efforts in the instrumentation area (*24*).

The approach should be to utilize the instruments currently available which have the required sensitivities (or, where sensitivity requirements are unknown, to use the most sensitive instruments available), and to repackage them according to the ARINC design criteria. As new instruments of greater accuracy, sensitivity, and reliability become available, they can replace those currently in use. The main objective in any commercial aircraft monitoring system, aside from quality measurements, should be the reliability of the instrumentation system. The instruments must also be maintained on a noninterference basis. Modular construction, interchangeability, and self-interrogation are mandatory in order to ensure no aircraft scheduling difficulties.

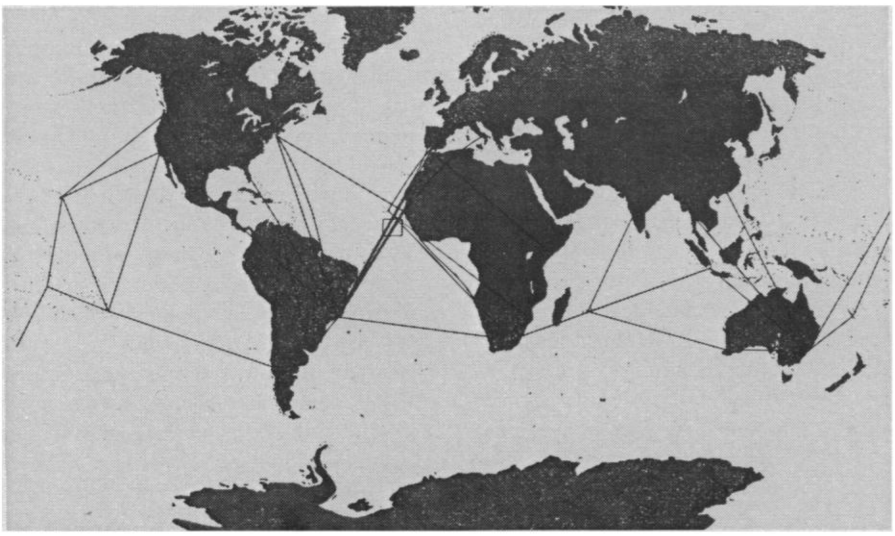

Fig. 2. Commercial aircraft routes in the tropical troposphere and planned site of the 1974 GATE experiment.

