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Overview of the field phase of the Fronts and Atlantic Storm-Track Experiment (FASTEX) project

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Summary

The field phase of the FASTEX project took place between 5 January and 27 February 1997 with the deployment of a unique set of observing facilities across the North-Atlantic. The major objective was to document the life-cycle of a representative set of mid-latitude cyclones. Other objectives were to test the practical feasibility of "adaptive" observations with a view to improving the prediction of these same cyclones and to document the internal structure of the associated cloud systems using combined airborne Doppler radars and dropsondes. Another goal of FASTEX was to measure air-sea exchange parameters under conditions of strong winds with high seas.

These objectives were successfully achieved. Intensive Observation Periods were conducted on 19 occasions. High-resolution vertical profiles through the same cyclones at three different stages of their life-cycle have been obtained on more than 10 occasions. Calculation of areas where observations were needed to keep the growth of forecast error under control was undertaken using different techniques, and flights were planned and executed in these areas on time. Combined dropsonde and Doppler radar observations of cloud systems are available for 10 cases. A unique air-sea turbulent exchange dataset has been obtained.

Keywords: Cyclogenesis Field experiment Predictability Mesoscale observations

1. Introduction

(a) Background and summary of scientific objectives

The Fronts and Atlantic Storm-Track Experiment (FASTEX) is a decade-long project meant to bring to bear both the recent advances in dynamical meteorology and new observing technologies on mid-latitude marine cyclones, especially those reaching the west coast of continents (Europe in the present case). As a scientific project, FASTEX started in 1993 first as a joint project between French and UK atmospheric groups and soon continued as a fully international operation. Field measurements culminated in an international field experiment in January and February 1997 involving facilities and personnel from 11 nations. The project area covered the entire North-Atlantic basin from the North-American east coast to the European west coast. Aircraft, ships, sounding,

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surface and satellite facilities were used for two months to document the precursors and characteristics of cyclonic storm evolution across this broad area. In addition, special model output and new observing techniques were used to assist in the planning and conduct of this complex field experiment.

A detailed account of the reasons that led to FASTEX, as well as the scientific objectives and initial plans, can be found in Joly *et al.* (1997). The considerable changes that have taken place in recent years in the theory of cyclogenesis are summarized there and will not be repeated here. The essential underlying motivation of FASTEX is the desire of the scientific community to make a concerted effort to address a practical forecast problem, namely the continuing inability of state-of-the-art numerical weather prediction systems to provide reliable warning of storms and related winds, clouds and precipitation FASTEX attempts to study this issue together with other aspects of cylones from many different standpoints.

The scientific objectives of FASTEX may be summarized as follows:

- *To verify cylogenesis theories.* A growing body of evidence (Malardel *et al.* 1993, Joly 1995 from a theoretical standpoint; Ayrault 1998 from a climatological one) strongly suggests that the genesis of a new, small-amplitude cyclone is a process that is relatively independent of its later amplification or development. Numerous mechanisms can be invoked to account for the former: instability mechanisms classically inspired by the Charney and Stern (1962) theorem, triggering of transient vorticity increase (non-modal growth in Farrell's 1984 terminology), control or triggering by environmental deformation, influence of non-local development, etc (selected examples are Schär and Davies 1990, Thorncroft and Hoskins 1990, Bishop and Thorpe 1994, Orlanski and Sheldon 1995, see also Appenzeller 1994 for a review and Ayrault *et al.* 1995 for remarks based on climatological data). The amplification phase, on the other hand, appears to involve a form of baroclinic interaction between vortices at low and upper levels. Related issues are the role of non-adiabatic processes as well as the relevance of the linear assumption to describe any of these mechanisms or phases.
- *To understand the predictability of and improve the forecasts for cyclones.* The recent history of numerical weather prediction is littered with examples of misforecasts of cyclogenesis events, often with associated damaging weather. This problem was at the heart of modern meteorology a century and a half ago, and still persists even with 4D-VAR data assimilation and global mesoscale mesh-size. Some published examples are The President's Day storm (e.g. Uccellini et al., 1984) or the european Great Storm of 15 october 1987 (Jarraud et al., 1989). See also Beugin et al. (1991) and for a very recent example, Hello et al. (1999). The symptom is a non-convergent series of forecasts for the same date and the problem is to identify and to stick to the right forecast.

  The close relationship between theories of cyclogenesis and cyclone predictability has been known since the time of Eady (1949). It has been revisited recently by Farrell (1990) with a pessimistic outcome: whereas Eady mentioned a limit of about 2 days, recent views on error growth reduce this to one day and less. However, in the course of preparing FASTEX, a possible practical answer to this problem emerged. It is called adaptive observing and it is meant to improve the control by observations of the most rapidly developing potentially erroneous structures. The principle is to compute, in advance, the flow structures that are bound to amplify in a given time. Assuming these structures are, at the time of an upcoming analysis, rather local, the idea is to concentrate measurements in this area, so that the structure in question is given its exact amplitude (see for example Snyder 1996). FASTEX is the first full-scale test of

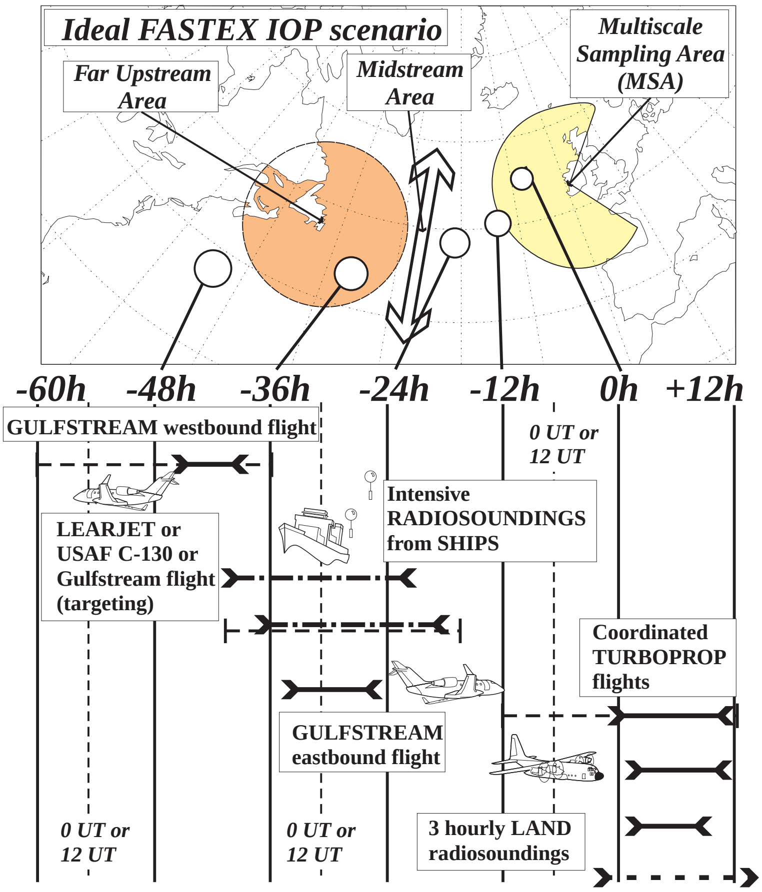

Figure 1. The map shows the North-Atlantic area divided into three adjacent zones where the FASTEX platforms were deployed sequentially. The lower part of the figure shows the ideal deployment along the track of a single event together with an idea of the time-scale.

adaptive observing.

- *To document the meso- and micro-scale organization of cyclone cloud systems.* On the longer time-scales, mid-latitude storm-track cyclones are essential components of the climate system. They generate most deep layer clouds at these latitudes; they also provide much of the significant rainfall. Thus FASTEX is also meant to study cyclones in the perspective of the GEWEX[*] Cloud System Study (GCSS) (Browning, 1994). There are two types of issues in this area:
  - to document the internal organization of layered clouds, which is very partially known at present (see Ryan 1996 and Stewart *et al.* 1998 for recent detailed reviews). An interesting feature is the multiple layering and the associated complex vertical distribution of latent heating and radiative feedback.
  - to study the importance of the fine structure underlying the average properties of these rather large-scale cloud decks. Most of these “anomalies” in the organisation are, in fact, mesoscale organizations taking the form of patches and bands

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[*] Global Energy and Water budget Experiment. Other acronyms are defined in Appendix A.

(see above references and e.g. Parsons and Hobbs, 1983). Although occupying a relatively small fraction of the whole system, they concentrate significant parts of the rainfall generation, stronger radiative impact through thicker or higher clouds, etc. The actual influence of these sub-structures, as well as their life-cycles and origins remain to be determined.

The longer term goals in this area are to establish the water budget and precipitation efficiency of these cloud systems together with a better knowledge of their radiative impact. In practice, this knowledge will be used possibly to develop and in any case to provide validation data for new-generation cloud parameterization schemes including at least one explicit condensed water variable. The better knowledge of the mechanisms leading to mesoscale structures will also help in improving local, short-range forecasting.

- *To measure turbulent air-sea fluxes under strong winds and high seas.* Important efforts have been made, in the past decade, to improve the description of turbulent exchanges between the earth's surface and the atmosphere. These processes are important for both short-range forecasting (prediction of near-surface conditions) and climate simulations. The recent field experiments have measured these fluxes over different types of ground and vegetation. However, most of the earth's surface is, in fact, a sea surface and little is known about turbulence in the middle of ocean basins during high wind speeds. There are very few or no observations available for winds stronger than 15 ms^{-1}. Thus FASTEX was also planned to obtain measurements in this particular parameter domain. The aim is to improve the parameterizations of turbulent fluxes as well as to be in a position to analyse the influence of these exchanges on the cyclone properties. Air-sea fluxes measurements were also the meteorological component of the Labrador Sea Deep Ocean Convection Experiment that took place at the same time as FASTEX (Marshall et al., 1998).

(b) Objectives of the field phase

Essential components of these objectives are difficult to address with existing datasets. The key to FASTEX as a field project is contained in the idea that the evolution of cyclones is likely to be more complex than the continuous growth of some kind of instability followed by a non-linear saturation process. This statement immediately leads to the requirement that entire *life-cycles* have to be documented. Important (and not so recent) ideas on cyclogenesis involve the existence of precursor systems and the possibility of transient interactions between such systems or other flow organizations such as fronts. In order to check these ideas on real cases as directly as possible, cyclones have to be tracked across the ocean throughout their life-history.

It follows that the primary experimental objective of the field phase of FASTEX is to perform numerous direct observations of the structure of the *same* cyclones at several key stages of their life-cycle. The data should, ideally, take the form of precise vertical profiles of the key dynamical quantities (wind, temperature, humidity) covering the whole depth of the troposphere and the lower stratosphere.

