The Fronts and Atlantic Storm-Track Experiment (FASTEX): Scientific Objectives and Experimental Design

Alain Joly,[a] Dave Jorgensen,[b] Melvyn A. Shapiro,[c] Alan Thorpe,[d] Pierre Bessemoulin,[a] Keith A. Browning,[e] Jean-Pierre Cammas,[f] Jean-Pierre Chalon,[a] Sidney A. Clough,[g] Kerry A. Emanuel,[h] Laurence Eymard,[i] Robert Gall,[j] Peter H. Hildebrand,[j] Rolf H. Langland,[k] Yvon Lemaître,[i] Peter Lynch,[l] James A. Moore,[m] P. Ola G. Persson,[n] Chris Snyder,[j] and Roger M. Wakimoto[o]

ABSTRACT

The Fronts and Atlantic Storm-Track Experiment (FASTEX) will address the life cycle of cyclones evolving over the North Atlantic Ocean in January and February 1997. The objectives of FASTEX are to improve the forecasts of end-of-storm-track cyclogenesis (primarily in the eastern Atlantic but with applicability to the Pacific) in the range 24 to 72 h, to enable the testing of theoretical ideas on cyclone formation and development, and to document the vertical and the mesoscale structure of cloud systems in mature cyclones and their relation to the dynamics. The observing system includes ships that will remain in the vicinity of the main baroclinic zone in the central Atlantic Ocean, jet aircraft that will fly and drop sondes off the east coast of North America or over the central Atlantic Ocean, turboprop aircraft that will survey mature cyclones off Ireland with dropsondes, and airborne Doppler radars, including ASTRAIA/ELDORA. Radiosounding frequency around the North Atlantic basin will be increased, as well as the number of drifting buoys. These facilities will be activated during multiple-day intensive observing periods in order to observe the same meteorological systems at several stages of their life cycle. A central archive will be developed in quasi-real time in Toulouse, France, thus allowing data to be made widely available to the scientific community.

1. Background

The theoretical and observational study of cyclogenesis has experienced a remarkable renewal of interest owing to the simultaneous emergence of new theoretical problems and new approaches to diagnose this phenomenon. The result is a significant change of perspective in cyclone conceptualization. It suggests, in turn, new approaches to observation and prediction of cyclones.

The new problems stem from the studies of cyclogenesis on the 1000-km scale. This scale of motion is the only one explicitly mentioned in the founding paper on the life cycles of cyclones by Bjerknes and

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[a] Météo-France, Toulouse, France.
[b] NOAA/ERL, National Severe Storms Laboratory, Boulder, Colorado.
[c] NOAA/ERL, Environmental Technology Laboratory, Boulder, Colorado.
[d] University of Reading, Reading, United Kingdom.
[e] Joint Centre for Mesoscale Meteorology, University of Reading, Reading, United Kingdom.
[f] Laboratoire d'Aérologie, Toulouse, France.
[g] United Kingdom Meteorological Office, Bracknell, United Kingdom.
[h] Massachusetts Institute of Technology, Cambridge, Massachusetts.
[i] Centre d'étude des Environnements Terrestre et Planétaires, Velizy, France.
[j] National Center for Atmospheric Research, Boulder, Colorado.
[k] Naval Research Laboratory, Monterey, California.
[l] Met Éireann, Dublin, Ireland.
[m] University Corporation for Atmospheric Research, Boulder, Colorado.
[n] NOAA Environment Technology Laboratory, Boulder, Colorado.
[o] CIRES/University of California, Los Angeles, Los Angeles, California.
Corresponding author address: Dr. Alain Joly, Météo-France, CNRM/GMME, 42, av. G. Coriolis, 31057 Toulouse cedex, France.
E-mail: alain.joly@meteo.fr
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Solberg (1922). This work related cyclones to previously existing fronts. The semigeostrophic theory of frontogenesis (Sawyer 1956; Eliassen 1962; Hoskins and Bretherton 1972) provides a simple but realistic description of atmospheric fronts. It may be worth recalling for reference that fronts combine rapid changes in temperature with vorticity maxima primarily localized near the vertical boundaries of the troposphere. Returning to 1000-km-scale cyclogenesis, the first idea was to provide an instability theory of frontal cyclogenesis in the same spirit as Charney (1947) and Eady (1949) did for the larger-scale cyclogenesis in jet flows. The fronts offer greater organization of the wind field than the simple baroclinic zone. This can lead to a new set of conditions under which normal mode instability can occur along a front. For example, remaining in the context of semigeostrophic theory see Schär and Davies (1990) or Joly and Thorpe (1990). The latter provides a review of a number of other approaches in a variety of dynamical frameworks. Malardel et al. (1993), however, point out that, on its own, the additional conversion mechanism that a frontal environment provides (downscale kinetic energy transfer due to the presence of wind shear) leads to active but short-lived systems with very little pressure deepening, in contrast to "bombs."

The new theoretical approaches result from the long-lasting questioning of the relevance of the normal mode stability analysis as a theoretical explanation of cyclogenesis. This question, together with the alternative approach of the development of already existing structures, had been voiced originally by Sutcliffe (1947), Kleinschmidt (1950), and Petterssen (1955); for a historical review, see Grønås and Shapiro (1997). Farrell (1985, 1989) provided the theoretical support to these views, applied originally to the explosive growth of large-scale waves in the context of quasigeostrophic dynamics. The general idea is that the same physical mechanisms present in the normal modes can be triggered much more efficiently by initial conditions involving organized precursors. The framework proposed by Farrell (1988) also addresses some of the difficulties noticed in the new work on frontal stability. For example, the timescale of frontogenesis is not different from that of frontal cyclogenesis, so the two mechanisms cannot be separated as neatly as the normal analysis requires. In the same spirit, it appears that time-dependent basic flows, not amenable to normal mode analysis in the strict sense [in spite of attempts such as Joly and Thorpe (1991)], can lead to new mechanisms for the development—or the absence of development—of cyclonelike features.

The combination of these new problems and approaches has led to new theoretical interpretations of cyclogenesis. Thorncroft and Hoskins (1990) illustrated the nonlinear development of a cyclone along the cold front of a baroclinic wave initiated by an upper-level (tropopause) feature. This upper anomaly overcomes the stabilizing effect of frontogenesis shown by Bishop and Thorpe (1994a,b). Bishop and Thorpe studied the effect of stretching deformation on moist frontal cyclogenesis. The effectiveness of the deformation to hinder cyclone formation is shown quantitatively. Bishop (1993) also explored the influence of deformation on the growth of a baroclinic wave. Joly (1995) generalized the results of Malardel et al. (1993) on the finite amplitude growth to a variety of initial conditions as well as to transient development: the baroclinic interaction appears to be the only mechanism that allows deepening greater than 10 mb. This does not imply that the nonbaroclinic systems are weak during their short life cycle: just the reverse, it shows that looking only at the pressure field can be misleading. It appears that a whole new set of ideas and hypotheses are now available for testing against observations. The meteorological subjects of interest are not the explosive large-scale waves but a wider spectrum of more or less modest cyclones, which form along preexisting fronts trailing behind large low pressure zones. These cyclones strongly depend on many properties of their environment: the baroclinicity; the presence of low-level frontal jets and frontogenetic forcing; and the existence of transient, organized features, for example, potential vorticity (PV) features. Figure 1 shows a recent example of the type of event of interest.

2. Why FASTEX?

The ultimate objective, numerical forecast of these frontal or more generally, these "end-of-storm-track" cyclones, remains a serious practical problem, in spite of the continuous progress in numerical weather prediction. This was noted in the report by the French forecasters Beugin and Rochard (1991) describing the numerous difficult cases of storm landfall seen during the winter of 1989–90, in spite of a new generation of forecast models. This is illustrated by Fig. 2 showing successive forecasts of the 1996 storm of Fig. 1 from the European Centre for Medium-Range

Weather Forecasts (ECMWF) operational suite. Although the general cyclone characteristics are well predicted, an accurate forecast of precipitation over Ireland and of the wind over the English Channel varied with every new forecast, leading to little confidence in quantitative forecasts of these and other parameters. Clearly, however, the problem is not simply the ability of these models to represent cyclones properly, as some of the forecasts for a given event are excellent. This situation calls for a different approach, something else than, for example, trying to improve parameterizations. The problem is indeed related to the sensitivity of these developments to initial conditions. Incidentally, the change of perspective advocated by Farrell in the theoretical understanding of cyclogenesis directly leads to expect such a problem with cyclone forecasting (Farrell 1990). The richness of possible mechanisms makes the difficulty even larger than with the pure baroclinic development problem.

Beside the need to evaluate the new theoretical ideas of cyclogenesis, there is also a demand for improved, validated, conceptual models of cyclogenesis, including improvements to physical process parameterizations, which can help the assessments of real forecasts. There is a real need to explore technologies to provide, with a given model, a series of consistent successive forecasts in the range of 24–96 h, or at least to know whether this is conceivable. These requirements motivated the design of the Fronts and Atlantic Storm-Track Experiment (FASTEX).

Further motivations for FASTEX are requirements for improved understanding of the organization of clouds and their resulting impact on radiative balance, the current interest in the mesoscale structure embedded within cyclones, and other topics developed in section 4 below. The continuing improvements in observational technology also gives impetus to new measurements of cyclone structure and air motions. These are the areas where better understanding and better observations will be translated into validation and improvements of parameterizations, especially through the handling of cloud processes and air–sea interactions.

