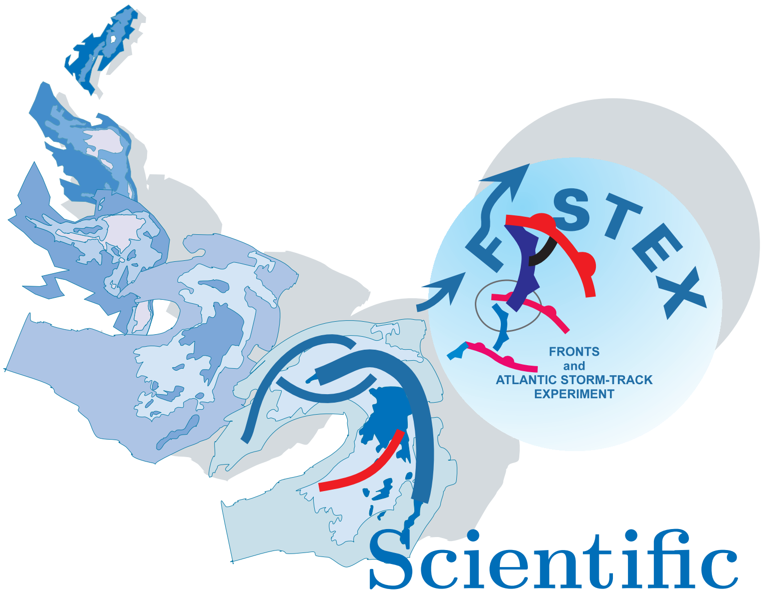

Part 1

Scientific objectives, observing strategy

by
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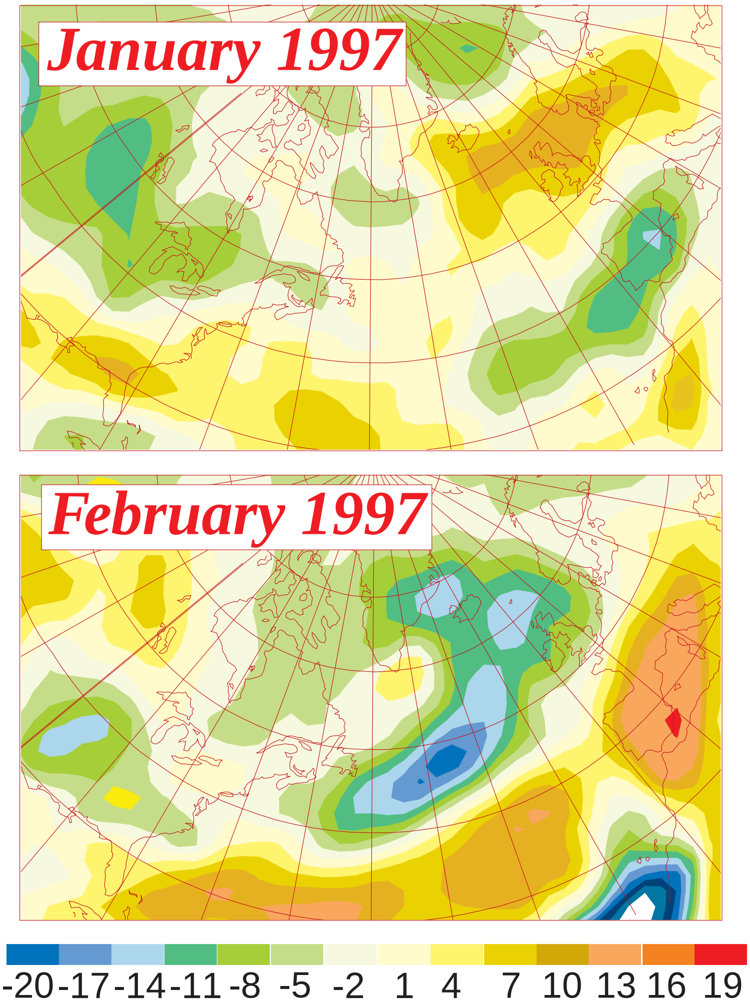


Figure 1.1: *Outgoing Longwave Radiation anomaly for January 1997 (top) and February 1997 (bottom). This figure is to be compared with the North-Atlantic Storm-Track at the same time: this comparison reveals that, in the presence of a well established Storm-Track, as was the case in February, the radiative anomaly results directly from the mid-latitude storms. Figure prepared by C. Piriou, from Météo-France, with data from NOAA/NESDIS.*

1.1 FASTEX : an experiment on Atlantic cyclones and cloud systems

Mid-latitude cyclonic storms, which occur predominantly in oceanic storm-tracks, are recognized as playing a crucial role in the climate system. Figure 1.1, compared to the actual tracks of storms (Figure SN1.2.2), shows, as an example, the impact of February's 1997 Storm-Track on the radiative budget of the atmosphere. Current and foreseeable global climate models inadequately resolve these storms ; it is critical that processes such as heat (radiative, sensible and latent), moisture, and momentum fluxes associated with these storms be properly understood and included in climate models (Browning, 1994b). Being essentially oceanic, these storms are poorly observed routinely and have been subject to only a few major observational campaigns (see Subsection 1.2.3 below). These have focused mainly on the western entrance of the North Atlantic storm-track where important but special conditions dominate, such as extremely strong ocean-air fluxes. The majority of cyclones are less dependent on such fluxes. A particular problem in the North-Atlantic is the secondary generation of storms along fronts towards the eastern end of the storm-track, on its european side (Ayrault et al., 1995).

The unique feature of the Fronts and Atlantic Storm-Track Experiment is the desire to provide a bridge, for the first time, between the large-scale dynamics of cyclogenesis and the consequent mesoscale and cloud-scale processes within the storms. This holistic approach is very demanding in requiring a description of features such as the upper jet stream on synoptic scales at the same time as detailed radiative, dynamical and cloud structures. This has not been attempted before but it is crucial if the phenomenon is to be described in a complete enough way for inclusion in, and verification of predictions from, large-scale numerical models.

A major issue is the two way interaction between the large-scale flow and the Atlantic storms. The latter have to be fairly precisely handled by climate models as the translation of climate evolution into changes in the frequency and intensity of storms must be established.

An especially important aspect of these storms which requires this holistic approach is the cloud systems. Cloud systems are to some extent the slaves of the large-scale forcing but they themselves alter the energy fluxes in the storms. The linkages between cloud microphysical, radiative, latent heating and dynamical processes must be established if meaningful parameterizations are to be established for climate and numerical weather prediction models. An example of such coupling on the mesoscale organization is discussed in Part 7.

These ideas leads to a long-term (typically 10 years) programme. This Report presents an overview of the first part of this programme, covering preliminary work and the large scale field phase. It is focused on the cloud-related results, but the other components of the programme are also outlined. The programme, and in particular the detailed analysis of the data collected during the field phase, two years ago, is undergoing. Part of this work is covered by the FASTEX Cloud System Study (FASTEX-CSS) project.

1.1.1 Goals of FASTEX

The ultimate aim of FASTEX is to provide the scientific understanding necessary to enable detailed diagnostic and predictive analyses of the *life-cycles* of Atlantic storms and cloud-systems. This involves study of the coupling between the cloud systems and their dynamics, the phases of development of the clouds, the embedded mesoscale substructures, microphysics and their modelling on a range of scales. These topics form the core of the FASTEX CSS project.

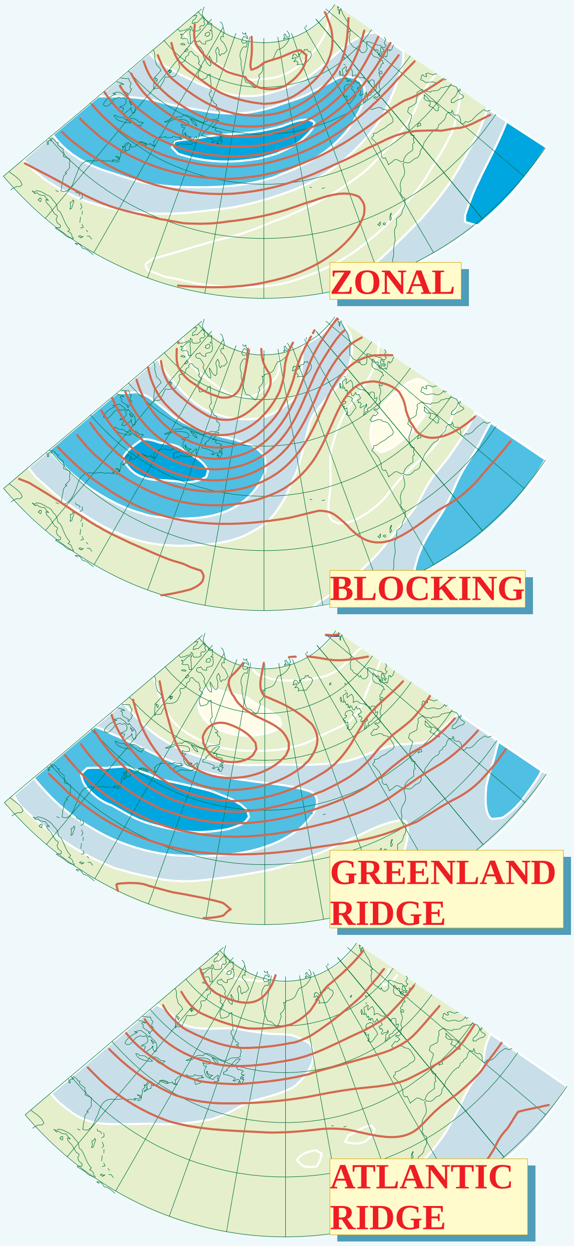
The present Report is concerned with the field experiment itself, the delivery of the FASTEX data base and the derivation of the first results. The measurable objectives of this project were:

- to conduct a field experiment concerning cloud systems within extra-tropical cyclones. This has provided a unique data set :

Short Note 1.1:
North-Atlantic weather regimes

by F. Ayrault, F. Lalaurette and C. Loo

Figure SN1.1.1: *The climatological definition of the North-Atlantic weather regimes. Dark-red lines: 700 mbar geopotential height (interval: 50mgp). White lines and shading: 300 mbar zonal wind (interval: 10m.s^{-1}).*



How to characterize the very large-scale, slow evolution of the weather, the environment within which cyclones form and evolve ?

Traditionally, this scale, which is a characteristic of the climate, is described on the basis of monthly averages. At mid-latitudes, the january average is contrasted with the july one. It turns out that such maps are not representative of the actual weather pattern because the variability on the same, large scale remains quite large. This variability is a critical parameter of actual weather and has to be described (Hoskins et al., 1983).

A different concept that accounts for this intraseasonal variability is therefore needed: the weather regimes.

The definition of weather regimes that appears to be both useful and dynamically relevant is the one proposed by Vautard et al. (1988). A weather regime is a 3D field pattern that is quasi-steady and therefore relatively persistent. Low depressions and cyclones account for the variability of the weather on the time scale of a day or so. Weather regimes account for the variability on time scales of a week or so. They have been defined originally by using the long time series of analysis from the National Weather Service. Fig. SN1.1.1 shows the approximation that has been derived in the course of FASTEX from the shorter by finer analyses from ECMWF between 1984 and 1994. They have been defined by combining a principal component analysis on a coarse grid (3°of resolution) and automatic clustering (Ayrault et al., 1995).

The large scale weather over the Atlantic evolves between the 4 patterns shown by the figure. The most characteristic features of the regimes are reasonably robust with respect to the base dataset and the construction technique. The regimes are shown through the 700 mbar geopotential height and the upper-level zonal velocity. The latter easily highlight the presence of a baroclinic zone, which is the environment needed by cyclone, their fuel reservoir, in a sense.

The first two regimes, respectively called "zonal" and "blocking", are the two most frequent. The zonal regime, with its long east-west baroclinic area is the one that brings Europe most of its cyclones, and therefore, rain. In this case, western Europe is influenced by oceanic conditions. The blocking regime, on the other hand, has a quickly interrupted baroclinic zone: the continental influence over Europe often dominates, while most cyclones are diverted towards Greenland and Iceland.

The link between regimes and the occurrence of cyclones over Europe is shown by Fig. 1.4.

The statistical distribution of the regimes (derived from the same sample) is given by Fig. 1.3. Variations about this statistical distribution generally translates into actual problems: a larger persistence of blocking leads to drought in the following summer. A larger persistence of zonal regime means floods at the end of the same winter or in the spring. A change of the climate that will impact Europe will most likely do so through a change of the regime patterns or time frequency distributions. Vautard (1990) presents a statistical analysis of regimes transitions, using a much larger sample. Vautard and Legras (1988) has confirmed the original work of Hoskins et al. (1983) about regime maintenance: the high frequency variability (namely the cyclones) plays the most important role. Weather regimes and cyclones seen as a population are one among many examples of two-way interaction, here on the seasonal scale. The relevant way to describe cyclone in this instance is by referring to the "storm-track" (see Short Note 1.2). It is also interesting to compare these averaged conditions with the actual weather in January and February 1997, described in section 2.2 (Part 2 , see Fig. 2.2). The forecast of weather regimes during the field phase is presented in Short Note 2.6.

  - –relating to the initiation of storms in the mid-Atlantic storm-track,
  - –relating to the structure of the developing cloud-cyclone system near western Europe.

- •to organize the data into an open and accessible Data Base.
- •to provide both raw and processed data, including analyzed fields obtained with both the operational and special data collected during the field phase.

1.1.2 FASTEX, the Environment and Climate Programme and the international context

The FASTEX project, considering the field phase and the subsequent analysis phase, is built to address the following tasks of the Programme :

- •Theme 1, Area 1.1, 1.1.1 Basic processes in the climate system, task 4 : *studies of radiative coupling in the (...) troposphere, including the role of (...) clouds and cloud systems and their dynamics (...).* See Parts 5, 6 and 7 for examples of preliminary results in this area. See also Short Note 2.2 for the contribution of a FASTEX-related programme (called CATCH) to Task 2, on the dynamics of air-sea fluxes.
- •Theme 1, Area 1.1, 1.1.3 Climate variability, simulation of climate and prediction of climate change, task 2 : (...) ; *dynamic assimilation of data and new methodologies (...).* (See Part 8 for some results.) Task 6 : *Development of improved forecasts of change in the type, distribution and frequency of meteorological extremes.* (The first part of this work has been to established a new climatology of cyclogenesis: derived results are shown in the present Part and the next one. See Short Note 1.5 for a summary or Ayrault (1998) for full results. See also the Short Notes 1.1, 1.2 and 2.6 on weather regimes, their strong link with the storm-track and their medium-range forecast.)

