Joint Global Ocean Flux Study: The 1989 North Atlantic Bloom Experiment

By Hugh W. Ducklow

In 1989, JGOFS begins a six-nation, eight month investigation of biogeochemical processes in the North Atlantic Ocean.

For the past two years, oceanographers in North America and Europe have been preparing a new study of a familiar oceanographic process: the spring phytoplankton bloom. Study of the bloom will be coordinated through the Joint Global Ocean Flux Study (JGOFS), whose principal objective is to understand on a global scale the processes controlling the fluxes of carbon and other biogenic elements in the ocean. In 1989, JGOFS begins a six-nation, eight month investigation of biogeochemical processes in the North Atlantic Ocean. This experiment will emphasize observation of the spring phytoplankton bloom and its biogeochemical consequences along longitude 20°W, between 15° and 60°N latitude, from March to October. The North Atlantic Bloom Experiment is intended to be a pilot study for future JGOFS experiments, but its origins go back exactly a century, to the studies of the German oceanographer Victor Hensen.

Hensen first applied the term 'plankton' to the small plants and animals that lack sufficient locomotory ability to move against ocean currents. He also introduced quantitative sampling of planktonic organisms into oceanography (Hensen, 1887). His Plankton Expedition (Fig. 1, p. 5) first showed that plankton abundance in the surface ocean is greatest at temperate and subarctic latitudes, in dramatic contrast to terrestrial vegetation (Krümmel, 1892). The results of Hensen's cruise fueled a controversy which dominated German biological oceanography for twenty years (see sidebar). Present day German oceanographers under the direction of Berndt Zeitzschel are commemorating the Hensen expedition with a series of cruises in spring 1989 aboard the new *Meteor*. This centennial expedition provided the impetus for planning the JGOFS Pilot Study.

The Bloom Cycle

Spring blooms are characterized by rapid increases in phytoplankton populations in lakes and large areas of the coastal and open sea. In some regions chlorophyll concentrations may increase from less than 1 to over 20 micrograms per liter in ca. 10 days anywhere between February and May. At least in shelf waters, the spring bloom period accounts for about half the annual primary production, and possibly a greater fraction of the new production the primary production fueled by NO_3 and available for export (Walsh, 1988). The timing and amplitude of the spring "outburst" depend on winter mixed layer depths, surface nutrient levels, and the annual cycles of light and temperature, all of which vary with latitude. At Bermuda, where we have a good record of phytoplankton stocks and production, the bloom occurs in February-March and reaches about 0.5 μg Chl l^{-1} (Menzel and Ryther, 1960). At Ocean Weather Station India (59°N, 19°W), the bloom is in May and exceeds 2.5 μg Chl l^{-1}. Blooms in coastal and shelf waters commonly exceed 10 μg Chl l^{-1} (Walsh, 1988). Colebrook (1979) and colleagues have synthesized data from the Continuous Plankton Recorder (CPR) Survey, providing a valuable, truly basin-scale view of spatial and temporal variability of plankton cycles across the North Atlantic. Except for the CPR Survey, which documents only large-celled diatoms and dinoflagellates and zooplankton greater than 270 μm, our observations of spring blooms and other seasonal phenomena in the plankton are limited to a few oceanic sites and a larger collection of coastal observations. More oceanic data are needed for the wider range of properties we can now measure routinely.

Why do blooms occur? Gran and Braarud (1935) stated that net growth of phytoplankton could only begin after cells were no longer mixed below the depth at which their respiration was balanced by photosynthesis. The modern quantitative theory of bloom development goes back to Sverdrup's (1953) mathematical formulation of the theory of critical depth, which built on Gran's ideas. Deep mixed layers in spring provide ideal conditions for light limitation of phytoplankton growth. Biomass, nutrients and temperature as well as respiration and other loss processes (grazing, sinking and exudation) are at least hypothetically constant through the mixed water column in early spring, while photosynthesis is proportional to light intensity and therefore decreases exponentially with depth. It follows that there is some critical depth at which the average light intensity experienced by mixing phytoplankton cells is just sufficient to balance the integrated removal processes. As the solar elevation rises in spring, the

