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

By ALAIN JOLY[1]*, KEITH A. BROWNING[2], PIERRE BESSEMOULIN[1], JEAN-PIERRE CAMMAS[3], GUY CANIAUX[1], JEAN-PIERRE CHALON[1], SIDNEY A. CLOUGH[4], RICHARD DIRKS[5], KERRY A. EMANUEL[6], LAURENCE EYMARD[7], ROBERT GALL[8], TIM D. HEWSON[2], PETER H. HILDEBRAND[8], DAVE JORGENSEN[9], FRANÇOIS LALAURETTE[1], ROLF H. LANGLAND[10], YVON LEMAÎTRE[7], PATRICK MASCART[3], JAMES A. MOORE[5], P. OLA G. PERSSON[9], FRANK ROUX[3], MELVYN A. SHAPIRO[9], CHRIS SNYDER[8], ZOLTAN TOTH[9] and ROGER M. WAKIMOTO[11]

[1]*Météo-France, France*
[2]*Joint Centre for Mesoscale Meteorology, Reading, UK*
[3]*Laboratoire d'Aérologie, CNRS, France*
[4]*UK Meteorological Office, UK*
[5]*University Corporation for Atmospheric Research, USA*
[6]*Massachusetts Institute of Technology, USA*
[7]*Centre d'étude des Environnements Terrestre et Planétaires, CNRS, France*
[8]*National Center for Atmospheric Research, USA*
[9]*National Oceanic and Atmospheric Administration, USA*
[10]*Naval Research Laboratory, USA*
[11]*University of California at Los Angeles, USA*

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SUMMARY

The field phase of the Fronts and Atlantic Storm-Track EXperiment (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. The calculation of critical areas where further observations were needed to limit the growth of forecast error, was undertaken using different techniques, and flights were planned and executed in these areas in time to achieve this. 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 Mesoscale observations Predictability

1. INTRODUCTION

(*a*) *Background and summary of scientific objectives*

FASTEX[†] is a decade-long project meant to bring both recent advances in dynamical meteorology and new observing technologies to bear on mid-latitude marine cyclones,

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* Corresponding author: Météo-France, CNRM/GMME/RECYF, 42 av. Coriolis, F-31057 Toulouse Cedex 1, France.

[†] Acronyms not explained in the text are listed in appendix A.

especially those reaching the west coast of continents (Europe in this 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, soundings, 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 for 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 forecasting 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 cyclones from many different standpoints.

The scientific objectives of FASTEX may be summarized as follows:

(i) *To verify cyclogenesis theories.* A growing body of evidence (Malardel *et al.* (1993) and 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 a 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.

(ii) *To understand the predictability of and improve the forecasts for cyclones.* The recent history of numerical weather prediction is littered with examples of poor forecasts of cyclogenesis events, often with associated damaging weather. This problem was at the heart of meteorology a century and a half ago, and still persists even with 4-dimensional variational (4D-VAR) data assimilation and with mesoscale mesh-size used over the whole globe. Some published examples are The President's Day storm (e.g. Uccellini *et al.* 1984) and the European Great Storm of 15 October 1987 (Jarraud *et al.* 1989). See also Beugin and Rochard (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 adaptive observing.

(iii) *To document the mesoscale and microscale 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 Global Energy and Water Budget Experiment (GEWEX) Cloud System Study (GCSS; Browning 1994). There are two types of issues in this area:

- the documentation of the internal organization of layered clouds, knowledge of which is very incomplete 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.
- the study of 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 (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, have 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 parametrization schemes including at least one explicit condensed-water variable. Better knowledge of the mechanisms leading to mesoscale structures will also help in improving local, short-range forecasting.

(iv) *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 sea, 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 m s^{-1}. Thus FASTEX was also planned to obtain measurements in this particular parameter domain. The aim is to improve the parametrizations of turbulent fluxes as well as to be in a position to analyse the influence of these exchanges on the cyclone properties. Air–sea flux 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 nonlinear 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 objectives of the field phase of FASTEX are 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 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 structures 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 as possible with a regular grid for 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 provides an indication 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. Following this, 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 seeking 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 are 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', centred on the airport of St John's in Newfoundland, the 'Mid-stream Area', centred about longitude 35°W and the 'Multi-scale Sampling Area' (MSA). The MSA 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 Mid-stream Areas 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 encounters with the strong winds and high seas required for the measurements of air–sea fluxes.

Finally, the MSA is where the mature cyclones and their cloud systems are to be observed with, as the name suggests, the possibility of collecting 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 of instruments and facilities can be found in Joly *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 adopted to deploy these facilities during 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 30 h to 42 h is needed for logistical reasons. The 'constitutive' decision to launch an IOP has to be taken, therefore, on the basis of 84 h or 96 h forecast products. It depends on the strong expectation of a significant cyclone moving into the MSA; the estimated time for this to happen sets the reference date, denoted 0 h in Fig. 1. This decision-taking problem can be 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 GTS 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 provided by 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 enhanced 4 of their stations but on an alert basis. Furthermore, the number of drifting buoys in the central Atlantic was also 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 assisted by two C-130s from the USAF. The MSA was covered by the C-130 from the 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 mid-stream observations is a set of up to four ships.

Early in the planning of FASTEX, it was realized that the ships, in order to be useful all the time, would have to remain in the vicinity of the main baroclinic zone.

TABLE 1. MAJOR FACILITIES AND PARTICIPATING INSTITUTIONS

Facility	Instruments, functions, staff	Owner, crew's home institution	Funding agency
CC ÆGIR	radiosoundings (GPS)	Icelandic Coastguard (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)	UKMO	UKMO
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	6 h soundings	CAN, Greenland, IS, IE, UK, F, SP, Azores (P), Bermuda, DK	Countries, WMO, EC
Increased soundings on alert	6 h soundings 3 h soundings	USA IE, F, UK	NCAR, NOAA Countries
Buoys	surface obs.	EGOS	EGOS
Operations Centre at Shannon	monitoring and forecasting	Aer Rianta (IE)	EC
Staff of Shannon Ops Centre and Specific 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), UKMO(UK)	Institutions, NSF, EC
Staff of US targeting operations	forecasters, scientists	MIT(USA), NCEP(USA), NCAR(USA), Penn State University(USA), University of Wisconsin(USA)	NOAA, NSF

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

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 cyclones themselves. Practical experience during FASTEX revealed that this idea