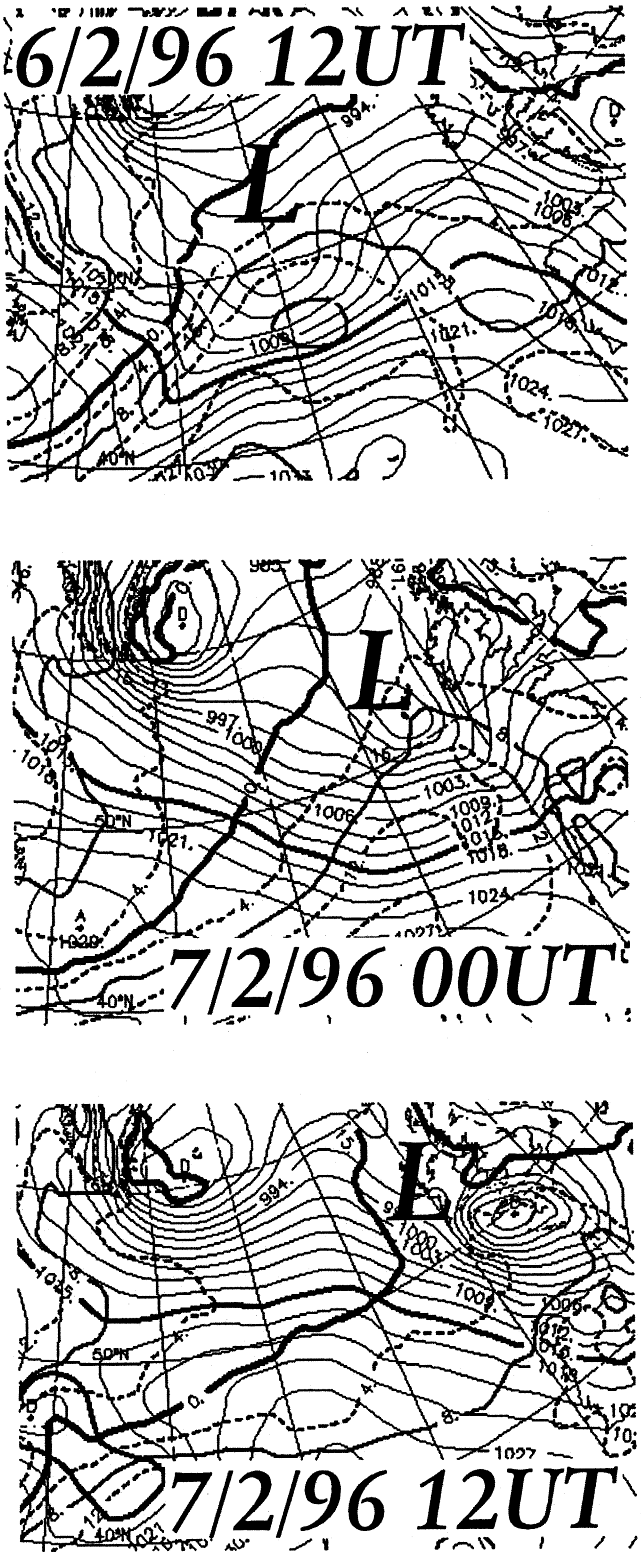

FIG. 1. An example of cyclone life cycle of interest to FASTEX. Within 24 h, the cyclone forms in the middle of the ocean as an open wave and hits the west coast with gale force winds. The cyclone is indicated by the large black L. The maps are a series of analyses from the Météo-France data assimilation system Arpège. Thin solid lines are surface pressure, contour interval 3 mb, except the 1015-mb reference contour, which is a heavy solid line. Other heavy lines, alternatively solid and dotted, are 925-mb wet bulb potential temperature.

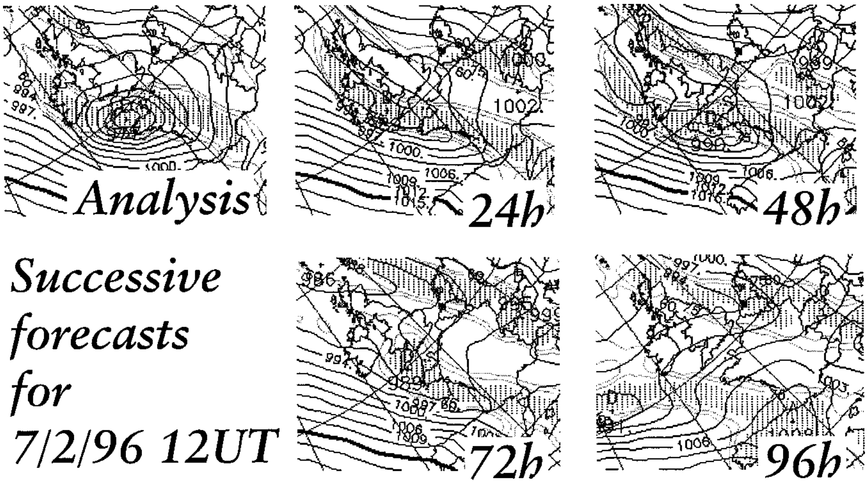

FIG. 2. A series of forecasts for 2 February 1996 1200 UTC, the same cyclone as in Fig. 1, together with the verifying analysis, taken from the ECMWF operational dissemination. Contours: mean sea level pressure every 3 mb. Shaded areas: 700-mb relative humidity larger than 80%.

The design of FASTEX benefited from two previous sets of field studies that were focused on cyclogenesis and frontal dynamics. The first was a series of field experiments conducted along the east coast of North America in the 1980s: the Genesis of Atlantic Lows Experiment (GALE; Dirks et al. 1988), the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA; Hadlock and Kreitzberg 1988), and the two successive field phases of the Canadian Atlantic Storms Program (CASP; Stewart et al. 1987; Stewart 1991). These experiments provided an understanding of the process of rapid or even explosive cyclogenesis taking place along the western boundaries of oceanic basins, a category of cyclones that is not the focus of FASTEX. The second series of field campaigns was European: the FRONTS-87 project (Clough and Testud 1988), organized by the United Kingdom and France to collect data to validate the semigeostrophic theory of frontogenesis and study frontal precipitation (see, e.g., Lagouvardos et al. 1993). More recently, the United Kingdom conducted the FRONTS-92 project (Browning et al. 1995) that extended the previous FRONTS work and laid the ground work for FASTEX.

The first outline of the main objectives of FASTEX and its proposed observing systems was prepared by Joly and Lalaurette (1991). They stressed the need to concentrate on life cycles rather than the mature stage and on weakly or moderately deepening systems. Shortly thereafter, because of strong links with long-term coooperation on theoretical work with the United Kingdom and with FRONTS 92, FASTEX became a French and U.K. initiative. The preparatory work begun in 1993, after plans describing the preliminary project design had been reviewed by a panel that included a number of U.S. scientists. The first meeting of the Core Steering Group, including several U.S. representatives, took place in Toulouse, France, in 1993. U.S. agency participation was formulated at the first meeting of the Scientific Steering Group under the chairmanship of A. Thorpe in Silver Spring, Maryland, in March 1995. An outgrowth of this meeting was the addition of several key additional scientific objectives related to the testing of adaptive observation strategies (see section 4b below) as a practical methodology of providing forecast improvements. Following inquires to Canada and a number of European countries, FASTEX soon became a large, joint project strongly supported by both American and European scientists and research and operational agencies, with regular planning meetings and production of documents, most notably the FASTEX Science Plan (Thorpe and Shapiro 1995), the FASTEX Operations Overview (Jorgensen and Joly 1995), and the FASTEX Operations Plan (Jorgensen et al. 1996a).

The present article summarizes these plans, beginning by defining the cyclones of interest (section 3) and formally presenting the scientific objectives (section 4). Section 5 presents the observing system and sampling strategies followed by a summary of the experimental design and decision making (section 6). Finally, the data management approach is outlined (section 7).

3. Climatology of FASTEX cyclones

The objectives of climatological studies of Atlantic cyclogenesis are (i) to characterize properties of cyclones affecting the west coast of Europe, (ii) to determine frequencies of occurrence, and (iii) to derive some picture of their life cycle. The detailed results of the first part of this work are to be found in

Ayrault et al. (1995). This study has evolved into building a new, quantitative classification of North Atlantic cyclones. The results, derived from an automatic tracking algorithm (Ayrault 1995) employed here to tackle item (iii), will be published in due course.

The starting point for establishing the climatology of FASTEX cyclones is the classical work of Sanders and Gyakum (1980) and of Roebber (1984). These studies emphasize cyclones in the Pacific and Atlantic Oceans. They concentrated on explosively deepening cyclones and, from that point of view, find very little activity near the European coasts. This picture does not coincide with those of the French and U.K. community, who find that cyclones are reasonably frequent in the eastern Atlantic. The reason for the viewpoint discrepancy is that eastern Atlantic cyclones rarely develop into "bombs" (as defined in the above references) and their spectral properties are significantly different. This is clearly shown by Ayrault et al. (1995) based on an examination of ECMWF operational analyses of the winter seasons of 1984 to 1994 at full time resolution (6 h). With this approach, it is possible to analyze the "ultra-high" frequency variability of the atmosphere, and Ayrault et al. (1995) finds a peak at 0.5–1.5 days.

A distinctive characteristic of eastern Atlantic atmospheric circulation is the nature of its low-frequency variability (characteristic period > 10 days): it is maximum. This means that the large-scale flow pattern, or the environment in which the cyclones evolve, undergoes large changes. To study cyclones in relatively homogenous large-scale environments, it is necessary to separate the large-scale flow in different weather regimes. Following the definition of Vautard et al. (1988), weather regimes are defined as persistent patterns of the large-scale flow. Three such persistent regimes are seen in the Atlantic. The *zonal* regime and the *Greenland anticyclone* regime correspond to a zonally extended baroclinic zone, more to the south in the second case. The *blocking* regime conversely correspond to a jet-flow deviated to the north near 40°W. For cyclones reaching Europe from the west, one of the first two regimes has to establish itself. The empirical frequency of occurrence of these regimes is shown by Fig. 3. It appears that the most favorable period for a zonal-like regime is the first half of January, with about 60%.