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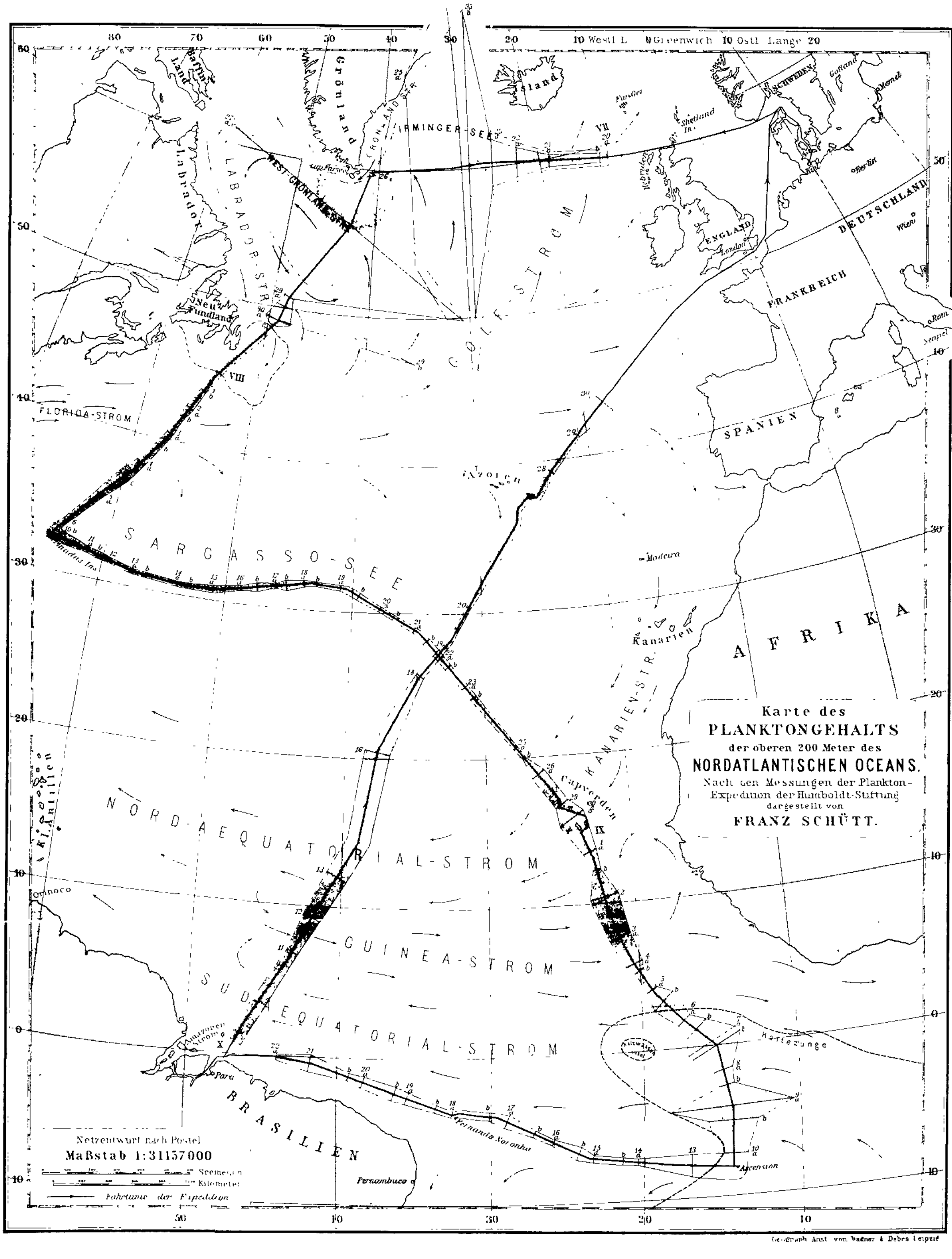

It has seldom been determined unequivocally whether grazing, sinking or nutrient limitation was responsible for the decline of a given bloom.