At the international level, FASTEX is an integral component of the World Climate Research Programme (WCRP) through its Global Energy and Water Cycle Experiment (GEWEX). Recognising the importance of the large-scale effects of clouds as one of the largest sources of uncertainty in climate prediction models, WCRP/GEWEX has established the GEWEX Cloud System Study (GCSS). The primary aim of GCSS

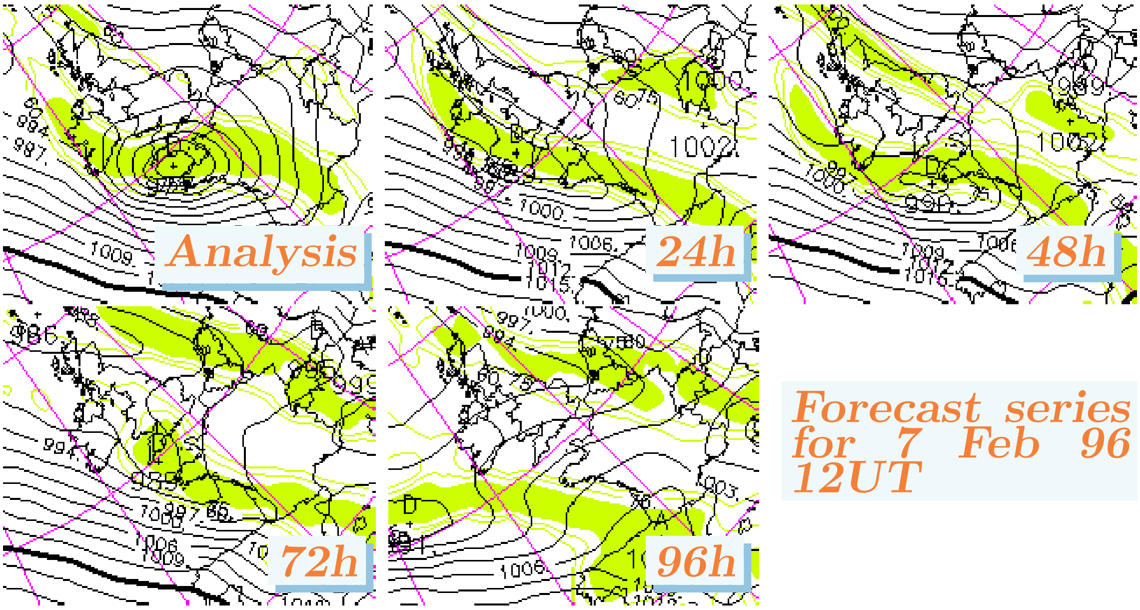


Figure 1.2: *A series of forecast for the 7/2/96 12UT together with the verifying analysis, taken from the ECMWF operational dissemination. Contours: mean sea level pressure every 3 mbar. Shaded areas: 700 mbar relative humidity larger than 80 %.*

is to develop better understanding of cloud systems leading to improved parameterization of cloud processes within climate models (Browning, 1994). GCSS is subdivided into four components, each of them being dedicated to a class of cloud system. FASTEX is a key observational component of the GCSS group on Extratropical Layer Cloud Systems.

Through GEWEX/GCSS and COMPARE, FASTEX is a collaboration with Canadian groups. Because of its scale and universal scope, FASTEX involve a cooperation with US scientists.

In France, FASTEX is the priority project of the national programme Programme Atmosphère et Océan à Mésoéchelle (PATOM) coordinated by the Institut National des Sciences de l'Univers for the period 96–98 and sponsored by several institutions (Météo-France, IFREMER, etc). In the UK, FASTEX is a priority project of the Joint Centre for Mesoscale Meteorology (JCMM) ; the JCMM is supported by the UK Met Office, NERC and the University of Reading.

1.2 Cyclogenesis: a short review

During the last few years, the theoretical study of cyclogenesis has experienced a remarkable renewal of interest. This is due to the simultaneous emergence of new problems in dynamical meteorology and of new approaches to solve them. The result is a drastic change of perspective in the way cyclogenesis is understood conceptually by most meteorologists. This in turn impacts the way this phenomena should be observed or predicted.

Short Note 1.2:
Storm-Track and tracks of storms

by Ch. Baehr and F. Ayrault

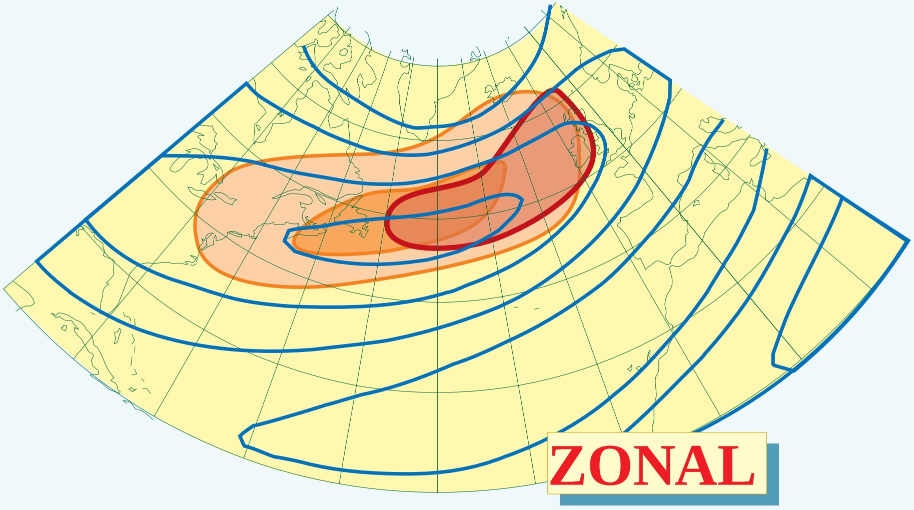


Figure SN1.2.1: *The classical (orange shading) and improved classical (red shading) definition of the storm-track during the zonal regime. The fields are the high frequency variability (2–6 days) and ultra-high frequency variability (0.5–2 days). From Ayrault et al., 1995.*

What is the North-Atlantic storm-track ? As the name suggests, it represents the preferred location of evolving cyclones and storms. Like the weather regimes (Short Note 1.1), storm-tracks are concepts that stemmed from the new approach to the description of the climate started by Blackmon et al. (1977) and based on time series of analysed fields. This approach separates the components of the climate and weather into categories according to the time-scale of their variability. The weather regime are quasi-steady persistent patterns that account for the low frequency variability. The latter results from applying a low-pass filter to the time-series at each grid-point.

The storm-tracks are originally defined as maxima in the so-called "high-frequency" variability (with eigenperiods of 2–6 days). For the Atlantic, using the same ECMWF analyses as in the construction of Fig. SN1.1.1 , this classical definition of a storm-track is shown by Fig. SN1.2.1. It is shown in relationship with the upper-level wind, highlighting its stronger orientation towards the north-east.

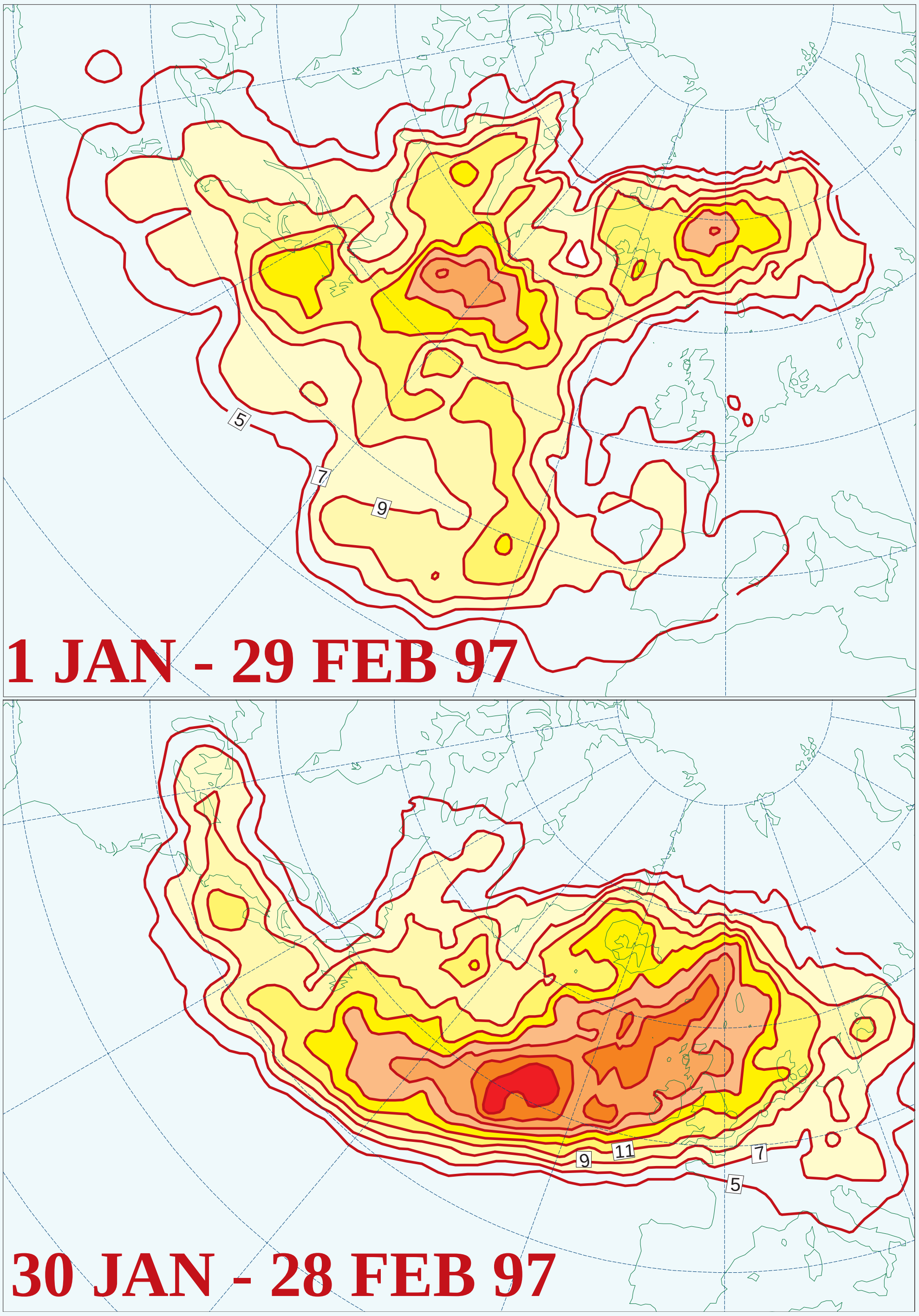
This definition is not satisfactory since it gives the strong impression that cyclones are mostly present in the western part of the North-Atlantic basin: Europe appears to be marginally reached by storms. This is not exactly what the synoptic experience suggests.

When Ayrault et al. (1995) take into account the "ultra-high" frequency variability (with eigenperiods in the range 0.5–2 days), a more realistic distribution emerges. The map then suggests that it is useful to distinguish between the main storm-track cyclones that are closely tied to the regime baroclinic zone and the end-of-stormtrack cyclones, that evolve more rapidly and depend on transient features of the main cyclones such as their fronts. FASTEX has been started as a project studying end-of-stormtrack systems, since they appear to be the ones that reach Europe.

Although this separation is sometimes useful, a more direct definition of the storm-track is possible, and indeed, necessary since the cut-off at 2 days between high and ultra-high frequency is somewhat arbitrary, perhaps artificial. Following Ayrault et al. (1995), a cyclone of practically any amplitude can be defined using its vorticity signature. Ayrault (1995) has devised an automatic algorithm that enables to track a cyclone from one analysis to the next: as a result, large sets of trajectories and life-cycles can be extracted. The storm-track is revealed by computing the density of trajectories: the number of cyclone tracks that moves over a given grid-point, each system being counted once at that point.

This technique has been applied to the analyses of the FASTEX period included in the Data Base (see Part 4). The results are presented in two sets (Fig. SN1.2.2) in order to highlight the dependence of the storm-track on the weather regime. In periods of blocking and weak Greenland Ridge regime, as in January 1997, cyclones form at their usual location but then fork, a branch moving towards Iceland, another towards Spain. During a long spell of zonal regime, such as in February 1997, cyclone cross the ocean zonally. Note that the largest density is reached near Europe, not near the East-Coast of America, clearly showing the importance of this phenomena for our continent.

Figure SN1.2.2: *Map of density of trajectories computed from the analyses in the FASTEX Data Base using the automatic tracking algorithm of Ayrault (1995) that follows the 850 mbar vorticity maxima. These maps provide a direct picture of the cyclone tracks as well as their number.*



1.2.1 Theoretical perspective

The new problems are the studies of cyclogenesis on the 1000 km horizontal scale. This scale is the only one that is explicitely mentioned in the founding paper on the life cycles of cyclones by Bjerknes and Solberg (1922): it is not new. The semi-geostrophic theory of frontogenesis of Hoskins and Bretherton (1972) provides a simple but realistic description of an atmospheric front: here lies the novelty. With respect to the classical cyclogenesis model of baroclinic instability (Charney, 1947, Eady, 1949), the fronts have a richer organization of the wind field than the simple baroclinic zone. This can lead to different instabilities. Schär and Davies (1990) or Joly and Thorpe (1990) show, for example, under which conditions normal mode instability can happen along a front within the context of semi-geostrophic theory.

The new approaches, on the other hand, result from the parallel questioning of the relevance of the normal mode stability analysis as a theoretical explanation of cyclogenesis. This is mostly the work of Farrell (1984, 1985, 1989) and it applied originally to the explosive growth of large scale waves. The general idea is that the same physical mechanisms present in the normal modes can be triggered much more efficiently by initial conditions involving organized precursors. This work provides a theoretical support to ideas that had been voiced for a long time (*e.g.* Sutcliffe, 1947 Kleinschmidt, 1950). Some details of the evolution of the theoretical framework are given by Short Note 1.3. The framework proposed by Farrell (1988) is also more suitable to address some of the difficulties noticed in the new work on frontal stability. For example, the time scale of frontogenesis is not different from that of frontal cyclogenesis, so the two mechanisms cannot be separated as neatly as the normal analysis requires it. In the same spirit, it appears that time-dependent basic flows, not amenable to normal mode analysis in the strict sense (in spite of attempts such as Joly and Thorpe, 1991), can lead to new mechanisms for the development — or the absence of development — of cyclone-like features.

The combination of these new problems and approaches led to a series of new theoretical results about cyclogenesis. Thorncroft and Hoskins (1990) exhibited the non-linear development of a cyclone along the cold front of a baroclinic wave triggered by an upper-level feature. This anomaly overcomes the stabilizing effect of frontogenesis clearly shown by Bishop and Thorpe (1994a, 1994b). The latter studied the effect of stretching deformation on moist frontal cyclogenesis the effectiveness of the deformation to hinder cyclone formation is quantified. Another series of results address the relationship between pressure deepening, cyclone activity and the mechanisms for cyclogenesis. Malardel *et al.* (1993) pointed out that, on its own, the additional conversion mechanism that a frontal environment provides (due to the presence of wind shear) leads to short-lived systems with very little deepening. Joly (1995) fully generalizes this result to a wide variety of initial conditions as well as to transient development: the baroclinic interaction appears to be the only mechanism that allows deepening larger 10 mbar. That does not imply that the non-baroclinic systems are weak during their short life-cycle: just the reverse, it shows that looking only at the pressure field can be misleading.

It appears, therefore, that a whole new set of ideas and hypotheses are now available for testing against observations. The meteorological subjects of interest are not the explosive large-scale waves but a wider spectrum of cyclones more or less modest that form where fronts are present: in the wake of these large waves, in the middle or eastern part of oceanic basins such as the Pacific or the Atlantic one. These cyclones strongly depend on many properties of their environment: the baroclinicity, the presence of low level frontal jets but also that of frontogenetic forcing, the existence of moving, organised features, etc.

Short Note 1.3:
A cloud of physics in the Report: linear theories of mid-latitude cyclones

by A. Joly

1.3.1 From necessary conditions for instability...

Up to the mid-eighties, the “standard model” for providing an explanation of mid-latitude cyclones was built along the lines proposed by Bjerknes (1927). It is called *linear normal mode stability analysis* and is imported from fluid mechanics. One seeks to identify the newly developing cyclones with a spontaneously growing perturbation of a “basic flow”.

This basic flow represents the large scale context within which cyclones are thought to form. It is assumed to be steady and it also is low-dimensional (1D or 2D). Bjerknes had in mind, originally, the Polar Front, an extreme steady separation between two air masses. None of the solutions can convincingly be associated with actual cyclones (Orlanski, 1968). Following the same method, but using a simple *jet-stream flow*, a smooth transition from warm to cold air, Eady (1949) and Charney (1947) obtained very convincing results.

A fundamental concept was, furthermore, introduced by both papers: the troposphere, on the scale of cyclones, is close to some *balance*. The state of the atmosphere can be described with few variables (one, with boundary conditions, is enough). This idea has many consequences (see Short Note 1.6) and remains an essential, reliable, reference up to this day.