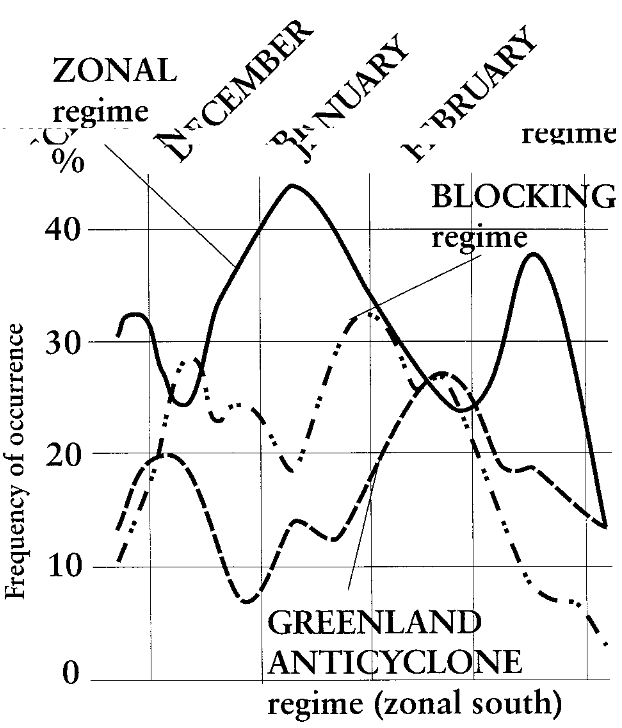

FIG. 3. Climatological frequency of weather regimes over the North Atlantic during the winter months. Derived from ECMWF analyses from 1986 to 1994. The onset of the zonal or of the Greenland anticyclone regimes implies cyclogenesis events for FASTEX, unlike the blocking regime. (Courtesy of Franck Ayrault.)

Another distinctive property of eastern Atlantic cyclogenesis is its characteristic timescale. The maximum of variability in the 2–6-day range is, during the zonal regime, centered near 50°N and 45°W. The maximum of variability in the 0.5–1.5-day range is centered near 55°N and 25°W, that is at the eastern end of the high-frequency variability maxima that is often used to define the "storm-track." It has an amplitude in that range and area that is comparable to that in the 2–6-day range. This means that the FASTEX cyclones can be expected to be an equal mixture of rather well known baroclinic systems and a different kind that evolves more rapidly. The latter category indeed appears to be impossible to separate spectrally from fronts (in the temporal sense considered here), and so the successful techniques introduced by Blackmon et al. (1984) cannot be employed to outline the properties of these cyclones. Instead, an event-oriented technique must be employed. Using a simple approach, Ayrault et al. (1995) isolate two types of such frontal cyclones. Type 1 is a reduced-scale baroclinic wave that grows along a cold front. Type 2 grows as a warm-front-like feature in a predominantly diffluent, frontolytic environment. These preliminary results confirm two important ideas outlined in the introductory section: (i) the reduced scale (in time and space) of the cyclones that develop near the end of the classical storm tracks and (ii) the existence of newly identified types of cyclone that depend more on environmental properties, such as deformation, than baroclinicity. Similar remarks can be derived from a case study approach and conceptualization: see Browning and Roberts (1994) and Rivals et al. (1997). The latter in particular shows deformation fields and their influence.

These conclusions are currently being confirmed and sharpened by the use of a much more sophisticated tracking and relocating technique (Ayrault 1995). Some of these results are very useful for FASTEX planning. The events of interest are defined using vorticity at 850-mb level [pressure deepening is not a relevant criterion; see Ayrault et al. (1995)]. In addition, another criteria is that the cyclone must be reachable from Ireland (the reasons for this are given in section 5 below) and it must have a large enough amplitude ($\zeta_{\max} \geq 10^{-4}\,\mathrm{s}^{-1}$, where ζ is the relative vorticity). Figure 4 provides a detailed definition and shows the time distribution of these events for the past Januarys and Februarys for which ECMWF analysis is homogenous enough in a statistical sense. Over this period there are, on average, 11 cyclones within these 2 months. However, the interannual variability is large, with very active winters like 1990, which motivated a program like FASTEX in France, and uneventfull ones like 1989.

An important conclusion to be drawn from Fig. 4 is that cyclones rarely come as isolated individual events. On the contrary, they happen in surges, with very close chaining of two, three, or even more events. This is reminiscent of the Norwegian idea of “families” of cyclones. This chaining of events greatly effects the logistics and flight-planning strategy of FASTEX.

The climatology of events reveals information about cyclone life cycles. The result is shown in Fig. 5. The large black dots suggest the most frequent low-level path followed by these cyclones (although it is not an actual track). The dashed contours define areas that enclose 60% of the trajectories of the cyclones. The change in shape and, even more so, area conveys an idea of the dispersion of the trajectories at low levels. A drastic change of area can be seen between –48 and –60 h. It is not due to a sudden concentration of trajectories but to a dramatic increase of the total number of cyclones as time passes. In other words, quite a few new cyclones form within the large –48 h area. The upper-level components (at 300 mb) are indicated by the white dots on the figure. Their motion is significantly (and not surprisingly) more rapid. The dispersion is also larger and indicates that the notion of “most frequent location” is really meaningless. The –36 h upper-level area covers a fair

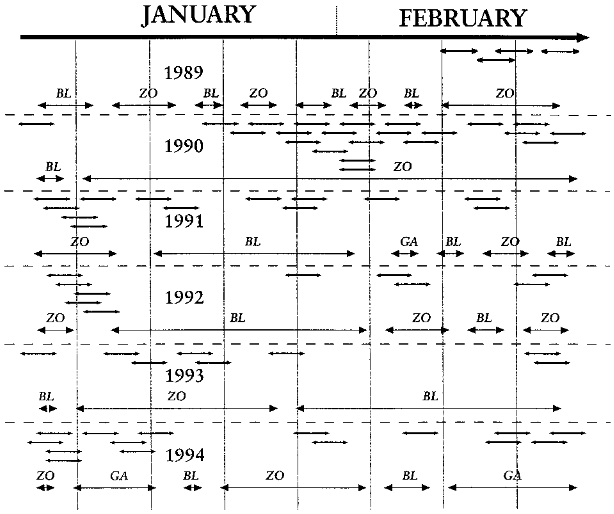

FIG. 4. An automatic tracking algorithm has been applied to 6 pairs of January and February months of ECMWF analyses. Cyclones having moved within a range of 800 km from western Ireland, with a maximum vorticity at 850 mb larger than $10^{-4}\,\mathrm{s}^{-1}$ having increased in the previous 12 h, define a suitable event (a developing cyclone of significant amplitude). Each event is shown by a thick arrow at the time it occurred. The arrows of variable length correspond to the weather regime: ZO for zonal, GA for Greenland anticyclone, and BL for blocking. (Courtesy of Franck Ayrault.)

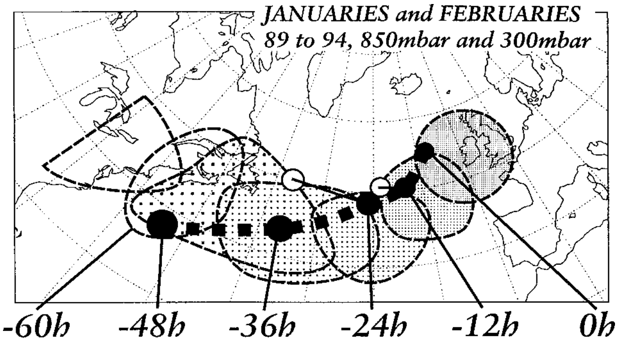

FIG. 5. Another result from the automatic tracking algorithm. Cyclones reaching the easternmost circle have been backtracked at two levels. Circles show the most frequent location: black circles at 850 mb, white ones at 300 mb. A pseudotrack is suggested by joining these independent modal locations with the heavy square dashes: this does not correspond, however, to an actual track and it only provides a rough order of magnitude of the phase speed. The areas enclosed by the dashed lines contain 60% of all trajectories at 850 mb, to give an idea of the dispersion between 0 h and –72 h (left-most dashed area). (Courtesy of Franck Ayrault.)

amount of eastern Canada, including the Baffin Land, the south of Greenland, the Labrador Sea, and the Atlantic over to 40°W. This diagram denotes the timescale and locations that have to be sampled if the entire life cycle of cyclones is to be studied. The implication of this spread of locations to FASTEX targeting strategies is discussed in the following sections.

4. Scientific objectives

Sections 1 and 2 explain the reasons that led us to propose FASTEX. To a large extent, these reasons determine the scientific objectives.

a. Dynamics of frontal cyclones

The recent theoretical results presented above, supported by new case studies (e.g., Rivals et al. 1997), suggest the following hypotheses:

- The appearance or genesis of a cyclone at low levels (step 1) involves a variety of mechanisms, but its subsequent development (step 2), if it occurs, involves only one mechanism, a baroclinic interaction with upper levels. These two stages may be separated by a few days of essentially nondevelopmental behavior.
- The genesis mechanisms include (1) the presence of a dynamically unstable quasi-steady low-level frontal environment [(in the sense of Charney and Stern 1962)] or (2) the triggering of the same energy conversion mechanisms as in the instability theory by a precursor structure in an environment that then does not need to be unstable. Also (3), the active participation of the environmental flow is expected to play a crucial role through, for example, its induced deformation field.
- The development mechanism, the baroclinic interaction, results primarily from either upper-level preexisting potential vorticity anomalies or from the upscale growth of the new, low-level cyclone generating its own upper-level component. A consequence is that a cyclone can go through several stages of baroclinic development with transient upper-level coupling.

To address these issues, thermal and dynamical observations have to be collected when a low-level cyclone forms, possibly prior to this on occasion, as well as when it develops or reaches its mature stage. Also, not only the cyclone should be measured, but a fair portion of its environment as well.

b. Cyclone predictability

FASTEX is also motivated by the practical forecast problem continuously posed by these cyclones. Part of the answer is to obtain, as a result of the dynamical objectives, a new set of theoretically and observationally validated conceptual models. These will identify the key properties of the flow that need to be observed and analyzed properly.

There is another approach, though, that is complementary to the previous one. Indeed, it may not be enough to get the generating mechanisms right to obtain a good forecast. It is also necessary to keep the error level in other parts of the flow as low as possible. FASTEX cyclones may form, as has been said above, in several different ways. This also means that small initial errors in the analysis have just as many different ways to grow, sometimes very rapidly, and wreck the forecast. The predictability of cyclogenesis depends, therefore, on improved control of analysis and forecast error growth.