Another goal of the field phase is to perform the first real-time implementation of an adaptive observing system for reducing forecast errors for selected cyclones. This requirement is *a priori* quite independent from the one of adapting the observing system in order to capture the growth of an actual cyclone. Since forecast-error control involves the use of well defined numerical algorithms in order to determine the key areas, the FASTEX scientists tended to call this component of FASTEX "objective targeting". The

TABLE 1. Major facilities and participating institutions

Facility	instruments, functions	owner, crew's home institution	Funding agency
CC ÆGIR	radiosoundings (GPS)	Icelandic Coast Guard (IS)	EC
RV KNORR	radiosoundings, (Ω) profilers, fluxes	Woods Hole (USA)	NOAA
RV LE SUROÎT	radiosoundings, (GPS) profilers, fluxes	IFREMER (F)	CNRS, EC
RV V. BUGAEV	radiosoundings (GPS)	UkrSCES (Ukraine)	Météo-France
C-130 (UK)	dropsoundings (GPS)	UK Met Office	UK Met Office
C-130 (USA)	dropsoundings (Ω)	US Air Force	US Air Force
ELECTRA	Doppler radar	NCAR (USA)	CNRS, NSF
GULFSTREAM-IV	dropsoundings (GPS)	NOAA (USA)	NOAA, Météo-France, CNRS, NRL
LEARJET	dropsoundings (GPS)	FIC (USA)	NSF
WP-3D (P3)	radars (1 Doppler), dropsoundings (GPS)	NOAA(USA)	NOAA, CNRS, Météo-France
Increased soundings on a regular basis	6h soundings	CAN, Greenland, IS, IE, UK, F, SP, Azores (P), Bermuda, DK	Countries, WMO, EC
Increased soundings on alert	6h soundings	USA	NCAR, NOAA
	3h soundings	IE, F, UK	Countries
Buoys	surface obs.	EGOS	EGOS
Operations Centre at Shannon	monitoring, forecast	Aer Rianta (IE)	EC
Staff of Shannon Ops Centre and Scientific crews	forecasters, scientists	CNRS(F), CMC(CAN), JCMM(UK), Met Eireann(IE), Météo-France(F), NCAR(USA), NOAA(USA), NRL(USA), UCAR(USA), UCLA(USA), UK Met Office(UK)	Institutions, NSF, EC
Staff of US targeting operations	forecasters, scientists	MIT(USA), NCEP(USA), NCAR(USA), Penn State U.(USA), U. of Wisconsin(USA)	NOAA, NSF

Agencies without direct participation: European Commission (EC),
European Group on Ocean Station (EGOS),
National Science Foundation (USA),
World Meteorological Organisation (WMO).
GPS: wind measurement technique based on the satellite Ground Positioning System.
Ω: wind measurement technique based on the Omega navigation system.
see Appendix A for other acronyms.
Selected Country Codes: CAN: Canada, DK: Denmark, F: France, IE: Ireland,
IS: Iceland, P: Portugal, SP:Spain.
For details on instruments and platforms, see either Joly et al. (1997)
or the FASTEX Data Base online documentation (section 8).

task of observing different stages in the cyclone life-cycle, on the other hand, depends on reading synoptic charts and looking at satellite images with concepts in mind, and in this case the method of selecting critical features was commonly referred to as "subjective targeting".

The primary objective concerning the organisation of mature cyclones was to describe their three-dimensional precipitation and wind structure over a 1000 by 1000 km domain using a combination of dropsondes and airborne Doppler radar. These sensors were deployed in a manner that systematically covered as much of the cyclone with a regular grid of data assimilation and validation of numerical simulations.

Finally, another objective deriving directly from the scientific objectives mentioned previously is to document turbulent fluxes in high winds in mid-ocean. The article by Eymard et al. (1999) provides the details and some results.

The present overview is meant to give a first idea of how well these goals have been reached. It is laid out as follows. The next section summarizes the plans for operations and the facilities available and section 3 summarizes the large-scale weather characteristics during FASTEX. Then, two examples of FASTEX cases are presented so as to convey an impression of the type of systems of interest and of the type of operations. These sections are meant for readers who are looking for story-like accounts of what FASTEX operations really are. Those readers only looking for overall information may skip these sections and go directly to a summary of all operations and a preliminary subjective characterization of all the cases which is presented in section 6. Two short sections address the forecasts (section 7) and the Data Base (section 8). The article concludes with comments on the outcome of the operations (section 9).

2. Observing strategy and platforms

In order to achieve the primary experimental objective of FASTEX, namely to follow a number of cyclones throughout their life-cycle, a special distribution of observing facilities had to be devised (Fig. 1). The North-Atlantic area has been divided into three adjacent areas: the "Far Upstream Area", centered on the airport of St John's in Newfoundland, the mid-stream area, centered about the longitute 35°W and the Multiscale Sampling Area (often termed MSA). The Multiscale Sampling Area was focused on Shannon airport in Ireland.

The purpose of enhancing observations in the Far Upstream Area is to observe the early stages of the formation of a new cyclone, possibly its genesis. The Far Upstream Area is also the primary area for collecting the observations for the predictability (targeting) objectives.

The purpose of enhancing observations in the midstream area is to fill, as well as possible, the well known "data void" in the middle of the oceanic basin. It is located at the end of the most persistent (or least variable) part of the storm-track, a very good place to catch the developing phase of many cyclones. It is also a good location for frequent encounts of the strong winds and high seas required for the measurements of air-sea fluxes.

Finally, the Multiscale Sampling Area is where the mature cyclones and their cloud system are to be observed with, as the name suggests, the possibility to collect data on their structure at several different scales.

Table 1 summarizes the observing platforms and instruments available for FASTEX. It also provides the list of institutes, agencies and organizations that have supported the project. A much more detailed table on instruments and facilities can be found in Joly

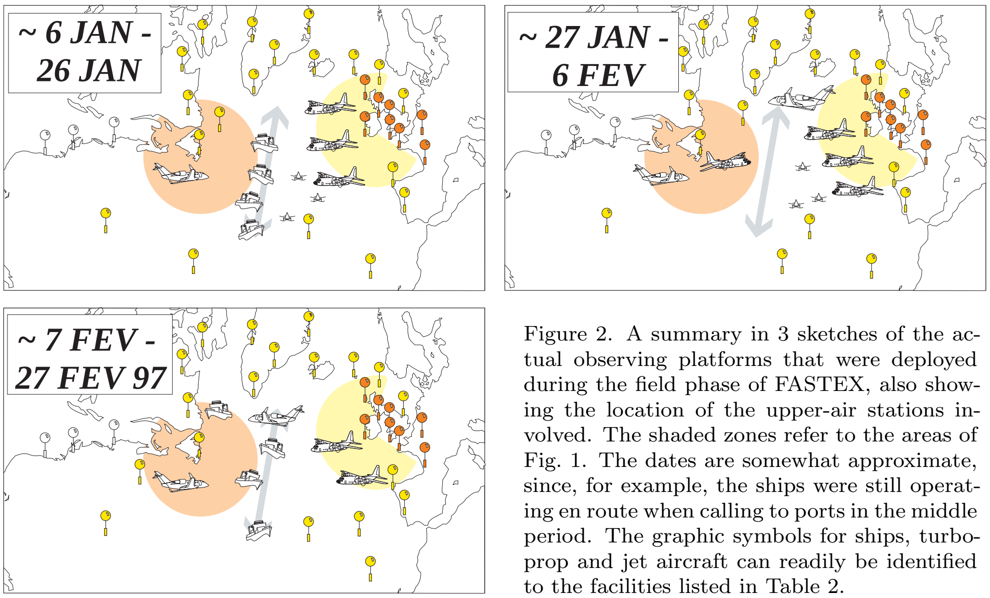


Figure 2. A summary in 3 sketches of the actual observing platforms that were deployed during the field phase of FASTEX, also showing the location of the upper-air stations involved. The shaded zones refer to the areas of Fig. 1. The dates are somewhat approximate, since, for example, the ships were still operating en route when calling to ports in the middle period. The graphic symbols for ships, turboprop and jet aircraft can readily be identified to the facilities listed in Table 2.

et al. (1997). The present table has been updated with the actual facilities available, but there are few changes.

The bottom half of Fig. 1 shows the basic strategy to deploy these facilities in the course of a FASTEX Intensive Observations Period (IOP), namely successively in time, for a period that can be as long as 60 h. A further lead time of 30h to 42h is needed for logistical reasons. The “constitutive” decision to launch an IOP has to be taken, therefore, on the basis of 84h or 96h forecast products. It depends on the strong expectation of a significant cyclone moving into the Multiscale Sampling Area: the estimated time for this to happen sets the reference date, denoted 0h in Fig. 1. This decision-taking problem can by called the “FASTEX dilemma”: FASTEX is motivated by the difficulty of making reliable cyclogenesis forecasts at practically any range but for FASTEX to collect the data required to understand this problem, reliable medium-range forecasts are required. One practical step that was taken was to transmit in real time via the Global Telecommunication System as many extra observations as possible so as to improve the performance of the operational numerical weather prediction systems.

The diagram in Fig. 1 also shows the main facilities and the way they were employed in FASTEX. It does not show the significant uplift of the background observation network made from the conventional World Weather Watch upper-air stations: from Canada to Bermuda, including Greenland, Iceland, the Faroes, Ireland, the Azores and the European west coast, about 30 stations performed 6-hourly soundings during the whole two months of the FASTEX field phase. A number of commercial ships equipped for launching sondes more or less automatically also contributed to this improvement. The USA similarly re-inforced 4 of their stations but on an alert basis. Furthermore, the number of drifting buoys in the Central Atlantic has also been significantly increased. In these ways, practically *all* cyclogenesis events that took place within the two months are better documented than usual.

The main aircraft employed during FASTEX are a LearJet based in St-John’s and operating in the Far Upstream Area, temporarily reinforced by two C130s from the US Air Force. The Multiscale Sampling Area was covered by the C-130 from UKMO, the Electra from NCAR and one P3 from NOAA. All areas could be reached by the Gulfstream IV jet of NOAA, normally based in Shannon, but located in St-John's on occasions. Finally, the backbone of the midtsream observations is a set of up to four ships.

Early in the planning of FASTEX, it was realised that the ships, in order to be useful all the time, would have to remain in the vicinity of the main baroclinic zone. The effectiveness of this approach was demonstrated in an idealized observing system simulation experiment (Fischer *et al.*, 1998). The idea of having ships moving with a weather feature in the middle of the ocean generated many comments from reviewers of the project. The idea, however, was simply to compensate for the relatively slow meridional motions resulting from the low frequency evolution of the flow, not to track the cyclone themselves. Practical experience during FASTEX revealed that this idea was quite feasible: the predictability on this scale was good enough and the resulting displacements manageable in spite of difficult seas.

A climatological study partly summarized by Ayrault *et al.* (1995) suggests that, in order to be able to sample ten cyclones well, a period of two months is needed. FASTEX was planned on that basis. The detailed plans of operations, together with the various flight patterns to be considered for the different types of aircraft and missions, are described in the FASTEX Operations Plans (Jorgensen *et al.*, 1996). The actual observing system available during the two months field season is shown in Fig. 2. Roughly speaking, the observing problems divided into three periods. During the first period the Gulfstream aircraft was largely unavailable. During the second period, the ships had to call into ports. During the last period the Electra aircraft had to be withdrawn for mechanical reasons. One of the ships (the RV Knorr) was reassigned to another project, the Labrador Sea Deep Convection Experiment (Marshall et al., 1998). However, the crew still maintained a link with FASTEX and actually took part in some IOPs. On the positive side, the first period was run with four ships as planned and an intercomparison of the flux measurements took place; all the other components performed quite well. In particular, the first complex coordinated flights in the Multiscale Sampling Area were a success. In the second period, the Gulfstream became fully available and two C-130 were provided by the US-Air Force: they took part mostly to the test of adaptive observations but, to some extent, they also replaced the ships (as in IOP 9, for example). Finally, during the last period, when some of the most interesting cyclones occurred, all the available components were employed at their full potential.

3. Meteorological conditions

The notion of weather regime, as defined by Vautard *et al.* (1988), is useful for highlighting conditions favourable to the type of event of interest to FASTEX. A regime, in this sense, is a quasi-steady configuration of the large-scale flow. The regimes, listed in order of increasing suitability for FASTEX, are known as the Blocking regime, the Greenland Anticyclone (or Southern Zonal) regime and the Zonal regime.