Returning to the stability analysis and in order to be specific, let X be a meridional axis pointing towards warm air at the equator, Z be the vertical and Y the zonal direction. The basic flow is in strict balance, since it is steady. It comprises a zonal wind flow $\overline{V}(X,Z)$ in *geostrophic* equilibrium with a thermal field $\overline{\theta}(X,Z)$ (Fig. SN1.3.1). These fields can equivalently be represented through a distribution of *potential vorticity* (the single summary field appropriate here, see again Short Note 1.6) $\overline{P}(X,Z)$ and boundary conditions provided by $\overline{\theta}(X,Z=0)$ at the “surface” (actually, the top of the boundary layer) and $\overline{\theta}(X,Z=H)$ at the top of the domain considered (the tropopause or sometimes, higher).

The question is *can a perturbation* Φ' *to the basic flow grow spontaneously,* and if so, what does it look like ? The potential perturbation Φ' is the single variable needed to represent the state of the balanced perturbation. Using once more the idea of balance, it is possible to recover the dominant wind and temperature perturbations from equations like $u' \sim -f^{-1}\partial_Y\Phi'$, $v' \sim f^{-1}\partial_X\Phi'$ and $\theta' \sim (g/\theta_0)\ \partial_Z\Phi'$. A linear normal mode is a solution of the form:

$$\Phi' \;=\; \widehat{\Phi}(X,Z)\, e^{i\,\ell Y}\; e^{\sigma\, t}, \qquad \text{(SN1.3.1)}$$

where ℓ is the zonal wavenumber or scale of the perturbation and σ its complex growth rate $\sigma = \sigma_r + i\,\sigma_i$. A spontaneously growing solution exists as soon as one can find a function $\sigma_r(\ell,\overline{P}) > 0$.

Certainly the most powerful and elegant result of this body of work is the *Charney and Stern (1962) theorem*. The ambition of this theorem is to predict which basic flows will support unstable waves and will, therefore, be conducive to cyclogenesis. It is a kind of existence theorem for solutions of the form of Eq. (SN1.3.1). It takes the form of integral constraints, such as:

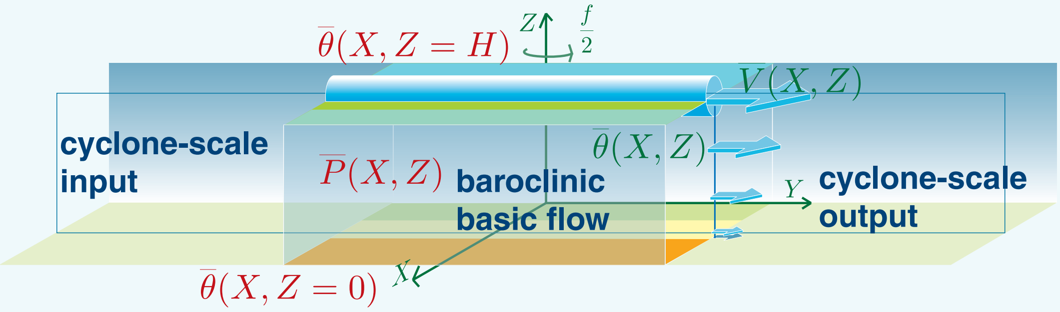
$$\sigma_r \left[\int_0^{L_x}\!\int_0^{H} \frac{f}{\overline{P}J}\left(\frac{\partial\overline{P}}{\partial X}\right)_{\overline{\theta}} A^2(X,Z)\ r dX dZ \right. \qquad \text{(SN1.3.2)}$$

$$\left. + \int_0^{L_x} \left[\frac{f^2}{\overline{P}}\left(\frac{\partial\overline{\theta}}{\partial X}\right) A^2(X,.)\right]_0^H dX \right] \;=\; 0$$

where the positive real number

$$A^2(X,Z) \;=\; \frac{\left|\widehat{\Phi}(X,Z)\right|^2}{\sigma_r^2 + \left(\ell\overline{V_g}(X,Z)+\sigma_i\right)^2}$$

Figure SN1.3.1: *Example of geometry and notations employed to study the origin of mid-latitude cyclones in a baroclinic zone. The latter is represented by the combination of the jet-stream (blue tube) in balance with a moderate horizontal gradient of potential temperature θ.*



is a measure of the unstable wave amplitude. Eq. (SN1.3.2) is an example of a *necessary condition for instability*. Since for non zero σ_r to exist, the integrals must be zero, $\left(\partial \overline{P} / \partial X\right)_{\overline{\theta}}$ must change sign in the interior (there must be an extremum of $\overline{P}$) or $\left(\partial \overline{\theta} / \partial X\right)$ at $Z = 0$ and $Z = H$ must have different signs. There are also constraints on the phase speed and scale of the perturbation.

The interpretation of normal mode analysis is plainly stated for example by Eady (1949). It can be stated as follows Let E_G be an overall measure of the wave amplitude, for example its energy (but many others can be named and employed):

$$E_G \left\langle \Phi', \Phi' \right\rangle = \frac{1}{2} \frac{1}{L_x L_y} \int_0^{L_x} \int_0^{L_y} \int_0^{H} f^{-2} \left[\left(\partial_Y \Phi'\right)^2 + \left(\partial_X \Phi'\right)^2 \right] + \frac{\theta_0}{g} \frac{f \overline{J}}{\rho_0 \overline{P}} \left(\partial_Z \Phi'\right)^2 \ \rho_0 dX dY dZ. \quad \text{(SN1.3.3)}$$

The normal modes form a basis onto which any perturbation can be projected. Let $\{\mathbf{\Phi}_k\}_{k=1,K}$ be the normal modes. All kinds of small amplitude, unorganized perturbations enter the basic flow. Any such perturbation can be expanded in the normal mode basis as: $\mathbf{\Phi}' = \sum_{k=1}^{K} b_k \, \mathbf{\Phi}_k$, with a flat series of b_k. Consider now that the energy can be said to change between an initial time t_0 and a final time t_1 as:

$$E_G \left\langle \Phi', \Phi' \right\rangle = \sum_{k=1}^{K} \left|b_k\right|^2 e^{2\sigma_{kr}(t_1 - t_0)}. \quad \text{(SN1.3.4)}$$

In the presence of a large dominant instability characterized by σ_{xr} this expansion reduces to:

$$E_G \left\langle \Phi', \Phi' \right\rangle \sim \left|b_x\right|^2 e^{2\sigma_{xr}(t_1 - t_0)} :$$

any arbitrary perturbation tends to behaves and to look like the most unstable normal mode. The other solutions seem not to be useful. *The basic flow kind of generates perturbations that look like the most unstable normal mode (Fig. SN1.3.2).*

1.3.2 ...to sufficient conditions for linear development

An important assumption is made, more or less implicitely, in order to write Eq. (SN1.3.4): the normal modes have to be orthogonal to one another in the sense of energy. The change of energy for an arbitrary perturbation between times t_0 and t_1 is, in fact:

$$E_G \left\langle \Phi', \Phi' \right\rangle = \sum_{k=1}^{K} \sum_{j=1}^{K} b_k \overline{b_j} \, e^{(\sigma_k + \overline{\sigma_j})(t_1 - t_0)} \, E_G \left\langle \mathbf{\Phi}_k, \mathbf{\Phi}_j \right\rangle , \quad \text{(SN1.3.5)}$$

where $E_G \left\langle \mathbf{\Phi}_k, \mathbf{\Phi}_j \right\rangle$ is the scalar product of the two normal modes $\mathbf{\Phi}_k$ and $\mathbf{\Phi}_j$ that can be constructed from the norm E_G , energy. In other words, $E_G \left\langle \mathbf{\Phi}_k, \mathbf{\Phi}_j \right\rangle$ says how two normal modes are energetically correlated in a given basic flow. The classical interpretation of normal mode theory, and indeed its usefulness, crucially depends on the fact that normal modes are energetically independent. In this case, only unstable modes in the sense of Eq. (SN1.3.1) can grow.

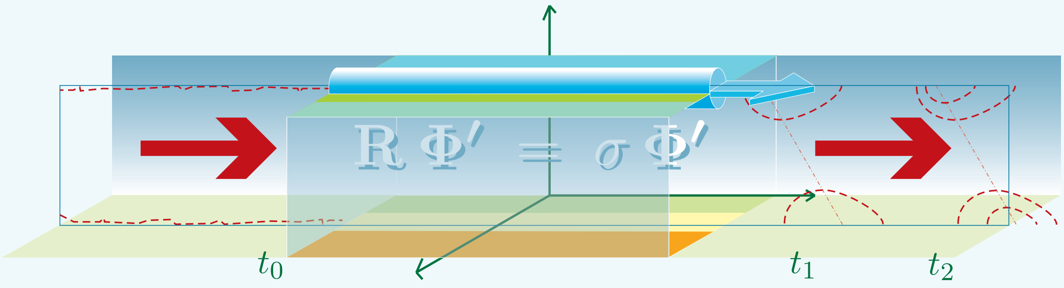
Eq. (SN1.3.5) suggests that this is *not required* any more when normal modes are not energetically independent. For the sake of example, consider a set of *neutral* modes: $\forall k \in \{1, \ldots, K\}$, $\sigma_{kr} = 0$, but such that two modes are correlated in the sense of energy, modes 1 and 2, say: $E_G \left\langle \mathbf{\Phi}_1, \mathbf{\Phi}_2 \right\rangle > 0$. Then, let Φ' be the perturbation which is the sum of these two modes. Eq. (SN1.3.5) reads:

$$E_G \left\langle \Phi', \Phi' \right\rangle = 2 \cos\left[(\sigma_{1i} - \sigma_{2i})(t_1 - t_0)\right] E_G \left\langle \mathbf{\Phi}_1, \mathbf{\Phi}_2 \right\rangle.$$

This perturbation amplifies and then decays: *transient growth* becomes possible, *even in the absence of instability*. However, it can also decay and then perhaps grow, if not destroyed by turbulence: *the initial phase, more generally the initial conditions become essential*, while they did not matter in the normal mode analysis. In reference to the description of cyclogenesis made by synopticians (Sutcliffe, 1947, for example), this kind of evolution that depends more on initial conditions than on the presence of an instability can be called *linear development*.

It appears, then, that if two normal modes or more, with close phase speeds, can easily be correlated in the sense of energy, linear development and the related solutions cannot be ruled out as a possible explanation for systems like cyclones. In the presence of unstable normal modes, this process provides additional transfers that will boost the effective growth rate of certain combinations of normal modes. These facts were pointed out essentially by Farrel (1984, 1985).

Figure SN1.3.2: *The classical perspective: the baroclinic zone in the atmosphere acts as a generator of phase-locked cyclones. The equation represents the eigenvalue problem that defines the normal modes.*



In this new perspective, the question addressed by Charney and Stern has to be restated. They asked "which basic flows support unstable waves". Today's question is "which basic flows support non-orthogonal normal modes", unstable or not. In the present case of energy as defined by Eq. (SN1.3.4), the correlation between two modes can be written:

$$E_G \langle \mathbf{\Phi}_k, \mathbf{\Phi}_j \rangle = -\int_0^{L_x}\int_0^{H} \frac{i\,\ell}{\overline{\overline{PJ}}} \left(\frac{\partial \overline{P}}{\partial X}\right)_{\overline{\theta}} \left(\frac{\overline{\widehat{\Phi}_j}\widehat{\Phi}_k}{s_k} + \frac{\overline{\widehat{\Phi}_k}\widehat{\Phi}_j}{s_j}\right) \rho_0 dX dZ \qquad \text{(SN1.3.6)}$$
$$+ \int_0^{L_x} i\,\ell \left[\frac{\partial\overline{\theta}/\partial X}{\overline{P}} \left(\frac{\overline{\widehat{\Phi}_j}\widehat{\Phi}_k}{s_k} + \frac{\overline{\widehat{\Phi}_i}\widehat{\Phi}_j}{s_j}\right)\right]_0^H dX,$$

where $s_k = \sigma_{kr} + i\ (\sigma_{ki} + \ell\overline{V_g})$. As long as $\left(\overline{PJ}\right)^{-1}\left(\partial\overline{P}/\partial X\right)_{\overline{\theta}}$ and $\overline{P}^{-1}\left(\partial\overline{\theta}/\partial X\right)(Z = 0, H)$ are constants, this scalar product reduces to the canonical form and nothing unexpected happens.

However, as soon as these are functions of space, even trivial ones, canonical orthogonality will be lost. The non-separability that results from this prevents, in general, the integrals to be trivially zero. Such is the *very weak sufficient condition for allowing transient linear development* (Joly, 1995).

In other words, one can expect linear development even in basic states that are stable in the sense of Charney and Stern.

As Farrell (1989) as shown for classical baroclinic instability problems, or Joly (1995) for fronts, this mechanism is, in fact, *extremelly efficient* in the atmosphere. A new "standard model" is emerging, as a result. It consists of looking for the *initial conditions* that will get the largest energy $E_G \langle \Phi', \Phi' \rangle$ (or any other measure of growth) in a given time. In this perspective, *the basic flow kind of amplifies some of the initial perturbations that enter it* (Fig. SN1.3.3), while others decay (Farrell, 1994).

1.3.3 Some consequences

The normal mode analysis has provided a very clear depiction of the physical mechanism that enables the growth of large scale mid-latitude cyclones: it is called *baroclinic instability*. The same mechanism operates in the new solutions, but more efficiently and at different scales and in different basic flows: it can be called *baroclinic interaction*.

The normal mode analysis predicts likely time and space scale for the cyclones as well as a space scale below which cyclones should not exist. It strongly suggests, as well, that the growing systems should have a fixed shape in space (represented by $\widehat{\Phi}(X, Z)$): this is called *phase-locking*. The shape amplifies and propagates, but it is not deformed. Unlike the mechanism for growth, these other features do not match observations well, as is the case for a number of necessary conditions for instability. As a consequence (or a symptom of its limitations), this theory had very little influence on practical forecasting, synopticians finding many of its features hard to swallow.

Consider the time scale: the normal mode theory predicts a time scale of about 2 days for conditions close to the climatological jet-stream. Some say that, indeed, this is the order of magnitude of the evolution of a cyclone. However, it means literally, according to (SN1.3.1), that the initial amplitude, assumed to be barely measurable, is about trebled in 2 days. Starting from 1 mbar (but in principle, even less), it takes 2 days to reach 3 mbar, 4 days to get to 9 mbar. Now, according to, for example Ayrault (1998), the typical deepening of cyclones is between 10 and 20 mbar in *1 day*. There is a confusion between the time scale of a full life-cycle (2 days indeed) and the meaning of the growth rate σ_r, which needs to be very large to allow the most unstable mode to emerge and reach finite amplitude in a matter of *hours*. The new, finite-time analysis provides much more realistic answers.

The most rapidly growing initial conditions are combinations of normal modes. As a result, the separability of the time dependence built in a single normal mode is lost: *the most rapidly growing solutions undergo significant changes of shape: this also fits observations better.*

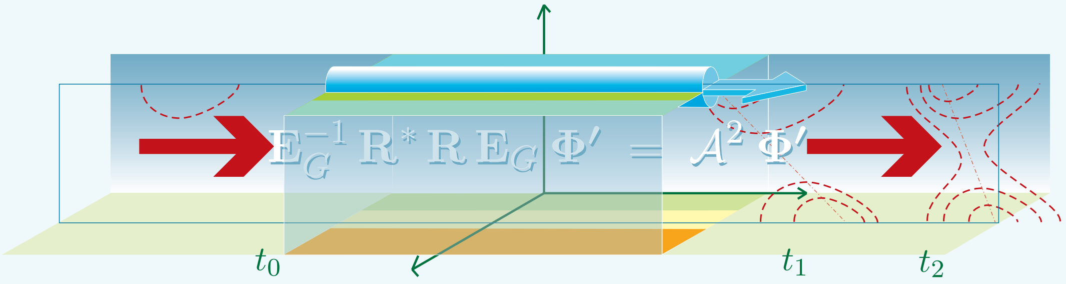


Figure SN1.3.3: *The current perspective: the baroclinic zone in the atmosphere acts as an amplifier of pre-existing precursors of cyclones, which yeields shape-changing systems. The equation represents the eigenvalue problem that defines the modes that have a maximum amplification of energy in a given time, the singular vectors of* $\mathbf{R}^*\mathbf{R}$.

