OVERVIEW OF THE FGGE OBSERVING SYSTEM

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1. HOW THE FGGE CAME ABOUT

Thanks to the pioneering work on numerical weather prediction by the von Neumann-Charney group in Princeton, in the wake of the development of the first electronic computers, and the subsequent development of general circulation models for numerical experimentation or for actual weather forecasting, it had become clear, already in the early 1960s, that the lack of adequate observations was the block which prevented taking full advantage of this powerful new technique and was hampering further progress in model development. Despite the ingenuity of atmospheric modellers, numerical prediction could not be better than the observations which went into the definition of the initial state of the atmospheric circulation. Such observations were scarce or altogether lacking over too many regions of the world.

On the other hand, the success of the first dedicated weather satellite TIROS-1 launched in 1960, only two and a half years after the orbiting of Sputnik-1, brought home the concept of global environmental observations from space. Admittedly, the first Television and Infra-Red Observation Satellites did not provide the growing community of numerical modellers with the pressure-temperature-wind data they wanted to initiate or to verify global atmospheric circulation predictions. The early TIROS spacecraft yielded only images depicting qualitatively the cloud patterns associated with weather systems and radiation flux measurements. Thus, they were mainly of interest to synoptic forecasters and the radiation science community. Nevertheless, the USA National Academy of Sciences had, as early as 1961, issued a report describing the prospects for developments in atmospheric sciences based on the exploitation of meteorological observations from space. On the basis of these scientific findings and at the initiative of the United Nations Committee on the Peaceful Uses of Outer Space, the UN General Assembly adopted the celebrated December 1962 Resolution on international cooperation for the development of meteorology and atmospheric sciences, recommending that: "WMO, in consultation with other UN agencies, governmental and non-governmental organizations (ICSU), develop plans for an expanded programme to strengthen meteorological services and research, placing particular emphasis on the use of meteorological satellites". Thus, the two major issues of this directive, the World Weather Watch and GARP, were from the very beginning, firmly based upon the application of space observations to meteorology and atmospheric sciences. These inspired views expressed by the United Nations did not, however, register too well with the practising numerical forecasters who disregarded space observations to a large extent, or rejected them outright, so that they would not "contaminate" the supposedly valid information provided by honest aerological measurements from surface stations and radio-sonde ascents.

In the meantime, many a committee, commission or working group kept reviewing the concept of global atmospheric investigations and the IUGG Committee on Atmospheric Sciences even proposed (in 1966) that 1972 be "designated a year for an intensive, international, observational study of the global circulation of the troposphere and lower stratosphere".

It also recommended that prior to 1972 "a large number of preliminary studies should be planned and completed". These and other deliberations finally climaxed in a very original, and at that time novel, planning and brainstorming exercise, the GARP Study Conference called by ICSU in Skepparholmen, Sweden (June 1967).

2. THE SPIRIT OF SKEPPARHOLMEN

Fifty-three "scientists" nominated by the ICSU/IUGG Committee on Atmospheric Sciences and "technologists" nominated by COSPAR spent two weeks discussing the status of modelling the general circulation of atmosphere, expressing the objectives which could be achieved by a global atmospheric research programme and reviewing the observational techniques (mainly remote sensing from space) which could be brought to bear on the problem. This was the first instance of a dialogue between the atmospheric modellers and the so-called technologists (many of whom were scientists in their own right, also deeply interested in using the data) who invented, designed and built instruments and observing systems. From this first encounter, it was clear that a serious difference of opinion existed between these two groups. In its pristine simplicity, the modellers' concept of the ideal observational system for GARP was an extension of the same synoptic upper-air sounding network, which existed over North America and Europe, to cover the whole earth and provide pressure-temperature-wind data with a uniform 500x500 km resolution in the horizontal plane and about 10 levels in the vertical direction. Indeed, this statement of global data requirements remains, to this day, the unattained, possibly unattainable, objective of global atmospheric observations (see GARP Publications Series No. 11 and WCRP Publications