***Fig. 1:** The route of Victor Hensen's Plankton Expedition in the Atlantic Ocean in 1889 (Krümmel, 1892). The width of the shaded region along the track is proportional to plankton abundance in the surface layer as collected with the first quantitative plankton net, which Hensen developed. He also invented the term plankton. The main JGOFS stations will be located at 33°, 47° and 60°N along 20°W. (Map courtesy Berndt Zeitzschel, Institut für Meereskunde-Kiel, Federal Republic of Germany).*

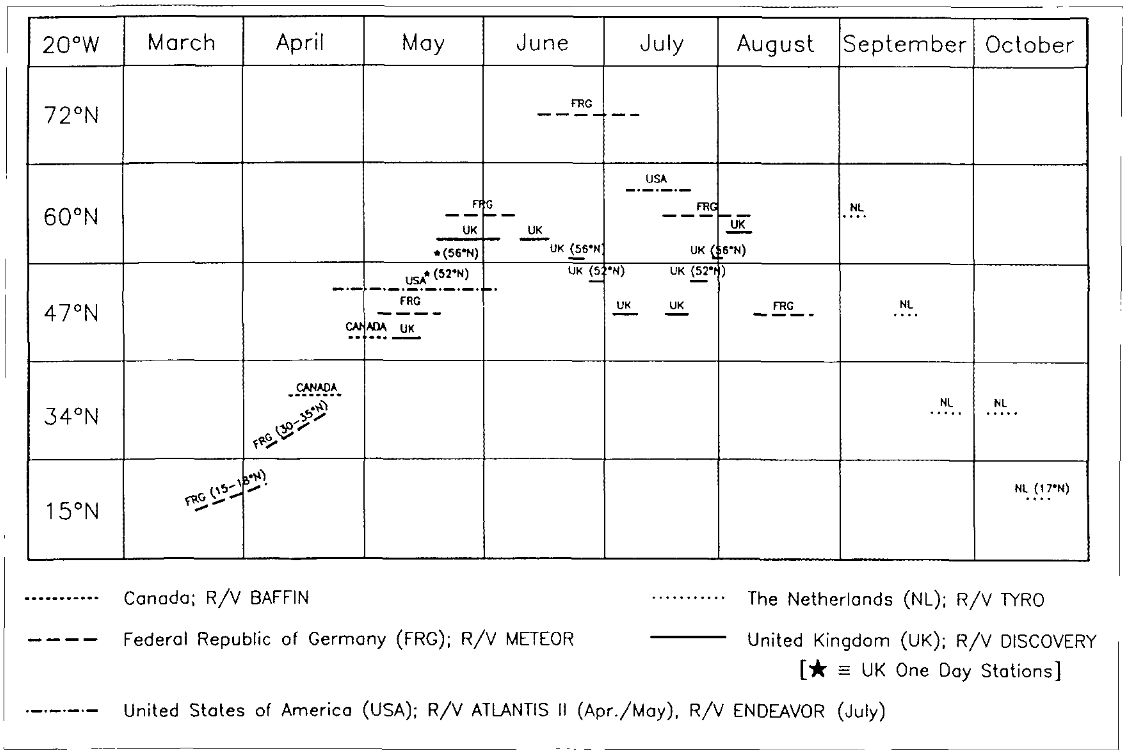

Fig. 2: *Schedule of research cruises in the 1989 JGOFS North Atlantic Bloom Study. Cruises and overflights will begin in March and continue through September, 1989, concentrating on biogeochemical processes at 33°, 47° and 60°N latitude along 20°W. (Chart courtesy of Steve Piotrowicz, NOAA-AOML, Miami, FL).*

Models of particle composition further point to the role of events like blooms as important sources of biogenic carbon in the deep sea.

critical depth at any given location will descend and the mixed layer will shoal. In some areas, depending on the depth of winter mixing and the size of the overwintering zooplankton stock, the bloom will be triggered by stratification and the rise of the mixed layer. In others, the descent of the critical depth below the mixed layer will cause the onset of a bloom (Colebrook, 1979).