A possible practical solution is to concentrate measurements in the areas where small uncertainties may cause the greatest threat to the forecast quality. These areas, assumed to be few in numbers and relatively local in space, will obviously depend on the current flow. Hence the idea of an *adaptive observing system.*

The basic concept is to concentrate measurements on areas that are dynamically critical for a proper prediction of cyclogenesis downstream of these zones in the next 24 to 36 h. Another key idea is that these areas should be objectively determined or predicted. At least part, and perhaps all of, the answer can be provided by adjoint models.

FASTEX is designed to allow the first full-scale feasability test of one or several adaptive observation strategies. This relates FASTEX to the U.S. Weather Research Program. A more detailed discussion of this new approach to observation can be found in Snyder (1996) or Palmer et al. (1997).

c. Cyclone cloud systems

Cloud-microphysical processes can be critical to the detailed evolution of cyclones and are essential to their impact on climate. There are two important issues that call for detailed measurements, using new technologies, of the cloud systems associated with FASTEX cyclones.

1) Internal structure of layer clouds

The first issue is to improve the understanding of the internal organization and properties of the clouds themselves. The characteristic feature of these clouds is their arrangement into layers and bands. A recent review of the current knowledge as well as of the gaps in this knowledge is offered by Ryan (1996).

There are several critical aspects of the vertical structure of the cyclone clouds.

- The first is the multiple layering of clouds, including the vertical distribution of the microphysical composition, especially at cloud top and base, and in the melting layer. The radiative properties of the cloud system will, for example, primarily depend on the optical properties of the cloud top and bottom boundaries. The presence of a melting layer implies a region of enhanced liquid water that is important both radiatively and for precipitation rate control.
- Another critical aspect of layered clouds is the distribution of latent heating, an essential part of the dynamical and microphysical feedback.
- Within a storm, the horizontal distribution of these vertical profiles is inhomogeneous and a better knowledge of their distribution is required. The water budget and precipitation efficiency of these cloud systems is not well known either.

Deficiencies or uncertainties in the knowledge and treatment of these properties within models impacts on the long-term effect of these systems seen as a population (the role of these cloud systems in the climate). It also strongly influences the interpretation of radiative measurements, such as in remote sensing inversion. The latter is an often downplayed issue but is essential if satellite-based measurements of temperature and water distribution are to be used more.

In this area, FASTEX is a contribution to the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study program (Browning 1994). The impact of layer clouds on climate and the need for documenting the related processes are defined by R. Stewart et al. (1996, manuscript submitted to *Advances in Geophysics*). A gap in the present datasets identified in these two papers is a series of measurements performed well off the coasts, above the open ocean.

The cloud system associated with a FASTEX storm must be observed on at least two scales. To understand the coupling with the dynamics on the scale of the cyclone, an overall knowledge of the large-scale ascent zones and cloud areas is required. At the same time, the internal distribution of vertical layering, water distribution, and heating is needed. Airborne Doppler radars such as ASTRAIA/ELDORA mounted on the National Center for Atmospheric Research (NCAR) Electra aircraft (Hildebrand et al. 1996), and the National Oceanic and Atmospheric Administration (NOAA) P-3 (Jorgensen et al. 1996b), aided by some in situ microphysical measurements, can provide this multiple-scale information. In vertical mode, it can also describe cloud layering.

2) Cloud-embedded mesoscale dynamics

The second issue related to the cyclone cloud system is that its organization is affected by various kinds of mesoscale activity. One aspect is the presence of rainbands: examples relevant to the kind of systems observed on the European west coast can be found in Lemaître and Scialom (1992) and Browning et al. (1997). Besides the reorganization of the synoptic-scale ascent, there is also the breakup of frontal zones or precipitating bands into line segments and sometimes into mesoscale vortices. An example of the former is given by Browning and Roberts (1996). An example of vortices within a (strong) midlatitude low is studied by Neiman et al. (1993). The processes involve complex interactions between diabatic processes (moist processes, surface fluxes) and dynamical ones. Many unsolved questions relating to the formation and structure of these features require, as for the larger-scale ones, the documentation of their life cycle. Because they occur within cloudy air, the same new airborne Doppler radar technology can often provide the required data. The origin of some mesoscale bandedness appears to depend on dynamical conditions at the rear part of the cyclone (e.g., Browning et al. 1995). This can be studied using dropsondes.

In agreement with the Gewex Cloud System Study (GCSS) plans, results in these areas will be translated into work done on the parameterization of cloud processes for large-scale models. Browning (1994) outlines a strategy that links uneven observations of cloud systems to their parameterization.

d. Air–sea interaction objectives

Very little is known of the behavior of the atmospheric boundary layer and its interaction with the ocean surface in areas combining large fetch and strong winds (> 15 m s^{-1}). Outstanding issues for understanding high-wind, open-ocean processes are similar to those already dealt with for lower wind speeds (e.g., Dupuis et al. 1995; Fairall et al. 1996). These include the relationships of the coefficients for drag, sensible and latent heat fluxes to the environmental wind speed, stability, and sea state; the feedback relationship between the sea state (e.g., directional wave-height spectrum) and the drag coefficient via the surface roughness; the applicability of relationships relating stress to ocean-surface roughness. Also of interest are the role of sea spray for the latent heat flux (e.g., Fairall et al. 1995); the accuracy of various flux sampling methods; and the impact of nonsteady state atmospheric and oceanic conditions; the structure and variability of the midocean, extratropical, atmospheric boundary layer.

Although the parameterizations of the air–sea interaction processes are quantitatively uncertain for these strong-wind conditions, the processes are important for atmospheric modeling. Since model representations of the lower troposphere over the oceanic regions have minimal input from data, the representations are very dependent on the accuracy of the model, including the parameterizations of the air–sea exchange processes and atmospheric boundary layer associated with moderate-to-strong winds and rough seas. However, since current parameterizations are not based on data relevant to these extreme conditions, these cases will likely generate significant errors, especially in the downwind half of the ocean basin. How important are such model errors? Sensitivity studies show that air–sea exchanges of heat and momentum, especially before the rapid deepening stage and in the warm sector of the storm, have a significant impact on the development of extratropical marine cyclones (Davis and Emanuel 1988; Kuo et al. 1991; Langland et al. 1995). Increases in the surface roughness due to increases in the wind speed have also been shown to impact idealized marine cyclogenesis (Doyle 1995).

Because of the lack of data just described, parameterization uncertainties, and the apparent importance of the air–sea interaction processes, the most important experimental objective of the air–sea interaction component of FASTEX is to obtain a ship-based collection of rare measurements of heat, moisture, and momentum fluxes in a high wind speed (> 15 m s^{-1}), open-ocean environment; the necessary associated sea state measurements; and the quasi-continuous monitoring of the midoceanic boundary layer structure. These will provide the necessary input to develop new schemes and study their impact in new case studies.

Furthermore, the purely marine cyclones that ultimately hit the west border of the ocean form in the area where the Gulf Stream is disrupted into several branches and vorticies. There also is a maximum loss of heat in the same location that, most likely, benefits to the atmosphere. It could favor cyclogenesis by reducing the tropospheric static stability (the preconditioning mechanism).

e. *Other objectives*

Another FASTEX objective is to gather high-quality datasets to test a variety of data assimilation methods, such as a variational approach (in three and ultimately four dimensions) that will utilize the dropsondes. A series of observing system experiments will be conducted to determine the data requirements (precision and resolution) that are needed to properly reconstruct the structure and evolution of synoptic and subsynoptic cyclones. The importance of a good knowledge of the distribution of water vapor and of condensed water will also be studied. The results can then be translated into an assessment of the ability of current and future remote sensors of temperature and water vapor to provide the required information.

This broad set of objectives has been constructed and will be studied by the FASTEX Scientific Steering Group (Table 1). An appendix is provided that expands the many short form terms used in this paper.

5. The FASTEX observing system

To address the two primary FASTEX science objectives, a relatively large observing system is required. A summary of all sounding platforms and facilities is presented in Table 2. Multiple scale observations are required, particularly from the incipient stage, where both the environment and cyclone precursors are of interest. At the mature stage, the mesoscale features and their environment are of interest. The requirement is, thus, for multiple time and multiple scale sampling. Furthermore, because of the wide geographic distribution of Atlantic cyclones and their precursors, the observing system must be mobile.

a. *Overview*

One of the most challenging aspects of FASTEX is to observe a cyclone throughout its life cycle. Our approach is to define several adjacent areas of observations in the Atlantic, in a flexible way, correspond-

TABLE 1. FASTEX Scientific Steering Group.*

A. J. Thorpe, chairperson	Univ. of Reading (UK)	R. Langland	NRL (USA)
P. Bessemoulin	Météo-France (F)	Y. Lemaître	CETP (F)
K. A. Browning	Univ of Reading (UK)	A. Lorenc	UKMO (UK)
D. Cadet	INSU-CNRS (F)	P. Lynch	Met Éireann (IRL)
J. P. Cammas	Lab d'Aérologie (F)	B. Martner	NOAA (USA)
J. P. Chalon	Météo-France (F)	P. Mascart	Lab d'Aérologie (F)
S. A. Clough	UKMO (UK)	S. Nelson	NSF (USA)
Ph. Courtier	CNES (F)	T. E. Nordeng	DNMI (N)
P. Dubreuil	AES (CA)	H. Olafsson	VI (ICL)
K. A. Emanuel	MIT (USA)	J. Pailleux	WMO/COSNA
L. Eymard	CETP (F)	P. O. G. Persson	CIRES/NOAA (USA)
C. Fairall	NOAA (USA)	J. Rasmussen	NOAA (USA)
R. Gall	NCAR (USA)	F. Roux	Lab d'Aérologie (F)
T. Hewson	UKMO (UK)	M. A. Shapiro	NOAA (USA)
P. Hildebrand	NCAR (USA)	C. Snyder	NCAR (USA)
P. V. Hobbs	Univ. of Washington (USA)	A. Staniforth	AES (CA)
A. Joly	Météo-France (F)	R. Stewart	AES (CA)
D. Jorgensen	NOAA (USA)	J. Testud	CETP (F)
T. Johannesson	VI (ICL)	C. Velden	Univ. of Wisconsin (USA)
K. Katsaros	IFREMER (F)	R. Wakimoto	UCLA (USA)
D. Keyser	SUNY (USA)		

*Country key—CA: Canada; F: France; ICL: Iceland; IRL: Ireland; N: Norway; UK: United Kingdom; and USA: United States.

ing to various stages of cyclone evolution. Then, appropriate facilities are distributed in these areas.