Averaged meteorological conditions relevant to the FASTEX period are displayed in Fig. 3. Analysed fields have been projected on the weather regime fields to determine, daily, the closest one. On this basis, it appears that there are three distinct periods. The year 1997 starts with a fortnight of Greenland Anticylone regime, although in practice, it is more an Icelandic ridge than a true anticyclone. The actual mean flow for this period, although close to this reference climatological regime, also shares some characteristics of the highly unfavourable Blocking Regime. Thus systems remain at relatively southern latitudes in general but are able, on occasion, to move north-eastwards and to establish

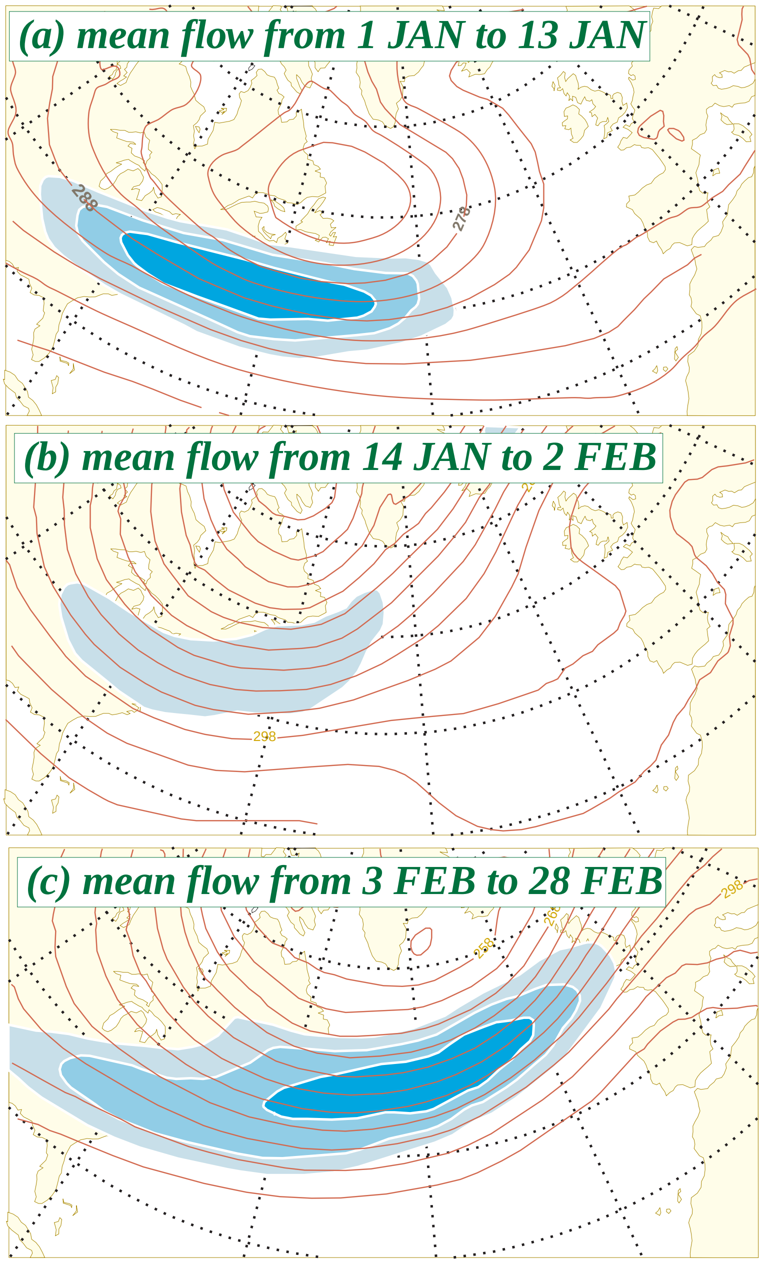
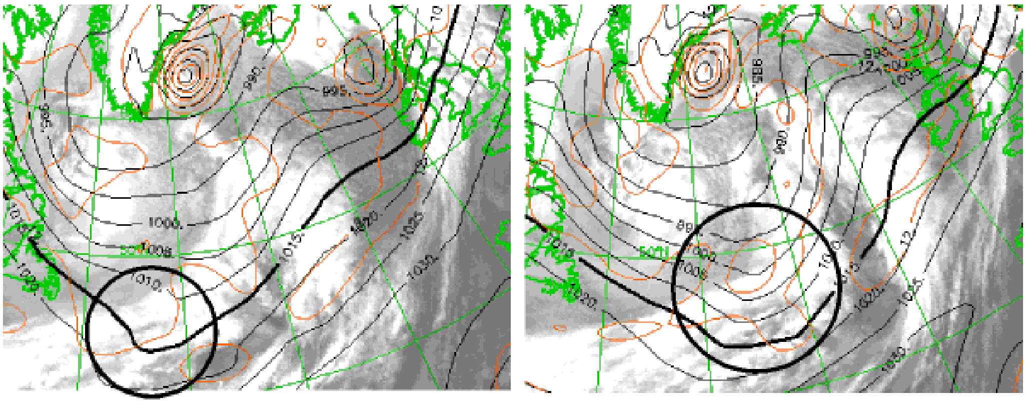


Figure 3. A summary of the averaged meteorological conditions during FASTEX. Contours are 700 mbar geopotential (every 5 damgp) and the three intensities of shading indicate 300 mbar wind in excess of 40, 45 and 50 ms^{-1}. Figure prepared by B. Pouponneau, Météo-France, using the ARPEGE analyses included in the Data Base.

(a) 9 FEB 97 00UTC (b) 9 FEB 97 06UTC



(c) 9 FEB 97 12UTC (d) 9 FEB 97 18UTC

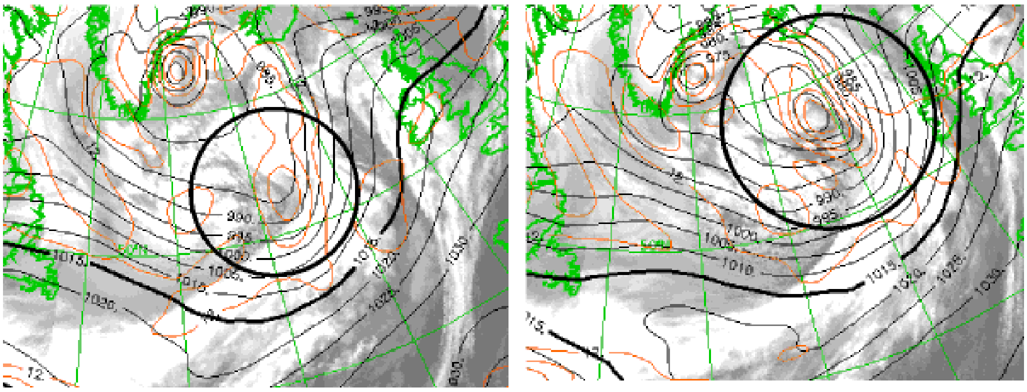


Figure 4. Development of Low 34 on 9 February 1997, FASTEX IOP 12. Low 34 is encircled by a heavy black line. Images are in the infra-red channel and are a composite of METEOSAT and GOES. Two fields from the operational Météo-France analysis (that includes FASTEX data) are superimposed. The dark grey lines are absolute vorticity at 850 mbar from 1.2×10^{-4} s^{-1} every 0.5×10^{-4} s^{-1}, unlabelled. The light black lines are mean-sea-level isobars, drawn every 5 mbar, with reference contour drawn heavier.

temporarily a baroclinic area extending from the end of the average wind maximum to iceland. It also means that the baroclinic driving of the weather systems near the European side is quite weak (on average) and their behaviour sometimes unusual.

The second half of January is dominated by Blocking.

The whole of February, finally, is characterized by the desired Zonal regime. It is associated with rather low total variability, meaning that it is very stable. On average, the wind at 300 mbar is 10 ms^{-1} stronger than its climatological value, with a baroclinic guide extending unbroken from Halifax to Kerry in Ireland. Around 17 February, the jet peaks at about 100 ms^{-1} for about two days. These conditions provide suitable cyclone events.

During FASTEX, all the lows moving over the North-Atlantic ocean have been numbered sequentially. During the two months of the field experiment, about 50 lows have crossed this broad area. A complementary description of the FASTEX period is given in terms of cyclone tracks by Baehr *et al.* (1999) in this issue.

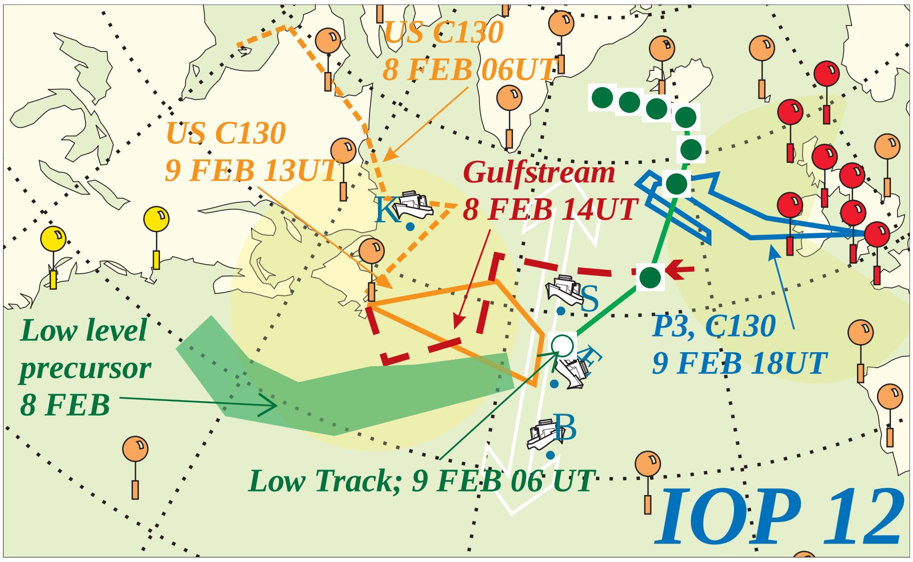


Figure 5. Schematic diagram of the operations during IOP 12. The large dots form the track of Low 34, marked every 6h, an open circle corresponding to an open wave. The dotted area indicates the zone where the surface precursor formed. The ships are shown at their location during the phase of intensive soundings. All upper-air stations shown (balloon symbols) were operating every 6h except the darkest ones which were operating every 3h. The tracks show the various successful flights. The difficult and eventful St-John's–Shannon flight of the Gulfstream IV on 9 Feb is not shown because no data were taken.

4. Example of an Intensive Observations Period: IOP 12

The best way to convey a flavour of FASTEX operations is to summarize the story of one Intensive Observing Period. Readers familiar with field operations spanning several days from one side of an ocean to the other may jump to the general overview in section 6. Because of its unique mixture of exciting meteorology and dramatic operational events, IOP number 12 is now presented.

The meteorology is discussed first. IOP 12 is conducted on Low 34. This cyclone undergoes, on 9 February 1997, the most explosive deepening of the period: roughly -54 mbar in 24h, with a phase of -23 mbar in 6h. This very rapid development goes along with a very short life-cycle. It is summarized by Fig. 4. The background shows infra-red images composited from both geostationary satellites GOES and METEOSAT. The figure also shows the mean-sea-level pressure and low-level vorticity analyzed by the Météo-France operational suite ARPEGE. An individual vorticity maximum can be tracked from 9 February 00UTC onwards, whereas closed isobars can be seen only when the low is fully developed, after 18UTC. The analysed sea-level pressure falls from about 1015 mbar on 8 February 18UTC to 961 mbar on 9 February 18UTC. Between 6UTC and 18UTC 9 February, Low 34 moves about 1700 km at a phase speed of nearly 40 ms^{-1}.

The first tentative plan for a possible IOP 12 on a Low 34 is drafted on the basis of the forecasts starting on 5 February 00UTC and, for the ECMWF model, 4 February 12UTC. As the Low is expected to be in the western part of the MSA on 10 February 00UTC, it is important to note that these are 120h and 132h respectively. As summarized in section 7 below, decisions for FASTEX are prepared using an “ensemble” of many different numerical models. Needless to say that there is a wide discrepancy in the various forecasts, but at the same time, there is enough consistency to convince the team of forecasters that a new IOP may be declared. As soon as 5 February 12UTC, a westbound flight of the Gulfstream-IV jet aircraft is planned for 8 February, a return flight on 9 February and a coordinated MSA flight of turboprop aircraft on 10 February. The case is believed, at that time, to be a rapid deepener.

These decisions are confirmed on the following day, that is 2 days prior to the first airborne operation relating to IOP 12, and 3.5 days before the cyclone speeds into the MSA. The ships are informed of the likely IOP scenario and that they will have to perform 3h radiosoundings for 24 hours as from 8 February 12UTC. On 6 and 7 February, the day prior to the beginning of IOP 12, the discrepancy between the various forecasts becomes quite large and Low 34 turns into an unexceptional event except in the 72h ARPEGE forecast. These are signs that the case is a good one for testing the adaptive observation strategy: specific targets for this system are determined by the various groups involved in this aspect of FASTEX: the NRL in Monterey, NCEP in Washington, ECMWF in Reading and Météo-France in Toulouse. Contacts are made between the project headquarters at Shannon and Washington to try to coordinate "targeting" flights between aircraft already based in St-John's and the Gulfstream-IV, set to join them on 8 February. A few more soundings are ordered from the ships in order to face new possibilities, including another wave cyclone.