This evolution of the theoretical framework for understanding cyclogenesis has consequences that reach beyond the history of ideas. Observation, for example. Normal mode instability analysis supports the idea that the cyclone scale evolution is enterely determined by the basic flow: it is sufficient, therefore, to set up an observational network that concentrates on the large scale basic flow, the rest being deduced. The new perspective insists on the importance of initial conditions, that is the motion on the cyclone scale itself. The observational network has to address both the basic flow scale *and* the pre-existing subtle features on the cyclone scale itself.

Furthermore, Eady (1949) also interpreted the existence of time scales provided by such linear models in terms of predictability, and this remains true, normal mode or not. The time scale of the largest amplification defines the predictability: beyond this time scale, small errors will have grown enough so as to reach amplitudes of the same magnitude as the real solution and the forecast becomes highly uncertain. The time scale suggested by the transient development perspective is reduced to 0.5 to 1 day. The consequences of this rather bad news on the prediction of cyclone events are discussed in Short Note 1.4.

1.2.2 Practical forecast perspective

At the same time, the objective, numerical forecast of these frontal or more generally, these “end-of-storm-track” cyclones remains a serious practical difficulty in spite of the continuous progress of numerical weather prediction. This was noted in the report by the french forecasters Beugin and Rochard (1991) after the numerous trying cases they had to face during the winter 1989–1990. A new generation of models is now available, and yet the difficulty is still there.

This is illustrated by Fig. 1.2 showing the successive forecasts of a 1996 case of interest from the ECMWF operational suite. Although the general characteristics are well predicted, an accurate forecast of precipitations over Ireland and, most important, of the wind over the Channel appears to be impossible, because they are different at every new run. Clearly, however, the problem is not simply in the ability of these models to represent cyclones properly: some of the forecast for a given event are excellent. The solution calls for a different approach than, for example, trying to improve parameterizations. The problem is related to the sensitivity of these developments to initial conditions.

In spite of undisputable progress in Numerical Weather Prediction, that improve forecast on average, this particular but economically important problem still arises (recall the Christmas day 1997 storms). This situation encourages the in-depth study of the parallel approaches put forward in FASTEX.

Beside the need to check the new theoretical ideas on cyclogenesis, there is also a demand for improved, validated, conceptual models of cyclogenesis that can help assessing real forecasts and a demand for exploring possible solutions to stabilize forecasts in the range 24h–96h. These questions asked by the forecasters and users of weather forecast to the meteorological scientific community have motivated the launch of the Fronts and Atlantic Storm-Track Experiment (FASTEX).

1.2.3 Observational perspective

The continuing progress in observational technology is a further motivation. From this point of view, FASTEX is the offspring of two streams of field studies focused on cyclogenesis and frontal dynamics. The first one is the series of field experiments conducted along the East-Coast of North-America in the eighties: the Genesis of Atlantic Lows Experiment (GALE; Dirks *et al.*, 1988), the Experiment on Rapidly

Intensifying Cyclones over the Atlantic (ERICA; Hadlock and Kreitzberg, 1988) and the two successive field phases of the Canadian Atlantic Storms Program (CASP; Stewart *et al.*, 1987, Stewart, 1991). These experiments were meant to provide an understanding of the process of rapid or even explosive cyclogenesis taking place along the western boundaries of oceanic basins, a category of cyclones that is not the focus of FASTEX. The second stream of field projects is European: the FRONTS-87 (Clough and Testud, 1988) was organized by the UK and France to collect data to validate the semi-geostrophic theory of frontogenesis and study frontal precipitations. More recently, the UK conducted the FRONTS-92 project (Browning *et al.*, 1995) as a pilot experiment preparing the grounds for FASTEX.

1.2.4 Short history of FASTEX

The first papers outlining the main objectives as well as the characteristic set-up of the observing system that are the hallmark of FASTEX were written at Météo-France in 1991 (Joly and Lalaurette, 1991). Very soon, however, because of its strong links with ongoing theoretical co-operation and with FRONTS 92, FASTEX became a French and UK initiative (the name has been coined by Keith Browning). The preparatory work begun in 1993 in both countries, after the first drafts describing the project had been evaluated by a panel including a number of US scientists. A first meeting of the Core Steering Group, including US representatives, took place at the end of 1993 in Toulouse. The US participation took shape at the first meeting of the Scientific Steering Group in Washington in March 1995. It included the key addition to the scientific objectives of the testing of the adaptive observation strategy as a practical method to tackle the forecast problem.

Since then, FASTEX is a large, joint project strongly supported by both American and European scientists and organizations, with regular planning meetings and production of documents, most notably the FASTEX Science Plan (Thorpe and Shapiro, 1995), the FASTEX Operations Overview (Jorgensen and Joly, 1995) and the FASTEX Operations Plan (Jorgensen *et al.*, 1996). Table 1.4 presents an overall time-table of the project. This Part summarizes these plans, beginning by defining the cyclones of interest (section 1.3) and formally presenting the scientific objectives (section 1.4). Section 1.5 presents the observational objectives of the field phase. They are followed by a summary of the observing system and sampling strategies (section 1.6), with details of the options available to gather data on the cloud system in the Multiscale Sampling Area (section 1.7). The outcome of the field phase is presented in Part 2. The sample of cases observed is summarized in Part 3.

1.3 Climatology of FASTEX cyclones

The aim of a climatological study of Atlantic cyclogenesis are *(i)* to characterize the existence of the specific properties of the cyclones hitting the west coast of Europe *(ii)* to determine the time of year when they are most frequent *(iii)* to derive some picture of their life cycle. The detailed results of the first part of this work is to be found in Ayrault *et al.* (1995). It has evolved into building a new, quantitative classification of North-Atlantic cyclones (Short Note 1.5). The results, derived from an automatic tracking algorithm (Ayrault, 1995) employed here to tackle item *(iii)*, will be published in due course.

The starting point is the classical work of Sanders and Gyakum (1980) and of Roebber (1984). Both studies cover the Pacific and Atlantic oceans. They concentrate

Short Note 1.4:
Why is the forecast of cyclogenesis difficult ?

by F. Lalaurette and A. Joly

Assuming that nowadays weather forecast rely on numerical models, possible causes of forecast errors are *(i)* model errors, *(ii)* uncertainties in the initial conditions and *(iii)* an intrinsically low predictability of the atmosphere. The first generations of models, in the sixties and seventies, met some serious difficulties when simulating after the fact cyclogenesis cases, so that possibility *(i)* remained important. However, since the early eighties, it can be said that models have reached an extremelly reasonable level of realism. Although model errors, specifically, simplifications with respect to the actual atmospheric dynamics, still exist, they do not appear to be the major source of forecast error. The effort was then brought to bear on item *(ii)* by improving the observational network on one hand, mostly with remote sensing (the surface based in-situ observations are not really on the upside) and, on the other hand, by making a better use of observations in the process of analysis, namely the preparation of initial conditions for a forecast (see Part 8 for details). Yet, the hope that, eventually, deterministic forecast were possible until 10 to 15 days or so remained widely accepted: very few people had really realized that such a thing as *(iii)* could exist. It is a limitation that is out of our control, that will still be there even if we can get precise data from all over the Earth and put in into a perfect model.

Figure SN1.4.1: *Six of the 51 solutions proposed by ECMWF ensemble forecast in the presence of a well established zonal regime, all showing possible solutions valid at the same time. The field shown is mean sea level pressure over the Atlantic. Even on this very small subsample, the diversity is stricking.*

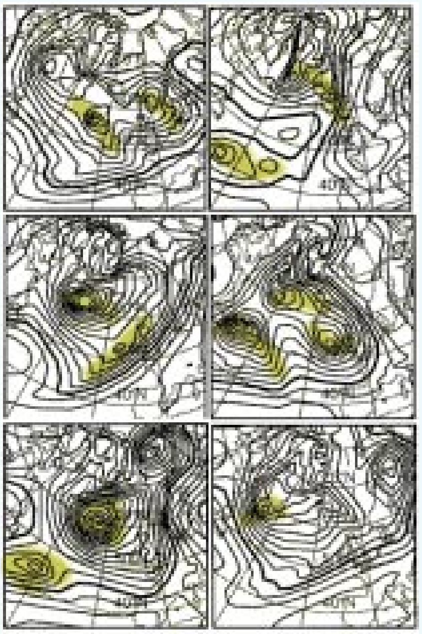
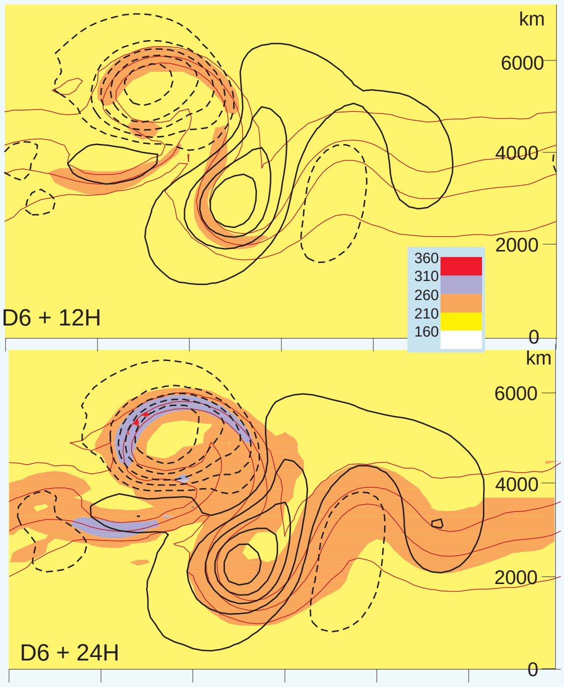


Figure SN1.4.2: *The natural growth of uncertainty in the course of a numerical weather forecast is shown in an idealized simulation. Black contours: surface geopotential. Dark-red contours: surface potential temperature. Shading: variance of surface potential temperature forecast error, a direct measure of uncertainty. It is small (yellow) and uniform at initial time.*



Following stricking examples of misforecast of rapid cyclogenesis events with fine models, it became apparent that there was room for a stochastic approach to weather forecast. Ensemble forecast systems were developed (see e.g. Molteni et al., 1996). Their existence allows, among other things, to get a direct impression of *(iii)*. Figure SN1.4.1 is an example of the dispersion of possible solutions that result from the small uncertainties in the initial conditions in the presence of a well established zonal regime. A whole range of possibilities are shown for western Europe: from fair weather in the right corners to very nasty storms, as in the middle right panel. There are 45 other solutions available. It is important to realize the following facts: *(a)* the model employed here is a state of the art one, with the resolution that was employed operationnally in the eighties, when one and only one run was performed, *(b)* the initial conditions are perturbed, but the amplitude of the changes remains within the bounds of analysis error and *(c)* such a wide dispersion of possibilities does not occur every day, in spite of *(b)*. This is the fact that reveals that a source of forecast error of kind *(iii)* exists independently of *(ii)*.

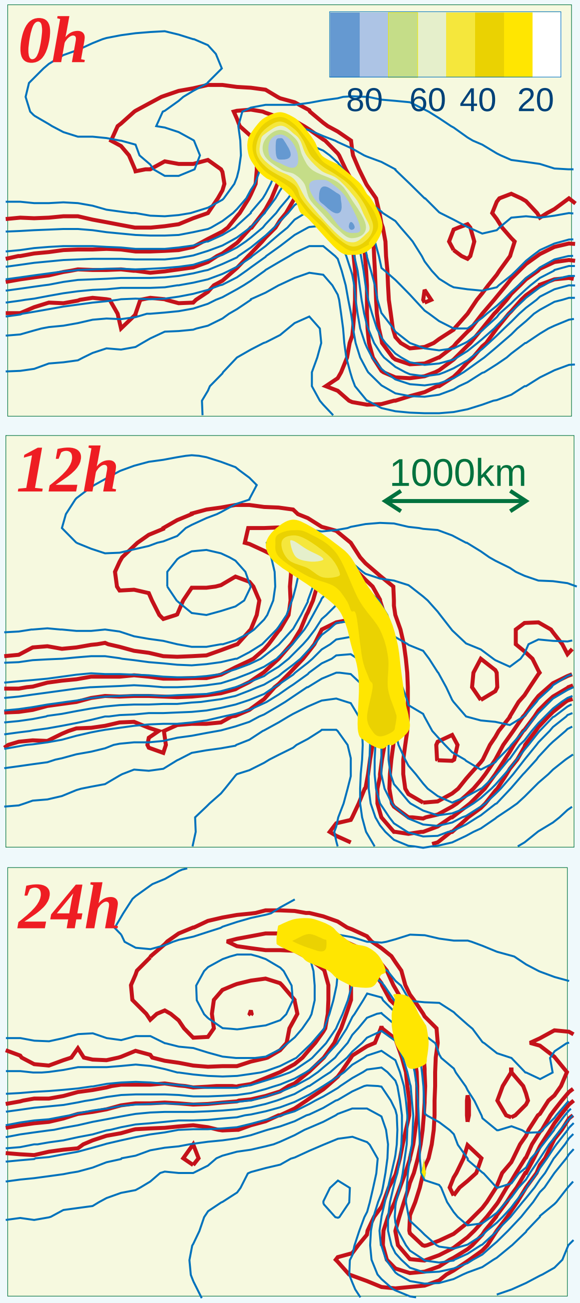
The presence of a strong baroclinic zone is, by itself, a source of forecast uncertainty, the main reason why the deterministic forecast of cyclogenesis remains a major difficulty. The Ensemble Prediction illustrates this at medium but also at short ranges, since a dispersion such as in Fig. SN1.4.1 can sometimes be seen as soon as two or three days. In the short range, an even better grasp of this intrinsic predictability can be achieved. One can make the assumption that errors evolve linearly. It is then possible to compute explicitely the evolution of second order statistical moments, without being limited by the size of an ensemble sample and the unavoidable representativeness problems. This explicit calculation is, however, very expensive: it can be done either locally with a sophisticated model or globally, but with a simplified model.

The second approach is meaningfull to outline the link between predictability and the essential dynamics of cyclogenesis. The results are illustrated by Figure SN1.4.2. A generic large scale cyclone development event in a baroclinic zone is simulated and this reference solution is shown by the contours. The important information is contained in the shading. It shows a direct measure of uncertainty, the field of the variance of forecast error of the low level potential temperature. In this experiment, it is assumed that, initially, the uncertainty is small and is the same everywhere. It turns out that uncertainty does *not* remain uniform: very quickly, areas of large uncertainty develop. Within 24 h, it appears to embody the whole of the baroclinic zone itself, with large peaks in the frontal areas. The scale and amplitude of the variance reached within 24 h are large enough so that it is impossible to know whether waves will be present or not along the fronts. This is why the forecast of mid-latitude cyclones is difficult.

A slightly different view of the same thing is shown by Figure SN1.4.3. This time, the impact of more observations somewhere in the baroclinic zone has been simulated by including an area of reduced initial variance. The area has been chosen arbitrarily, as happens with an observational system that depends on ships or aircraft of opportunity. Is this of any benefit ? The example shown says "no" (except where the observation was made): very quickly, the baroclinic zone supresses the benefit of the better knowledge of the weather, and the extra data has no impact far downstream, beyond the trough, for example.