Series No. 2). The practically-minded technologists argued, not unreasonably, that such an "ideal" observational network could never be brought into existence, seeing that it would require a large number of additional upper-air sounding stations, in excess of 1000, to augment the basic World Weather Watch network, and expensive stations for that matter, since most would be at sea or located in desolate places. They kept insisting on the promising results obtained by experimental, spaceborne instruments to infer the temperature profile in clear-air columns or estimate the horizontal wind velocity from the drift of clouds which could be seen from geostationary orbit. Obviously, each of these new schemes suffered from evident shortcomings; they compared rather poorly with the "ground truth" provided by existing radiosondes , they did not provide a synoptic view of the whole atmosphere at a single time and the data coverage had large and systematic gaps, especially where heavy clouds were present. For those reasons, the practice in operational meteorological analysis schemes was, actually, to reject (or drastically reduce the impact from) additional temperature and wind data provided by space observations whenever they did not conform to the a-priori first guess fields used by the particular numerical weather prediction unit. Note that first guess fields were based solely upon conventional observations and therefore heavily biased by the prediction model outside the northern hemisphere continental areas. Space observations were also rejected whenever they were obtained too far from synoptic map times 00 or 12 GMT, i.e., most of the time. This all was the cause for very lively discussions during the Skepparholmen Conference. As stated in a nutshell by a famous participant: "Don't tell me how to run my model and I won't tell you how to build your satellites". Yet, it was in everybody's mind that common ground for agreement had to be found, lest a great opportunity be missed to promote meteorology and atmospheric sciences to the level of other successful disciplines like nuclear physics. This is the reason of the sudden enthusiasm for the concept of automatic instrumented weather stations carried aloft by "constant-level balloons" drifting along a quasi-horizontal path with atmospheric winds and transmitting their data via a satellite communication link. One can see why the constant-level balloon idea appeared so appealing in the early planning phase of the FGGE. It satisfied the modellers by providing actual in-situ aerological observations including extremely precise wind measurements. This idea was also attractive from a practical implementation standpoint because it led to an intrinsically global observing system (constant-level ballons drift around the world) and was making efficient use of space techniques, thus being eligible for support by the (then) affluent space agencies. It was even said that Professor Charney's endorsement to the whole concept of a global atmospheric research programme was based upon the vision of a global observing scheme using thousands of constant-level ballons randomly distributed at all latitudes and altitudes. Thus it was that the fragile constant volume mylar balloons saved the day in the early beginning of GARP.

3. JOC AND COSPAR WORKING GROUP VI

The Joint Organizing Committee for GARP, established by WMO and ICSU according to the prescription of their Agreement on the Global Atmospheric Research Programme, met for the first time in April 1968 and recognized the fact that the ideas put forward by the space scientific community, united behind COSPAR Working Group VI, constituted a useful basis for planning a global observing system for GARP. On the bidding of

JOC, Working Group VI thus made "a critical appraisal of satellite observational facilities, including those recently developed, those in the planning stage and those conceivable in the future, giving emphasis to the consideration of possible satellite systems that could optimally yield the required observational coverage" (GARP Publications Series No. 2).

The colourful, but always constructive, exchanges of views between strong personalities on both the COSPAR Working Group and the JOC, led to very rapid conceptual advances towards designing the desired global observing system. It is instructive to note that the one fault with the first proposal made by the COSPAR Group was the omission of automatic drifting buoys which, eventually, became one of the major special observing systems in the FGGE and, conversely, placing excessive emphasis on constant-level balloons. Quite appropriately, the COSPAR proposal addressed only space-based observing systems including remote sensing instruments on various satellites and satellite-tracked instrumented platforms. Discounting an early attempt to programme a low-altitude equatorial orbiter into the system, it became an accepted viewpoint that adquate meteorological coverage of the global atmosphere would be provided by a system of two polar-orbiting satellites and four (more practically five) geostationary satellites evenly distributed around the earth. The spacecraft in medium altitude polar orbits were to provide temperature profiles with a global coverage, and to support the automatic instrumented platforms deployed in the atmosphere with tracking and data-collection services. The geostationary satellites were to provide continuous surveillance of weather systems and wind vector estimates within a wide zonal belt along the equator.

It was left to the JOC to determine the optimal combination of conventional observations (World Weather Watch), additional surface-based "special observing systems" and space observations which was to become the distinctive achievement of FGGE. Two major findings emerged from these early deliberations in 1968-69:

- the GARP global observing system required merging observations obtained by different techniques (either direct in-situ measurements or indirect inference from remote sensing data) with quite different errors and sampling characteristics.

- the reconstruction of the basic meteorological fields describing instantaneous states of the global atmosphere (as required by numerical weather prediction considered as an intial value problem) required merging non-simultaneous observations obtained at different times in different places along the track of the polar orbiting meteorological satellites.

The first point was certainly the most difficult to take and led to endless assessments of the discrepancies between new types of observations and established methods. This topic will be discussed by the next lecturer. It is fair to say that the issue was never fully resolved before or during the FGGE, but it was a big achievement of GARP to bring about the recognition that an optimal combination of both conventional and space-based observations was better than either kind separately.