Phytoplankton dynamics was thus intimately wedded to the physics of the upper ocean. Besides Gran's observations in the Bay of Fundy and Sverdrup's in the Norwegian Sea, critical depth theory has been used to examine bloom phenomena in the North Atlantic, including warm core rings (Bishop *et al.*, 1986) and the subarctic Pacific, a region where the bloom is manifested as increased production without an increase in biomass (cf. Evans and Parslow, 1985). Yet while critical depth theory explains the timing and distribution of blooms reasonably well, especially in marginal seas, it has never been rigorously tested in the open ocean through coordinated measurements of optics, loss rates and other parameters.

Data on the space and time scales characteristic of phytoplankton blooms are scarce. It appears that blooms last ca. 10 days in upwelling and coastal areas and perhaps for weeks or months in some oceanic regions. Perhaps because of the simplified nature of the ocean in late winter compared to its physical and biological state in late spring or early summer, the factors governing the decline of phytoplankton blooms have proved to be much more difficult to understand than the initial stages. Phytoplankton blooms signal the recovery of plankton ecosystems in temperate latitudes from the winter period of minimal biological activity. In most regions characterized by a deep mixing cycle, populations of grazers and bacteria are low in late winter, and nutrients levels are high. Thus blooms occur not only because phytoplankton are released from light limitation as the critical depth intersects the pycnocline, but because losses to herbivores are low (Evans and Parslow, 1985). But grazers respond to increased supplies of food and rising temperatures, narrowing the gap between production and consumption. At the same time, primary production consumes the nitrate stock in the mixed layer leading to nutrient limitation and slowing growth rates. Nutrient limitation may also increase sinking rates for diatoms (Smayda, 1970; Smetacek, 1985). At some stage in the evolution of these processes, losses surpass production and the phytoplankton stock declines.

These factors are well known, but their interaction and relative importance are not. It has seldom been determined unequivocally whether grazing, sinking or nutrient limitation was responsible for the decline of a given bloom, or if any one of these factors routinely supercedes the others in a given location. For example, Radach (1984) was unable to state with certainty whether the bloom in the North Sea, studied ambitiously during the Fladenground Experiment (FLEX '76), declined because of increased grazing, sinking or nutrient limitation. Recent developments in ocean optics, sediment traps, trace-metal-free measurements of primary production, high sensitivity analyses of respiration, nutrient uptake, grazing, pigments, CO_2 and dissolved organic content (DOC), as well as powerful new modeling capabilities, have poised the oceanographic community for a new attack on these bloom problems.

Bloom Consequences and Significance in the Global Carbon Cycle

A series of important new observations, technological innovations and modeling results form the scientific justification for a new, ambitious study of the spring bloom phenomenon. One aspect of the JGOFS program is a quantitative evaluation of the "biological pump" of carbon dioxide on a basin-to-global scale. This term refers to the coupled processes of biological fixation and transformation of CO_2 in the upper ocean and the enrichment of CO_2 in the deep sea through decomposition of biogenic carbon formed in the surface: biological processes "pump" carbon from the atmosphere to depth. The present oceanic uptake is estimated to be 2.5 billion tons per year—the same as the current atmospheric increase (Moore and Bolin, 1986). Some of the details of the pump components have been worked out over the past decade, and they highlight the importance of the seasonal repetition of blooms in the global carbon cycle.

An early scientific stimulus for a basin-scale bloom study came from studies of the vertical flux and deposition of particulate matter in the deep ocean. Time series deployments of deep (3000m) sediment traps at Bermuda (Deuser, 1986) and elsewhere have shown clearly that there is a seasonal cycle of particle flux exemplified by a springtime maximum following the surface bloom. Observations from benthic camera systems show the sudden arrival of large (10-50 mm) aggregates of phytodetritus during late spring and early summer (Billett *et al.*, 1983). This "fluff" appears to consist mainly of diatoms rather than fecal pellets, suggesting that the primary loss mechanism linking the decline of the bloom to the vertical flux at depth is sinking hastened by nutrient depletion. Models of particle composition further point to the role of events like blooms as important sources of biogenic carbon in the deep sea (Watson and Whitfield, 1985). The overall implication of these observations is that seasonal phytoplankton blooms are important mechanisms for the fixation of atmospheric CO_2 and its transportation to depth. Blooms are a key component of the biological pump. The biogeochemical consequences of grazing versus sinking losses might be significantly different, and determining the relative importance of these major pathways requires further study.