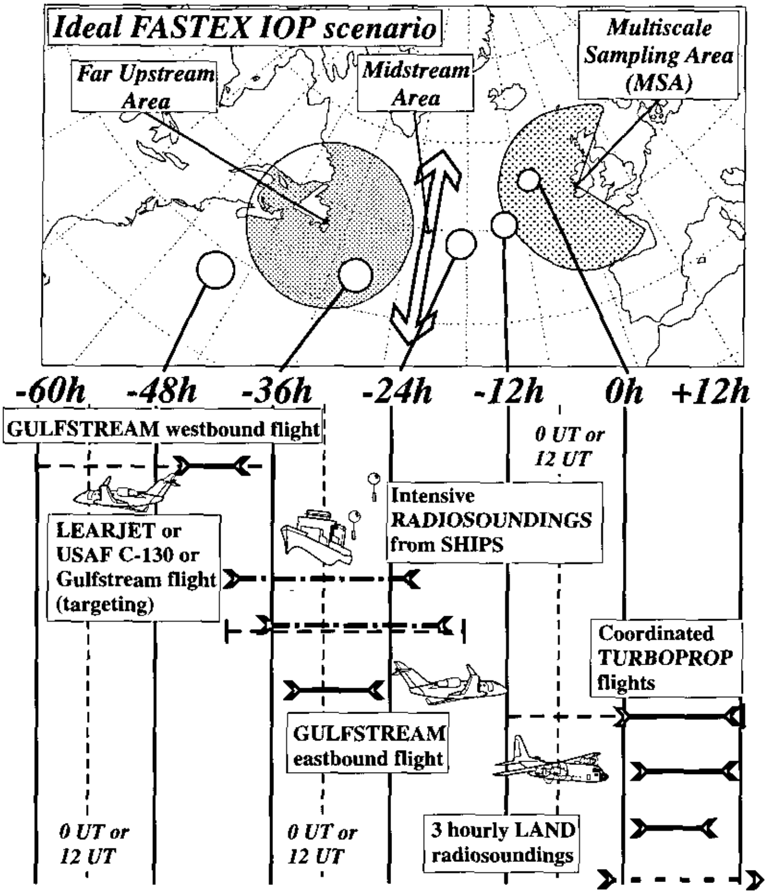

Figure 1. The map shows the ideal FASTEX Intensive Observation Period (IOP) scenario with the North Atlantic area divided into three adjacent zones where the FASTEX platforms were deployed sequentially. The lower part of the figure shows the ideal deployment along the track of a single event together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

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-month 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 co-ordinated flights in the MSA

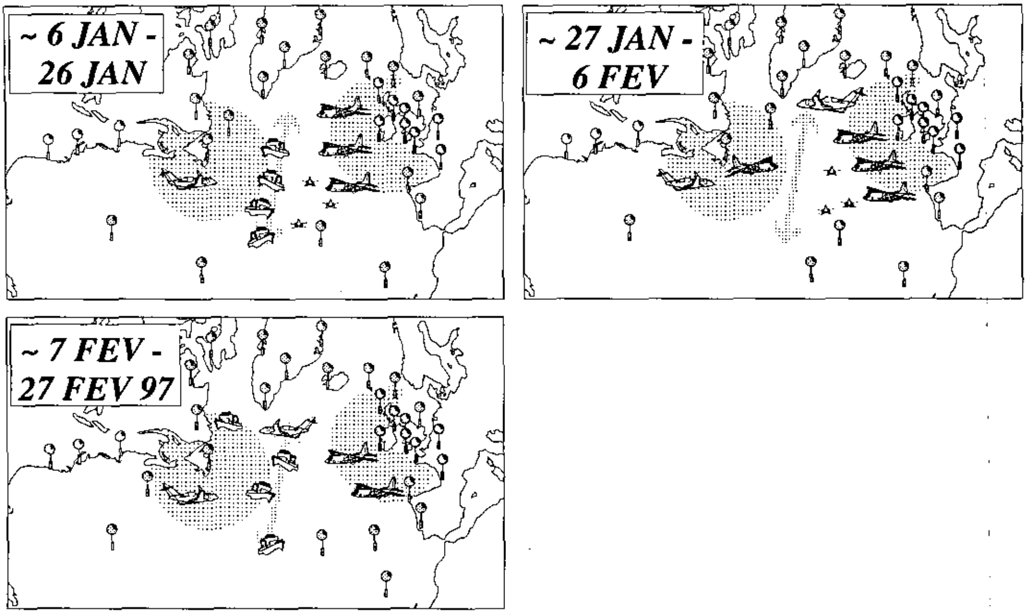

Figure 2. A summary in 3 sketches of the actual observing platforms that were deployed during the field phase of FASTEX, also showing the locations of the upper-air stations involved. The shaded zones refer to the areas of Fig. 1. The dates are somewhat approximate, since, for example, the ships were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

were a success. In the second period, the Gulfstream became fully available and two C-130s were provided by the US Air Force; they took part mostly in the test of adaptive observations but, to some extent, they also replaced the ships (as in IOP9, 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 a 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 onto 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 Anticyclone 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 temporarily a baroclinic area extending from the end of the average wind maximum to Iceland. It also means that the baroclinic driving of the

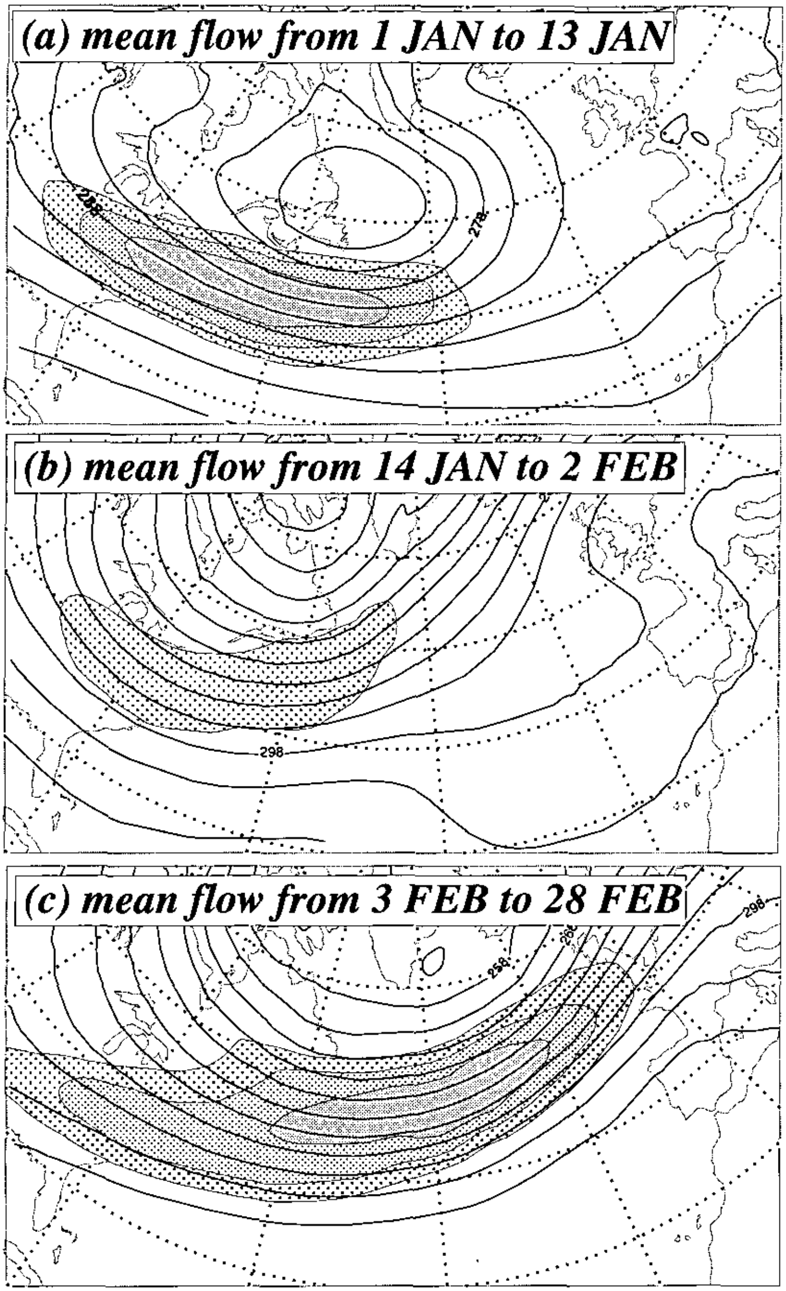

Figure 3. A summary of the averaged meteorological conditions during FASTEX. Contours are 700 mb geopotential (every 5 damgp) and the three intensities of shading indicate 300 mb winds in excess of 40, 45 and 50 m s^{-1}. (Figure prepared by B. Pouponneau, Météo-France, using the ARPEGE analyses included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

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.
- Finally, the whole of February 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 mb is 10 m s^{-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 m s^{-1} for about two days. These conditions provide suitable cyclone events.