Three areas have been defined (Fig. 6). Cyclones at their mature stage will be observed in the vicinity of the west coast of Europe. Given the dominant northeastern orientation of storm tracks in all weather regimes, the appropriate base from which to investigate mature cyclones with turboprop aircraft is a far west location in northen Europe, namely Ireland. This area is called the multiscale sampling area (MSA). The regions upstream of the MSA are suitable for the observation of incipient conditions or precursors to cyclogenesis. The westernmost upstream region is termed the far upstream area (FUS). As seen in Fig. 5, the FUS would normaly be the location of cyclone precursors 48 or 60 h before reaching the MSA. The region of the central Atlantic (near upstream domain or NUS) will be the location of the early stages of cy-

TABLE 2. FASTEX Observing Systems and Modeling Support.[1]

System	Agency/nation/system type (location/base)	Number deployed	Measurements	Comments
Ships				
R/V *Ægir*	Icelandic Coast Guard (along 35°W)[3]	1	Soundings	Full field project[2]
R/V *Knorr*	Woods Hole, USA (along 35°W)[3]	1 Air–sea interaction	Soundings	3–21 January
R/V *Le Suroît*	IFREMER, France (along 35°W)[3]	1 Air–sea interaction	Soundings	Full field project[2]
R/V *Victor Bugaev*	Ukrainian Centre for the Ecology of the Sea (along 35°W)[3]	1	Soundings	Full field project[2]
Surface				
Wind Profiles	France, Germany, Netherlands, Switzerland, United Kingdom	6 stations	Wind profiles, signal to noise ratio, spectrum width	Full field project, hourly measurements
GTS	Various	Numerous	State[4]	As available
Buoys	European Group of Oceanic Stations(EGOS)	Numerous	SST, pressure	6 h, as available
Aircraft				
Electra L188-L	NSF/NCAR (Shannon, IRL)	1	Air motion, thermodynamics, cloud physics	6 Jan–28 Feb mesoscale dynamics, microphysics, ASTRAIA/ELDORA
WP-3D (N-42)	NOAA/AOC (Shannon, IRL)	1	Air motion, thermodynamics, cloud physics	6 Jan–28 Feb mesoscale dynamics, microphysics, Doppler radar
Gulfstream IV (G IV)	NOAA/AOC (Shannon, IRL; St. John's,[5] NFL)	1	Air motion	6 Jan–28 Feb GPS dropsondes
C-130	U.K. RAF (Lyneham, UK)	1	Air motion, thermodynamics, cloud physics	6 Jan–28 Feb GPS and Omega dropsondes
Lear 36	Flight International Inc. (St. John's, NFL)	1	Air motion	6 Jan–28 Feb GPS dropsondes,
	Aircraft Automated	Numerous aircraft	Temperature, wind, pressure	Full field season as available

TABLE 2. *Continued.*

System	Agency/nation/system type (location/base)	Number deployed	Measurements	Comments
ACARS/AMDAR	Reporting System (various commercial carriers from North America to Europe across North Atlantic)			
Soundings				
Canada	Atmospheric Environment Service	4 stations	State	2 Jan–28 Feb 4 day, continuous VIZ (mix) systems
Denmark, including Greenland	Danish Meteorological Institute	5 stations	State	2 Jan–28 Feb 4 day, continuous Vaisala Omega systems
Iceland	Iceland Meteorological Office	1 station	State	2 Jan–28 Feb 4 day^{-1}, continuous Vaisala Omega systems
Ireland	Met Eireann	1 station	State	2 Jan–28 Feb 4 day^{-1}, continuous Vaisala Omega systems 8 day^{-1} during IOP
France	Météo-France	3 stations	State	2 Jan–28 Feb 4 day^{-1}, continuous Vaisala Omega systems 8 day^{-1} during IOP
Portugal	INMG	2 stations	State	2 Jan–28 Feb 4 day^{-1}, continuous Vaisala Omega systems
Spain	INM Servicio de Observation	1 station	State	2 Jan–28 Feb 4 day^{-1}, continuous Vaisala Omega systems
United Kingdom	U.K. Meteorological Office	7 stations	State	2 Jan–28 Feb 4 day^{-1} continuous Vaisala Loran systems 8 day^{-1} during IOP
United States	NOAA, National Weather Service	3 stations	State	2 Jan–28 Feb 4 day^{-1} during IOP VIZ (mix) systems

TABLE 2. *Continued.*

System	Agency/nation/system type (location/base)	Number deployed	Measurements	Comments
Integrated sounding system	NSF/NCAR	2 systems (Le Suroît, Knorr)	State, low-level wind profiles	4 day^{-1} continuous, 90 min launches during IOP, NCAR Omega system on Knorr
GPS dropwindsondes	NSF/NCAR, Vaisala	3 systems (G-IV and Lear 36, C-130)	State	Deployed as required during flight operations
Omega dropwindsondes	USAF	2 systems	State	25 Jan–5 Feb Deployed as required during flight operations
ASAP	Denmark (DMI), France (CGM), SwedoIcelandic	3 systems on average	State	4 day^{-1} in FASTEX domain, during IOP for France. Vaisala Omega systems
Satellites				
DMSP F10 to *F13*	U.S. Department of Defense	Polar orbit	Liquid water, water vapor, windspeed	Variable times, 2 day^{-1}
ERS-2	ESA	Polar orbit	Windspeed, wave spectra, SST	Variable times, 2 day^{-1}
GOES-8	NOAA/NESDIS	Geostationary	Visible, IR, water vapor, derived windfields[6]	5 channels, variable hourly resolution interval
Meteosat	EUMETSAT	Geostationary	Visible, IR, water vapor	Hourly, variable resolution
NOAA-12, -14	NOAA/NESDIS	Polar orbit	Visible, IR, ozone, windspeed	Variable times, twice daily
Models				
ARPEGE/IFS	Météo-France	2 day^{-1}	Global model, variable resolution, and adjoint products	6 h interval to 96 h on 1.5° grid, 3 h interval to 48 h on 0.5° grid
CMC	Canadian Meteorological Center Regional Model	2 day^{-1}	Variable resolution model	12 h interval to 72 h
HIRLAM	High-resolution limited area model, via Met Eireann	4 day^{-1}	Limited area	6 h interval to 48 h

TABLE 2. *Continued.*

System	Agency/nation/system type (location/base)	Number deployed	Measurements	Comments
IFS/ARPEGE	European Centre for Medium-Range Weather Forecasts	1 day^{-1}	Global model and adjoint products	6 h interval to 96 h, 12 h interval to 240 h
Ensemble forecast	European Centre for Medium-Range Weather Forecasts		Global models	50 runs, 12 h interval for 72–168 h
MRF	U.S. NCEP Medium Range Forecast	1 day^{-1}	Ensemble products	12 h interval to 240 h
NOGAPS	U.S. Naval Research Laboratory, Operational Global Atmospheric Prediction System	1 day^{-1}	Global model and adjoint products	As needed for IOP, 12 h interval
UKMO LAM	U.K. Meteorological Office Limited Area Model	4 day^{-1}	Limited area	3 h interval to 48 h
VAGATLA	Météo-France	1 day^{-1}	Sea state model	6 h interval to 48 h

[1] More detail on these systems and support contained in FASTEX Operation Plan.
[2] One port call (approximately 7 days) during the 2-month field season.
[3] Ships nominally spread between 40°–50°N at 35°W. Movement in any direction is possible.
[4] State parameters = temperature, pressure, relative humidity, wind direction, and speed.
[5] G-IV may recover and operate from St. John's for 2–3-day periods.
[6] Provided by University of Wisconsin, Cooperative Institute for Meteorological Satellite Studies.

clogenesis, which Fig. 5 suggests will be active 24 to 36 h before the mature cyclone reaches the MSA.

The measurements taken in the upstream areas will address the dynamical and predictability objectives, as well as surface flux measurements, since they are part of the initiation problem. The cloud system objectives, as well as dynamics studies of mature cyclones and verification for predictability, will be performed from data collected in the MSA. The name MSA arises from the need for a multiscale sampling strategy to observe both the overall cyclone structure and its evolution, as well as the embedded mesoscale substructures.