The actual operations managed on this case are summarized by Fig. 5. Low 34 behaves more or less as anticipated from the 48h or so forecast runs. The Gulfstream-IV properly samples the predictability "target". The ships, although fully in the track of the cyclone and accompanying gale force winds, manage to perform the required soundings. The USAF C-130 flight on 9 February samples the wake of Low 34 in case a secondary Low 34B shows up (the data may help explain why it did not). However, shortly after the Gulfstream-IV took off from St John's for what should be an optimal flight sampling the structure of a deepening cyclone, one of its electric generators stops functioning. The flight is completed safely, albeit with much anxiety. Then, there is the possibility to study the detailed structure of the cloud system with dropsondes from the C-130 and both airborne Doppler radars. The UKMO C-130 and the P3 aircraft take off successfully but the mechanical problem of the Electra prevents it to join them. Radio communications with the other two turboprops allows for in-flight adjustment of the plans to compensate for the absence of the Electra and a successful operation results. Valuable data has been obtained at various stages of the evolution of Low 34 .

Figure 6 illustrates features of interest during the development of Low 34, as seen from the ships. The Ægir Coast Guard vessel was directly in the path of the cyclone and its low-level thermal structure clearly shows up, between 0 and 6 on 9 February in the form of a narrow warm conveyor belt. Most interesting, however, is the tropopause anomaly that can be seen moving above the Ægir during the evening of 8 February. As shown in the figure, this anomaly is on the wrong side of the low for constructive baroclinic interaction. Analyses show that it takes place earlier on 8 February, but the upper-level anomaly moves eastward at 43 ms^{-1}, while the surface precursor, a warm maximum in the soundings from the Ægir travels at 19 ms^{-1}. The rapid development is due instead to the influence of a second upper-level anomaly, more intense, that can be seen in the soundings from the Suroît ship at 12UTC on 9 February.

From the point of view of the dynamical objectives of FASTEX, this case shows the reality and importance of transient baroclinic interaction between two features as well as the fact that a strong cyclone does not emerge from continuous growth. Rather, it grows in steps and each can involve different features. This indicates that one needs to be very careful when defining a system of interest.

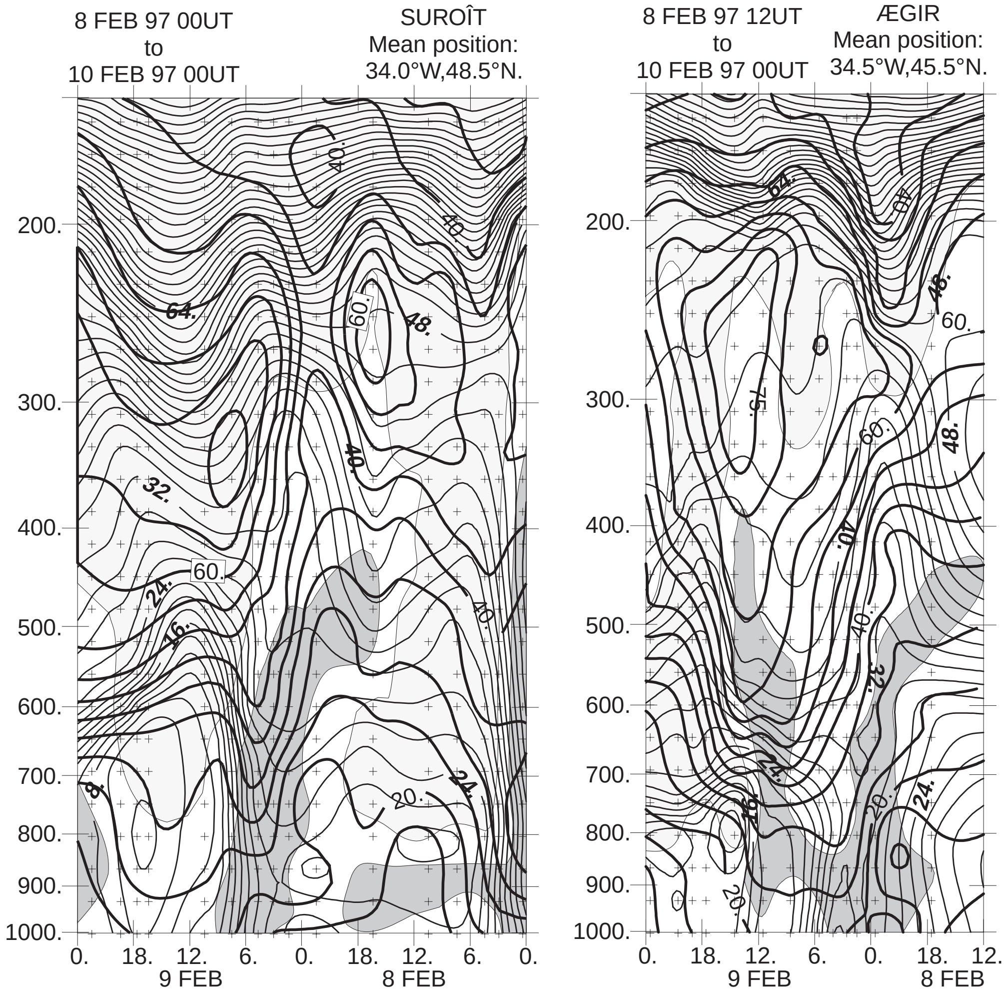


Figure 6. Vertical-time cross-sections derived from the radiosoundings taken from RV Suroît (left) and CC Ægir (right) during IOP 12. The time scale has been reversed so that the figures are suggestive of vertical cross-sections with West to the left and East to the right. The heavy solid lines show the wind speed every 5 ms^{-1}. The light solid lines are θ_w every 2 K. Light grey shading marks the location of very dry air (less than 40 % relative humidity). Darker shading indicates likely cloudy areas (more than 80 % relative humidity). The small crosses indicate the data points. The analysis has been performed with spline functions. Figure derived from the soundings from the FASTEX Data Base, courtesy of G. Desroziers from Météo-France for the analysis.

5. The Lesser Observations Periods during FASTEX

According to the previous section critical decisions regarding IOP 12 are taken 3 days before the system even existed. Difficulties raised by the differences between forecasts have been alluded to, and there are others resulting from operational constraints. It is because of the operational constraints that Low 33 (top right corner of Fig. 4(a)), although the type of system of interest to FASTEX, was not the subject of intensive observations: the rapid succession of IOPs 9 to 11 imposed a break in the operations.

Yet Low 33 is by no means totally deprived of special observations. 54h prior to Low 33 entering the MSA, a long flight of an USAF C-130 from St-John's covered the

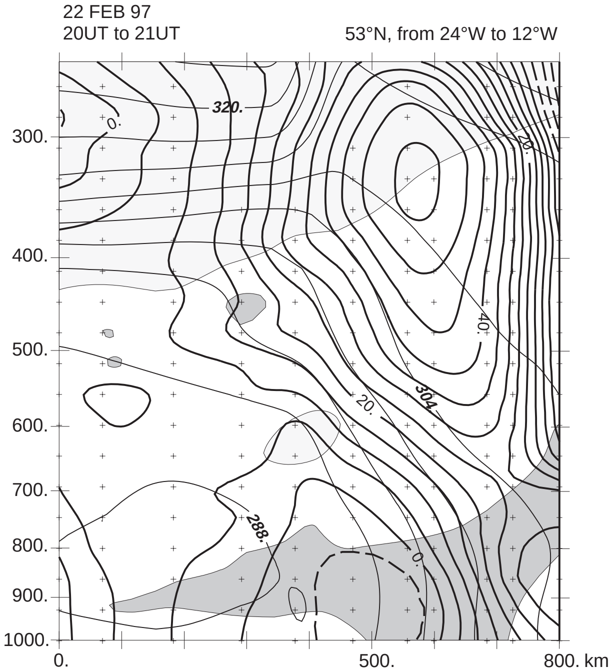


Figure 7. Vertical cross-section derived from the dropsoundings taken from the Gulfstream-IV aircraft at the end of a flight part of IOP 18, but describing the cyclone 42B that was not selected for an IOP. Contours and shading are as in Fig. 6, except θ_w drawn every 4 K. The analysis has been performed with spline functions by G. Desroziers using the FASTEX Data Base.

broad area around 50°W and 45°N where the low starts to form later. The ships are on the track of this low as well and performed 8 soundings per day on 7 and 8 February as Low 33 developed. And finally, as the Gulfstream flies towards St-John's on 8 February, it samples the same low, still undergoing deepening, with a series of dropsoundings, providing a minimum set of data in the MSA. These are the components of a mildly successful IOP and so this case has been included in the FASTEX set. It was, indeed, labelled IOP 11A for a time.

Low 33 is not an isolated case. After the field phase was completed, a second set of systems has been added to the main FASTEX Intensive Observations Periods: the FASTEX Lesser Observations Periods (FLOP). They fall into two categories: the first is made up of the cases like Low 33 that are only partially covered for logistical reasons. The second category is, given the objectives of the project, quite an important one: it contains the cases only partially covered because they are wrongly anticipated by the forecasts. They epitomise the "FASTEX dilemma" mentioned in section 2 Since FASTEX is about understanding predictability, looking back on these cases can be helpful. Figure 7 illustrate a case falling in the second category, one model only having predicted its existence at the time a decision had to be made for an IOP 18. This figure also shows the capabilities of the Gulfstream-IV to map cyclone-scale features. These two cases are now included in this series of interesting cases as LOP 2 and LOP 5.

6. Summary of operations and overview of cases

This section takes a broader perspective and presents the complete set of FASTEX cases. There are 25 of them: 19 IOPs were declared and run as such, 6 LOPs were included at the end of the field phase, when the whole period was reassessed (FASTEX was initially planned to allow the study of 10 cases). Almost all cases concentrate on a particular type of cyclone or on a feature such as a front that did not allow for a cyclone

TABLE 2. Summary of operations on each FASTEX case

	Soundings at 3 successive stages	Upstream data for targeting	Ship data for targeting	Upstream data for dynamics	Ship data for dynamics	MSA sampled with dropsondes	Airborne Doppler data in MSA	3hourly European west-coast soundings
IOP 1	–	–	–	–	end ampli	●	ss **	**
LOP 1	–	–	24h	–	beg ampli	–	–	**
IOP 2	●	36h	48h	–	–	●	mi ***	**
IOP 3	–	48h	24h	gen	ampli	–	–	**
IOP 4	–	–	48h	–	organ	–	–	**
IOP 5	●	48h	36h	–	organ	●	mi **	**
IOP 6	–	–	18h	–	beg sup	●	–	**
IOP 7	–	–	18h	–	front	● ●	ss ***	**
IOP 9	●	42h	(C130)	ampli	(circl)	●	mi **	***
IOP 10	●	18h	30h	gen	beg gen	●	ss ***	***
IOP 11	●	36h	18h	beg ampli	front	● ●	ss **	**
LOP 2	●	48h	18h	–	ampli	●	–	–
IOP 12	●	30h	12h	rear gen	beg ampli	●	ss **	***
IOP 13	–	48h	48h	circl	beg dec	–	–	–
LOP 3	–	48h	48h	–	beg gen	–	–	–
IOP 14	–	48h	24h	–	beg dec	–	–	–
IOP 15	●	24h	18h	rear	ampli	●	ss **	*
IOP 16	●	24h	12h	–	beg gen	●	ss ***	***
LOP 4	–	48h	24h	–	clust	–	–	***
IOP 17	●	42h	18h	ampli 1	wave	● ●	ss ***	***
LOP 5	–	–	36h	–	beg gen	●	–	–
IOP 18	●	36h	12h	gen	ampli	●	mi **	***
LOP 6	–	48h	36h	–	beg dec	–	–	***
IOP 19	●	30h	24h	wave	sup waves	●	–	**

Abbreviations for life-cycle stages:
beg: early step of stage
gen: genesis
rear: rear (western) component
circl: soundings all around system
clust: cloud cluster
ampli: amplification, deepening stage(s)
organ: organisation, "shaping"
sup: suppression (of waves)
dec: decay.

Symbol ● means "yes" or "present"
Symbol ● ● marks that 2 sets are available.

Targeting lead times: the figures are orders of magnitude based on the life-cycle of the systems. They are not the exact values employed by a particular targeting group.