With respect to the assimilation of non-synoptic data, it certainly came as a shock to the numerical weather forecasters that they had been practising four-dimensional analysis without knowing it, much like the classical character, in Molière's theatre play, was speaking in prose. Since the "memory" of the global atmospheric flow (and GCMs) exceeds the interval between successive map times, the "first guess" used in the analysis of a new batch of synoptic data is no guess at all, but the synthesis of information from previous data batches received and assimilated 12, 24, 36 hours or even longer before. In fact, this capability to carry forward the memory of past observations compensates for the large data gaps occurring in any single synoptic map. Nevertheless, the road which led to satisfactory schemes for merging data distributed in space and time was long and arduous. A good part of the pioneering work to solve this problem was in fact done by the "technologists", supported by space agencies, who arranged to conduct their own numerical experiments to show that non-simultaneous satellite data were just as unable as synoptic ground-based observations for the purpose of initializing a GCM forecast. The ECMWF made a historical contribution in being the first operational numerical weather prediction group which gave full attention to four-dimensional data assimilation.

4. TEMPERATURE SOUNDINGS FROM SPACE

The one instrumental advance which made global atmospheric research conceivable is due to the inspired American physicists and engineers who developed an observing method, pioneered by astronomers, based on analysing the spectrum of emitted (thermal) radiation emerging from the atmosphere in the vicinity of a strong absorption band of a well-mixed atmospheric constituent. The absorption band of CO_2 in the infrared or that of oxygen in the microwave region are usually selected for this purpose.

Now, it is well known that radiation coming from an external source (like the sun) and absorbed by the atmosphere, deposits its energy in an atmospheric column according to a bell-shape absorption profile. In the case of an isothermal atmosphere, this would be the classical Chapman profile, with a peak value at the altitude where the atmospheric optical depth is equal to 1 and with a vertical spread of about 2 scale-heights. Conversely, by virtue of the principle of detailed balancing of absorption and emission, the origins of photons which are emitted by atmospheric molecules and finally emerge from the atmosphere are distributed according to the same profile, also known as "weighting function". By providing several spectrometric channels at different wavelengths which are absorbed at (moderately) different rates by the atmospheric mix of molecules, one can select, by design, weighting functions spanning the vertical spread of the atmosphere. Obviously, such weighting functions overlap vertically to a substantial extent but one can, by a careful process of inversion, transform the monochromatic radiances of telluric radiation measured in space into estimates of the mean atmospheric temperature under each individual weighting function and thus infer the vertical temperature profile.

Needless to say, meteorologists are far more demanding than astronomers with respect to accuracy (who is going to measure ground-truth and show an astronomer to be wrong?). As a consequence, the actual implementation of this spectrum-inversion method to provide usable atmospheric temperature estimates, is fraught with difficulties of a mathematical, instrumental and meteorological nature. We shall not dwell on this topic which will be discussed more appropriately in the next talk. It suffices to say that the problems were progressively reduced to acceptable error limits in the course of a dogged effort of a whole community of physicists, mathematicians and meteorologists who worked in cooperation with space engineers to develop the TIROS operational vertical sounder instrument, carried on TIROS-N and later series of operational NOAA satellites (still used to this day) and to devise the data processing-inversion scheme for the retrieval of atmospheric information. This effort was successful in meeting the schedule of the FGGE, if not the formal GARP requirements for accuracy and spatial coverage.

5. WINDS FROM SATELLITE IMAGES

Many meteorologists were aware of the value of earth-synchronous satellites placed in a geostationary orbit, at an altitude of some 36,000 km above the earth's surface, to provide continuous surveillance of weather systems on the surface of the earth. However, Professor Vern Suomi of the University of Wisconsin, was the first to realise that the tremendous gyroscopic stability of a well-balanced spinning satellite in space offered the potential means to obtain nearly identical successive views of weather phenomena so that apparent cloud velocities could be determined by comparing one image with the next. The first opportunity to test this idea came with the Application Technology Satellite programme which included two large spinning spacecraft ATS-1 and ATS-3, designed for testing various electronic components and space communication equipments.

It was no small achievement of Professor Suomi that he obtained permission from NASA's management to introduce a small scanning telescope on-board these satellites, only a few months before launch of the first one. Time has passed since this pioneering age and project management procedures have now been perfected to the point that the repetition of such brilliant improvisation is forever impossible. As it happened, Professor Suomi's gadget, consisting of a small 6-inch aperture telescope on gimbals, a tilting mechanism and a photomultiplier, was mounted on the cylindrical structure of the spacecraft so as to scan the face of the earth once on each revolution around the north-south spinning axis. Because of the action of the tilting mechanism, different lines are scanned on successive revolutions so as to constitute, line-by-line, a full television image of the earth. A measure of the reproducibility of this process was given by the jitter in the positions of various fixed landmarks on successive images. This jitter did not exceed 1 km in general, i.e. an angular error of less than 5 arc-seconds.