An important effort is also being made to improve data gathering along the boundaries of the main observation areas. This is important for future modeling experiments. Many rawinsonde sites around the North Atlantic basin will increase their sounding frequency to 4 per day. Many countries are involved and it represents a significant contribution to FASTEX. On the east side of the Atlantic, Ireland, France, and the United Kingdom will perform soundings every 3-h during intensive observing periods (IOP). A number of extra drifting buoys will also be launched to help determine surface conditions in the NUS. Platforms of opportunity such as commercial aircraft (temperature and winds during ascents), ASAPs (semiautomatic soundings from ships enroute during transatlantic cruises), and satellite data will be included in the database (section 7 below). Figure 7 presents a schematic summary of the observing system. Table 3 lists the institutions and countries supporting this observing system.

b. Upstream observations: Ships

The backbone of the regular observations in the upstream areas will be provided by four ships. The main task of these ships is to perform 6-h radiosoundings during the whole FASTEX period. Furthermore, during IOPs, they will launch radiosondes every 1.5 h for 18 h centered on the crossing of an incipient low. This enhanced data should pro-

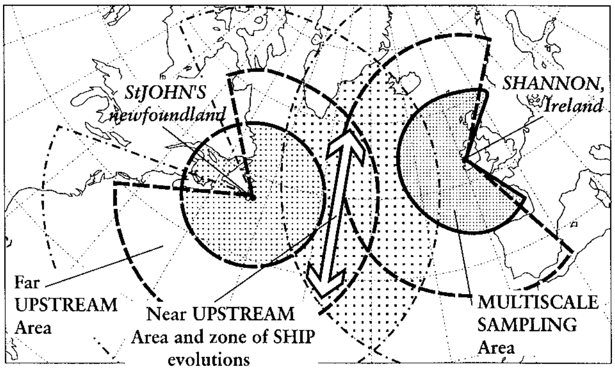

FIG. 6. The areas of operations of FASTEX. The area defined by the heavy solid line is centered over Shannon, Ireland. It defines the inner boundary of the multiscale sampling area (MSA) and corresponds to the maximum ferry distance of a P-3-like aircraft in the absence of wind (~1050 km). The heavy long-dashed line is centered over St. John's, Newfoundland. It defines the inner boundary of the far upstream area and is the maximum ferry distance of a Learjet-like aircraft (~980 km). The heavy dashed lines and dash–dotted lines correspond respectively to ~1820 and ~2720 km. They correspond to the maximum ferry time of the Gulf Stream and two thirds of its maximum range. The intersection loosely defines a near upstream area. The elongated arrow marks the area within which the research ships will ply.

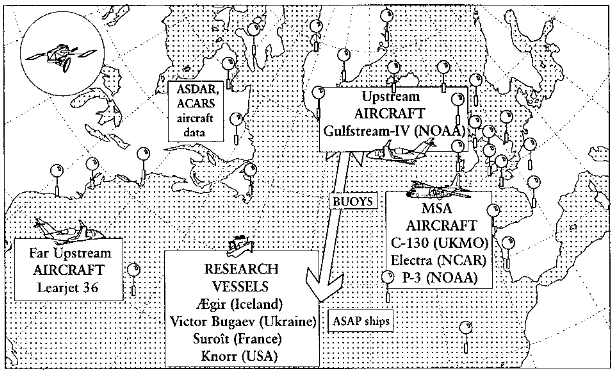

FIG. 7. Summary of the observing system. The upper-air measurements stations operating 4 day^{-1} instead of 2 are indicated by a radiosonde-like symbol.

vide a sampling of a phenomena with a horizontal scale of about 1000 km moving at 20 m s^{-1}. Up to 10 IOPs are budgeted during FASTEX.

The high-quality vertical profiles obtained from the rawinsondes are expected to have a dramatic impact on the reduction of the overall uncertainty of the forecasts near the coasts of Europe, as seen by a series of numerical experiments performed by Fischer (1996). A convenient measure of uncertainty at the range of 48 h is provided by the variance of the forecast error. A filtered model representing a generic large-scale cyclogenesis event has been employed using a Kalman filter approach. The evolution of the forecast error variance has been computed with various distributions of data upstream of the cold front of the cyclone. The variance along the surface cold front downstream of the source of data is most reduced when the source of information is permanent and located within the main baroclinic zone. For this reason, the ships will not remain at fixed geographic locations but will move to follow the low-frequency evolution of the large-scale Atlantic flow. If conditions and distances allow, the ship positions will be adjusted so that they can perform the high-frequency soundings in the optimal location near the baroclinic zone.

Two of the ships will also carry instruments to measure turbulent fluxes in the marine boundary layer. They will also obtain detailed observations of the low-level jets in frontal areas. Together with the data from buoys, this will be a rich dataset with which to address air–sea interaction objectives.

The ships that will take part in FASTEX are the research vessels *Le Suroît*, from the French fleet of IFREMER oceanographic vessels, and the *Victor Bugaev* from the Ukrainian Scientific Centre for the Ecology of the Sea. The third ship is the *Ægir*, provided by the Icelandic Coast Guard. Finally, the NOAA-sponsored, Woods Hole–owned research vessel, R/V *Knorr* will also be part of the ship array at the beginning of FASTEX. It will be equipped for flux measurements and will also carry a gyrostabilized UHF radar. Furthermore, a sensitive, vertically pointing S-band Doppler radar will enable the *Knorr* to collect valuable information on clouds, cloud layering, and precipitation in midocean.

c. *Upstream aircraft observations*

Although the ships will provide invaluable information about the environment and large-scale conditions associated with rapid cyclogenesis, they are not mobile enough to be able to observe the smaller scales corresponding to actual incipient cyclone elements or precursors to cyclogenesis (such as potential vorticity anomalies). These critical observations will be provided by two high-flying jet aircraft, the NOAA Gulfstream-IV (G-IV), and a Lear-36 operated by Flight International and leased for FASTEX by the U.S. National Science Foundation. The primary observations provided by these aircraft will be made with a dropsonde system employing the Global Positioning System (GPS) technology. This system provides wind finding substantially improved over previous drop-

TABLE 3. Organizations supporting FASTEX

Support of the use of large facilities	
CNRS/INSU	France
European Commission	
Météo-France	France
NOAA	U.S.
NRL, ONR	U.S.
National Science Foundation	U.S.
UK Meteorological Office	U.K.
Other sources of support	
Atmospheric Environment Service	Canada
Danish Meteorological Institute	Denmark
ECMWF	
EGOS	
Icelandic Meteorological Service	Iceland
Joint Centre for Mesoscale Meteorology	U.K.
Met Éireann	Ireland
NCAR/MMM	U.S.
WMO/COSNA	

sonde technology using either Omega or Loran signals. Up to 4 dropsondes can be tracked simultaneously, providing a horizontal data spacing of about 150–200 km. The dropsonde data from the G-IV will be encoded in near real-time and transmitted by a satellite communications system to the Global Telecommunications System (GTS) so the data can be used by real-time data assimilation and forecast models.

In the upstream areas, the aircraft will employ two targeting strategies. The first strategy addresses the predictability objectives. Specific algorithms (using forecast models and adjoint or breeding techniques) will determine the areas where data is required to limit the growth of the errors in the subsequent forecast steps. An example from such an algorithm is shown in Fig. 8. The growth of errors appears to be determined primarily by the existence of a nonzero projection of the analysis error on the first singular vector. To reduce this component, the actual amplitude of these singular vectors must be known accurately. The rate of sampling must be compatible with the scales handled by the present global data assimilation schemes: it is planned to drop a sonde about every 200 km. The structures that appear to control forecast error are strongly baroclinically tilted, with a maximum amplitude in the low levels. Their horizontal scales are of the order of 1000 km along the baroclinic zone and 2 or 3 times this across owing to deformation effects. Because the area of interest is determined automatically and the sampling rate is simple and uniform, this strategy is called “objective targeting.” Verification should be provided by similar measurements (at least) when the cyclone will or should be in the MSA.

The second type of targeting strategy addresses objectives associated with defining cyclogenesis precursor structure. Information will be obtained on incipient structures, such as the low-level distribution of vorticity and potential vorticity anomalies along a surface front, perturbations aloft including features such as jet streaks. Case studies indicate that incipient cyclone components are often part of the upper-level jet flow yet can come from different directions. They are often not associated with cloud or precipita-

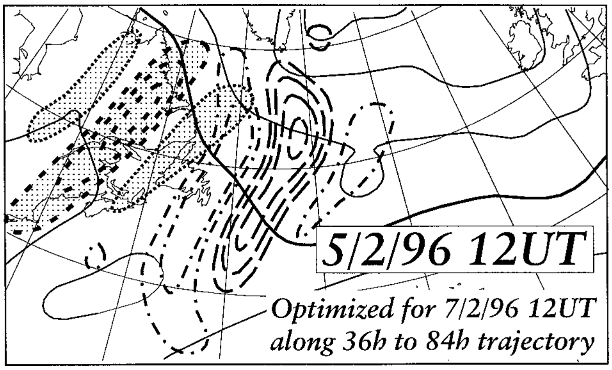

FIG. 8. An example of the kind of structure that will be sampled as part of the predictability objectives by the upstream aircraft. It is the most unstable singular vector that maximizes the low-level enstrophy near Ireland on 7 February 1996 at 1200 UTC for a given amount of total energy 48 h before. This structure has been computed from a 84-h forecast of the same case as the one shown on Figs. 1 and 2, but with the Météo-France Arpège model. Solid lines: mean sea level pressure, contour interval 5 mb, reference (bold) 1015 mb. Dashed and dash–dotted lines, vorticity perturbation of the singular vector at 850 mb. Shaded areas and dotted lines, vorticity perturbation at 300 mb. Signs and contour interval are arbitrary. (Courtesy of Thierry Bergot.)

tion. These structures will be sampled at the highest possible rate in order to allow for model-independent analysis afterward. This strategy is termed "actual structure sampling" or "subjective targeting" to distinguish the approach from targets selected by numerical methods.

If practical, targets for dropsonde investigation will be selected in order to assess new satellite-based remote sensing technology (such as interferometry) by collocating targets with satellite overpasses.

The Lear-36 will perform approximately 15, 5-h flights, all of them dedicated to "objective targeting." It will be based in St. John's, Newfoundland. The G-IV will fly up to 20 missions, evenly distributed between the two kinds of targeting strategies. The G-IV will be based in Shannon, Ireland, along with a number of other aircraft to facilitate NUS and MSA missions, but will recover occasionally in St John's, to facilitate coordinated "objective targeting" flights with the Lear-36.

To determine targets for the adaptive observation strategy several products will be generated in several centers: the Naval Research Laboratory (NRL) will run an adjoint code at their facility in Monterey, California, the same basic tool will be employed at the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, United Kingdom, and at Météo-France (Toulouse, France). In addition, calculations performed at NOAA's National Centers for Environmental Prediction (NCEP) should derive the areas of interest from products such as the bred vectors.

d. Observations of mature cyclones

Three long-range turboprop aircraft will operate in the MSA. They will collect in situ and remote sensing (i.e., Doppler radar) data to address the dynamical and cloud system objectives. They will also provide observations to evaluate the predictability objectives. Listed by decreasing order of range, these aircraft are the C-130 owned by the U.K. Meteorological Office (11-h endurance), one of the P-3 aircraft operated by NOAA (9 h), and the Electra belonging to NCAR (7 h).