Coverage in the MSA:
ss: systematic survey
mi: mesoscale investigation
**: 70–80% sucess rate of sampling
***: 100% success rate of sampling.
From IOP 12 onwards, the Electra is removed.

European west-coast radiosoundings:
* means that only the UK stations actually on the west coast were active.
** means that only the stations actually on the west coast were active.
*** means that all the participating stations were active.

to form. All these cases are in line with the objectives of the project: the sole exception is IOP 8. IOP 8 takes place, during the blocking period, when no cyclone can possibly reach the eastern Atlantic. In order to maintain a minimum of activity, a flight from the Gulfstream is set up and directed towards Greenland in order to document upper-level lee waves. However, apart from the fact that the flight intersects a coastal front, this IOP is difficult to include in the summary tables fitted for cyclones.

The achievements of the field phase of FASTEX are summarized in Table 2. Ap-

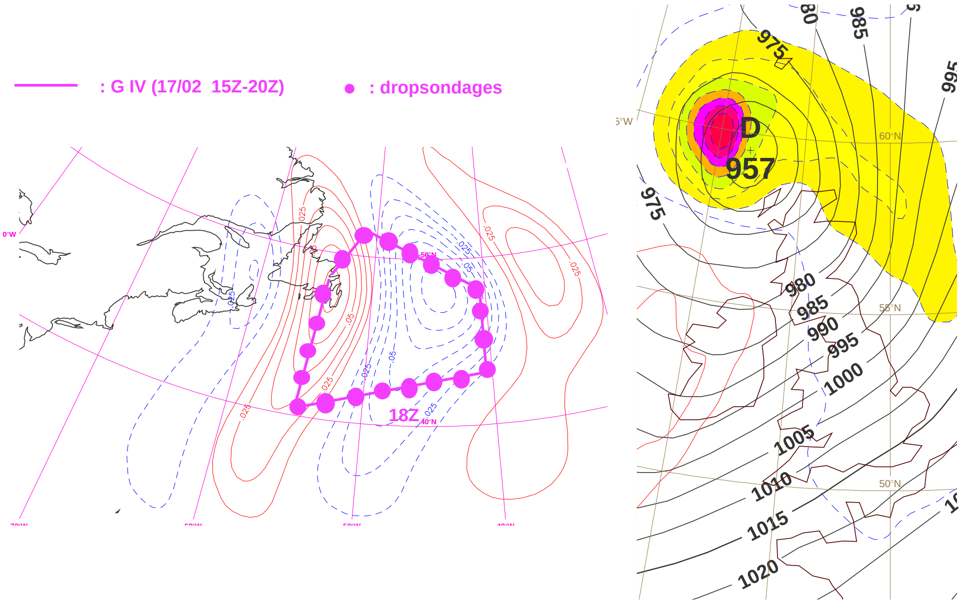


Figure 8. An example of practical adaptive observation and of its impact. Using a forecast starting 16 February 00UTC, singular vectors maximizing the growth of enstrophy anomalies between 17 February 18UTC and 19 February 12UTC and ending in the vicinity of Ireland have been computed at Météo-France in Toulouse from a terminal in Shannon in the morning of 16 February. This computation uses the tangent linear and adjoint version of the global ARPEGE model. The left panel shows the 700 mbar temperature perturbation of the most unstable singular vector on 17 February 18UTC and the flight plan proposed for the Gulfstream IV at that time, all this having been derived and decided on 16 February. The right panel shows the mean sea level pressure field on 19 February 12UTC (black lines, every 5 mbar) and the impact of the data collected by the Gulftstream flight (thin dashed lines and shading, contour interval 2 mbar), transmitted in real time and assimilated in Toulouse in the ARPEGE operational suite. Similar calculations were performed in Monterey, at NRL, in Washington at NCEP and in Reading at ECMWF. Figure courtesy of T. Bergot, Météo-France.

pendix B provides more detailed information on each FASTEX case (including IOP 8): key dates and locations, flights and other operations: Table B.1 presents the Intensive Observations Periods and Table B.2 the Lesser Observations Periods.

(a) Potential for dynamical meteorology studies

The primary objective of the field operations was to collect special data, in the form of vertical profiles, at three or more stages of the evolution of a number of cyclones. The first column of Table 2 shows that this is achieved in 12 cases. The criteria for success are: special soundings have been taken successively in *(i)* the Far Upstream Area either at an early stage of the weather system of interest or in a likely sensitive area for predictability; *(ii)* the Midstream Area, mostly by the ships or by the Gulfstream or a C-130; and *(iii)* in the Multiscale Sampling Area, the last two being within or close to the weather system.

There is, of course, a hierarchy amongst the successful cases, depending on the number of completed soundings, their location in space and time with respect to the system, the presence of upper-level data or the number of samples collected. The most comprehensively observed one is IOP 17. It takes place from 17 to 20 February. The weather system, Low 41, forms off the East-Coast of America from multiple precursor features. It has been tracked for 67h, over a distance of 5500 km. The ships are properly located, the Suroît having moved in time to be on the track of this low. They manage, in spite of the wind and the sea, to perform soundings every 90 minutes as the low moved over them. Five successive flights are performed and another earlier flight, on the 16th, can perhaps also be included, from the predictability point of view. During three of these flights, dropsondes are launched from above the tropopause. About 400 soundings are taken in and around Low 41, 230 of which are made from the ships and the aircraft. Dynamically, this low illustrates many of the features or behaviour that led to FASTEX: non-spontaneous genesis in a complex environment, multiple phases of growth, temporary tendency to split into two lows with forecast development of these centres varying greatly between models and explosive deepening. Some of these features are discussed in Arbogast and Joly (1998) and in the IOP 17 trilogy of Cammas *et al.* (1999), Mallet *et al.* (1999a, 1999b).

It can be said, therefore, that the key experimental objective of FASTEX has been reached. There are, furthermore, significant data for addressing more focused dynamical issues. There are a number of rapidly developing cyclones (see Table 3 for a summary) but, as a control for checking current ideas on the way development can be hindered under certain circumstances, there are a few non-developing systems as well (see the work of Chaboureau and Thorpe, 1999 and Baehr *et al.* 1999). As will be discussed below, a large number of types of systems has been collected; several critical features or phases have been directly observed, such as the genesis of a wave (IOP 10), a number of cases of the amplification phase, jet inflows and outflows. The most characteristic ones are listed in columns 4 and 5 of Table 2.

(b) Potential for adaptive observations studies

The numerical products needed for "objective targeting" operations have been exploited in two different places: the NCEP products were analysed in Washington (USA) while the NRL, Météo-France and ECMWF products were interpreted in Shannon. Coordination was made possible by the presence of a representative of the Washington group at Shannon, Dr. Snyder. See e.g. Bishop and Toth (1999), Gelaro *et al.* (1999), Bergot *et al.* (1999), Langland *et al.* (1999) for more details.

As a result, a large amount of data are available for impact studies on predictability. Column 2 of Table 2 lists the cases for which datasets have been obtained in the Far Upstream Area; the corresponding forecast range is also given. Note that in relative terms the quality of short-range forecasts for some FASTEX cyclones was below that of longer lead time forecasts. The data from the ships can be used in studies of predictability at the shorter ranges. They are very often well located with respect to sensitive areas.

An important aspect not reflected in this table is the experience gained in the actual practice of "targeted observing". The general approach is to take a 96h or 72h forecast (typically) and to calculate where data should be collected during the next 24h in order to reduce the uncertainty at the end of the upcoming 48h forecast over a given area or system. The earliest calculations are needed to book airspace. The next batch of calculations can be used to construct a flight plan. In order for the sensitive areas to be of a reasonably small size, it is necessary to focus the verification area on a particular system in the forecast. It has been generally possible to fly to the location determined by the predictability calculations, but not always, because of air traffic control constraints. The actual flight time depends on a highly complicated mixture of meteorological and logistical constraints, and so it is not practical to work with set times: all the time parameters have to be adjusted "on the fly". The most successful groups were those that considered the need for this flexibility in their planning. The feasibility of real-time

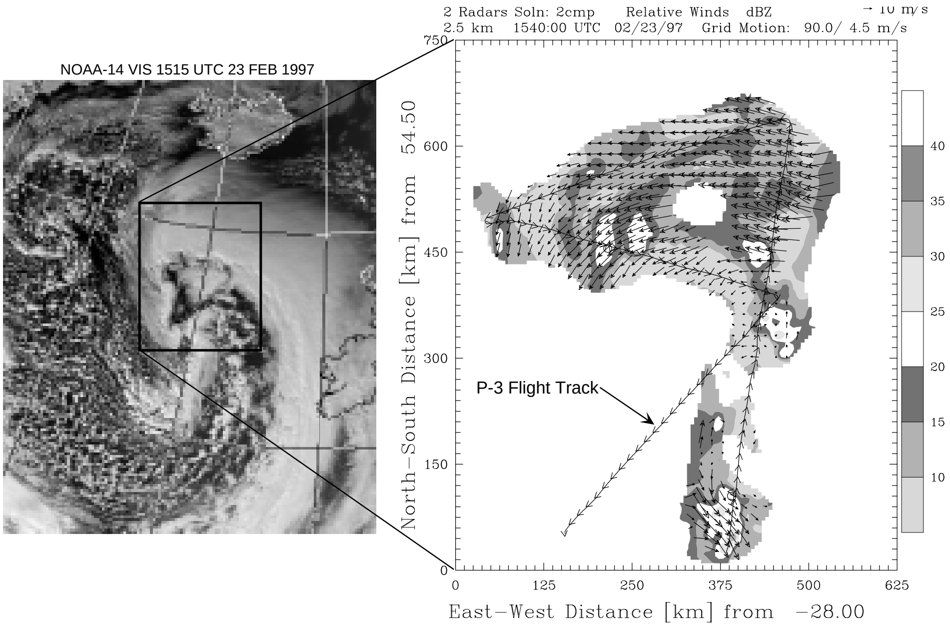


Figure 9. NOAA-14 visible image of the cyclone of IOP 18 at 1515 UTC (left panel). Airborne Doppler analysis of system relative winds at 2.5 km at 1540 UTC (right panel). The analysis domain of the Doppler wind field is shown by the box on the satellite image. Shading on the radar image shows the reflectivity. Figure courtesy of D. Jorgensen from NOAA.

adaptive observing has been demonstrated, but the degree of flexibility required is very significant. An example of target determination, associated flight plan and impact of the data collected as a result is shown in Fig. 8. The effectiveness of this strategy is discussed in the work of Szunyogh *et al.* (1999), Bergot (1999b), Bishop and Toth (1999), Langland *et al.* (1999) and Pu and Kalnay (1999).

(c) Potential for cloud-system and mesoscale studies

This category of objective has suffered from the premature withdrawal of the Electra. Nonetheless, good datasets were collected from the very start of the field phase as indicated in the last three columns of Table 2. This is due, to a large extent, to the high degree of cooperation achieved very early in the project by the scientists involved as well as to their ability to explain their operations to the aircraft crews. The success is also attributed to the development, by the JCMM and NSSL scientists of software to perform system-relative, multiple-aircraft flight planning. The complexity of coordination resulted from the need subsequently to analyse the structure of the core of the cyclones with quasi-regular flight pattern in system-relative space. In one configuration, the same sampling area is to be covered by both dropsondes and adjoining airborne Doppler radar swaths. This mode of operation, called “systematic survey” has been tested succesfully in the very first IOP. The flight planning problem is not simple and its proper handling by scientists and crews is one significant accomplishment of the project.