These fundamental numerical experiments indicate that it may well happen that the predictability of rapid cyclogenesis may be as low as half a day or one day. The objectives of FASTEX dealing with the theories of cyclogenesis are meant to help understanding the fundamental reasons for the rapid build up of error variance in a baroclinic area, much more rapid than anticipated by linear normal mode approaches: see subsection 1.2.1 and the Short Note 1.3 on this topic. The arbitrary addition of observations does not seem to help. Yet, these experiments heavily underline the fact that predictability is flow dependent. It might be possible, therefore, to perform a deterministic cyclogenesis forecast in the short range by having a flow dependent observation system. Its purpose will be to reduce to a minimum the initial forecast error variance *where* it is going to grow most rapidly. The predictability objectives of FASTEX have been set up to study this last "chance": see subsection 1.4.3 and Short Notes 1.7 and 1.8.

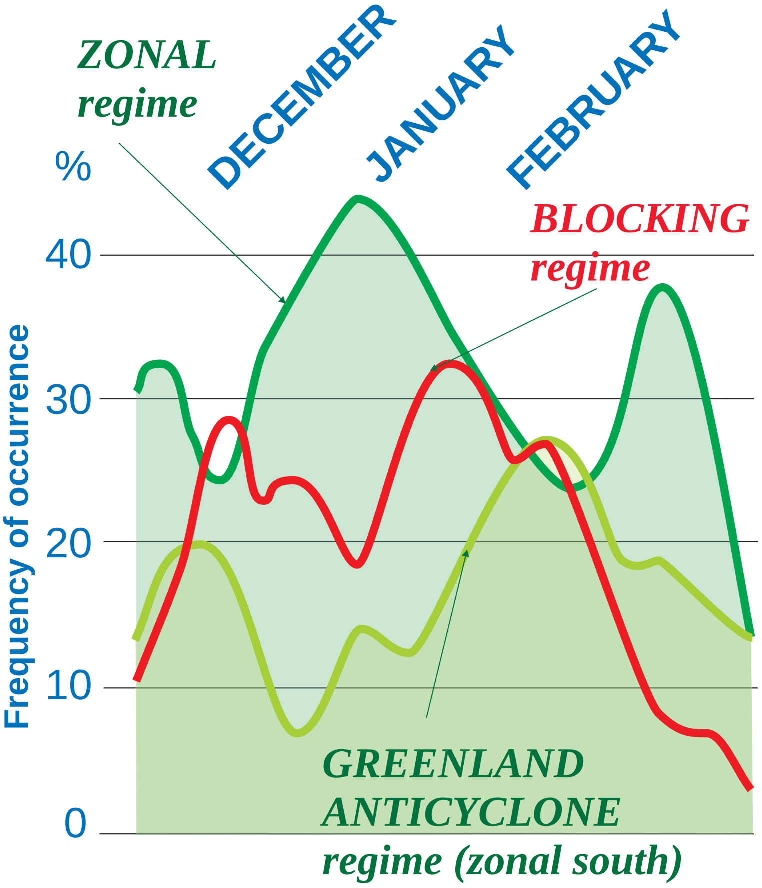
Figure SN1.4.3: *In another similar situation, two runs with locally different initial variance are compared. The contours are the upper-level geopotential (blue lines) and potential temperature (dark-red lines). The shading shows the area of lesser uncertainty that can result from having, for example, more observations: precisely, it shows the percentage of variance reduction in the reference and "improved" runs. The result is that the benefit of a better knowledge of the flow dissipates extremelly rapidly.*



on explosively deepening cylones, and, from that point of view, find very little activity off the European coasts. This does not fit with the feeling of the European people, who find that cyclones are reasonably frequent. The reason, of course, is that these cyclones turn into "bombs" (as defined in the above references) very unfrequently and their spectral properties are significantly different. This is clearly shown by Ayrault *et al.* (1995) based on an extraction from ECMWF operational analyses between 1984 and 1994 at full time resolution, namely every 6 hours. (Only the winter season has been included.) It becomes possible to analyse the "ultra-high" frequency variability, with a period in the range 0.5–1.5 days.

A first distinctive property of the Eastern end of an oceanic basin like the Atlantic is its low frequency variability (characteristic period > 10 days): it is maximum. This means that the large scale flow pattern, or the environment in which the cyclones evolve, undergoes large changes. In order to study cyclones in relatively homogenous large-scale environments, it is necessary to separate the large-scale flow into different weather regimes (see Short Note 1.1). Following the definition of Vautard *et al.*

Figure 1.3: *Climatological frequency of weather regimes over the North-Atlantic during the winter months. Derived from ECMWF analyses from 1986 to 1994. The onset of the zonal or of the Greenland Ridge regimes implies cyclogenesis events for FASTEX, unlike the blocking regime. The statistical distribution of regimes roughly estimated here is a critical characteristic of climate. (Figure after F. Ayrault, Météo-France.)*



(1988), weather regimes are defined as persistent patterns of the large scale flow. Various techniques lead to the definition of four regimes over the Atlantic. The Zonal regime and the "Greenland Ridge" regime correspond to a zonally extended baroclinic zone, more to the south in the second case (see Fig. SN1.1.1). The Blocking and Atlantic Ridge regimes conversely correspond to a jet-flow deviated to the north as soon as 40°W. As a result, cyclones reaching Europe from the west occur during spells of the first two regimes. The empirical frequency of occurrence of these regimes is shown by Fig. 1.3. It appears that the most favourable period for a zonal-like regime is the first half of January, with about 60 %.

The second distinctive property of Eastern oceanic basin cyclogenesis is their characteristic time scale. The maximum of variability in the 2–6 days range is, during Zonal regime, centered on 50°N and 45°W. The maximum of variability in the 0.5–1.5 days range is centered on 55°N and 25°W, that is at the eastern end of the high-frequency variability maxima that is often used to define the "Storm-Track". It has an amplitude in that range and area that is comparable to that in the 2–6 days range. This means that the FASTEX cyclones can be expected to be an equal mixture of rather well known baroclinic systems and of a different kind that evolves more rapidly. The latter category indeed appears to be impossible to separate spectrally from fronts and so the successful techniques introduced by Blackmon *et al.* (1984) cannot be employed to outline the properties of these cyclones. Instead, an event-oriented technique must be employed.

A whole new set of cyclone prototypes has thus been obtained by Ayrault (1998). These results confirm two important ideas outlined in the introductory section: the reduced scale (in time and space) of the cyclones to be met at the end of the classical storm-tracks, the existence of new types that depend on environmental properties differing from the baroclinicity (Short Note 1.5). Similar remarks can be derived from a case study approach and conceptualization: see Browning and Roberts (1994) and Rivals *et al.* (1998).

Some of Ayrault's (1995) results were very useful to plan FASTEX. The events of interest are defined using vorticity at 850 mbar (as pressure deepening is not a relevant criterion): the cyclone must be reachable from Ireland (the reasons for this are given in section 1.7 below), must have a large enough amplitude ($\zeta_{\max} \geq 10^{-4}$ s^{-1}, where ζ is the relative vorticity) and must have developed somehow in the previous 12 h. Figure 1.4 shows the time distribution of these events for the past januaries and februaries for which ECMWF analysis is homogenous enough in a statistical sense. Over this period, there are, on average, 11 cyclones within these two months. However, the interannual variability is very large, with very active winters like 1990 — that motivated a programme like FASTEX in France — and very, very dull ones like 1989. This, of course, introduces an element of risk in FASTEX.

An important conclusion to be drawn from Fig. 1.4 is the fact that cyclones rarely comes as isolated individual events. On the contrary, they happen in surges, with very close chaining of two, three or even more events. This is reminiscent of the Norwegian idea of "families" of cyclones. This fact has borne on the logistics of FASTEX (see section 2.4).

This collection of events can then be back-tracked, so that a rough idea of their life-cycle can be obtained. The result is shown by Fig. 1.5. The large black dots suggest the most frequent low level path followed by these cyclones. The dashed contours define areas that enclose 60 % of the trajectories of the cyclones. The change in shape and, even more so, of area, conveys an idea of the dispersion of

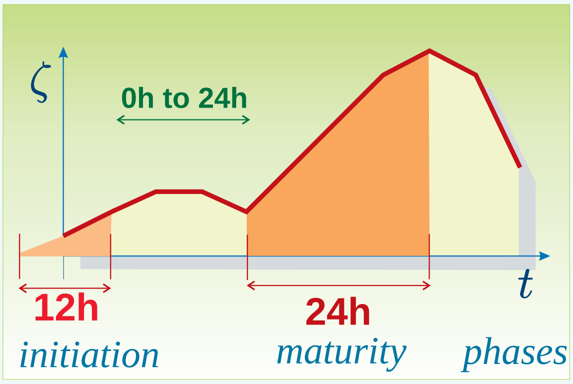
Short Note 1.5:
New climatological types of cyclones

by F. Ayrault

1.5.1 Classification methodology

The new semi-automatic classification of North-Atlantic cyclones is fully described in Ayrault (1998). The data is provided by the first ECMWF re-analysis of the period 1979–1993 (Gibson *et al.*, 1993). From the global T106L31 set of re-analysed fields, 14 "winter" seasons extending from 16 october to 15 april have been extracted over the north-american continent, the north-Atlantic ocean and western Europe. The automatic tracking technique of Ayrault (1995), much employed, has been primarily applied to these 14 years of data, yielding part or all of the life-cycle of 24514 events at 850 mbar and 30926 at 300 mbar.

Figure SN1.5.2: *Example of life-cycle retrieved from the tracking algorithm. The two stages that have been isolated and ordered into classes are defined on this figure: the initiation and maturation stages.*



The classification is based on partial time-series of fields extracted in square boxes with 2500 km side and centered on the event. Looking at the trajectories revealed such a wide range of possibilities that it seemed impossible to classify entire life-cycles. Based on the 850 mbar trajectories, two independent classifications have been undertaken (and the process has been repeated using the 300 mbar trajectories): a classification of the *initiation stage*, during which new events are created. It extends over 12h (−6h, 0h, +6h). Then, independently, a classification of the *maturation stage* is performed. It covers the 24h preceding the time of maximum amplitude (Fig. SN1.5.2). The fact that the two classifications are very different, leads to conclude that the genesis of a low is a process quite independent from its subsequent development.

Consider the classification of the maturation period: each trajectory having a maturation period contained within 2500 km of the domain boundary (reducing the available set to 1648 trajectories) becomes a set of $15 \times 15 \times 4 \times 5 = 4500$ values. No automatic classification algorithm can deal with such an amount of data. A reduction is performed, first. The temperature fields are turned into anomalies, all the fields are normalised and a principal component analysis is performed on the resulting grids. The number of components retained for the classification is obtained after many sensitivity tests (this is why the method is "semi" automatic).

The reduced trajectories are organized into classes using hierarchical clustering. At each iteration, each set is splitted into 2 subsets obtained by minimizing the resulting intra-class variance. The process is initiated by simply assuming that all the events are in one set. The main advantage of this technique is that the number of classes is determined from the results rather than imposed. A useful classification emerges when, roughly speaking, the variances are about half the initial variance.

Figure SN1.5.1: *The structure of the 7 maturation classes at the beginning of their 24 h development phase. The top-left one corresponds to rapidly deepening systems. The number of cases in the composite and its frequency in shown in boxes. Purple contours: 850 mbar vorticity; brown contours: 850 mbar* θ_e*; orange contours: 300 mbar vorticity.*

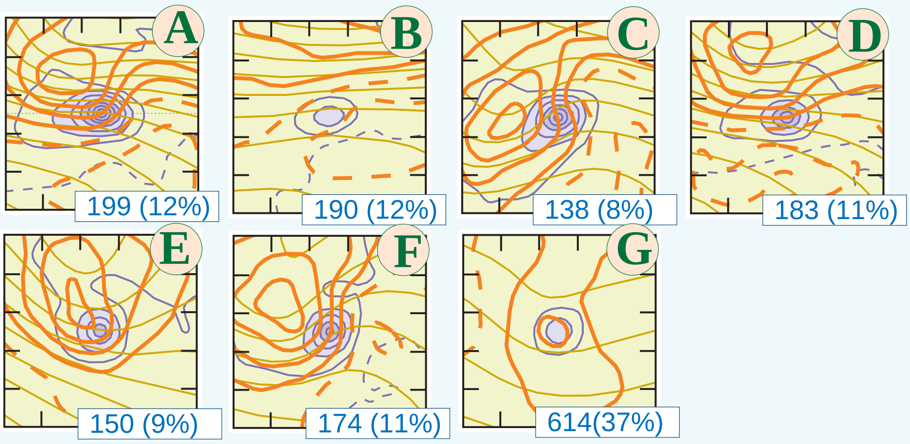
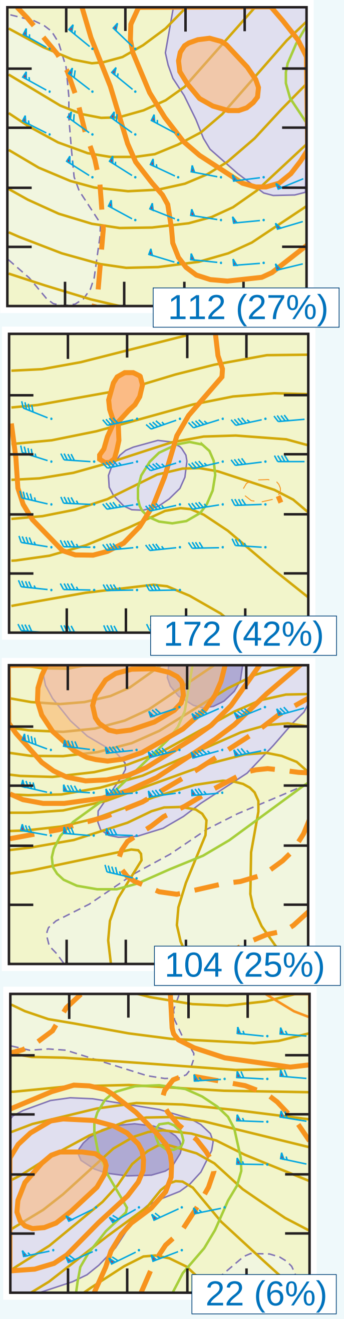


Figure SN1.5.3: *There are 12 classes that describe the various ways in which a new cyclone forms. One way of trying to condense the information is to gather them into larger "families", as done here. Purple contours: 850 mbar vorticity. Brown contours: 850 mbar θ_e. Green contour: large 700 mbar relative humidity. Orange contours: 300 mbar vorticity. Blue arrows: 300 mbar wind. From top to bottom: cold air cyclogenesis; cyclogenesis initiated by an upper-level maximum; cyclogenesis in a complex jet-entrance/front system; splitting of an older system.*



Now the key idea to recover geophysically meaningful "paradigmatic" events is to forget about the principal component reduction. Instead, once events are classified in this way, the composite event is built from averaging the *original* fields themselves.

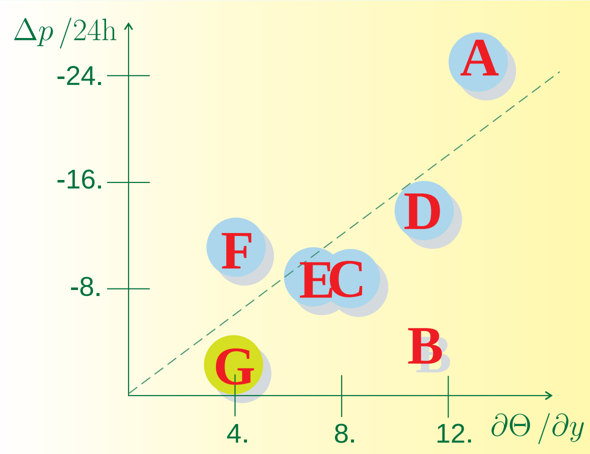
1.5.2 Maturation and initiation classes

The maturation stage based on 850 mbar trajectories can be described by 7 classes (Fig. SN1.5.1). Most of them (5 out of 7) involve some form of baroclinic interaction. The initiation stage, on the other hand, reveals 12 classes. For the sake of brevity, they can (roughly) be divided into 4 super-classes or families: lows initiated by a pre-existing upper-level precursor, lows forming in the cold air, lows created in a complex jet-inflow/front-like environment and lows resulting from the breakdown or splitting of entire older, pre-existing systems (Fig. SN1.5.3).