The most dramatic evidence for the widespread occurrence and importance of the spring bloom is the archived imagery collected by the Coastal Zone Color Scanner (CZCS), which flew on *Nimbus-7* during 1979-86. CZCS imagery has already proved to be a powerful tool for studying the spring bloom (Brown *et al.*, 1985). The North Atlantic spring bloom is seen as one of the dominant seasonal signals in the global ocean (See front and back covers). In monthly composite CZCS images, the North Atlantic bloom is first seen off the southeastern US in February and evolves in a northeasterly direction, reaching the east basin by April. The conspicuous influence of the Gulf Stream and North Atlantic Current System in time and space was not anticipated but is currently stirring exciting debate. The most important early conclusion from the CZCS effort and the models is that the bloom is a basin-scale phenomenon that requires long-term international collaboration to clarify the issues discussed here.

The JGOFS North Atlantic Bloom Experiment unites oceanographers from Canada, Great Britain, the Netherlands, Federal Republic of Germany, and the US (Fig. 2). French scientists will begin a complementary study of foodweb dynamics and carbon fluxes in oligotrophic, mesotrophic and eutrophic waters off West Africa at the same time. The experiment includes deep sediment trap deployments at 33°, 47° and 60° N on 20° W longitude, an aircraft-borne remote sensing program, and a wide variety of individual and group scientific components on six different research vessels. These latter projects will provide in many cases new state-of-the-art measurements of biomass, nutrients, particulates, optics, radionuclides, trace metals, CO_2 and oxygen, dissolved organic carbon and nitrogen, and an array of rate measurements, including primary and bacterial production, grazing, nutrient cycling and respiration. An allied US program, the Marine Light-Mixed Layer experiment, will begin near the Ocean Weather Station (OWS) India site with a deployment of moored upper ocean sensors in April. The U.K. BOFS (Biogeochemical Ocean Flux Study), and Dutch and German programs will continue in 1990.

These ambitious "pilot" experiments are designed to set the stage for more fully basin scale JGOFS studies now being planned for the next decade. The advent of basin scale studies of the biogeochemical state of the ocean await collaboration with the World Ocean Circulation Experiment (WOCE), the International Geosphere-Biosphere Program (IGBP), and especially the successful orbiting of the next ocean color instrument (SeaWiFS) in 1991.

The conspicuous influence of the Gulf Stream and North Atlantic Current System in time and space was not anticipated.

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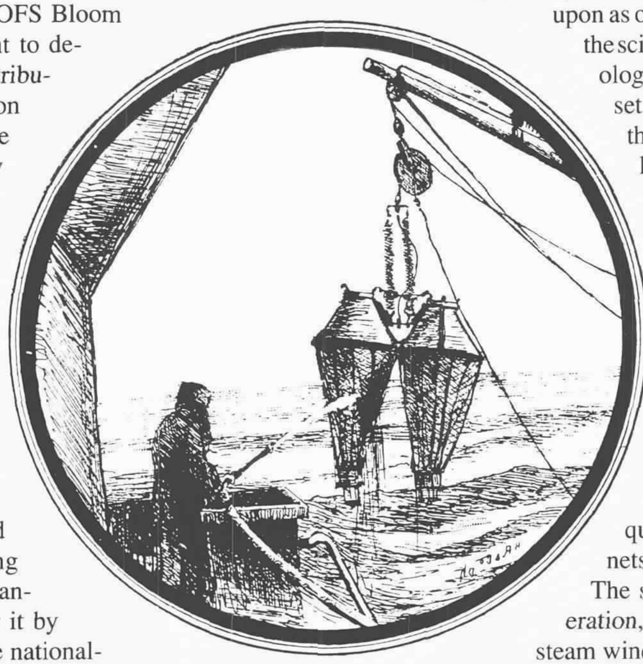
Victor Hensen's Plankton Expedition