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

4. EXAMPLE OF AN INTENSIVE OBSERVATION PERIOD: IOP12

The best way to convey a flavour of FASTEX operations is to summarize the story of one IOP, namely IOP12, selected because of its unique mixture of exciting meteorology and dramatic operational events. (Readers familiar with such field operations may wish to jump to the general overview in section 6.)

The meteorology is discussed first. IOP12 was conducted on Low 34 (L34). This cyclone undergoes, on 9 February 1997, the most explosive deepening of the period: roughly −54 mb in 24 h, with one phase of −23 mb in 6 h. This very rapid development goes along with a very short life cycle. It is summarized in 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 analysed by the Météo-France operational suite ARPEGE. An individual vorticity maximum can be tracked from 0000 UTC 9 February onwards, whereas closed isobars can only be seen when the low is fully developed, after 1800 UTC. The analysed sea-level pressure falls from about 1015 mb at 1800 UTC 8 February to 961 mb at 1800 UTC 9 February. Between 0600 UTC and 1800 UTC 9 February, L34 moves about 1700 km at a phase speed of nearly 40 m s^{-1}.

The first tentative plan for a possible IOP12 on L34 is drafted on the basis of the forecasts starting from 0000 UTC 5 February and, for the ECMWF model, 1200 UTC 4 February. As the low is not expected to be in the western part of the MSA until 0000 UTC 10 February, it is important to note that the forecast periods involved are 120 h and 132 h respectively. As summarized in section 7 below, decisions for FASTEX are prepared using an 'ensemble' of many different numerical models. Needless to say there is a wide discrepancy in the various forecasts, but in this case there is enough consistency to convince the team of forecasters that a new IOP may be declared. As early as 1200 UTC 5 February a westbound flight of the Gulfstream-IV jet aircraft is planned for 8 February, a return flight on 9 February and a co-ordinated MSA flight of turboprop aircraft on 10 February. The cyclone 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 IOP12, 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 3-hourly radiosoundings for 24 hours from 1200 UTC 8 February. On 6 and 7 February, the days prior to the beginning of IOP12, the discrepancy between the various

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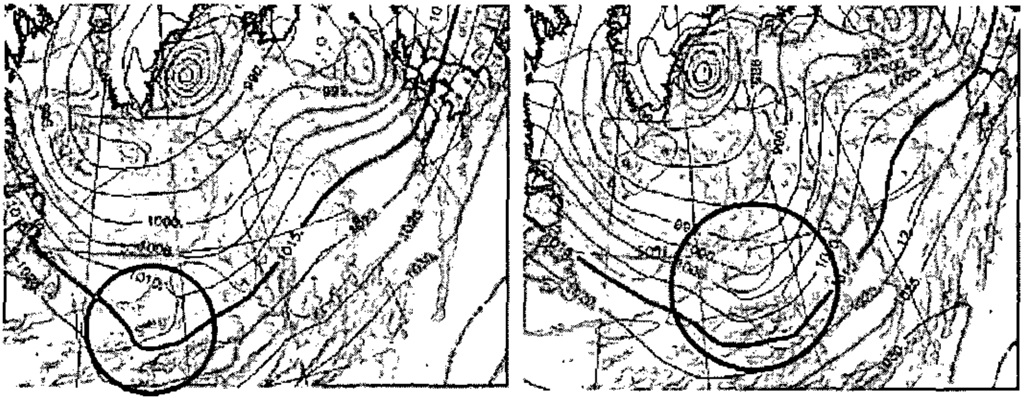

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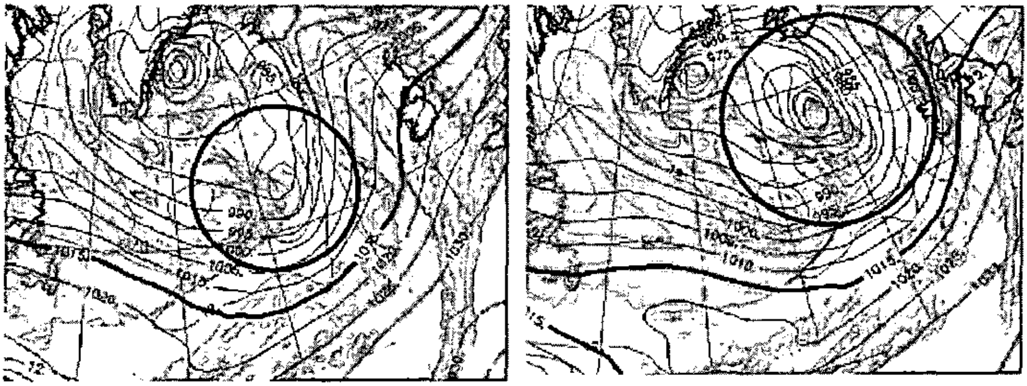

Figure 4. Development of Low 34 on 9 February 1997, FASTEX IOP12. Low 34 is encircled by a heavy black line. Images are in the infra-red channel and are a composite from METEOSAT and GOES. Two fields from the operational Météo-France analysis (that includes FASTEX data) are superimposed. The grey lines are absolute vorticity at 850 mb from 1.2×10^{-4} s^{-1} every 0.5×10^{-4} s^{-1}, unlabelled. The black lines are mean-sea-level isobars, drawn every 5 mb, with one bolder reference contour (1015 mb). See text for further details.

forecasts becomes quite large, and L34 turns into an unexceptional event except in the 72 h ARPEGE forecast. These are signs that the case is a good one for testing the adaptive observation strategy, and 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 co-ordinate '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 provide for new possibilities, including another wave cyclone.

The actual operations managed on this case are summarized in Fig. 5. L34 behaves more or less as anticipated from the 48 h or so forecast runs. The Gulfstream-IV successfully 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 L34 in case a secondary L34B 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

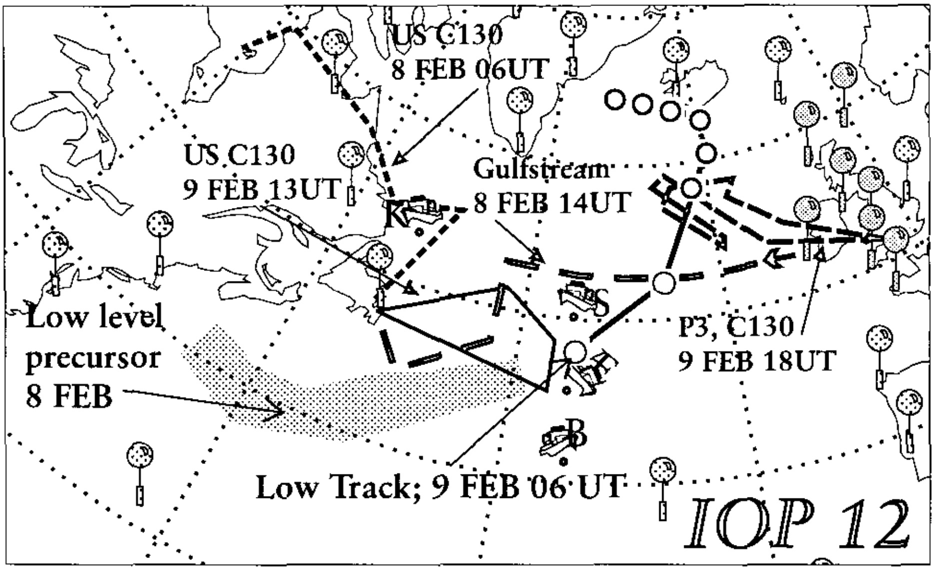

Figure 5. Schematic diagram of the operations during FASTEX IOP12. The large dots form the track of Low 34, marked every 6 h, an open circle corresponding to an open wave. The dotted area indicates the zone where the surface precursor formed. The ships are shown at their location during the phase of intensive soundings. All upper-air stations shown (balloon symbols) were operating every 6 h except the ones with darkest shading which were operating every 3 h. The tracks show the various successful flights. The difficult and eventful St John's to Shannon flight of the Gulfstream-IV on 9 February is not shown because no data were taken.