The most important characteristic of this classification is that all the features it reveals are quantitative: the frequency of the classes, the transitions giving the initiation classes of a given maturation class, the amplifications and many other parameters since each type is a series of gridded fields.

The most dangerous cyclones belong to Maturation Class A: they are the rapid deepeners. Fig. SN1.5.4 shows this clearly. It appears, however, that a large baroclinicity does not, on its own, imply that such an extreme event will occur: the figure shows that Class B also occurs in a strongly baroclinic environment, but does not deepen. Looking back at Fig. SN1.5.1, it appears that the other necessary ingredient is the presence of a significant upper-level precursor that the classifications show to be independent from the initial surface cyclone.

Figure SN1.5.4: *The maturation classes (shown by Fig. SN1.5.1) are plotted in a 24h pressure fall/background baroclinicity space. This shows that large baroclinicity is necessary but not sufficient to lead to rapid deepening.*



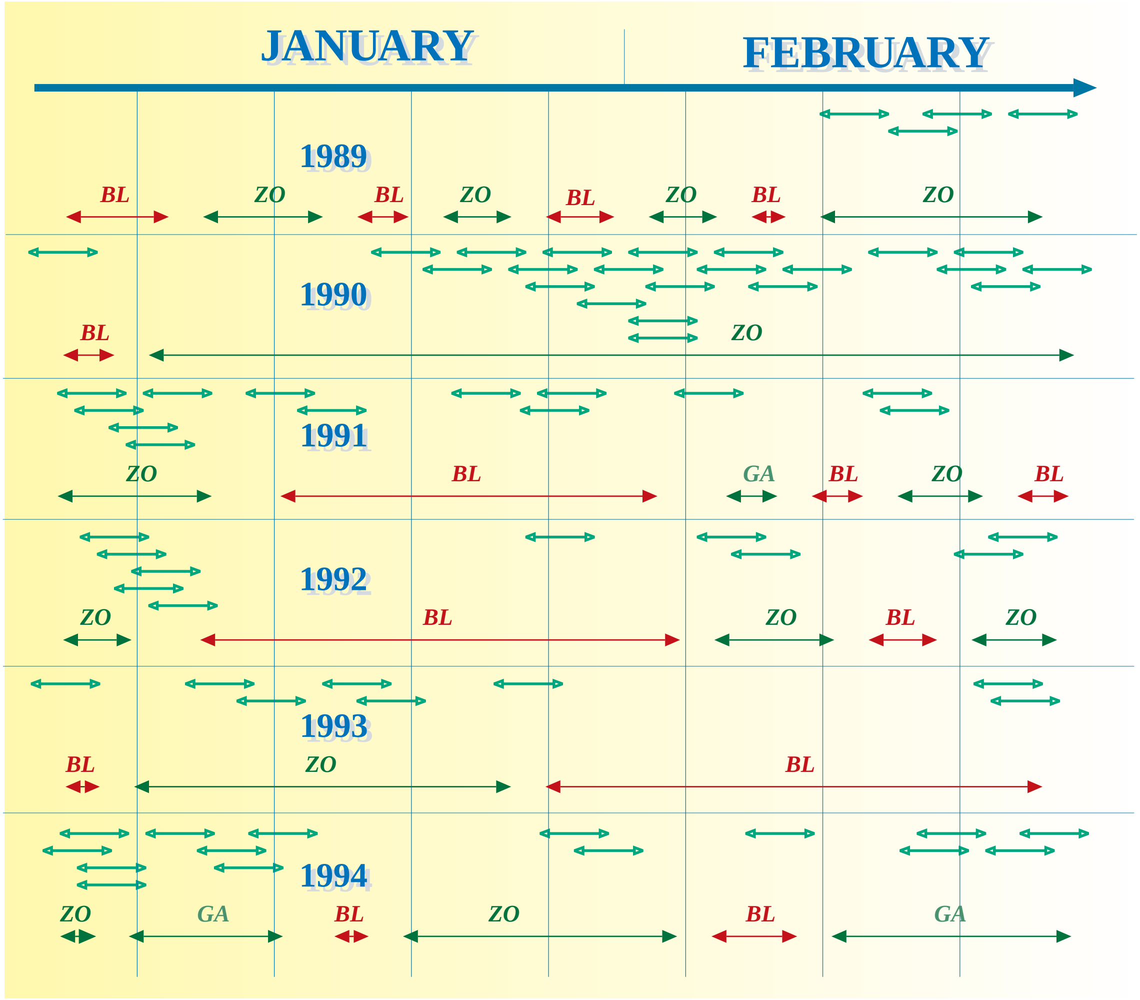
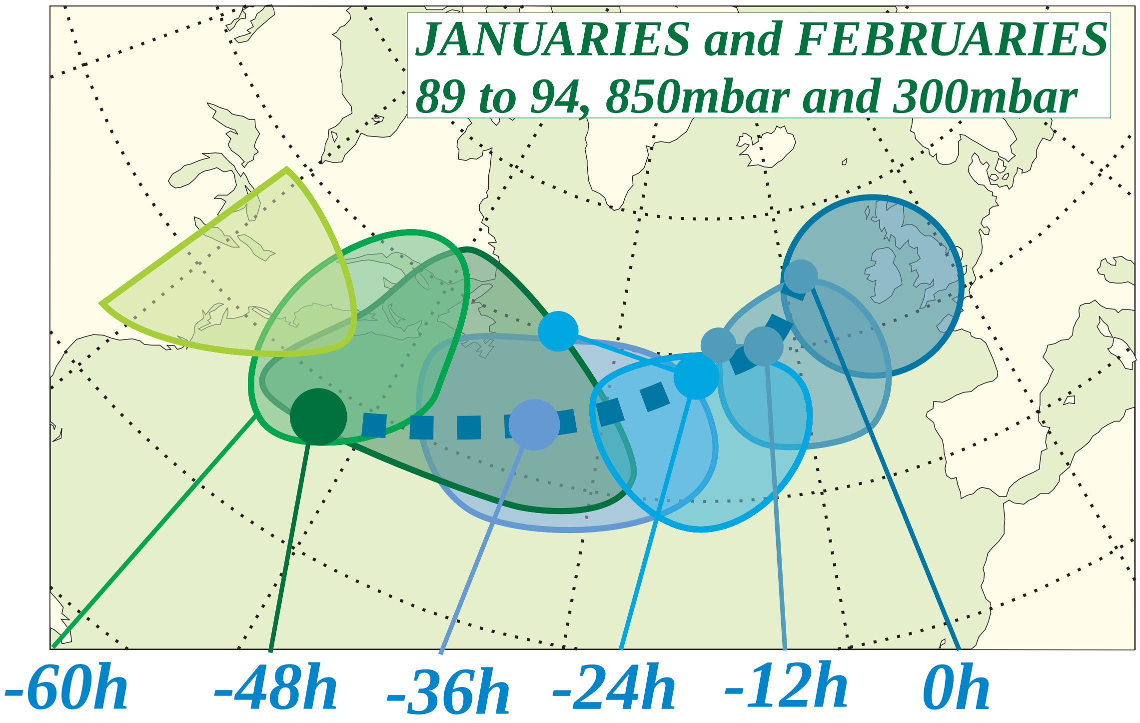


Figure 1.4: *An automatic tracking algorithm has been applied to 6 pairs of January and February months of ECMWF analyses. Cyclones having moved within a range of 800 km from western Ireland, with a maximum vorticity at 850 mbar larger than* $10^{-4}s^{-1}$ *having increased in the previous 12h define a suitable event (a developing cyclone of significant amplitude). Each event is shown by a thick arrow at the time it occurred. The arrows of variable length correspond to the weather regime: ZO for zonal, GA for Greenland Ridge and BL for Blocking. This figure shows the link between regimes and cyclogenesis as well as the large year to year variability. (Figure prepared by F. Ayrault, Météo-France.)*

the trajectories at low levels. The fact that a drastic reduction can be seen between −48 h and −60 h is not due to a sudden concentration of trajectories, but to a sudden reduction of the total number. In other words, quite a few new cyclones form within the −48 h area. The upper-level components (at 300 mbar) can be followed as well: see the white dots on the figure. Their motion is significantly (and not surprisingly) more rapid. The dispersion is also much more important. This diagram helps picturing the time scale and locations that have to be sampled by a field experiment such as FASTEX that is focused on entire life-cycles rather than a particular time of them. This will become apparent in the presentation of the scientific objectives.

Figure 1.5: *Another result from the automatic tracking algorithm. Cyclones reaching the easternmost circle have been backtracked at two levels. Circles show the most frequent location: black circles at 850 mbar, white ones at 300 mbar. The areas enclosed by the dashed lines contain 60% of all trajectories at 850 mbar, their areas convey an idea of the dispersion. (Figure prepared by F. Ayrault, Météo-France.)*



1.4 Scientific objectives

Section 1.2 explains the reasons that led to prepare FASTEX. To a large extent, these reasons determine the scientific objectives.

1.4.1 Cyclone cloud systems

There are two important issues that call for detailed measurements, using new technologies, of the cloud systems associated with FASTEX cyclones.

Internal structure of layer clouds

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

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

- The first one is the vertical distribution of the microphysical composition, especially at cloud top, and cloud base as well as in the melting layer. The radiative properties of the cloud system will, for example, primarily depend on the optical properties of the cloud top and bottom boundaries. The presence of a melting layer implies a region of enhanced liquid water that is important both radiatively and for precipitation rate control.

- Another critical aspect of layered clouds is the distribution of latent heating, an essential part of the dynamical and microphysical feedback.
- A property has been noted and is gathering interest as it could have a strong influence on other aspects: the multiple layering of these clouds.
- Within a storm, the horizontal distribution of these vertical profiles is inhomogeneous and a better knowledge of their mapping is required. The water budget and precipitation efficiency of these cloud systems is not well known either.

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

The impact of layer clouds on climate and the need for documenting the related processes are defined by Stewart *et al.* (1994). One further gap in the present datasets identified in this and the previous review is a series of measurements performed well off the coasts, above the open ocean.

It is apparent that the cloud system associated with a FASTEX storm must be observed on two scales at least. In order to understand the coupling with the dynamics on the scale of the cyclone, an overall knowledge of the ascent zones and clouds is required. At the same time, the internal distribution of vertical layering, water distribution and heating is needed. An airborne Doppler radar such as ASTRAIA/ELDORA (Hildebrand *et al.*, 1996), aided by some in situ microphysical measurements, can provide this multiple scale information. In vertical mode, it can also describe cloud layering.

Cloud-embedded mesoscale dynamics

The second issue related to the cyclone cloud system is that its organization is conducive to all kinds of mesoscale activity. One of its aspect is the presence of rainbands: an example that is relevant to the kind of systems observed on the European West Coast can be found in Lemaître and Scialom (1992). Beside the re-organization of the synoptic scale ascent, there is also the breakup of frontal zones or precipitating bands into mesoscale vorticies. An example of such evolution within a (strong) mid-latitude low is studied by Neiman *et al.* (1993). The processes involve complex interactions between diabatic processes (moist processes, surface fluxes) and dynamical ones. Many unsolved questions relating to the formation and structure of these features require, very much as on the larger scale, the documentation of their life-cycle. Because they occur within cloudy air, the same new airborne Doppler radar technology can provide the required data.

1.4.2 Air-Sea interaction objectives

Very little is known of the behaviour of both atmospheric and oceanic boundary layer in areas combining large fetch and strong winds. It is doubtful that the dramatic change in the shape of the interface that results from these forcings have no effect on the fluxes. See Short Note 2.2 for a few details.

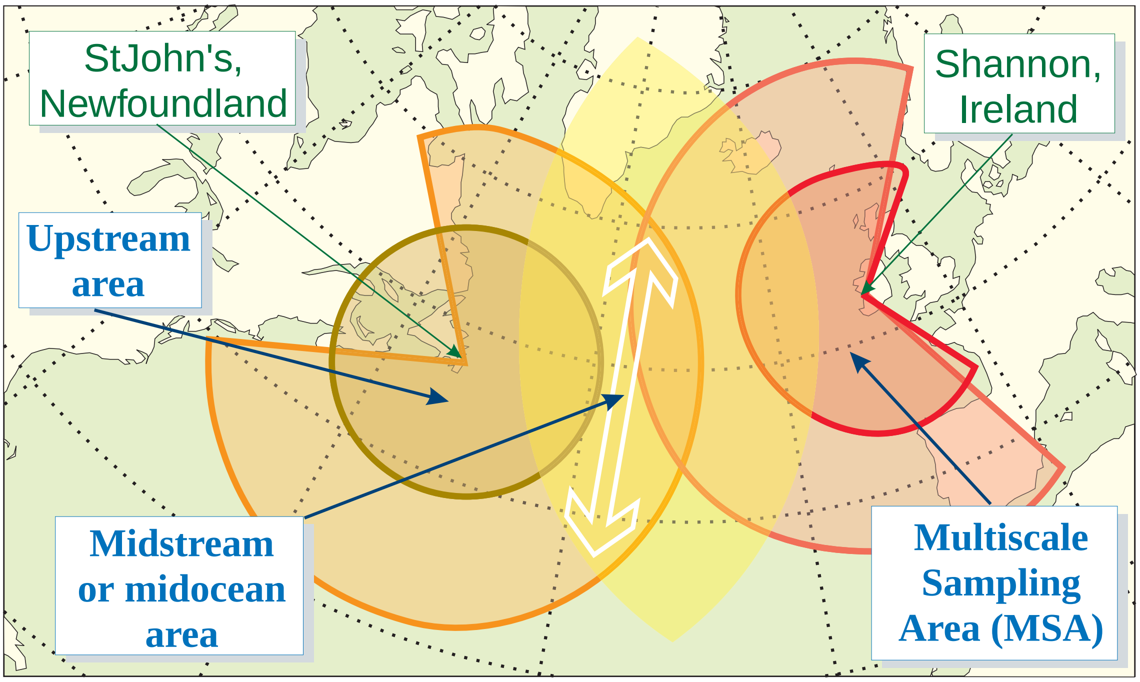


Figure 1.6: *The areas of operations of FASTEX. The heavy solid line is centered over Shannon, Ireland. It defines the inner boundary of the Multiscale Sampling Area (MSA) and corresponds to the maximum ferry time of a C-130 like aircraft in the absence of wind (∼ 1500 km). The heavy long-dashed line is centered over St John's, Newfoundland. It defines the inner boundary of the Upstream Area and is the maximum ferry time of a Learjet-like aircraft (∼ 980 km). The heavy dashed lines and dash-dotted lines correspond respectively to ∼ 1820 km and ∼ 2720 km. They correspond to the maximum ferry time of the Gulfstream (flying at high level) and two thirds of its maximum range. The intersection loosely defines the Midstream Area. The elongated arrow marks the area within which the ships, the main component in this area, will evolve, moving along it following the evolution of regimes.*

At the same time, the effects of these exchanges are suspected to be of influence in the genesis of cyclones (Davis and Emanuel, 1988, Langland *et al.*, 1995). The purely marine cyclones that ultimately hit the west border of the ocean form in the area where the Gulfstream is disrupted into several branches and vorticies. It also looses heat in the same location. This heat most likely goes into the atmosphere. It could favour cyclogenesis by reducing the tropospheric static stability (the pre-conditioning mechanism).

1.4.3 Cyclone predictability

FASTEX is also motivated by the practical forecast problem continuously posed by these cyclones. Part of the answer is to obtain, as a result of the dynamical objectives, a new set of theoretically and observationally validated conceptual models. These will point out the key properties of the flow to observe and analyze properly.