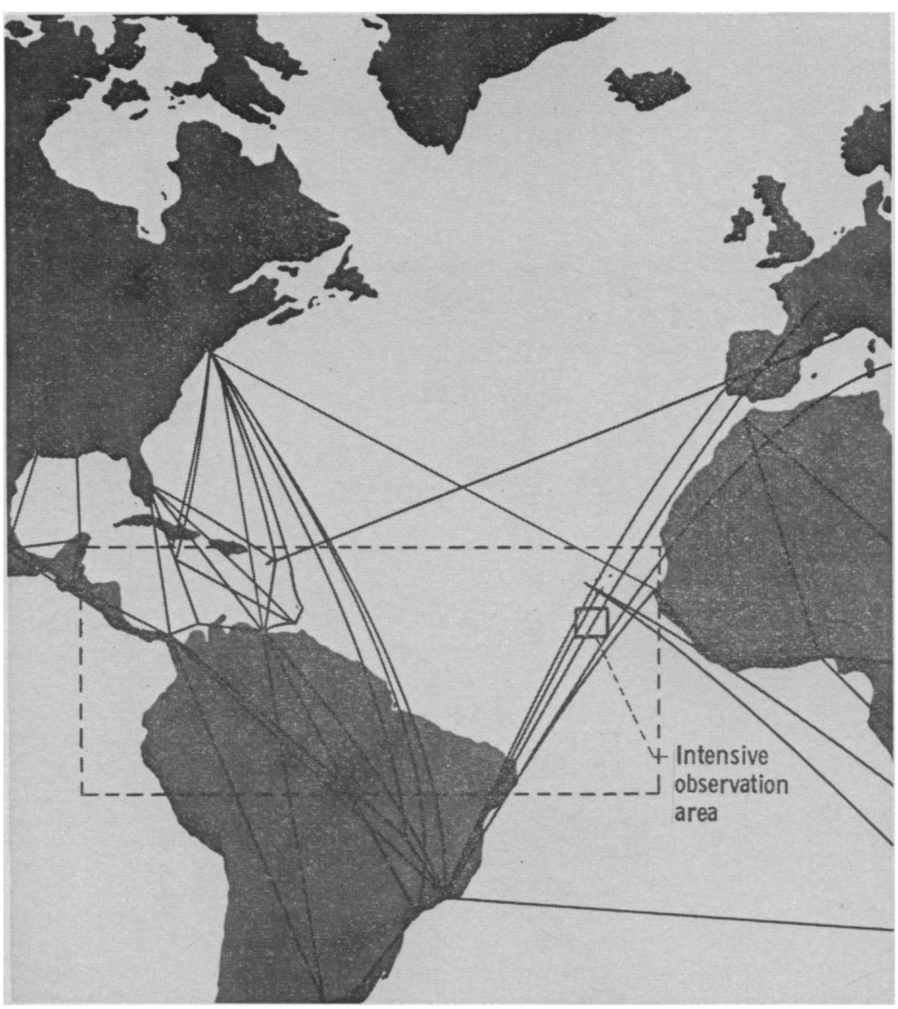

Fig. 3. Commercial airline flights through the area of the GATE experiment (broken lines). Intensive observation will be carried out in the area marked by square.

Application to Meteorology

While the ability to forecast weather has in general improved considerably over the years, nowhere has our lack of knowledge and understanding been more apparent than in the tropics (*25*). The tropics, of course, play a crucial role by providing much of the energy that drives the major circulation patterns of the atmosphere. Our lack of predictive skill, despite the increasing sophistication of computerized atmospheric models and satellite-based observational techniques, is due in part to our inability to obtain precise synoptic data and in part to the complexity of the atmospheric processes occurring in the tropics. We urgently need an economical way to measure midtropospheric wind velocities in the tropics at one or more levels (*26*). Much of the tropical atmosphere is over water, and thus few permanent weather stations exist. In all of the Pacific there are only 15 rawinsonde stations (*27*). Recently, one of two weather ships stationed in the Pacific was withdrawn and the U.S. moving ship rawinsonde program of the National Oceanic and Atmospheric Administration was eliminated (*28*). To exacerbate the situation, the AIREP reporting network for the Southern Hemisphere does not appear to be functioning satisfactorily (*29*).

At present there are about 1000 aircraft per week originating in the Southern Hemisphere and flying through the tropical troposphere (Fig. 2). It should not be difficult to instrument 10 to 20 of these aircraft to provide information on wind velocity, air temperature, and pressure at various altitudes. However, there would be a problem of getting the data to where it could immediately be used. For meteorological information a tape data storage and retrieval system by itself would be of little use. Fortunately, there is a simple solution to this difficulty. The stationary meteorological satellite due to be launched in late 1973 could very easily interrogate these aircraft to provide up-to-the-minute synoptic meteorological data. This, of course, would be supplying data from a narrow band of reference levels (9 to 12 km) and leaves much to be desired; but it does offer the immediate availability of significant meteorological data from a region where very little data has been available in the past. With the expected increase of commercial traffic in the Southern Hemisphere, there is no doubt that a reevaluation of current data-gathering facilities in that area should be made.

GATE, the Atlantic tropical experiment of the global atmospheric research program (GARP) (*30*), scheduled for 1974, is another example of how commercial aircraft can play a significant role in global meteorology. The primary goal of GATE is to study the exchange of energy between the various scales of motion that occur in the tropical atmosphere. Accurate measurements of wind field, temperature, and pressure at various altitudes will be of concern in this program. The territory covered in GATE will include the area on either side of the equator, from Central America to the eastern edge of Africa (the area included by the broken line in Fig. 3). Intensive observations will be concentrated in an area about 1000 km square in the eastern Atlantic, south of the Cape Verde Islands. It should be noted that the air corridor from South America to Europe passes just to the south of the Cape Verde Islands in the precise area where intensive GATE measurements are to be made. This is indeed a fortunate occurrence. Based on present airline schedules, during the 3-month period in which GATE will be carried out, there will be approximately 1700 commercial flights passing through the intensive monitoring region (*31*). While a large number of these flights will be made at altitudes between 9 and 12 km, about 10 percent will be flights to Dakar and the Cape Verde Islands, and these could provide measurements at many different altitudes. Because there would be no need to obtain the data immediately, satellite interrogation would not be required and tape storage of the data would be adequate.