These aircraft are very well equipped for meteorological in situ measurements, including microphysics and turbulence. A unique aspect of FASTEX is the combined use of remote sensing instruments, primarily airborne Doppler radar with GPS dropsondes. The U.K. C-130 will deploy an array of dropsondes at the same time that the two other turboprop aircraft are collecting Doppler information. On the Electra, the main instrument is the ASTRAIA/ELDORA X-band dual-beam Doppler radar. It has been developed jointly by NCAR's remote sensing facility (RSF) and by the Centre d'étude des Environments Terrestre et Planétaires (CETP), of the Centre National de la Recherche Scientifique (CNRS) in France.

The sonde deployment strategy for the C-130 will be such as to obtain regularly spaced vertical profiles relative to the whole wave cyclone, from front to rear (with respect to cyclone motion). Sondes will be dropped from heights varying from 6 to 8 km, depending on aircraft weight and air traffic constraints. In winter, this should be near the tropopause in the dry slot in the rear of the cyclone. For a large system, the G-IV may share this task. This strategy provides a cyclonewide description of the thermal and wind fields as well as water vapor. The flight strategy will involve flying a series of 4 to 6 legs spaced 100–200 km, about 500-km long, from the front to rear of the cyclone and oriented perpendicular to the system motion. The sondes will be dropped about every 100 km.

The two Doppler radar–equipped aircraft (P-3 and Electra) will follow two basic targeting strategies while the C-130 drops sondes. The first strategy is a systematic, regular survey using flight legs similar to those used by the C-130. The P-3 and the Electra will fly parallel legs spaced by about 100 km, providing continuous Doppler radar (and derived wind field) coverage. The leg lengths are about 500 km across the system and perpendicular to the cyclone motion vector. At regular interval along these legs (about every 120 km), complete 360° turns will be executed, providing a kind a vertical conical scan similar to a ground-based Velocity Azimuth Display (VAD) (Protat et al. 1997). This type of scanning allows for the unambiguous recovery of the terminal falling velocity of the reflecting hydrometeors. This strategy is called the "lawnmower" or "systematic survey" pattern. This pattern is a highly coordinated, multiaircraft one. The Electra will fly at a height of 3 km, the P-3 at 1.5 km.

A well-suited technique to invert the combined measurements from the Doppler systems is the MANDOP programme (Scialom and Lemaître 1990; Dou et al. 1996). It is designed to recover the 3-D wind field and its main derivatives on a relatively large regular grid.

The mesoscale substructures and, in particular, their own life cycles will be investigated with the second flight strategy, called the "phenomena investigation" pattern. The flights are coordinated by a mission coordinator on one of the aircraft. The P-3 takes off about an hour earlier than the Electra and enters the system at the same time as the C-130 begins its survey. The P-3, however, will perform an α-like pattern covering the cloud head and frontal systems within 3 to 4 hours (1 to 1.5 h per leg) and centered on the position of suspected storm "center." The idea is to derive a map of the precipitating structures present in the cyclone using the lower fuselage radar. Based on this information, the Electra is directed toward mesoscale substructures of interest. These can be cold frontal rainbands, cloud head (the cloudy area located on the advancing edge of a cyclone), or warm frontal rainbands or convective structures in the cold air. Rainbands can be studied in two possible ways. A front-relative pattern will give an indication of along-front variability, as the same portion of front is covered from two sides. The front is defined, as before, as an area of maximum vorticity but, for practical reasons, the actual location will be refined using precipitation activity. A band-relative pattern will enable the use of the highest rate sampling capabilities of ASTRAIA/ELDORA and give access to the internal structure of the band. The objectives here are to derive life cycles of mesoscale features and frontal evolution on the mesoscale. The retrieving techniques and the kind of results that can be obtained are shown by Wakimoto et al. (1992) in an explosive extreme cyclone. Although the activity in these cyclones is generally much stronger than in FASTEX cyclones, the contribution of vertical circulations to the overall energy budget is one of the challenging questions of FASTEX.

Figure 9 provides an idea of these flight strategies shown on the objective composite of one type of frontal wave derived from Ayrault (1995). The P-3 and the Electra will be based at Shannon (Ireland). The C-130 will be in Lyneham, England, about 50 min flying time from Shannon. The entire low-level airspace to be sampled by these flights will be blocked about 24 h in advance. Up to 10 cases will be sampled.

6. FASTEX operations

a. Project schedule

A comprehensive analysis of historical data for storms of interest to FASTEX (Ayrault et al. 1995)

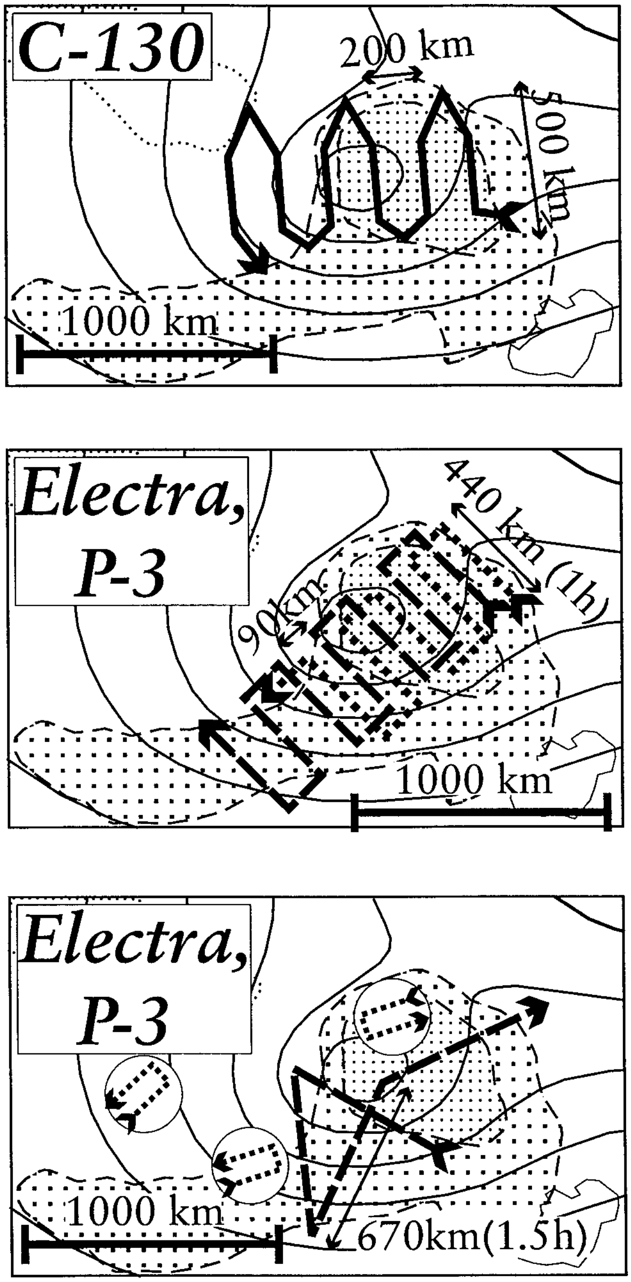

FIG. 9. Schematics of system-relative flight patterns to be employed by the turboprop aircraft in the MSA. The flight tracks are overlayed on the new composite structure for the type 1 frontal wave rederived from automatic tracking and automatic classification of trajectories covering the mature stage. The solid lines are surface pressure, and the shaded areas represent upward vertical velocity at 700 mb. The dotted line denotes an area of descent. The top panel shows the UKMO C-130 pattern going toward the clear air, low tropopause, part of the cyclone. The two other panels show the two main alternatives for the NCAR Electra (dotted track) and NOAA P-3 (dashed track). The middle panel shows the so-called "lawnmower pattern" from which an overall observation of the ascent zone will be derived. The lower panel shows the overall exploration of the wave by the P-3, while circles mark possible areas where the Electra could perform mesoscale sampling of rainbands and other structures. (Objective composite frontal wave is courtesy of Franck Ayrault.)

suggested that the preferred period for operations will be during January and February of any given year. According to the climatology, a period of 2 months is required to get the 10 complete cyclone cases with more frequent event occurrences during the month of January. Figure 3 also supports the preferred January period for cyclonic events. Field operations will take place during January and February 1997. An important setup phase will occur in December so that most participants are ready for operations early in January. Table 2 shows the timing availability of major observing systems during the field season.

b. *Operations coordination*

The FASTEX Operations Center will be located at Shannon, Ireland. The position is noted in Fig. 5. The Operations Center will function to provide scientific guidance, operational coordination, and forecasting support to the project during the 2-month field season. These activities will be managed by scientists and forecasters and carry out some specific tasks discussed below.