There is another approach, though, that is complementary to the previous one. Indeed, it may not be enough to get the generating mechanisms right to obtain a good forecast. It is also necessary to keep the error level in other parts of the flow

Short Note 1.6:
Cyclogenesis as a finite amplitude interaction between pre-organized structures

by A. Joly after B.J. Hoskins, A.J. Thorpe and C. Bishop

Figure SN1.6.1: *Schematic representation of a developing weather system within a simple baroclinic zone. The tube is the jet-stream, blue arrows show the wind associated with the forming cyclone. The large arrows stand for the vertical motion, the ascending part of which yields precipitation.*

Another important theoretical model of cyclogenesis that has taken much more flesh in recent years is related to properties and concepts associated to the *potential vorticity* field. Potential vorticity has been introduced by Rossby (1940) and Ertel (1942) as a conserved variable representative of vorticity, very much like potential temperature is the conserved version of temperature. The perspective summarized in this note, however, stems from original ideas from Kleinschmidt (1950). The existence of detailed consistent global analyses and the development of powerful numerical techniques have led Hoskins, McIntyre and Robertson (1985) to revisit the various properties of potential vorticity.

They outline an "explanatory" framework that can handle the finite amplitude characteristics that seem to be present in most cyclogenesis events(see Short Note 1.5 for observation-based cyclone types). This framework is derived from the existence of an overall balance between the wind field on one hand and the thermal field on the other. As a result, the usual state parameters of the atmosphere are not independent: the distribution of potential vorticity and boundary conditions contain all the information needed to describe the balanced part of the flow. The process of recovering wind and temperature from potential vorticity is called potential vorticity inversion.

A further step is needed to build cause and effects relationships that can be used to express *and check* an understanding of a given cyclogenesis: it is called *attribution*. The potential vorticity field and related boundary conditions are not uniform: they can be viewed as the superposition of a background, reference component and of a number of *anomalies*. Although close to the framework of linear theory, the linear assumption is not required here. That part of the flow that results from inverting a given anomaly (coupled wind and temperature anomalies) can be attributed to this anomaly. This is very much like decomposing an electric field into the sum of individual fields, each of them resulting from given, local electric charges: the charges are replaced, here, by a potential vorticity anomalies. The classical and powerful idea of action at a distance, often employed in physics, can then be adapted, in a proper way, to understanding a weather situation (Bishop and Thorpe, 1994 , Thorpe and Bishop, 1995).

Figure SN1.6.1 shows an idealized developing system. At first sight, there is a single feature, the developing cyclone, with its many aspects, namely wind, clouds, temperature changes. It is possible to understand how this system works by decomposing it into three components (Fig. SN1.6.2), a baroclinic background and two anomalies that can be summarized by their potential vorticity signature, their "charge". The vertical motion that generates the clouds but is also responsible for converting the energy that accompanies the development results from the interactions between these component. The idea here is that each elementary components threatens the balance of the other structures and the vertical motion is the response that will maintain the overall balance.

FASTEX is to provide a series a well documented cases that can be employed as testbeds for this and other theoretical perspectives, such as the one presented in Short Note 1.3. See Short Note 2.3 for an application of inversion and attribution to find the precursor structures that have led to the development of FASTEX Low 41.

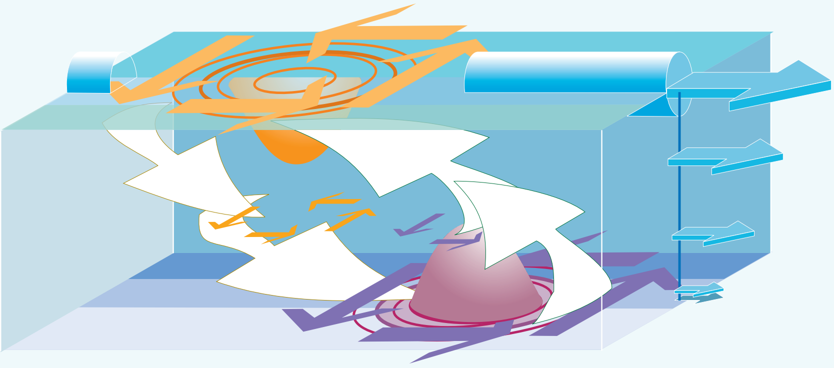


Figure SN1.6.2: *The system of Fig. SN1.6.2 can be understood as the result of the interactions between the three elementary "objects" represented by symbols with similar colours: the baroclinic zone (bluish), an upper-level anomaly (orangish) and a low level anomaly (purplish). The vertical circulation results from the interactions of two such objects at least.*

as low as possible. FASTEX cyclones may form, as has been said above, in several different ways. This also means that small initial errors in the analysis have just as many different ways to grow, sometimes very rapidly, and wreck the forecast. The predictability of cyclogenesis depends therefore on improved control of analysis and forecast error growth.

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

The basic concept is to concentrate measurements on areas that are dynamically critical for a proper prediction of cyclogenesis downstream of these zones in the next 24 to 36 hours. Another key idea is that these areas should be objectively determined or predicted. At least part, and perhaps all of the anwser can indeed be provided by adjoint models. Short Note 1.8 illustrates the principle of targeting in the idealized framework of observing system simulations of Short Note 1.7.

FASTEX is designed to allow the first full scale test of one or several adaptive observation strategies. This relates FASTEX to the US Weather Research Program. A more detailed discussion of this new approach to observation can be found in Snyder (1996) or Bergot et al. (1999). See Short Note 2.4 for some results.

1.4.4 Dynamics of wave cyclones

The recent theoretical results presented above (subsection 1.2.1, Short Note 1.3, Short Note 1.6), supported by new case studies (*e.g.* Rivals *et al.*, 1996), suggest that new important issues are:

- the appearance or creation of a new cyclone at low level involves a variety of mechanisms while its subsequent development, that may or may not happen, involve one and only one such mechanism, a form of baroclinic interaction with the

Table 1.1: *FASTEX Scientific Steering Group*

A.J. Thorpe, chairperson	Univ. of Reading (UK)
P. Bessemoulin	Météo-France (F)
K.A. Browning	Univ. of Reading (UK)
D. Cadet, CSG chair (93–96)	CNRS (F)
J.P. Cammas	Labo. d'Aérologie (F)
J.P. Chalon, CSG chair (96–)	Météo-France (F)
S.A. Clough	UKMO (UK)
Ph. Courtier	CNES (F)
P. Dubreuil	AES (CA)
K.A. Emanuel	MIT (USA)
L. Eymard	CETP (F)
C. Fairall	NOAA (USA)
R. Gall	NCAR (USA)
T. Hewson	UKMO (UK)
P. Hildebrand	NCAR (USA)
P.V. Hobbs	Univ. of Washington (USA)
A. Joly	Météo-France (F)
D. Jorgensen	NOAA (USA)
T. Johannesson	VI (ICL)
K. Katsaros	IFREMER (F)
D. Keyser	SUNY (USA)
R. Langland	NRL (USA)
Y. Lemaître	CETP (F)
A. Lorenc	UKMO (UK)
P. Lynch	Met Éireann (IRL)
B. Martner	NOAA (USA)
P. Mascart	Labo. d'Aérologie (F)
S. Nelson	NSF (USA)
T.E. Nordeng	DNMI (N)
H. Olafsson	VI (ICL)
J. Pailleux	WMO/COSNA
P.O.G. Persson	NOAA (USA)
J. Rasmussen	NOAA (USA)
F. Roux	Labo. d'Aérologie (F)
M.A. Shapiro	NOAA (USA)
C. Snyder	NCAR (USA)
A. Staniforth	AES (CA)
G. Stephens	NASA (USA)
R. Stewart	AES (CA)
J. Testud	CETP (F)
C. Velden	Univ. of Wisconsin (USA)
R. Wakimoto	UCLA (USA)

upper-levels, and these two steps may be separated by a few days of quasi-neutral behaviour,

- the creation mechanisms include the presence of an unstable quasi-steady environment (in the sense of Charney and Stern, 1962) or the triggering of the same conversion mechanisms as in the instability theory by a pre-existing, quasi-passive structure in an environment that then does not need to be unstable or also the active participation of the environmental flow, through, for example, its induced deformation field,
- the development mechanism, the baroclinic interaction, primarily result from upper-level incoming, independent vorticies rather than from the upscale growth of the new, low level cyclone generating its own upper-level component: this results from the small initial scale of the new wave. A consequence is that a cyclone can go through several stages of baroclinic development with transient upper-level coupling.

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

1.4.5 Other objectives

A further objective of FASTEX is Data Assimilation. A reference analysis is planned as part of the project, beyond the one already provided in the Data Base (see Parts 4 and 8). It will be a test the ability of the variational approach (in 4D mode) to use concentrated arrays of dropsondes.

Once this is achieved, it will be possible, through observing system experiments, to determine the data requirements in terms of precision and resolution that are needed to properly reconstruct the structure and evolution of synoptic and sub-synoptic cyclones. The importance of a good knowledge of the distribution of water vapour and of condensed water will be studied as well as the ability of satellite data to replace or not in-situ data.

This broad set of objectives has been constructed and will be studied by the scientists meeting in the FASTEX Scientific Steering Group shown by Table 1.1. Figure 1.7 shows how the FASTEX project has been organized to prepare and implement these ideas and the plans described below, while Table 1.2 shows the institutions and agencies supporting FASTEX.

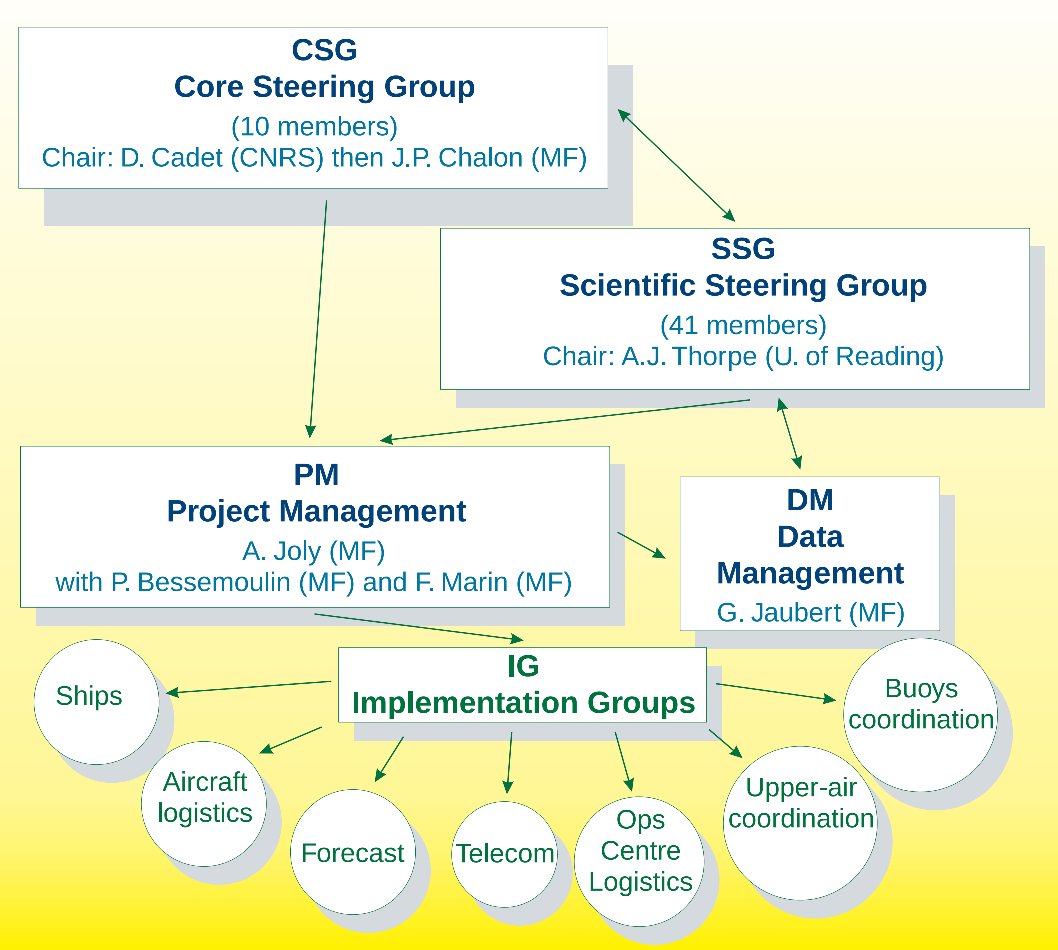


Figure 1.7: *A short schematic overview of the project organization. Decisions are ultimately taken by the Core Steering Group, where representatives of the funding agencies meet representatives of the scientists. The participating agencies are listed in Table 1.2. Objectives and plans where drafted and discussed by the Scientific Steering Group, which had a number of sub-planning groups not shown here. The work of the SSG is best illustrated by the FASTEX Operations Plans document, edited by D. Jorgensen from NOAA. These plans and decisions are implemented by the Project Management and the Implementation Groups.*

Table 1.2: *Organizations supporting FASTEX*

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

1.5 Specific 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 cylones 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. Most if not all past field projects dealing with mid-latitude cyclones have actually observed weather systems at one stage. The resulting studies are directed towards the structures of these systems. 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.

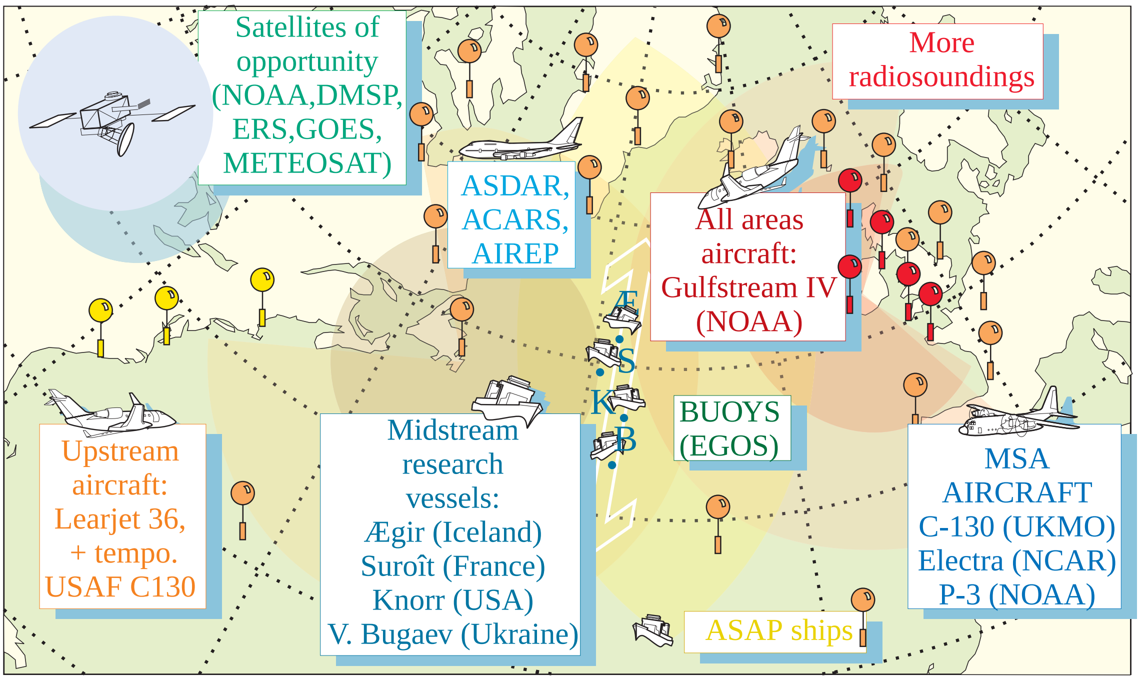
It follows that the primary experimental objective of the field phase of FASTEX is to perform numerous direct observations of the structure of the *same* cyclones at several key stages of their life-cycle. The data should, ideally, take the form of precise vertical profiles of the key dynamical quantities (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 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 numerical products needed for "objective targeting" were 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 (1998), Gelaro *et al.* (1999), Bergot *et al.* (1999), Langland *et al.* (1999) or Buizza and Montani (1999) for more details.