Assuming that enough geostationary meteorological satellites could be provided to observe the tropical belt around the earth, assuming also that there will be enough clouds to be tracked but not so many as to obscure the field of view, and finally assuming that clouds move with the wind at some level of the atmosphere (to be determined), Professor Suomi's invention provided the basis of a space observing system for measuring the velocity field in the tropics, where wind is the most essential information and where conventional upper-air observations are especially scarce. It was apparent to JOC that a system of four (or five) imaging geostationary satellites distributed more or less evenly in longitudes was an essential component of the FGGE observing system. Major efforts were made, both in Japan and in Europe, to obtain resources for geostationary satellite development programmes which would, in due course, complement the two Geostationary Environmental Observation

Satellites (GOES) planned by the USA. It is to the credit of all participants in those projects that the geostationary satellites GMS and Meteosat were approved, funded, designed, built and launched in time to be fully operational during the Global Weather Experiment. Credit should also be given to the European Space Agency and NOAA for filling the remaining gap over the Indian Ocean, at less than one year's notice, by moving one spare US-GOES spacecraft to the equatorial location 70°East and relaying the data flow through a European station in Spain.

6. THE FATE OF THE CONSTANT-LEVEL BALLOONS

A new plastic film, commercialised under the trademark Mylar, was introduced in the fifties for various applications, like magnetic recording tapes or wrapping material. Mylar is in an intermediate physical state between plastic and glassy materials. Like plastic materials it can be folded - to some extent - without breaking. Like glass it is essentially inextensible. Thus, a balloon envelope made of mylar and containing a lifting gas like helium will progressively inflate to full capacity as it rises in the atmosphere, and then develop an internal overpressure. When taut, such inextensible balloon envelope usually assumes the shape of a sphere with a fixed predetermined volume. If everything goes well, the craft will thus float at a prescribed constant-density level in the atmosphere, until diffusion or leaks deprive the balloon of its lifting gas. Constant-level balloons are, however, sensitive to many atmospheric phenomena like destructive buffeting by vertical draughts or the accumulation of ice crystals which would bring them down to the ground.

The technique of launching and tracking such balloons was first mastered by a very ingenious American experimenter, Vincent Lally of NCAR, who demonstrated the first circumnavigation of the earth by a balloon floating at the 200 millibar level. Following Lally's lead, a French team prepared a much more ambitious project based on a global location and data-collection system provided by the experimental EOLE satellite. Intensive experimentation by both groups showed that very long ballon lifetimes (a pre-requisite for cost-effectiveness) were indeed feasible in the lower stratosphere but that constant-level balloons did not usually survive beyond a few days in the more active parts of the troposphere. Some degree of success was achieved by flying overpressure balloons under the cloud base in the tropical atmosphere and a sizable number of such low-altitude balloons (about 100) were launched from Indian Ocean islands during Summer MONEX in 1979. But by and large, the dream of a uniform sampling scheme based on a large number of instrumented platforms floating at all significant levels in the atmosphere, could not become true. Constant-level balloons are restricted to stratospheric altitudes above 200 mb in the extra-tropics or 150 mb in the tropics. Nevertheless, both the French and the American groups planned to deploy a large number of such balloons during FGGE, and provisions were made to embark the Argos location and data-collection system, designed and built by France, on the US polar meteorological satellite series starting with the TIROS-N prototype. The current operational Argos location and data-collection system is a legacy of this FGGE development.

A joint French-Iranian project, to repeat for FGGE the same balloon launching programme as had been achieved during the EOLE experiment did not materialise. On the other hand, the NCAR team, responsible for the deployment of the Tropical Constant-Level Balloon (TCLB) system, successfully released about 150 balloons during each of the two Special Observing Periods (SOPs) of the FGGE, from three sites near the equator, namely, Canton Island and Guam in the Pacific and Ascension Island in the Atlantic. About 50% of the active TCLBs remained within the critical equatorial band 10°N to 10°S while the other balloons strayed away from the equator, generally towards the southern hemisphere (by design, the TCLB were destroyed when they moved too far north). Typical numbers of active TCLBs were 40 to 60 during SOP-I and 60 to 90 during SOP-II, thus providing a substantial augmentation of the density of wind observations at the nominal flight level (150 mb) near the equator.