The FASTEX Science Team will provide overall guidance to the project based on input from scientific, operations, and forecast staff. The Science Team, chaired by K. Browning, is composed of representatives of the agencies that have provided major funding support for FASTEX. The Operations Coordination Team will implement these decisions and keep track of system status, operations documentation, and facility updates throughout the field deployment. The Operations Coordination Team is lead by Operations Directors J. Moore and R. Dirks from the University Corporation for Atmospheric Research (UCAR). The group of participating investigators located in Shannon and elsewhere in Europe and North America will develop preferences and priorities for the scientific goals of each IOP. These proposals, submitted for consideration by the FASTEX Science Team, form the basis of the variety of investigations possible during FASTEX.

c. *Forecasting support*

The achievement of scientific objectives rely heavily on the monitoring and forecast of significant weather conditions in the project domain. FASTEX will take advantage of excellent forecast tools and support from an international group of forecaster in the Operations Center. Personnel and equipment from both operational and research branches of several national weather services including France, United Kingdom, Canada, and Ireland form the FASTEX forecast support teams and will be brought to Shannon. The coordinated deployment of facilities and execution of flight strategies require real-time data input, assessment, and decision making by these teams and other scientific and operational support staff.

d. *Operations Center capabilities*

The distributed nature of FASTEX observing systems across the entire North Atlantic Basin requires good data, voice, and facsimile communications. Support for these capabilities have been provided through contributions from all participants. The Operations Center will include four wide-bandwidth communications links to several national weather services and the general Internet for the timely receipt of operational and specially prepared products for use during FASTEX. The Center will also have local area network capabilities to enhance the exchange of data among the many participant workstations to be located in Shannon. This support is vital to the preliminary analysis efforts of the investigators and is crucial to the ongoing assessment of progress and setting of observational priorities.

e. *The FASTEX intensive observation periods*

The FASTEX Science Team will define IOPs as a method for focusing special high-resolution observations during the field season on weather phenomena of interest. The primary event that will cause an IOP to be called is the extreme likelihood that a mature cyclone will form or move into the MSA within 3 to 3.5 days. A start and stop time will be noted that encompasses the beginning and conclusion of any combination of special high-resolution observations. Such observations might include more frequent soundings from participating nations, more frequent shipborne soundings, or research aircraft operations from North America or Europe. An IOP will be a minimum of 24 h in duration and will likely extend for 2 or 3 days. Multiple IOPs may exist simultaneously, as attention is given to cyclones exiting the FASTEX MSA domain while the formative stages of a new disturbance may have begun upstream.

f. *FASTEX operations scenario*

The complex nature of the conduct of a FASTEX IOP is illustrated in Fig. 10. There are both temporal and spatial considerations because of the lead time requirements for operations alert and large distances and long timescales over which observations might be taken. The focus of observations of a particular cy-

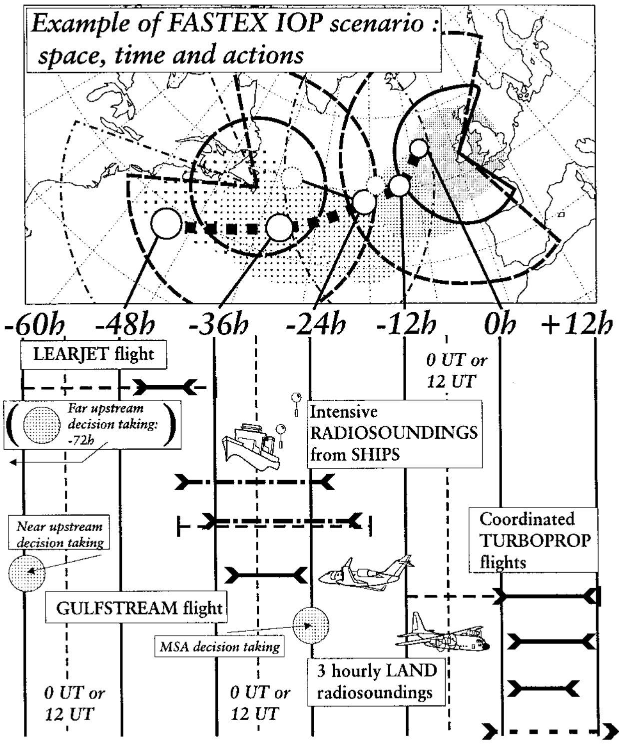

FIG. 10. Timelines and locations of the events composing a FASTEX IOP. Length of the heavy arrows are proportional to the duration of the flights (solid), the period of intensive soundings from ships (dash–dotted), the period of 3-h soundings from the United Kingdom, Ireland, and France (dashed). Note the lapse of time taken into account between the cyclogenesis timeline and the UTC clock that determines some of the activities (the upstream flights, for example). The important decisions may have to be taken 12 h earlier than shown when they imply a change from day to night flights.

clonic event is meant to coincide with its entrance into the MSA region. Therefore, the “0 h” (0 h in Fig. 9) is set for cyclone arrival in the MSA. The important point here is that planning and alerting for the start of an IOP must occur as much as 72 h in advance of the arrival in the MSA.

An IOP would begin when special upstream observations begin, in this case at the “–60 h” time in Fig. 9. Observations might include increased frequency of rawinsonde releases in the United States, as well as Learjet flight operations from St. Johns, Newfoundland, to address objective targeting issues. As the developing system moves within 48–36 h of the MSA, the G-IV aircraft will fly once and possibly twice, depending on storm speed, to provide dropsonde documentation over the open ocean. As the cyclone nears the MSA within “–24 h” in Fig. 9, special high-frequency sounding launches aboard the 4 FASTEX ships would occur to document the approach as passage of the system near 35°W. Thereafter, planning and execution of multiple aircraft flight operations occur using the U.K. C-130, NCAR Electra, and NOAA P-3. Special high-frequency soundings from selected European operational sounding sites will occur to further document approach and landfall of the cyclone in Europe.

Conducting of IOP activities require coordinated support from the FASTEX Science Team, Principal Investigators, Operations Coordination Team, and the international Forecast Teams. The development and planning of mission proposals must be closely coordinated among the investigators and Science Team. Virtually continuous input is required from the forecast groups to assess the timing and movement of the developing cyclone. The status of facilities and any ongoing IOP operations is monitored by the operations coordination team so that the impact on future decision making is known. All of this information is used by the scientists, Science Team, and Operations Team to plan, select, and carry out the multiple components of sampling the cyclone in the FASTEX domain.

7. Data management: The FASTEX Data Archive

FASTEX leadership has made a strong commitment to provide timely and efficient access to all special datasets collected during the field phase of the program. The primary point of contact and repository of archived data will be the FASTEX Central Data Archive (FCA) at Météo-France in Toulouse, France. Other organizations and agencies, however, will also maintain subsets of FASTEX data. Collectively, all of these data centers are referred to as the FASTEX Data Archive (FDA). All participating investigators are encouraged to forward appropriate data as quickly as possible to the FCA.

The FCA is already being prepared in Toulouse by a small unit of Météo-France scientists led by G. Jaubert. The main data providers are meteorological services from Canada, France, Iceland, Ireland, Portugal, Spain, Switzerland, United Kingdom, United States, and various research laboratories. The purpose of the FDA is to provide scientists performing research related to FASTEX with the meteorological and ancillary data collected during the field phase (January–February 1997).

The architecture for the FASTEX data archive:

- Establish a distributed network or a series of archive sites, specialized for each of the instruments (e.g., remote sensing or original in situ from aircraft) generating large data volumes, rather than construct a unique archive of all FASTEX data. In particular, these specialized sites can provide the original raw data.
- Prepare a central site (FCA) for selected processed datasets. Its content is described below.
- Provide, through the FCA, a centralized quick access to information about FASTEX data. This information will be reduced to a vital minimum, for example, what is available and where to access it.

The database within the FCA will cover 20°N, 140°W and 90°N, 40°E. It will include radiosondes from World Meteorological Organization (WMO) upper-air stations, ships equipped for ASAP soundings, and the FASTEX ships. The archive will consist of dropsonde data at high resolution as well as commercial aircraft data. There will be products derived from the remote sensing instruments: wind derived from the profilers on the ships or inland, radiometers, scatterometers, etc., and a number of ground weather radar scans. A limited number of wind and reflectivity fields from the airborne Doppler radars will eventually be provided by the radar scientists. A wide representation of satellite data for both geostationary [Geostationary Operational Environmental Satellite (GOES) and Meteosat] and polar-orbiting satellites (NOAA and DMSP ones) as well as GTS surface data from all land, ship, and buoy sites within the FASTEX domain will also be available.

Finally, operational analyses, and model reanalyses, when available, will provide a composite gridded dataset that will be suitable for diagnostic studies and model initialization. They will take the form of global fields. They will be provided by the Météo-France ARPEGE model, and possibly the United Kingdom Meteorological Office Unified Model. The former will employ a variational analysis technique.

The radiosonde and dropsonde data collected during FASTEX will circulate on the GTS. One purpose is to include some of this data in the operational data assimilation suites so that the planning of FASTEX MSA flights can benefit from (hopefully) better forecasts of cyclone positions and intensity. Another purpose is to construct the FCA in real time. A high-resolution FASTEX sounding set of the FCA will be quality checked using all available operational and research datasets by UCAR–JOSS.

FASTEX data will be available through electronic access from the FCA (for research and educational purpose only). The address is http://www.cnrm.meteo.fr:8000/dbfastex/. Final datasets will eventually be disseminated via CD-ROMs from the FCA.

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Appendix: Expansions of short form terms

ACARS	Aeronautical-radio-incorporated Communication Addressing and Reporting System
AOC	Aircraft Operations Center
AES	Atmospheric Environment Service
ASTRAIA/ELDORA	X-band dual-beam Doppler radar
ASAP	Semiautomatic ship soundings from enroute vessels
CETP	Centre d'éude des Environnements Terrestre et Planétaires
CMC	Canadian Meteorological Centre
CNES	Centre National d'Etudes Spatiales
CNRS	Centre National de la Recherche Scientifique
COSNA	Composite Observing System for the North Atlantic
DNMI	Norwegian Meteorological Institute
DMSP	Defense Military Satellite Program
EGOS	European Group on Ocean Stations

FCA	FASTEX Central Data Archive
FDA	FASTEX Data Archive
FUS	Far upstream area
ESA	European Space Agency
GPS	Global Positioning System
GTS	Global Telecommunications System
IFREMER	Institut Francais de Recherche pour l'Exploitation de la Mer
INSU-CNRS	Institut National des Sciences de l'Univers-CNRS
IOP	Intensive observing period
LAM	Local area model
MIT	Massachusetts Institute of Technology
MFR	Medium Range Forecast
MSA	Multiscale sampling area
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data and Information Service
NOAA	National Atmospheric and Oceanic Administration
NRL	Naval Research Laboratory
NSF	National Science Foundation
NUS	Near upstream area
ONR	Office of Naval Research
RAF	Royal Air Force
RSF	Remote Sensing Facility
SNR	Signal to noise ration
SUNY	State University of New York
UCLA	University of California, Los Angeles
USAF	U.S. Air Force
VAD	Velocity Azimuth Display
VI	Vedusitofa Islands (Icelandic Meteorological Services)
WMO	World Meteorological Organization

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