Broader Implications

Whichever system or combination of systems ultimately proves to be adequate for monitoring the atmosphere, it seems reasonable to expect that for the immediate future commercial aircraft platforms can play a significant part in any overall effort. The level of funding required to support such a monitoring program would, of course, depend on the number and type of aircraft involved, the extent of the modifications required, and the logistic support needed for instrument maintenance. While it would be extremely difficult at this stage to determine the cost of such an endeavor (*32*), it is clear that the expenditure involved would be only a small fraction of that necessary to operate and maintain a fleet of, for example, ten research aircraft each flying an average of 8 hours per day on a yearly basis. There is little doubt that if commercial platforms are used to their full potential, we can enhance our knowledge of atmospheric processes at an enormous saving in dollars.

The achievement of global monitoring with commercial aircraft is no small undertaking and will require the cooperation of governments as well as individual airlines and aircraft manufacturers. While it is expected that there might be an understandably cautious attitude among airline managements, there are indications of a cooperative spirit (*33*) which may be nurtured by the realization that atmospheric problems will only be magnified if left unresolved (*34*).

Summary

The role of commercial aircraft in monitoring meteorological parameters and atmospheric constituents has been limited in the former case and virtually nonexistent in the latter. I have tried to point out that this situation can and should be changed now. The new family of wide-bodied jets such as the 747, DC-10, and L-1011 aircraft can be used to supply important global atmospheric and tropical meteorological data for which there is a pressing need. While scientists are not in total agreement on the magnitude of the effect of particulates and gases on the atmosphere, there is almost unanimous concurrence that we are severely limited in information, and that global baseline concentrations must be established for particulates and gases in the troposphere and lower stratosphere as soon as possible. Also, more synoptic meteorological information from the tropical troposphere is highly desirable.

In the final analysis, commercial aircraft may offer the most inexpensive way to monitor our atmosphere in the near future. Much of the instrumentation technology is here and the rest is certainly within our grasp. The fact of the matter is that there are now over 220 Boeing 747's and Douglas DC-10's in service, flying an average of 10 hours a day. Long-range flights, such as those from Tokyo to Anchorage to London in the Northern Hemisphere and from Hawaii to Pago Pago to Sydney in the Southern Hemisphere, are commonplace. These aircraft are equipped with inertial navigation systems and central air data computers coupled to advanced data storage systems which can readily be interrogated by satellite. This means that there is now a large amount of snyoptic weather information which can be obtained with a minimum of effort and cost. Likewise, a start at obtaining measurements of atmospheric constituents on a global basis can be made now. All we need to do is make the effort.

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Enzyme Electrodes

Electrodes containing immobilized enzymes could be used to monitor specific metabolites.

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There is currently considerable interest in the development of biochemical-specific electrodes that could be used to monitor and regulate the concentrations of biochemicals in body fluids. Some very selective biochemical sensors have been made recently in which conventional solute-specific electrodes are used to monitor reactions catalyzed by immobilized enzymes. These devices can theoretically be made to determine metabolites, enzymes, coenzymes, or enzyme inhibitors, in situ, without special preparation of the sample. Widespread application can be predicted for such electrodes in both experimental and clinical medicine if they can be made to function specifically and accurately, and if they can be used for nondestructive, instantaneous, and continuous determinations in situ. Enzyme electrodes must not promote undesirable physiological responses, such as antigenic responses, thrombosis, or tissue reaction. In addition, they must be inexpensive, easy to operate, and have a long lifetime.

In this article we discuss the development of biochemical-specific electrode systems, present some of the foreseeable problems that might be associated with their use, and review the essential literature.

The basic functional concept of the "enzyme electrode" is the continuous, instantaneous, electrochemical monitoring of enzyme-catalyzed reactions, in which a substrate, coenzyme, or inhibitor is converted into a product by means of an enzyme. The relative concentration of the reactants can be varied so that analytical techniques are obtained in which the reaction rates or equilibrium concentrations are proportional to the limiting components. Electroactive species either produced or consumed by the reaction may be detected by commercial solute-specific electrodes, the signal thus produced being related to the limiting reactant. If a system can be designed such that the enzymes are immobilized or constrained to the immediate vicinity of the electrode—these enzymes being capable of continuous catalysis in complex physiological fluids—a new bio-

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