Before Victor Hensen sailed on the new steamer *National* on July 15, 1889, from Kiel, German oceanographers had never been more than 100 miles from land. His "Plankton Expedition" had much in common with today's major oceanographic expeditions, including the JGOFS Bloom Study. It sought to determine the distribution of plankton organisms in the open sea away from coastal and terrestrial influence, a subject rekindled by modern satellite observations and concerns about climate change and pollution. Hensen justified his undertaking and sought financial support for it by appealing to the nationalistic sentiments of Kaiser Friedrich III, citing previous deep-sea observations undertaken by the USA, France, Sweden, Italy and notably Britain on the HMS *Challenger*. The JGOFS study has been motivated less by nationalistic pride than by a recognition that international collaboration is required to address global problems, but national goals and concerns are as important in the international scientific arena today as they were a century ago. Like many modern oceanographers, Hensen believed he was grossly underfunded.



Hensen was a leader of German oceanography, and "...will always be looked upon as one of the founders of the science of marine physiology" (Gran, 1912). He set out to prove something he already believed deeply: that plankton were distributed uniformly in the sea, except when disrupted by physical processes. The *National* was 58 meters long, weighed 858 tons, and was equipped by Hensen with large quantitative plankton nets of his own design. The ship also had refrigeration, electric lights and steam winches. They occupied 278 stations (see Fig. 1 of the accompanying article) before returning in November with samples from 126 vertical plankton hauls from the upper ocean. Analyses of the samples and the problems arising from his defense of his ideas against Ernst Haeckel occupied Hensen and his colleagues, notably Karl Brant, Hans Lohmann, and Carl Apstein, for many years.

Note

This account is taken from the forthcoming history of biological oceanography in *This Blood of the Sea*, by Eric Mills of Dalhousie University. His book contains a long discussion of the controversy between Hensen and Haeckel. I am indebted to Mills and to Berndt Zeitzschel for providing information and illustrations about Hensen and the Plankton Expedition.

— Hugh Ducklow

Drawing

From report by Krümmel, 1892.

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By-Laws

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4. A quorum for the transaction of business at an Annual Meeting shall be at least two percent of the members present who are eligible to vote on May 1 of that year. The affirmative vote of a majority of the members present who are eligible to vote shall be required for the resolution of any question.

The Council may make other rules for meetings not inconsistent with the Articles of Incorporation or Bylaws. Business not set forth in the notice of the meeting shall not be transacted if three members eligible to vote object.

5 The Society may organize, sponsor, or co-sponsor such additional local, national, or international meetings as may be authorized by the Council.

6 The fiscal year of the Society shall conform to the calendar year.

ARTICLE XII. *Publications.*

The Society shall issue an official publication and such additional journals, papers, books and the like as may be authorized by the Council.

ARTICLE XIII. *Amendments to the Bylaws.*

1. No part of the Bylaws shall be amended or annulled except by mail ballot in the following manner: A proposed amendment shall be approved by the Council or submitted to the President in a petition signed by at least five percent of the members eligible to vote on the preceding May 1 The proposed amendment, with the reasons therefore, shall be published in the official publication of the Society at least ninety days before ballots for the amendment are mailed.

2. A proposed amendment, accompanied by a ballot, shall be mailed by the Executive Officer to each member eligible to vote at least sixty days prior to the designated date the ballots are to be counted. The ballots to be counted must be received by the Executive Officer on or before the designated date for counting the ballots.

3. The adoption of a proposed amendment shall require the affirmative votes of at least two-thirds of all members voting. ❑

Assimilation of Observations

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before the symposium starts. The extended abstracts of the papers (up to six pages) prepared according to the instructions to be distributed later should be submitted no later than December 15, 1989, to: The Secretary-General of WMO; Attention PTR; World Meteorological Organization; 41, av. Giuseppe-Motta; Case postale No 5; CH-1211 Geneva 20; with a copy sent to the chairman of the IPC: Dr. O. Talagrand; Laboratoire de Météorologie Dynamique; Ecole Normale Supérieure ; 24, rue Lhomond; F-75231 Paris Cedex 05.

Participants will be notified of the acceptance of their papers by the IPC before March 1, 1990. For further information concerning the symposium, please refer to the above mentioned two addresses. ❑

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