Systematic survey patterns have been achieved on 4 occasions with three aircraft and another 4 occasions with two aircraft. Bouniol *et al.* (1999) present results of such a flight made during IOP 16. In four other IOPs, detailed observations of mesoscale features embedded within the cyclones were obtained by airborne Doppler radars in an

TABLE 3. Subjective synoptic characterization of the FASTEX cases

	Comma cloud-like feature	Second generation wave	Rapid development stage	Clear stage of baroclinic interaction	Suppressed waves (stable front)
IOP 1	–	front	–	●	–
LOP 1	–	jet/front	–	–	–
IOP 2	●	front	–	–	slow gen
IOP 3	–	–	●	●	–
IOP 4	●	–	–	–	–
IOP 5	●	–	–	–	–
IOP 6	–	tempo	–	–	●
IOP 7	–	tempo	–	–	●
IOP 9	–	jet/front	–	●	–
IOP 10	–	front	–	–	–
IOP 11	–	–	●	●	–
LOP 2	–	front	–	●	–
IOP 12	–	jet/front	● ●	●	–
IOP 13	–	–	–	●	–
LOP 3	–	front	–	–	–
IOP 14	–	–	–	●	–
IOP 15	–	jet/front	●	●	–
IOP 16	–	jet/front	●	–	–
LOP 4	●	–	–	–	–
IOP 17	–	jet/front	●	●	–
LOP 5	–	front	●	–	–
IOP 18	●	–	●	●	–
LOP 6	–	fronts	–	–	–
IOP 19	–	front	●	●	tempo

Symbol ● means "yes" or "present"
An entry in column 2 means that the system started as a second generation wave. It gives an idea of its environment, “front” being obvious, “jet” meaning presence of a jet-streak or entrance, “tempo” meaning that waves existed temporarily or, in the case of IOP19, temporarily hindered.

environment sampled by dropsondes from the C-130. This is close to the target 10 cases. Fig. 9 illustrates the flow organisation within the cloud head of Low 44 (during IOP 18) derived from the P3 tail radar at NOAA/NSSL.

(d) *Potential for air-sea interaction studies*

This component of FASTEX started as a kind of opportunistic adjunct to the project. Its contribution to studying the complex influence of surface fluxes on cyclogenesis addresses a not well resolved question. At the same time, its contribution to the problem of parameterizing properly these fluxes in the presence of high sea and under strong winds is more clear-cut. In this area, a truly unique data set has been gathered by the Suroît and Knorr research vessels. The required conditions have been met (indeed, the ships were hit, on average, by a cyclone every other day) in a wide sample of vertical stability and temperature conditions. The reader is referred to the overview of Eymard *et al.* (1999) to see that this topic should soon benefit from FASTEX data.

(e) *The FASTEX cases*

Another important aspect is the sample of cyclone types that was covered by these measurements. One of the ideas underlying FASTEX is that there is a large variety of cyclones (Ayrault, 1998) and no such thing as a single type (for example, a system growing on a front, always going through the same set stages and having the same structure, as imagined earlier in this century). There is no single "typical" FASTEX cyclone. It is important that the FASTEX sample reflects this diversity.

More or less in real time, B. Pouponneau, from Météo-France, prepared a basic atlas of maps based on the operational analyses made during FASTEX which included a significant amount of special FASTEX data. These maps were soon complemented by satellite images provided by the Data Base group (see Jaubert et al. 1999). This enables a subjective classification of the cases to be performed based on the morphology of the system and its environment (Table 3).

FASTEX is primarily oriented towards cyclones forming well within the oceanic storm-track, in contrast to East-Coast cyclogenesis as studied in programmes such as ERICA (Hadlock and Kreitzberg, 1988) or CASP (Stewart, 1991). The cyclones in FASTEX could be called, using traditional synoptic parlance, frontal waves. However, a more general description might be second generation cyclones, suggesting they form in the wake of another system (considered to be the parent, although this may not be always correct). This is the label retained in Table 3, and the parent structure is indicated for cyclones falling in this category of primary interest. An even better description would be end-of-stormtrack cyclones, which simply locates them geographically in a broad sense. Different views relating to the definition and description of these cyclones can be found e.g. in Kurz (1995) in relation to satellite imagery, Hewson (1997) for determining waves automatically or Ayrault *et al.* (1995) and Ayrault (1998) for composite structures extracted from long series of analyses. Figure 10 shows a summary of the tracks of all the major cyclones during FASTEX.

Table 3 shows that, apart from the non-developing and temporary small amplitude cyclones, there was a mixture of three types of systems forming well over the ocean in the FASTEX sample: (1) cold-air cyclones dominated by convective activity and characterized by their comma-shaped cloud system north of the main baroclinic area (or storm-track, roughly), (2) actual frontal cyclones and (3) cyclones forming within a complex environment combining a low-level front-like feature and an upper-level jet-streak or jet-entrance. A case is entered in the first column when either a comma-cloud was involved in a life-cycle as precursor or the case itself was a comma cloud. The table also indicates the cases that developed explosively, using in a broad way the criterion of Sanders and Gyakum (1980): a phase of deepening equal to or larger than 24 mbar in 24h. The presence of such a phase is shown by a dot in the "Rapid development stage" column. This happens on 9 occasions.

Table 3 identifies those systems that have a clear-cut phase of baroclinic development during their life-cycle. It means that the development of the cyclone benefits from baroclinic interaction with an upper-level structure, typically an upper-level cyclonic anomaly: such cases are labelled as having a "clear stage of baroclinic interaction". Cyclones having as their only feature this characteristic type of evolution (the simplest cyclones, in that sense) are not the most frequent ones: IOP 3, 11, 13, 14. Most cases add another degree of complexity to simple baroclinic interaction, either when they are generated or by undergoing several phases of growth (see Baehr *et al.* 1999).

The last column of Table 3 lists the cases where structures such as fronts became wavy but the waves did not develop (dot), or developed very slowly (slow gen) or saw their development temporarily checked (tempo).

Table 3 illustrates two levels of diversity or complexity in the FASTEX sample: the existence of different types and the idea of complex life-cycles leading the same system to change type. Contrast IOP 10, that remains a frontal wave throught its marine life cycle

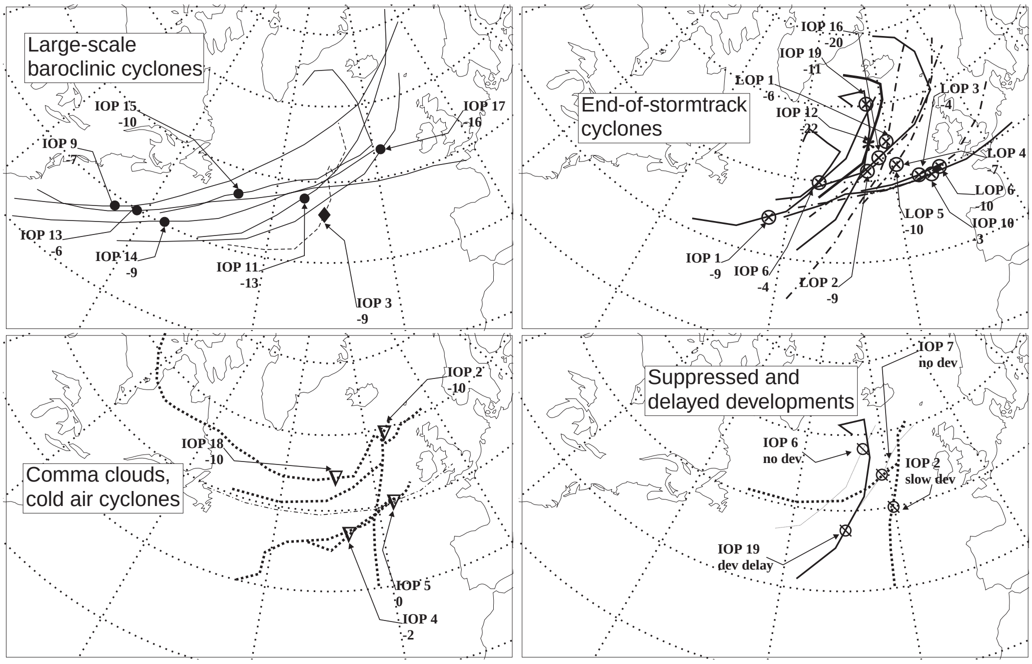


Figure 10. Maps showing the trajectories of the cyclones of interest to FASTEX, the location of maximum deepening and its amplitude in mbar/6h derived from the ARPEGE analyses. The trajectory lines and symbols marking the location of maximum deepening indicate the different types of cyclones resulting from the subjective classification of Table 3. Top left panel: light solid lines and filled circles: large scale baroclinic waves in zonal regime; light dotted line and diamonds: baroclinic waves in southern zonal regime. Top right panel: heavy solid line and asterisk: IOP 12 (largest deepener); medium solid lines and circled crosses: end-of-stormtrack cyclones in IOP, LOP are medium dash-dotted. Bottom left panel: heavy dotted lines and open triangles: comma-cloud like features, LOP are light dash-dotted. Bottom right panel: light dotted lines and empty sign: non developing waves. These trajectories have been constructed manually using the Data Base Atlas prepared by B. Pouponneau (Météo-France).

with IOP 12, that starts in the same category and ends as a full-scale storm. Another example is IOP 18, that turns into a major storm while beginning away from the main baroclinic area. Another subjective classification of the FASTEX cases is provided by Clough *et al.* (1998).

7. Forecasts during FASTEX

The forecast activity during the FASTEX field phase is, by design, an experiment within the experiment. The requirements is quite demanding: (1) produce once, and sometimes twice a day, medium-range forecasts of cyclone tracks, (2) refine forecast life-cycles enough to prepare flight plans, (3) monitor the evolution using fine-mesh models and satellite imagery in real time and over a long period.

The forecasts are prepared at Shannon operations centre by teams from four groups: the Canadian Meteorological Center, the Irish Meteorological Service, Météo-France and the UK Meteorological Office. An important aspect of this exercise is the cross-exchange of tools, concepts and approaches between members of these groups. All groups bring to Shannon their familiar working environments, namely their model output, display systems, etc. Most of the participants seem pleased with this approach and learn a lot from each other.

The diversity of models extends beyond the ones provided by these participating groups: the ECMWF model is available from several sources (for example, the Irish Met Éireann provides the 00UTC ECMWF run) and the Deutscher Wetterdienst model is also employed on the longer ranges. On occasions, results from US models are also available.

The main outputs of the forecast teams are: (1) a medium-range forecast based on the ECMWF ensemble, expressed in terms of weather regimes (as defined in section 3), a very good 7 day forecast of weather regime has been obtained), (2) maps of the dispersion of cyclone centers predicted by the different models, (3) a consensus 4-day forecast of cyclone tracks resulting from comparing and discussing all the available models explicitely identifying the uncertainties, for example by adding error-bars to the cyclone tracks, (4) a detailed 2-day forecast including winds and sea-state for each of the ships and (5) detailed weather information for each of the planned flights.

8. Data collection

Sections 4 to 6 show the wide scientific potential of the measurements performed during the FASTEX field season. An important aspect of the planning of FASTEX operations is the early recognition of the need for easy access to data products and documentation as important references for the operation planning and subsequent analysis of FASTEX cases. A FASTEX On-line Field Catalog is implemented in Shannon and made available through the World Wide Web to all participants from all nations. The catalog provides ready access to project facility status, IOP and individual facility mission summaries and special data products important to the field planning process. It now serves as a useful historical tool for analysis and other interested persons who wish to review FASTEX operations.

A critical aspect of such a project is the way these measurements are organized and made available to the scientific community at large. From this perspective, the most important legacy of FASTEX is the interactive Data Base built with these observations. The Data Base is planned early in the project. It can be accessed at the following electronic address: http://www.cnrm.meteo.fr/fastex/.

A large part of the Data Base has been assembled in real time: this includes all the operational World Weather Watch data in the area of interest plus a large sample of special FASTEX data, such as buoys or dropsonde profiles formatted as TEMP messages. As a result, the Data Base has been opened to *general* access to the scientific and educational community at large *three weeks* after the completion of the field operations.

The Data Base makes available most of the FASTEX special observations. Most of these sets have been checked and, sometimes, corrected. Also included is a full set of global analyses from the Météo-France ARPEGE suite that can be used either for diagnostic or forecast studies. There are also a number of datasets derived from satellite systems. The Data Base is also the place to find all kind of documentation on FASTEX and the instruments employed, including summary tables by platform, real-time reports, the Atlas of maps, a colour and self contained typeset report on the first five years of FASTEX, etc. There are links with other electronic FASTEX sites such as the JCMM in the United Kingdom (http://www.met.rdg.ac.uk/FASTEX/wsindex.html) and at NOAA/NSSL in the United States of America (http://mrd3.mmm.ucar.edu/FASTEX/FASTEX.html). Part of the data as well as the on-line field catalog can be obtained directly in the USA via the UCAR/JOSS FASTEX data site (http://www.joss.ucar.edu/fastex/).