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 from joining 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 have been obtained at various stages of the evolution of L34.

Figure 6 illustrates features of interest during the development of L34, as seen from the ships. The *Ægir* coastguard vessel was directly in the path of the cyclone and its low-level thermal structure clearly shows up, between 0000 and 0600 UTC 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 Fig. 6, 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 m s^{-1}, while the surface precursor, a warm maximum in the soundings from the *Ægir* travels at 19 m s^{-1}. The rapid development is due instead to the influence of a second, more intense upper-level anomaly, that can be seen in the soundings from the ship *Suroît* at 1200 UTC 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.

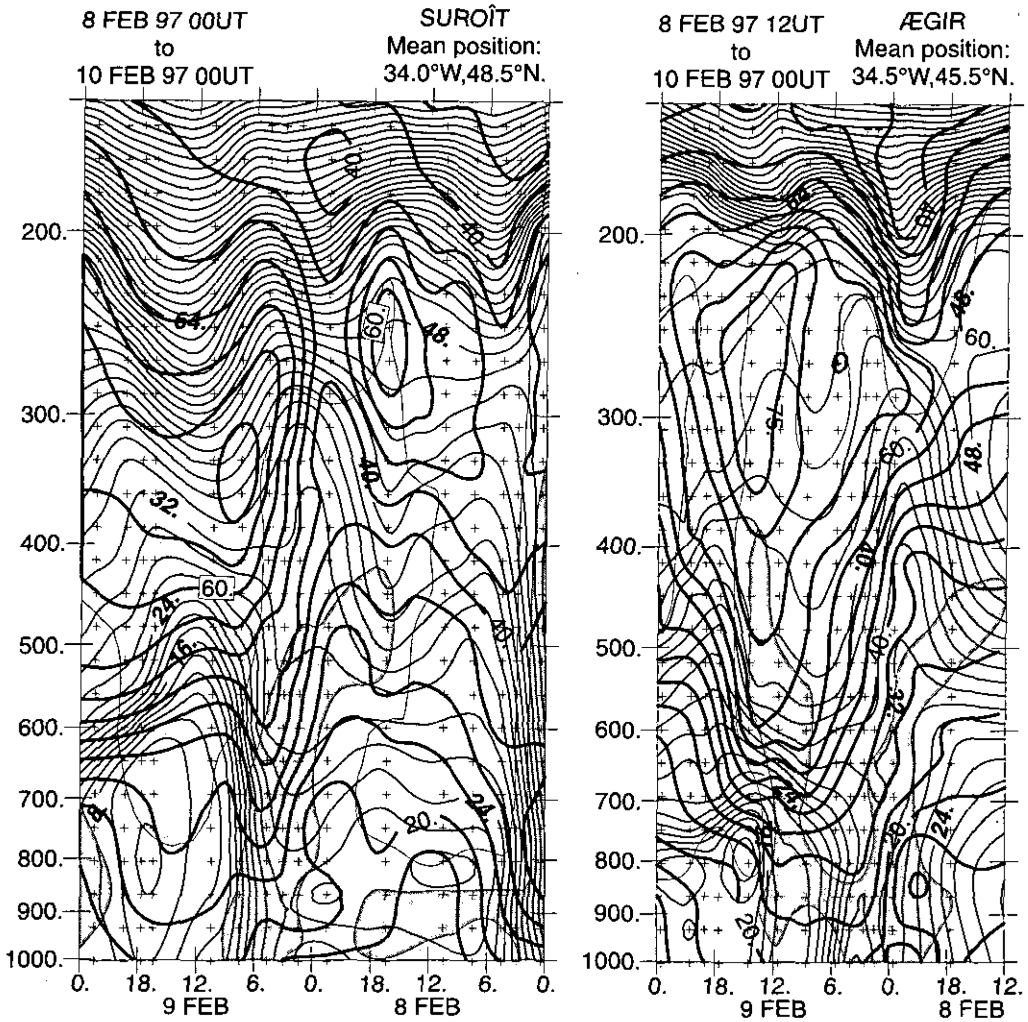

Figure 6. Height–time cross-sections derived from the radiosoundings taken from *RV Suroît* (left) and *CC Ægir* (right) during FASTEX IOP12. The time-scale has been reversed so that the figures are suggestive of geographical cross-sections with west to the left and east to the right. The heavy solid lines show the wind speed every 5 m s^{-1}. The light solid lines are wet-bulb potential temperature 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; analysis by courtesy of G. Desroziers from Météo-France.)

5. THE LESSER OBSERVATIONS PERIODS (LOPS) DURING FASTEX

According to the previous section, critical decisions regarding IOP12 were 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 L33 (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.

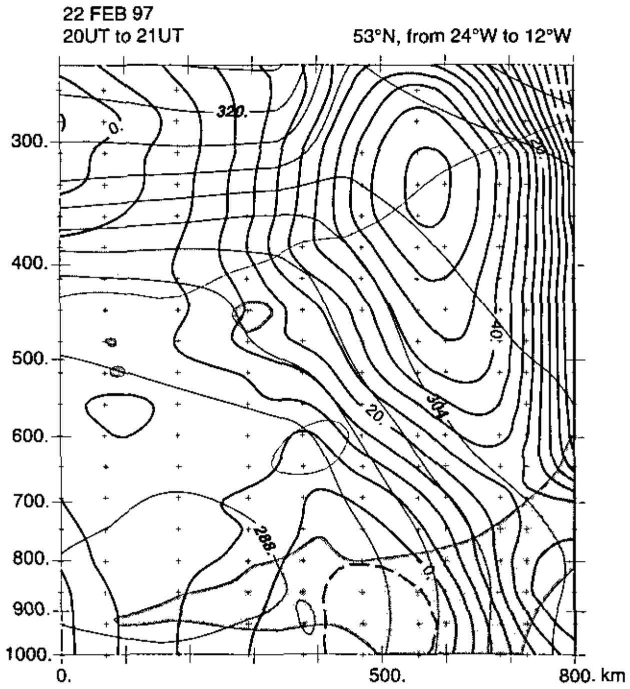

Figure 7. Vertical cross-section derived from dropsoundings from the Gulfstream-IV aircraft flying along 53°N from 24°W to 12°W at the end of FASTEX IOP18, but describing the cyclone L42B that was not selected for an IOP. Contours and shading are as in Fig. 6, except that the wet-bulb potential-temperature contours are drawn every 4 K. The analysis was performed with spline functions by G. Desroziers using the FASTEX Data Base.