The absence of mid-latitude constant-level balloons was compensated by the deployment of a remarkably successful network of instrumented buoys covering most of the oceanic area south of 20°S latitude. The Southern Hemisphere Drifting Buoy System, consisting of more than 300 platforms, was provided by the cooperative effort of eight participating nations. The buoys themselves were fairly simple spars, floating freely on the sea surface, and used the Argos location and data-collection system like the constant-level balloons. They were, basically, simplified automatic weather stations giving accurate readings of atmospheric pressure and sea surface temperature. Since the six participating countries, which actually produced the buoys, had their own experience and technology, there were six different designs of buoy hulls, sensors and Argos beacons, but most of the FGGE buoys performed so well that 150 to 200 buoys were active and reporting their data on the GTS during the whole year. A measure of the success achieved in defining the "reference surface" at altitude zero is given by the fraction of the area of the southern oceans between 20°S and the Antarctic continent which was within 500 km of an active buoy reporting valid surface pressure readings. This fraction was near 80% throughout SOP-II.

Thus, the original concept of a large network of constant-level balloons mapping the atmospheric flow was not realized during the FGGE. The main basic scientific results, which could be deduced from the trajectories of such quasi-langrangian tracers, had already been obtained from the preliminary GHOST and EOLE programmes. However, the original concept led to the development of the successful Argos system which, in turn, made the Southern Hemisphere Buoys possible and still provides, to this day. one of the most cost-effective techniques for observing the upper-ocean and air-sea interface phenomena on the global scale.

7. THE GROUND-BASED SPECIAL OBSERVING SYSTEMS

Long before these exciting new developments were completed, it was clear that the combined meteoreological satellite system and conventional ground-based observation network would not fulfil the space and time sampling requirements set forth by the founding fathers of GARP. At the bidding of JOC, the atmospheric circulation modelling groups were asked to investigate quantitatively the capability of CGMs for reconstructing without excessive errors, the global atmospheric mass and velocity fields from various sets of incomplete observations. The more-or-less universal outcome of these "Observing Systems Simulation Experiments" was that proper observations of the mass field (surface pressure and atmospheric temperature) were enough to reconstruct the wind velocity field, except in a fairly narrow band, 10°N to 10°S, around the equator. In that narrow equatorial band, however, the vertical structure of the wind field, simulated by the most comprehensive and highest resolution GCMs, could not be reconstructed from wind observations at one or two levels only, as was expected from cloud motions, tropical constant-level balloons and aircraft in-flight reports. However essential these systems were to provide a dense horizontal coverage in the lower and upper troposphere, continuous vertical soundings were still necessary near the equator according to the findings of numerical experimentation groups.

At this point, the only possible solution was to obtain additional resources to implement upper-air soundings from ship platforms or temporary island stations near the equator during the FGGE year, or failing that, during the two Special Observing Periods when intensive activities were planned. Tribute should be paid to the many Meteorological Services of the WMO Member-countries which united their efforts in the deployment of the Tropical Wind Observing Ships. A fleet of 38 ships, ranging from fully instrumented meteorological vessels to chartered boats carrying the newly developed Omega-Navaid balloon tracking system, participated during SOP-I, providing about 60 strategically located wind soundings per day. This performance was repeated during SOP-II with a total of 41 participating vessels.

In the meantime, US aircraft, flying daily meteorological reconnaissance flights from four locations in the tropics, launched a total of 70 to 80 dropwindsondes per day. Together with the 125 soundings provided daily by the operational World Weather Watch network within the latitude band

$10^\circ N$ to $10^\circ S$, these additional observations boosted the observational density to the remarkable figure of approximately 250 wind profiles per day within a 80×10^6 km^2 area, equivalent to a spatial resolution of roughly one sounding in each 600x600 km box.

8. IN LIEU OF CONCLUSION

Even though it is now five years since the completion of the experiment, the final FGGE quality-controlled data set is not yet fully available to the research community. Naturally, many investigations have already been conducted using interim data files. It is still early to assess the impact of this vast enterprise on the progress of meteorology, numerical weather forecasting and atmospheric sciences in general. It is hoped that this seminar, together with several other such working conferences organized during the autumn of 1984 and the the WMO/ICSU Conference on the Results of the Global Weather Experiments, planned to be held in Geneva next year, will give us material for a first assessment of the scientific impact of the FGGE. In any case, I feel that the FGGE with its failures and successes, was an immensely worthy enterprise of which those who participated in its planning or its implementation can be proud.

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