A more detailed description of the FASTEX Data Base is given in the paper of Jaubert et al. (1999).

9. Concluding remarks

Before going through the achievements of FASTEX, it is important to point out the difficulties that were met, if only to indicate the need to take care of them in future programs of similar ambition and size. In spite of the numerous meetings and discussions preceding the experiment, the coordination regarding implementation of the dynamical and predictability objectives and the related aircraft operations in the Midstream and Far Upstream Areas has been difficult throughout the experiment. The major reason was that the varied scientific aims of the investigators directly involved often turned out to be mutually exclusive because of resource-sharing and of many logistical constraints. The planning of the operations in the MSA and with the ships did not present such difficulties and a consensus amongst investigators was more easily reached; this was partly because inter-dependency of MSA resources was intrinsic to the achievements of MSA-specific objectives.

The planning phase failed to anticipate fully the requirements implied by some of the objectives. Thus, the implementation of an adaptive observing system is not just to find a target area in the genesis region and take measurements there; it also requires verification in the MSA. When the expected cyclone showed up, full-scale operations took place in the MSA and provided the verifying data. However, the plans did not allow for the situation when the expected cyclone failed to materialize in the MSA, and the verification in such cases relies on the 6-hourly soundings only from nearby land stations.

The most important logistical failure was related to air traffic control constraints for the jet aircraft. Useful contacts with the Air Traffic Control authorities in charge of the North-Atlantic air space were made at the beginning of the operations. The idea of the dropsondes falling into the crowded aircraft tracks raised some concern. This translated into a conservative position taken by most air traffic control centres. Most of the time, the Lear and Gulfstream had to fly below the commercial flight tracks. As a result, the in-situ description of upper-levels is poorer than anticipated. Moreover the range of the aircraft was much reduced by flying in denser air and the flight plans had to be simplified.

One lesson learnt during the field phase was that the IOP planning process would probably have benefitted from there being a collective focus, amongst *all* participants, on individual cyclones, instead of having Upstream and MSA teams which tended to pre-plan their own missions independently.

Consider now the positive side of things. The experimental objectives of FASTEX as a field project, as defined in section 1(b), have been fulfilled and most of this article justifies this statement. A number of cyclones have successfully been multiply sampled as they crossed the North-Atlantic. The cases sampled in this way and those observed in much more detail in the Multiscale Sampling Area, do reflect some of the variability of recent mid-latitude cyclone classifications typologies. Real time adaptation of the observations to areas critical to improving predictions for cyclones have actually been done for the first time. A unique turbulent fluxes dataset has been collected from the ships. The data have been made available to all within a short time scale.

There are other positive aspects of FASTEX. Between 1993 and 1996, as part of the preparations for the field season, focused scientific studies have been undertaken that proved to be useful to the project: the climatological study of Ayrault *et al.* (1995) determined the optimal period of year, locations and schedules, the idealized observing system experiments of Fischer *et al.* (1998) showed the necessity of the ships, Bishop and Toth (1999) provided some theoretical basis to adaptive observation, Bergot *et*

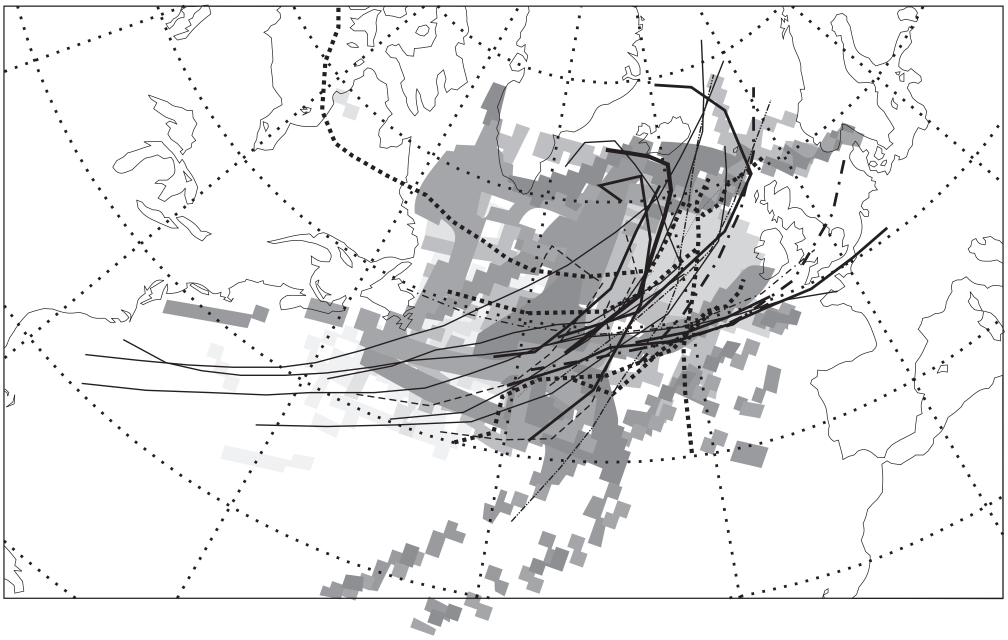


Figure 11. A summary of FASTEX: the trajectories of the lows of interest to the project (as in Fig. 10) are superimposed on the distribution of the vertical soundings taken by the ships (zones with the darkedt shading) and by the aircraft (lightest shading). This is only a part of the FASTEX data, but the fitting indicates the life-cycle tracking has been quite effective. Distribution areas provided by G. Jaubert, Météo-France, FASTEX Data Manager.

al. (1999) directly addressed practical issues relating to its implementation. In fact, numerical tools and techniques are now reaching a stage where many aspects of costly projects like FASTEX can and should be simulated beforehand. New tools for retrieval of 3D-fields on the mesoscale have also been prepared at that time. They combine Doppler radar measurements and other sources such as dropsondes (Protat *et al.* 1997, Protat *et al.* 1998, Montmerle and Lemaître 1997) Training forecasters and flight track planning scientists for FASTEX was carried out in the UK and France during the winter preceding the experiment: this is done for other projects and remains a condition of success. But one can now go much further than this and test the impact different distributions of platforms or observational procedures and limit the consumption of expensive resources for trial or test runs.

The mode of operation of the forecasters was successful throughout the project — actually, the forecasting routine was started early in December 1996, another condition of success. The consensus forecasts have proved to meet the needs of the project.

Another result is the demonstration of the feasibility of weather ships to be tied to the slowly migrating baroclinic area. Data systematically reaching upper-levels invaluable from a dynamical meteorology point of view have been obtained by the ships catching key components involved in the process of cyclogenesis. Current and future data impact studies add to the critical but successful character of this component of FASTEX (see e.g. Janisková *et al.* 1999 and Desroziers *et al.* 1999).

The daily running of FASTEX has shown the usefulness, indeed the necessity, of computer aided flight planning. It was required for the MSA operations in order to meet the multiple constraints: the intrinsic complexity of the reference flight patterns, the actual weather and the logistical and air safety regulations. It was found compulsory for operating the Gulfstream because most objectives required its full range. (The computer programs for the MSA were developed by the NSSL and JCMM groups, the one for the Gulfstream by the Laboratoire d'Aérologie.)

Above all, the field phase of FASTEX as a whole has demonstrated the feasibility, despite the manifest difficulties, of a coordinated multi-base, multi-objectives observing system covering a whole ocean and closely associating scientists and meteorologists from many different countries. This result is a nice example of scientific achievements that were made possible through the collaborative efforts of researchers working in different areas but within the same field experiment, and for the same overall goal: improving our understanding and forecasting ability of extratropical cyclones. One way of summarizing the effectiveness of the tracking of the North-Atlantic cyclones is given by Fig. 11, where the overall distribution of the soundings taken from the FASTEX main platforms is superimposed on the system trajectories: apart from the earliest phases of some of the cyclones, tracks and data distribution remarkably overlap throughout the ocean: for two-months, the Atlantic data gap has been filled.

Acknowledgment

This overview of the FASTEX field phase is dedicated to the many who were involved in it in one way or another: in launching radiosondes at unsocial times and/or in remote locations, monitoring logistical components of FASTEX such as money, goods and peoples' movements, producing and disemminating special products from numerical models and remote sensors, maintaining computers and telecommunication lines, producing forecasts, flying and maintaining aircraft, pushing back the limits of plans and regulations, and navigating and maintaining ships and their instruments in incredible conditions.

We also acknowledge constant and friendly support of the Aer Rianta staff in Shannon as well as the understanding of air traffic control authorities especially in Shannon, Prestwick, Gander and New-York.

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Appendix A

This appendix provides the list of the acronyms used in the text, se Table A.1.

Appendix B

The following tables provide some reference data on the 25 FASTEX cases. A few basic meteorological characteristics are provided on the top rows. More detailed meteorological parameters can be found in Clough *et al.* (1998) or in Baehr *et al.* (1999). The rest of the table summarize the operations in the three FASTEX areas.

The labelling of the tables is self-explicit, except for the layout described in the following table and regarding soundings:

TABLE A.1. List of acronyms

AES	Atmospheric Environment Service (Canada)	CETP	Centre d'étude des Environnements Terrestre et Planétaires
CMC	Centre Météorologique Canadien, Montréal, Canada	CNRS	Centre National de Recherches Scientifiques
COSNA	Composite Observing System for the North-Atlantic	EC	European Commission
EGOS	European Group on Ocean Stations	FASTEX	Fronts and Atlantic Storm-Track Experiment
FIC	Flight International Company	GPS	Global Positioning System
GTS	Global Transmission System (operated by WMO)	INSU	Institut National des Sciences de l'Univers
IOP	Intensive Observation Period	JCMM	Joint Centre for Mesoscale Meteorology
JOSS	Joint Office for Science Support	LOP	Lesser Observations Period (sometimes preceded by FASTEX)
MIT	Massachusetts Institute of Technology	MSA	Multiscale Sampling Area
NCAR	National Center for Atmospheric Research	NCEP	National Center for Environmental Prediction
NESDIS	National Environmental Satellite Data and Information Service	NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Reasearch Laboratory	NSF	National Science Foundation
NSSL	National Severe Storm Laboratory	UCAR	University Corporation for Atmospheric Research
UCLA	University of California, Los Angeles	UK	United Kingdom
USA	United States of America	WMO	World Meteorological Organisation

Sounding information layout in Table B.1 and Table B.2

Ship name	intensive period mid-time	duration of intensive period	number of profiles in Data Base
		(Ship location)	
Aircraft name	flight mid-time	duration of flight	number of dropsondes in Data Base

In other words, for the special FASTEX platforms, the information is generally the middle time of the intensive period. For land radiosoundings, beginning and sometimes end periods are specified. For the european radiosoundings, the number after the duration is the number of stations involved. The number of profiles refer to the high resolution soundings available in the data base in july 1999, as given by the data availability pages.