Yet L33 is by no means totally deprived of special observations. Fifty-four hours prior to L33 entering the MSA, a long flight of a USAF C-130 from St John's covered the broad area around 50°W and 45°N where the low later starts to form. The ships are also on the track of this low, and performed 8 soundings per day on 7 and 8 February as L33 developed. And finally, as the Gulfstream flies towards St John's on 8 February, it samples the same low, still 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 IOP11A for a time.

L33 is not an isolated case. After the field phase was completed, a second set of systems was added to the main FASTEX IOPs: the FASTEX Lesser Observations Periods (FLOPs or LOPs). They fall into two categories: the first is made up of cases like L33 that are only partially covered for logistical reasons. The second category is, given the objectives of the project, quite important: it contains cases that are only partially covered because they are wrongly forecast. They epitomize the 'FASTEX dilemma' mentioned in section 2. Since FASTEX is about understanding predictability, looking back on these cases can be helpful. Figure 7 illustrates a case falling in the second category, only one model having predicted its existence at the time a decision had to be made for an IOP18. This figure also shows the capability of the Gulfstream-IV to map cyclone-scale features. These two cases are now included in this series of interesting cases as LOP2 and LOP5.

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 to form, and are in line with the objectives of the project: the sole exception is IOP8. IOP8 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 by 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 not appropriate for inclusion in the summary tables for cyclones.

The achievements of the field phase of FASTEX are summarized in Table 2. Appendix B provides more detailed information on each FASTEX case (including IOP8): key dates and locations, flights and other operations: Table B.1 presents the IOPs and Table B.2 the LOPs.

(*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 was 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 MSA, 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 and the number of samples collected. The most comprehensively observed is IOP17, which takes place from 17 to 20 February. The weather system, L41, forms off the east coast of America from multiple precursor features. It has been tracked for 67 h, 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 moves over them. Five successive flights are performed and another earlier flight, on 16 February, 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 L41, 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, a 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 IOP17 trilogy of Cammas *et al.* (1999), Mallet *et al.* (1999a,b).

It can be said, therefore, that the key experimental objective of FASTEX has been attained. 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 Chaboureau and Thorpe 1999 and Baehr *et al.* 1999). As will be discussed below, a

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	3-hourly *European* west coast soundings
IOP1	–	–	–	–	end ampli	•	ss**	**
LOP1	–	–	24 h	–	beg ampli	–	–	**
IOP2	•	36 h	48 h	–	–	•	mi***	**
IOP3	–	48 h	24 h	gen	ampli	–	–	**
IOP4	–	–	48 h	–	organ	–	–	**
IOP5	•	48 h	36 h	–	organ	•	mi**	**
IOP6	–	–	18 h	–	beg sup	•	–	**
IOP7	–	–	*18 h*	–	front	••	ss***	**
IOP9	•	42 h	(C-130)	ampli	(circl)	•	mi**	***
IOP10	•	18 h	30 h	gen	beg gen	•	ss***	***
IOP11	•	36 h	18 h	beg ampli	front	••	ss**	**
LOP2	•	48 h	18 h	–	ampli	•	–	–
IOP12	•	30 h	12 h	rear gen	beg ampli	•	ss**	***
IOP13	–	48 h	48 h	circl	beg dec	–	–	–
LOP3	–	48 h	48 h	–	beg gen	–	–	–
IOP14	–	48 h	24 h	–	beg gen	–	–	–
IOP15	•	24 h	18 h	rear	ampli	•	ss**	*
IOP16	•	24 h	12 h	–	beg gen	•	ss***	***
LOP4	–	48 h	24 h	–	clust	–	–	***
IOP17	•	42 h	18 h	ampli 1	wave	••	ss***	***
LOP5	–	–	36 h	–	beg gen	•	–	–
IOP18	•	36 h	12 h	gen	ampli	•	mi**	***
LOP6	–	48 h	36 h	–	beg dec	–	–	***
IOP19	•	30 h	24 h	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.

• means 'yes' or 'present'
•• 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% success rate of sampling
***: 100% success rate of sampling.

From IOP12 onwards, the Electra is excluded.
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.

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 (IOP10), 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 while the NRL, Météo-France and ECMWF products were interpreted in Shannon. Co-ordination was made possible by the presence of a representative of the Washington group (Dr Snyder) at Shannon. 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 Table 2 is the experience gained in the actual practice of targeted observing. The general approach is to take a 96 h or 72 h forecast (typically), and to calculate where data should be collected during the next 24 h in order to reduce the uncertainty at the end of the upcoming 48 h 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 generally been 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 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 (1999), Bishop and Toth (1999), Langland *et al.* (1999), Montani *et al.* (1999) and Pu and Kalnay (1999).

(*c*) *Potential for cloud-system and mesoscale studies*

This category of objective 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 co-ordination resulted from the subsequent need to analyse the structure of the core of the cyclones with quasi-regular flight patterns 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' was tested successfully 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 IOP16. In four other IOPs, detailed observations of mesoscale features embedded within the cyclones were obtained by airborne Doppler radars in an environment sampled by dropsondes from the C-130. This is close to the target of 10

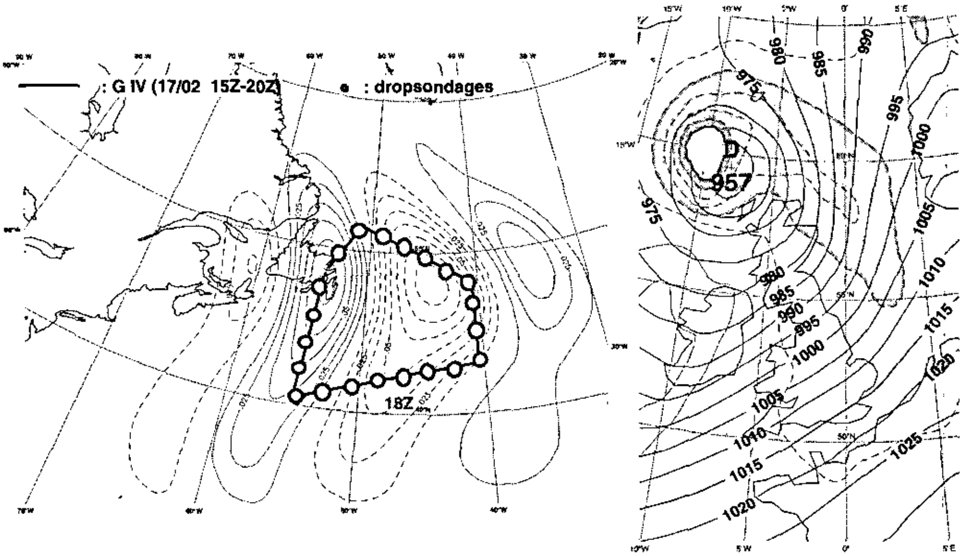

Figure 8. An example of practical adaptive observation and of its impact. Using a forecast starting 0000 UTC 16 February, singular vectors maximizing the growth of enstrophy anomalies between 1800 UTC 17 and 1200 UTC 19 February and ending in the vicinity of Ireland were computed at Météo-France in Toulouse from a terminal in Shannon during 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 mb temperature perturbation of the most unstable singular vector at 1800 UTC 17 February 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 at 1200 UTC 19 February (black lines, every 5 mb) and the impact of the data collected by the Gulfstream flight (thin dashed lines and shading, contour interval 2 mb), 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. See appendix A for acronyms.

cases. Figure 9 illustrates the flow organisation within the cloud head of L44 (during IOP18) 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 parametrizing these fluxes properly in the presence of high seas and under strong winds is more clear-cut. In this area, a truly unique dataset has been gathered by the RVs *Suroît* and *Knorr*. 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 different 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, and it is important that the FASTEX sample reflects this diversity.

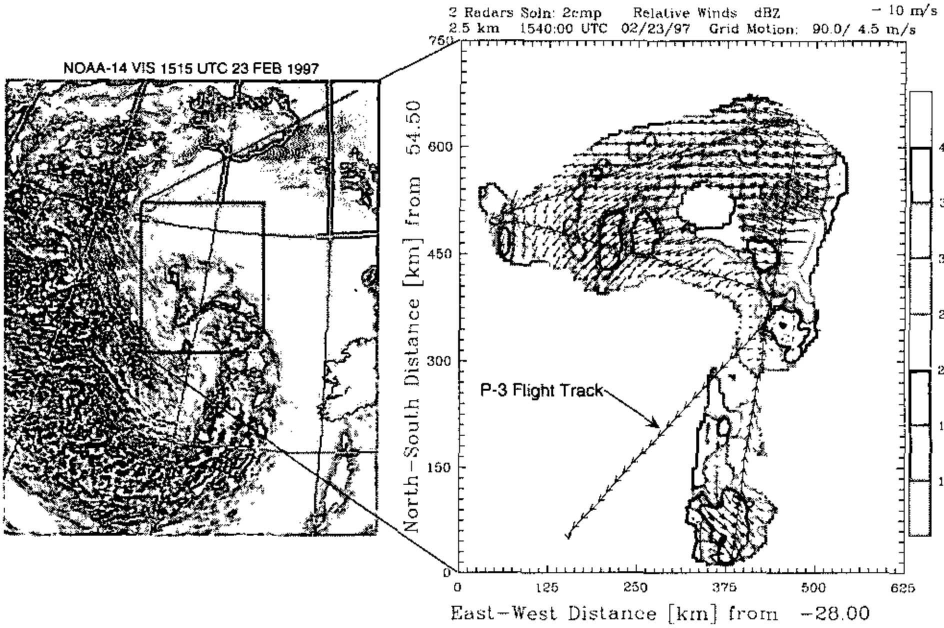

Figure 9. NOAA-14 visible image of the cyclone of FASTEX IOP18 at 1515 UTC 23 February (left panel). Airborne Doppler radar analysis of system-relative winds at 2.5 km at 1540 UTC (right panel). The analysis domain of the Doppler wind field is shown by the box on the satellite image. Shading on the radar image shows the reflectivity. Figure courtesy of D. Jorgensen from NOAA.

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 made 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-storm-track 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, 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 far out 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

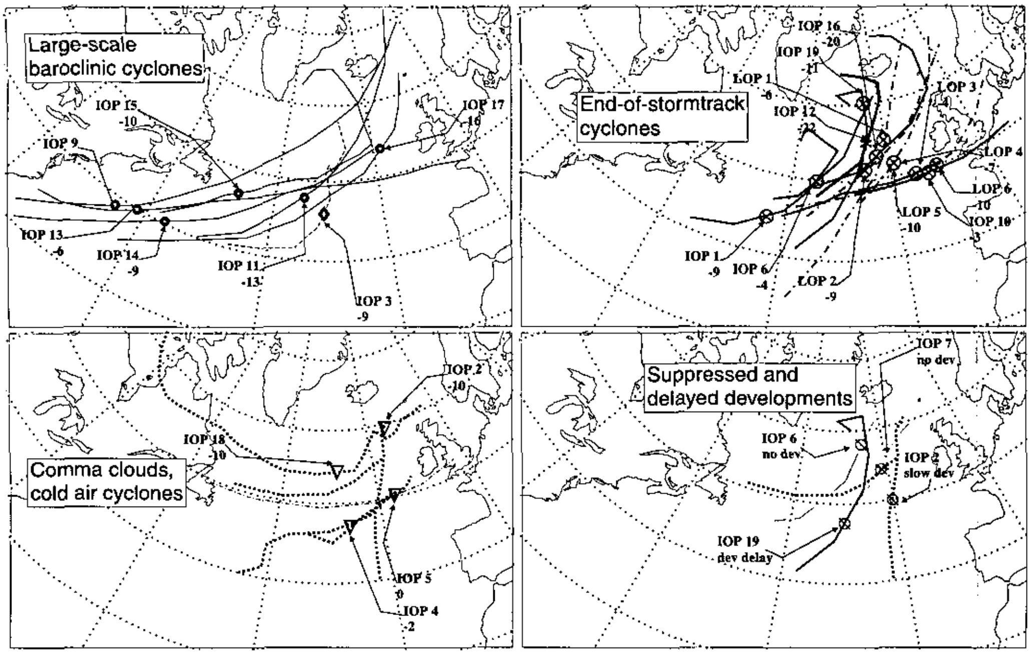

Figure 10. Maps showing the trajectories of the cyclones of interest to FASTEX, the location of maximum deepening and its amplitude in mb $6h^{-1}$ derived from the ARPEGE analyses. The trajectory lines and symbols marking the location of maximum deepening indicate the different types of cyclones resulting from the subjective classification of Table 3. Top left panel: light solid lines and filled circles indicate large-scale baroclinic waves in zonal regime; light dotted line and diamonds show baroclinic waves in southern zonal regime. Top right panel: heavy solid line and asterisk is IOP12 (largest deepener); medium solid lines and circled crosses show end-of-storm-track cyclones in IOPs and medium dash-dotted lines in LOPs. Bottom left panel: heavy dotted lines and open triangles indicate IOPs with comma-cloud-like features, and similarly light dash-dotted lines LOPs. Bottom right panel: light dotted lines and empty sign show non-developing waves; two cases with delayed or deferred development are shown again, IOP19 (heavy line) and IOP2 (heavy dotted lines). These trajectories have been constructed manually using the Data Base Atlas prepared by B. Pouponneau (Météo-France). See appendix A for acronyms.

(or, roughly speaking, the storm track); (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, broadly using the criterion of Sanders and Gyakum (1980): a phase of deepening equal to or larger than 24 mb in 24 h. 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: IOPs 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).

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)
IOP1	–	front	–	•	–
LOP1	–	jet/front	–	–	–
IOP2	•	front	–	–	slow gen
IOP3	–	–	•	•	–
IOP4	•	–	–	–	–
IOP5	•	–	–	–	–
IOP6	–	*tempo*	–	–	•
IOP7	–	tempo	–	–	•
IOP9	–	jet/front	–	•	–
IOP10	–	front	–	–	–
IOP11	–	–	•	•	–
LOP2	–	front	–	•	–
IOP12	–	jet/front	••	•	–
IOP13	–	–	–	•	–
LOP3	–	front	–	–	–
IOP14	–	–	–	•	–
IOP15	–	jet/front	•	•	–
IOP16	–	jet/front	•	–	–
LOP4	•	–	–	–	–
IOP17	–	jet/front	•	•	–
LOP5	–	front	•	–	–
IOP18	•	–	•	•	–
LOP6	–	fronts	–	–	–
IOP19	–	fronts	•	•	tempo

• means 'yes' or 'present'; •• means 'of extreme intensity'. An entry in column 2 means that the system started as a second-generation wave, and gives an idea of its environment: 'front' is obvious; 'jet' means the presence of a jet streak or jet entrance; 'tempo' means that waves existed temporarily or, in the case of IOP19, were temporarily hindered. For other details see text.