TABLE B.1. THE FASTEX INTENSIVE OBSERVATION PERIODS

	IOP 1			IOP 2			IOP 3			IOP 4			IOP 5			IOP 6		
cyclone number	8A			11			14			18			19 A/B			20		
formation date	8/1 06	(54W, 41N)		11/1 18	(23W, 40N)		13/1 12	(53W, 41N)		16/1 18	(33W, 47N)		22/1 00	(25W, 47N)		22/1 12	(43W, 46N)	
max deepening rate (mbar/6h)	8/1 12	(47W, 42N) -9		13/1 00	(18W, 53N) -10		14/1 12	(32W, 43N) -9		17/1 06	(27W, 47N) -2		no significant pressure deepening			23/1 00	(35W, 50N) -4	
max amplitude (mbar)	10/1 00	(33W, 54N) 968		13/1 00	(15W, 59N) tlw 978		15/1 18	(29W, 51N) 973		17/1 12	(25W, 48N) 995		22/1 18	(17W, 44N) 1008		23/1 00	(35W, 50N) 984	
end of tracking	11/1 00	(40W, 55N)		13/1 00	(15W, 59N)		16/1 06	(28W, 58N)		18/1 06	(15W, 52N)		23/1 06	splitting		23/1 12	(25W, 57N)	
RS US	8/1 18	⟶		⟶	12/1 18		13/1 06	14/1 06					19/1 18	20/1 18			22/1 18	
LearJet				11/1 1500	0345	12	13/1 1215	0430	14				20/1 1130	0445	16			
C130 USAF																		
Gulfstream (1)																		
KNORR	9/1 1200	24 (35W, 42N)	9	10/1 2230	15 (35W, 42N)	8	14/1 1800	24 (35W, 45N)	12	16/1 1500	18 (35W, 46N)	13	20/1 2100	18 (48W, 45N)	11	22/1 1200	24 (49W, 45N)	9
ÆGIR	9/1 0900	18 (35W, 46N)	7				15/1 0300	18 (35W, 49N)	9	16/1 1500	18 (35W, 50N)	15	21/1 0600	24 (35W, 52N)	7	23/1 0300	24 (35W, 51N)	7
SUROÎT	9/1 1200	24 (31W, 39N)	2	10/1 2230	15 (34W,41N)	4	14/1 0900	18 (41W, 46N)	11	16/1 1500	18 (43W, 47N)	12	20/1 2100	18 (35W,47N)	11	23/1 0300	24 (35W, 49N)	7
V. BUGAEV				10/1 1800	36 (35W,38N)	14	14/1 0900	18 (35W, 42N)	13	16/1 1500	18 (35W, 42N)	7	21/1 0600	24 (35W,45N)	9	23/1 0300	24 (35W, 45N)	10
Other ships				11/1 06-18	2 ASAP											23/1	1 ASAP	
Gulfstream (2)																		
C130	10/1 0745	0730	31	12/1 1500	0945	47							22/1 0915	0430	7			
P3 NOAA	10/1 0630	0840		12/1 1615	0900								22/1 1345	0930				
Electra	10/1 0600	0500	ss	12/1 1615	0700	mi							22/1 1200	0600	ss			
Gulfstream (3)										17/1 1215	0645	28	22/1 1215	0315	0	23/1 1945	0745	22
European RS	10/1 12	24	5	12/1 12	24	5	16/1 06	24	5	18/1 18 19/1 00	24 24	5 7	22/1 15	24	7	24/1 03	24	6
Other																		

Table B.1 continued

	IOP 7			IOP 8			IOP 9			IOP 10			IOP 11			IOP 12		
cyclone number	22 A/B			Greenland lee waves			27			28			30			34		
formation date	25/1 12	(27W, 50N)					30/1 12	(78W, 31N)		3/2 12	(40W, 45N)		4/2 06	(60W, 37N)		9/2 06	(35W, 48N)	
max deepening rate (mbar/6h)	25/1 06	(32W, 47N) < 1		Complex interaction low/orography			31/1 12	(66W, 37N) -7		4/2 12	(17W, 48N) -3		5/2 06	(39W, 44N) -13		9/2 12	(27W, 52N) -22	
max amplitude (mbar)	26/1 00	(18W, 55N) tlw 1012					3/2 06	(18W, 63N) 975		4/2 18	(10W, 50N) 1010		7/2 00	(5W, 68N) 950		10/2 06	(20W, 62N) 947	
end of tracking	26/1 12	(15W, 55N)					3/2 18	(2W, 68N)		5/2 12	(5E, 50N)		7/2 00	(5W, 68N)		11/2 00	(30W, 65N)	
RS US							31/1 06	⟶		⟶	⟶		⟶	4/2 00		8/2 06	⟶	
LearJet							1/2 0000	0330	11				4/2 1415	0330	16	8/2 0545	1100 (NB:C130)	11
C130 USAF				27/1 0100	0600	13				2/2 1700	1045	19	4/2 1615	0945	13	9/2 1315	0730	7
Gulfstream (1)							1/2 1145	0530 Sh →StJ	30							8/2 1215	0530 Sh →StJ	26
KNORR													6/2 0000	48 (51W, 51N)	15	9/2 1200	24 (51W, 56N)	8
ÆGIR	25/1 0600	24 (35W, 49N)	9							4/2 1200	24 (12W, 50N)	10	6/2 0300	24 (24W, 47N)	10	9/2 1500	24 (35W, 46N)	12
SUROÎT	25/1 0600	24 (35W, 52N)	8	29/1	(39W,45N)	5							6/2 1200	30 (31W,44N)	9	9/2 1500	24 (35W, 50N)	9
V. BUGAEV	25/1 0600	24 (35W, 45N)	8				2/2	24 (56W, 44N)	3	3/2 0600	24 (50W, 43N)	7	6/2 0300	24 (35W,41N)	5	9/2 1500	24 (35W, 41N)	14
Other ships																9/2	1 ASAP	
Gulfstream (2)	25/1 2015	0630	28	29/1 1230	0715	19				3/2 1815	0545 StJ →Sh	38					StJ →Sh	
C130	26/1 0030	0700	41							4/2 0930	0900	27	5/2 2300	1000	70	9/2 1745	1130	43
P3 NOAA	26/1 0100	0800					2/2 2000	0900	5 ss	4/2 1030	0915	1	6/2 0145	1000		9/2 1800	1000	ss
Electra	26/1 0245	0600	ss				2/2 2300	0700	mi	4/2 0915	0730	ss	5/2 2200	0700	ss			
Gulfstream (3)													6/2 0115	0530	42			
European RS	26/1 00	12	4				3/2 03	18	5	4/2 03	24	12	6/2 06	18	4	10/2 09	24	8
Other							Norssarsuaq 1/2 18 8			2 ARAT flights 4/2								

Table B.1 continued

	IOP 13			IOP 14			IOP 15			IOP 16			IOP 17			IOP 18			IOP 19		
cyclone number	35/35A			37			38			39A			41			44			46B		
formation date	8/2 06	(85W, 32N)		10/2 18	(77W, 28N)		13/2 12	(58W, 42N)		17/2 00	(37W, 49N)		17/2 12	(61W,35N)		22/2 12	(44W,54N)		26/2 12	(38W, 41N)	
max deepening rate (mbar/6h)	9/2 18	(62W, 39N) -6		11/2 18	(65W, 37N) -9		14/2 00	(50W, 46N) -10		17/2 06	(25W, 52N) -20		19/2 00	(22W, 51N) -16		23/2 00	(32W, 53N) -10		27/2 06	(23W, 60N) -11	
max amplitude (mbar)	10/2 18	(43W, 46N) 989		12/2 18	(45W, 43N) 986		15/2 18	(24W, 53N) 973		18/2 06	(12W, 68N) 943		20/2 00	(7W, 62N) 943		24/2 18	(4W, 60N) 950		27/2 12	(25W, 62N) 957	
end of tracking	13/2 00	(2W, 59N)		15/2 00	(3W, 48N)		17/2 18	(38W, 63N)		18/2 06	(12W, 68N)		20/2 00	(7W, 62N)		25/2 00	(4W, 60N)		28/2 06	(28W, 58N)	
RS US	⟶	9/2 18		11/2 06	12/2 06		13/2 06	14/2 00		15/2 12	⟶		⟶	18/2 00		19/2 18	22/2 18		23/2 18	27/2 00	
LearJet	10/2 1100	0500	19	12/2 1030	0415	23	14/2 1330	0400	19				18/2 0015	0245	15	22/2 0000	0400	18	26/2 0000	0345	17
C130 USAF																					
Gulfstream (1)							13/2 1430	0500 Sh →StJ	0	(17/2)	(06) Sh →StJ		17/2 1730	0500	22	22/2 1115	0630 Sh →Gob	28			
KNORR	10/2 1200	24 (54W, 57N)	6				13/2 1500	24 (55W, 59N)	8	16/2 1200	24 (53W, 61N)	8	18/2 1200	24 (51W,62N)	5	22/2 0600	24 (57W, 57N)	8	27/2 1200	24 (49W, 60N)	7
ÆGIR	10/2 2100	18 (35W, 46N)	10	13/2 0000	18 (35W, 46N)	6	14/2 1800	24 (35W, 46N)	7	16/2 2230	15 (35W, 52N)	6	19/2 0000	18 (35W, 52N)	9	23/2 0000	24 (28W, 60N)	7			
SUROÎT	10/2 2100	30 (35W, 52N)	18	13/2 0000	18 (38W,50N)	7	14/2 1800	24 (39W, 50N)	6	16/2 2230	15 (38W, 48N)	5	18/2 1800	18 (36W,46N)	15	23/2 0000	24 (42W, 48N)	9	26/2 1500	18 (40W, 45N)	13
V. BUGAEV	10/2 2100	24 (35W, 41N)	15	13/2 0000	18 (35W,41N)	7	14/2 1800	24 (35W, 41N)	7	16/2 2230	15 (35W, 41N)	6	18/2 1800	18 (35W,41N)	15	23/2 0000	24 (35W, 41N)	6	27/2 0000	18 (28W, 40N)	11
Other ships				13/2 06	1 ASAP		15/2 06	1 ASAP								23/2 06	1 ASAP				
Gulfstream (2)							15/2 0615	0630 StJ →Sh	30				18/2 1830	0700	54	22/2 1845	0445 Gob →Sh	33			
C130							15/2 1130	1100	40	17/2 0730	1100	45	19/2 0645	1030	46				27/2 0730	1100	42
P3 NOAA							15/2 1145	0830	ss	17/2 0700	0645	ss	19/2 0730	0900	ss	23/2 1515	0915	22 mi			
Electra																					
Gulfstream (3)													19/2 2030	0700	37				27/2 1345	0730	48
European RS							16/2 15	9	2	17/2 18	24	10	19/2 15	24	10	24/2 09	30	12	27/2 18	24	5
Other													Nors'aq 18/2 12 24 8			Nors'aq 22/2 00 24 8					

TABLE B.2. The FASTEX Lesser Observations Periods

	LOP 1		LOP 2		LOP 3		LOP 4		LOP 5		LOP 6	
cyclone number	10		33		35A		39B		42B		43A	
formation date	10/1 00	(37W, 40N)	7/2 00	(52W, 40N)	12/2 06	(10W, 54N)	17/2 06	(45W, 48N)	22/2 06	(27W, 47N)	24/2 00	(33W, 47N)
max deepening rate (mbar/6h)	11/1 00	(22W, 53N) -6	8/2 06	(29W, 50N) -9	12/2 18	(4W, 57N) -7	17/2 18	(20W, 50N) -7	22/2 12	(21W, 51N) -10	24/2 12	(16W, 49N) -10
max amplitude (mbar)	11/1 12	(29W, 59N) 973	9/2 06	(5W, 64N) 985	13/2 00	(2W, 58N) 977	17/2 18	(9E, 57N) 990	23/2 12	(1E, 63N) 967	25/2 06	(10E, 57N) 965
MSA location end of tracking	11/1 06 12/1 12	(20W, 56N) (1W, 68N)	8/2 18 9/2 12	(15W, 55N) (2E, 64N)	12/2 06 13/2 00	(10W, 54N) (2W, 58N)	17/2 18 19/2 00	(20W, 50N) (10E, 58N)	22/2 18 23/2 12	(15W, 54N) (1E, 63N)	24/2 12 25/2 06	(16W, 49N) (10E, 57N)
Upstream data	US RS		C130 US 5/2 1300 C130 US 6/2 0730	1030 18 1000 15	see IOP 13		US RS LearJet 16/2 1345	0830 21	US RS		US RS LearJet 22/2 2300	0200 10
Ships	3 ships 9/1 10/1 Bugaev 10/1	4 s/j K, Æ, S 8 s/j (35W, 38N)	Knorr 7/2 Ægir 7/2 Suroît 8/2 Bugaev	8 s/j (49W, 51N) 8 s/j (30W, 47N) 7 s/j (35W, 41N) 8 s/j (35W, 41N)	see IOP 13		3 ships 17/2	5 s/j K, Æ, B	3 ships 21/2	4 s/j Æ, S, B	Suroît 23/2 24/2 Bugaev 24/2	8 s/j (43W, 47N) 4 s/j (35W, 41N)
Europe, MSA data	Euro RS	→11/1 12	Gulfstream 8/2 1215	0530 26 en route			Euro RS	→18/2 18	Gulfstream 22/2 1845	0445 en route	Euro RS	→25/2 18

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