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 IOP10, which remains a frontal wave throughout its marine life cycle, with IOP12 that starts in the same category and ends as a full-scale storm. Another example is IOP18, which turns into a major storm but originates 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 are quite demanding: (1) produce once, and sometimes twice, each 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 CMC, Met Éireann, Météo-France and the UKMO. 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, Met Éireann provides the 0000 UTC ECMWF run) and the Deutscher Wetterdienst model is also employed for 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 (generally good 7-day forecasts of weather regimes were obtained); (2) maps of the dispersion of cyclone centres predicted by the different models; (3) a consensus 4-day forecast of cyclone tracks, resulting from comparing and discussing all available models' output and explicitly 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 experiment. 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 they are 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 catalogue 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 analyst and other interested persons who wish to review FASTEX operations.

A critical aspect of such a project is the way the 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 was planned early in the project. It can be accessed at the following Internet 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 was opened to general access to the scientific and educational community at large only 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 kinds 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 UK (http://www.met.rdg.ac.uk/FASTEX/wsindex.html) and NOAA/NSSL in the USA (http://mrd3.mmm.ucar.edu/FASTEX/FASTEX.html). Part of the data as well as the on-line field catalogue 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 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 programmes of similar ambition and size. In spite of the numerous meetings and discussions preceding the experiment, co-ordination 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 is that the varied scientific aims of the investigators directly involved often turned out to be mutually exclusive because of resource-sharing and the 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 airways raised some concern. This translated into a conservative position taken by most air traffic control centres. Most of the time, the Learjet 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; most of this article justifies this statement. A number of cyclones have successfully been intensively sampled as they crossed the North Atlantic. The cases sampled in this way and those observed in much more detail in the MSA, 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, focussed 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 the 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 a theoretical basis for adaptive observation; Bergot *et 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 three-dimensional 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, 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 by testing the impact of different distributions of platforms or observational procedures, and thus 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 that it is feasible for weather ships to be tied to a slowly migrating baroclinic area. Data consistently reaching upper-levels, invaluable from a dynamical meteorology point of view, were obtained by the ships, capturing 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. This 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 co-ordinated multi-base, multi-objective observing system covering a whole ocean, and of closely associating scientists and meteorologists from many different countries. This result is a nice example of scientific achievements made possible through the collaborative efforts of researchers working in different areas but within the same field experiment, and towards the same overall goal: improving our understanding of and ability to forecast 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 overlap remarkably throughout the ocean. For two-months the Atlantic data gap was filled.

ACKNOWLEDGEMENTS

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 disseminating special products from

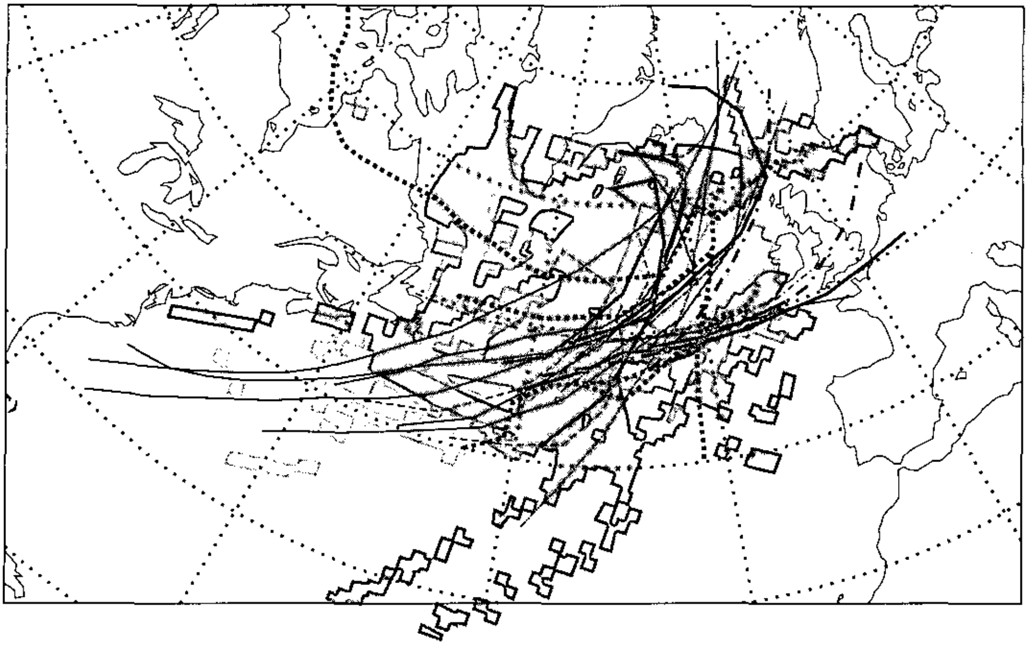

Figure 11. A summary of FASTEX: the trajectories of the lows of interest to the project (as in Fig. 10) are superimposed on the distribution of the vertical soundings taken by the ships (zones with the darkest shading) and by the aircraft (lightest shading). This is only a part of the FASTEX data, but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

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 the 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

Acronyms used in the text and appendix B

TABLE A.1. LIST OF ACRONYMS

AES	Atmospheric Environment Service (Canada)	JCMM	Joint Centre for Mesoscale Meteorology
ARAT	Avion de Recherche Atmospherique (French atmospheric research aircraft)	JOSS	Joint Office for Science Support

TABLE A.1. CONTINUED

ARPEGE	Action de Recherche Petite Echelle Grande Echelle (Météo France)	LOP	Lesser Observation Period (sometimes FLOP)
ASAP	Automated Shipboard Aerological Programme	MIT	Massachusetts Institute of Technology
CETP	Centre d'étude des Environnements Terrestre et Planétaires	MSA	Multiscale Sampling Area
CMC	Centre Météorologique Canadien, Montréal, Canada	NCAR	National Center for Atmospheric Research
CNRS	Centre National de Recherches Scientifiques	NCEP	National Center for Environmental Prediction
COSNA	Composite Observing System for the North Atlantic	NESDIS	National Environmental Satellite Data and Information Service
EC	European Commission	NOAA	National Oceanic and Atmospheric Administration
ECMWF	European Centre for Medium-Range Weather Forecasts	NRL	Naval Research Laboratory
EGOS	European Group on Ocean Stations	NSF	National Science Foundation
FASTEX	Fronts and Atlantic Storm-Track EXperiment	NSSL	National Severe Storm Laboratory
FIC	Flight International Company	UCAR	University Corporation for Atmospheric Research
GPS	Global Positioning System	UCLA	University of California, Los Angeles
GTS	Global Telecommunication System (operated by WMO)	UKMO	United Kingdom Meteorological Office
INSU	Institut National des Sciences de l'Univers	USAF	United States Air Force
IOP	Intensive Observation Period	WMO	World Meteorological Organisation

APPENDIX B

Tables B.1 (IOPs) and B.2 (LOPs) 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) and Baehr *et al.* (1999). The rest of each table summarizes the operations in the three FASTEX areas.

The labelling of the tables is mostly self explanatory. For the special FASTEX platforms, the information generally applies to the middle time of the intensive period, and the layout is described in the following table:

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

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 refers to the high-resolution soundings available in the database in July 1999, as given by the data availability pages.

TABLE B.1. THE FASTEX INTENSIVE OBSERVATION PERIODS

	IOP1			IOP2			IOP3			IOP4			IOP5			IOP6		
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	8/1 12	(47W, 42N)		13/1 00	(18W, 53N)		14/1 12	(32W, 43N)		17/1 06	(27W, 47N)			no significant		23/1 00	(35W, 50N)	
rate (mb/6 h)		−9			−10			−9			−2			deepening			−4	
max amplitude	10/1 00	(33W, 54N)		13/1 00	(15W, 59N)		15/1 18	(29W, 51N)		17/1 12	(25W, 48N)		22/1 18	(17W, 44N)		23/1 00	(35W, 50N)	
(mb)		968			tlw 978			973			995			1008			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			
C-130 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)																		
C-130	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

	IOP7			IOP8			IOP9			IOP10			IOP11			IOP12		
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	25/1 06	(32W, 47N)		Complex interaction			31/1 12	(66W, 37N)		4/2 12	(17W, 48N)		5/2 06	(39W, 44N)		9/2 12	(27W, 52N)	
rate (mb/6 h)		<1		low/orography				−7			−3			−13			−22	
max amplitude	26/1 00	(18W, 55N)					3/2 06	(18W, 63N)		4/2 18	(10W, 50N)		7/2 00	(5W, 68N)		10/2 06	(20W, 62N)	
(mb)		tlw 1012						975			1010			950			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	0330	11				4/2	0330	16	8/2	1100	11
							0000						1415			0545	(NB:C130)	
C-130 USAF				27/1	0600	13				2/2	1045	19	4/2	0945	13	9/2	0730	7
				0100						1700			1615			1315		
Gulfstream (1)							1/2	0530	30							8/2	0530	26
							1145	Sh → StJ								1215	Sh → StJ	
KNORR													6/2	48	15	9/2	24	8
													0000	(51W, 51N)		1200	(51W, 56N)	
ÆGIR	25/1	24	9							4/2	24	10	6/2	24	10	9/2	24	12
	0600	(35W, 49N)								1200	(12W, 50N)		0300	(24W, 47N)		1500	(35W, 46N)	
SUROÎT	25/1	24	8	29/1		5							6/2	30	9	9/2	24	9
	0600	(35W, 52N)			(39W, 45N)								1200	(31W, 44N)		1500	(35W, 50N)	
V. BUGAEV	25/1	24	8				2/2	24	3	3/2	24	7	6/2	24	5	9/2	24	14
	0600	(35W, 45N)						(56W, 44N)		0600	(50W, 43N)		0300	(35W, 41N)		1500	(35W, 41N)	
Other ships																9/2	1 ASAP	
Gulfstream (2)	25/1	0630	28	29/1	0715	19				3/2	0545	38					StJ → Sh	
	2015			1230						1815	StJ → Sh							
C-130	26/1	0700	41							4/2	0900	27	5/2	1000	70	9/2	1130	43
	0030									0930			2300			1745		
P3 NOAA	26/1	0800					2/2	0900	5	4/2	0915	1	6/2	1000		9/2	1000	ss
	0100						2000		ss	1030			0145			1800		
Electra	26/1	0600	ss				2/2	0700	mi	4/2	0730	ss	5/2	0700	ss			
	0245						2300			0915			2200					
Gulfstream (3)													6/2	0530	42			
													0115					
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							Narssarsuaq 1/2 18 8			2 ARAT flights 4/2								

TABLE B.1. CONTINUED

	IOP13			IOP14			IOP15			IOP16			IOP17			IOP18			IOP19		
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	9/2 18	(62W, 39N)		11/2 18	(65W, 37N)		14/2 00	(50W, 46N)		17/2 06	(25W, 52N)		19/2 00	(22W, 51N)		23/2 00	(32W, 53N)		27/2 06	(23W, 60N)	
rate (mb/6 h)		−6			−9			−10			−20			−16			−10			−11	
max amplitude	10/2 18	(43W, 46N)		12/2 18	(45W, 43N)		15/2 18	(24W, 53N)		18/2 06	(12W, 68N)		20/2 00	(7W, 62N)		24/2 18	(4W, 60N)		27/2 12	(25W, 62N)	
(mb)		989			986			973			943			943			950			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	0500	19	12/2	0415	23	14/2	0400	19				18/2	0245	15	22/2	0400	18	26/2	0345	17
	1100			1030			1330						0015			0000			0000		
C-130 USAF																					
Gulfstream (1)							13/2	0500	0	(17/2)	(06)		17/2	0500	22	22/2	0630	28			
							1430	Sh ⟶ StJ			Sh ⟶ StJ		1730			1115	Sh ⟶ Gob				
KNORR	10/2	24	6				13/2	24	8	16/2	24	8	18/2	24	5	22/2	24	8	27/2	24	7
	1200	(54W, 57N)					1500	(55W, 59N)		1200	(53W, 61N)		1200	(51W, 62N)		0600	(57W, 57N)		1200	(49W, 60N)	
ÆGIR	10/2	18	10	13/2	18	6	14/2	24	7	16/2	15	6	19/2	18	9	23/2	24	7			
	2100	(35W, 46N)		0000	(35W, 46N)		1800	(35W, 46N)		2230	(35W, 52N)		0000	(35W, 52N)		0000	(28W, 60N)				
SUROÎT	10/2	30	18	13/2	18	7	14/2	24	6	16/2	15	5	18/2	18	15	23/2	24	9	26/2	18	13
	2100	(35W, 52N)		0000	(38W, 50N)		1800	(39W, 50N)		2230	(38W, 48N)		1800	(36W, 46N)		0000	(42W, 48N)		1500	(40W, 45N)	
V. BUGAEV	10/2	24	15	13/2	18	7	14/2	24	7	16/2	15	6	18/2	18	15	23/2	24	6	27/2	18	11
	2100	(35W, 41N)		0000	(35W, 41N)		1800	(35W, 41N)		2230	(35W, 41N)		1800	(35W, 41N)		0000	(35W, 41N)		0000	(28W, 40N)	
Other ships				13/2	1 ASAP		15/2	1 ASAP								23/2	1 ASAP				
				06			06									06					
Gulfstream (2)							15/2	0630	30				18/2	0700	54	22/2	0445	33			
							0615	StJ → Sh					1830			1845	Gob → Sh				
C-130							15/2	1100	40	17/2	1100	45	19/2	1030	46				27/2	1100	42
							1130			0730			0645						0730		
P3 NOAA							15/2	0830	ss	17/2	0645	ss	19/2	0900	ss	23/2	0915	22			
							1145			0700			0730			1515		mi			
Electra																					
Gulfstream (3)													19/2	0700	37				27/2	0730	48
													2030						1345		
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													Narssarsuaq 18/2 12 24 8			Narssarsuaq 22/2 00 24 8					

TABLE B.2. THE FASTEX LESSER OBSERVATIONS PERIODS

	LOP1		LOP2		LOP3		LOP4		LOP5		LOP6	
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	11/1 00	(22W, 53N)	8/2 06	(29W, 50N)	12/2 18	(4W, 57N)	17/2 18	(20W, 50N)	22/2 12	(21W, 51N)	24/2 12	(16W, 49N)
rate (mb/6 h)		−6		−9		−7		−7		−10		−10
max amplitude (mb)	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	11/1 06	(20W, 56N)	8/2 18	(15W, 55N)	12/2 06	(10W, 54N)	17/2 18	(20W, 50N)	22/2 18	(15W, 54N)	24/2 12	(16W, 49N)
end of tracking	12/1 12	(1W, 68N)	9/2 12	(2E,64N)	13/2 00	(2W, 58N)	19/2 00	(10E,58N)	23/2 12	(1E,63N)	25/2 06	(10E,57N)
Upstream data	US RS		C-130 US 5/2 1300 C-130 US 6/2 0730	1030 18 1000 15	see IOP13		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, 451N) 8 s/j (30W, 47N) 7 s/j (35W, 41N) 8 s/j (35W, 41N)	see IOP13		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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