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.

Figure 1.8: *The observing system planned for FASTEX. The special facilities are explicitely listed in the schematic as well as in Table 1.3. The "environment" of the cyclogenesis area is monitored by an increase of upper-air measurements: this increase is indicated by the color code of radiosonde-like symbols: yellow, 6 h on alert; orange, 6 h all the time; red, 3 h on alert.*



1.6 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. 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 (Fig. 1.6).

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

Table 1.3: *Major facilities and participating institutions*

Facility	instruments, functions	owner, crew's home institution	Funding agency
CC ÆGIR	radiosoundings	Icelandic Coast Guard (IS)	EC
RV KNORR	radiosoundings, profilers, fluxes	Woods Hole (USA)	NOAA
RV LE SUROÎT	radiosoundings, profilers, fluxes	IFREMER (F)	CNRS, EC
RV V. BUGAEV	radiosoundings	UkrSCES (Ukraine)	Météo-France
C-130 (UK)	dropsoundings	UK Met Office	UK Met Office
C-130 (USA)	dropsoundings	US Air Force	US Air Force
ELECTRA	Doppler radar	NCAR (USA)	CNRS, NSF
GULFSTREAM-IV	dropsoundings	NOAA (USA)	NOAA, Météo-France, CNRS, NRL
LEARJET	dropsoundings	FIC (USA)	NSF
WP-3D (P3)	radars (1 Doppler), dropsoundings	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).

see Appendix A for other acronyms.

Selected Country Codes: CAN: Canada, DK: Denmark, F: France, IE: Ireland,
IS: Iceland, P: Portugal, SP:Spain.

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. More to the west, they are still forming with a small amplitude. More to the east, it may be difficult to cope with the large low-frequency variability that causes big changes in the location of the storm-track. It is also a good location for frequent encounts of the strong winds and high seas required for the measurements of air-sea fluxes, as well as for making oceanographic observations: it coinicides with the eastern part of the zone where the Gulf Stream current splits into several “drifts”.

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. How this is achieved is told in Section 1.7.

Table 1.3 and Figure 1.8 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 can be found in Joly *et al.* (1997). The present table has been updated with the actual facilities available.

Figure 1.9 shows how these platforms should have been employed, under ideal circumstances, in the course of a FASTEX Intensive Observations Period (IOP). The first thing to note is the long duration of an IOP: activities related to an individual cyclone event occur over 48h to 60h. A lead time of 30h to 42h is needed, for logistical reasons, to analyse the situation and to plan the activities. 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. 1.5. 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 to help solve what was, indeed, the main difficulty of the operation 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. Several forecast centres made the necessary changes for this data to be included in their assimilation suite.

The diagram in Fig. 1.9 also shows the main facilities and the way they were employed in FASTEX. The scenario for an ideal IOP are exposed in the Short Note 1.9. The first thing to note is a significant uplift with respect to the background observations 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.

Short Note 1.7:
Simulating FASTEX on the computer

by C. Fischer and A. Joly

The most original component of the observing system proposed for FASTEX is the midstream one (Fig. 1.6): it consists of vertical profiles from the low stratosphere to the surface in the middle of the North Atlantic ocean, where only a few ships and occasional aircraft data provide some coverage at one or the other level, and low resolution remote sensing. This midstream part is, furthermore, essential to all FASTEX objectives. This is obvious for the documentation of life-cycles. The midstream data is to provide also well defined western boundary conditions to the studies on the mature system, a reliable information on a significant part of their input budget.

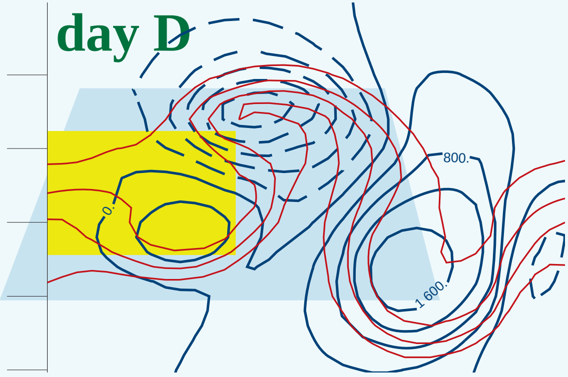
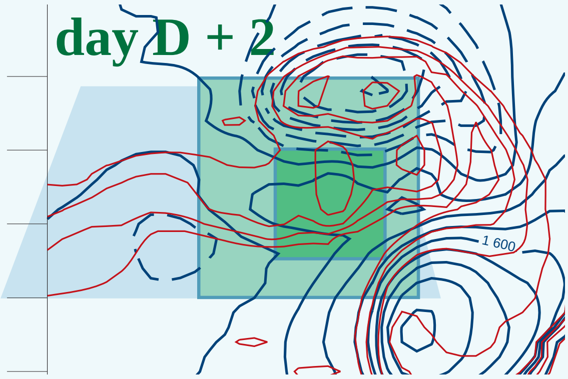


Figure SN1.7.1: *The generic, idealized situation employed in the simulations of upstream observing system for FASTEX: a large scale baroclinic storm that generates a front over the "Atlantic" area (blue shaded zone), where cyclones may or may not develop. A period of two days, shown here, has been employed. Top: initial conditions and upstream area (green-yellow shading). Bottom: solution 2 days later. The shaded boxesare the verification areas. Dark-red lines: surface potential temperature, interval 4K. This field will be used as the reference background in subsequent figures. Blue lines: surface geopotential, negative values dashed. Interval: 400 J/kg.*



How to turn the idea of in-situ observations midstream into something real ? One possibility is to dedicate one aircraft at least to quasi-regular missions, for example 1 or 2 days ahead of a system of interest reaching Europe. This aircraft would cross the main baroclinic zone meridionally, providing a detailed, north-south vertical cross-section: this is the solution proposed in the earliest project documents, with the possibility of using remotely controlled aircraft. Another possibility is to station ships in the area. This is costly and, given that most cyclones travel through this zone while developing, it can also be dangerous. There are also questions relating to the location of these ships and their possible displacements. In order to ground the decisions on a minimum of scientific basis, it was decided quite early to try to address these questions through computer simulations.

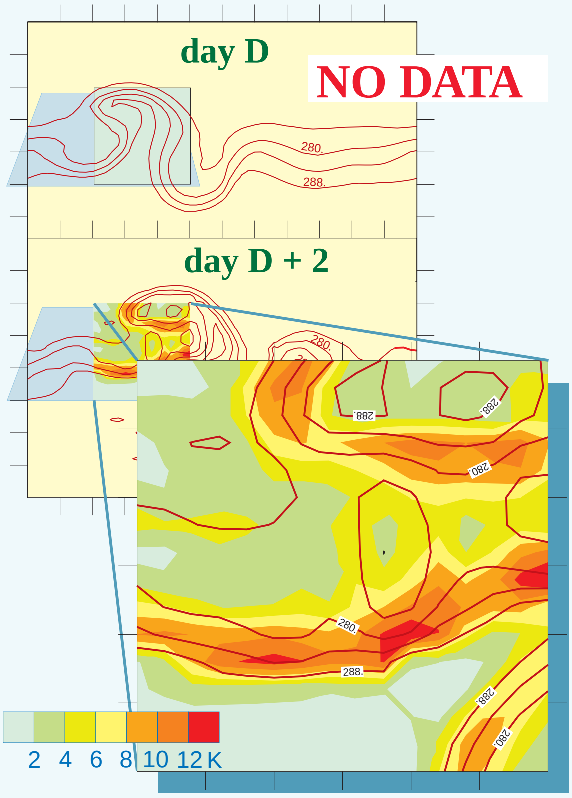


Figure SN1.7.2: *The various possible observing systems are evaluated through their impact on the uncertainty, represented here by the variance of forecast error of the surface potential temperature (shading), not on the solution itself, which is not changed. Results are compared to the variance generated in the absence of data, shown on the present figure. The initial variance (top) is uniform. After 2 days (bottom and blow up), as shown in Short Note 1.4, the variance is a complex function of space, with several maxima of large uncertainty along the frontal areas.*

The approach chosen is to study the behaviour of the *second order* moments, representing the statistics of forecast error, rather than gathering a collection of "typical" cases and to influence the solution itself. There are too many possible transitions, as the climatology of cyclones indicate. It is hoped that the dynamics of the variance and covariance embodies all the possible sources of cyclogenesis. This is strictly correct only as far as the evolution is linear. A single non-linear trajectory has been, therefore, employed. Figure SN1.7.1 shows its main features as well as the relevant domains. This trajectory is the final phase of growth of a large scale cyclone. It sets up a cold front in its wake out of which waves may develop.

The mechanism from which waves could grow generate variance, that is uncertainty in the forecast, as explained in Short Note 1.4. Figure SN1.7.2 gives the maximum variance generation assuming a small uniform uncertainty at the beginning of the period of interest: it is a pure dynamical evolution of the initial variance/covariance matrix.

This is an idealized context simulated with a simplified model that allows for explicit calculation of the evolution of the full error statistics matrix. The impact of observations is studied only through their effect on the variance: a piece of data reduces the variance where it has been taken and around it, the projection being made essentially according to the local covariance function between the data point and its neighbours. This area of reduced variance is then propagated or advected by the flow and influenced by the sources of variance in the course of time (see Fig. SN1.4.3 for an example of evolution). The impact is judged after 2 days. The time evolution and assimilation are performed together, following a Kalman filter algorithm (Fischer et al., 1998).

Figure SN1.7.3 illustrates two configurations of the observing system. One represents the "ships" solution: a regular and constant source of data at fixed locations. Provided the ships are within the baroclinic area, this turned out to be the best solution tested. The best that can be obtained from aircraft, employed in the spirit of "adaptive observation" explained in Short Note 1.8 is also shown. The initial idea of making a straight cross-section, based on common sense, has been ruled out by this study: it has a weak impact only. Similarly, these simple experiments have shown that ships away from the baroclinic area are useless. For this reason, it is important that the ship keep with the (slow) meridional displacements of the jet-stream.

These experiments are representative of what current assimilation systems can do (3D-VAR and non-cycling, short period 4D-VAR), starting with isotropic covariance functions. Since assimilating tools of that kind were to be employed during FASTEX and for some time afterwards, the experiments led us to insist on having ships involved.

But the Kalman filter developed for this study allows for a little anticipation on future evolution, as shown in Short Note 1.8.

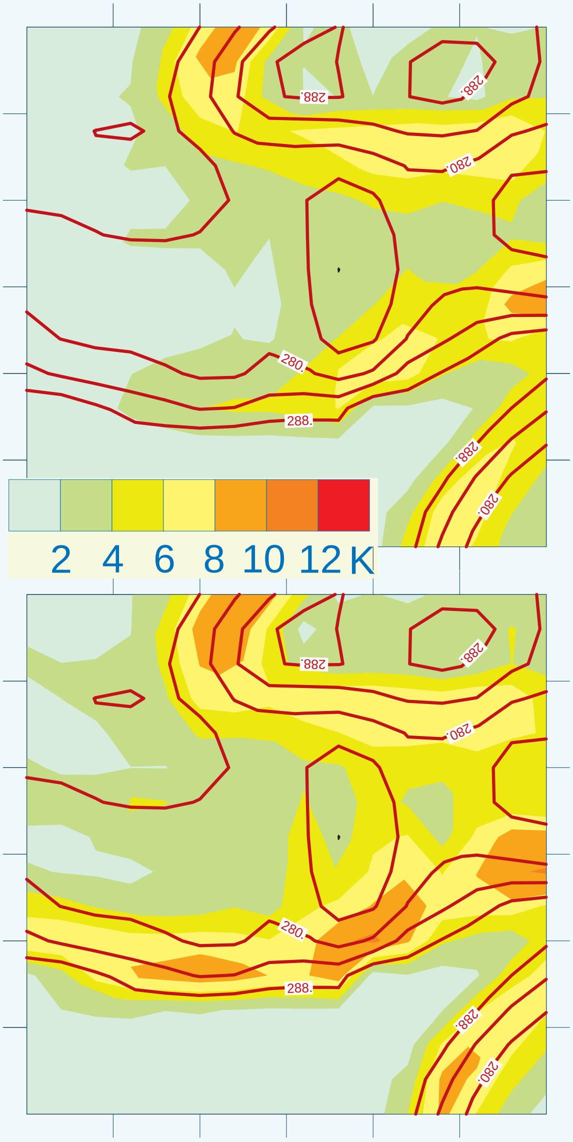


Figure SN1.7.3: *Two examples of impact of simulated observing system on the variance of forecast error of surface potential temperature. Top panel: impact of two fixed sources sending new data continuously every 6 h ("ships"). The ships are in the middle of the surface baroclinic zone and upper-level baroclinic zone respectively, and this is very important. Bottom panel: impact of multiple sources upstream assimilated during the first 6h only, using isotropic covariances ("aircraft dropsondes").*

Short Note 1.8:
The principle of adaptive observation and its potential

by C. Fischer and A. Joly

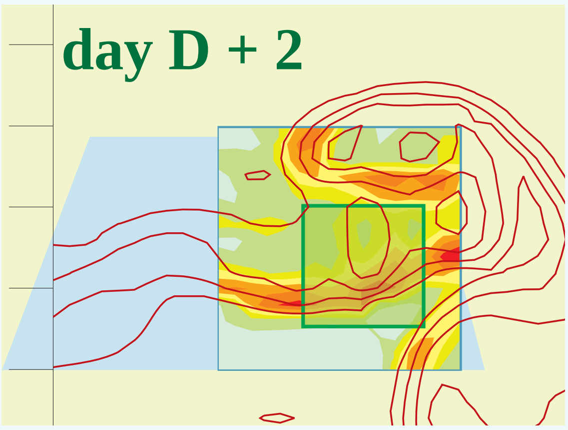
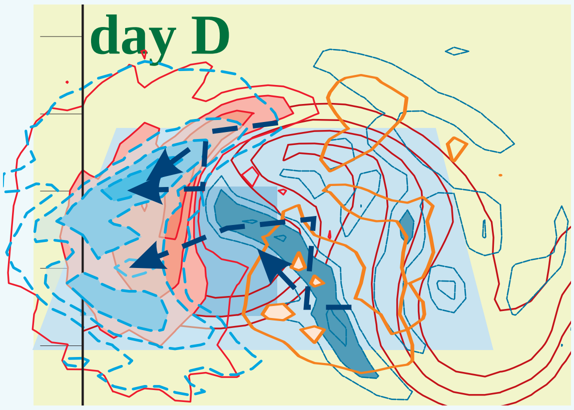


Figure SN1.8.1: *Assume that this is time* $D-1$ *or* $D-2$*. Adaptive observation addresses the following question: given a forecast to time* $D+2$*, where to put observations at time* D *in order to minimize the growth of uncertainty within a selected area between* D *and* $D+2$ *? The top panel shows the expected uncertainty that will result from the growth of a cyclone over the Atlantic in the absence of data (see Short Notes 1.7 and 1.4). The area where the uncertainty must be minimized is shown by the green square. One possible answer is to compute in advance the singular vectors that will generate the most variance between* D *and* $D+2$ *on the verification domain. Observing facilities can then be directed (adapted) towards the critical area pointed out in this way and sample the flow there. The bottom panel shows the structure of the most unstable of these singular vectors. The field shown is the temperature anomaly at the surface (red and dark blue shading) and at the model top (tropopause, light blue and orange shading). Blueish dashed contours are for negative values, the amplitude is arbitrary. The dark-red contours on both panels are the background, large scale cyclone used as the reference solution. The arrows show the track of a simulated flight sampling this structure at time* D*.*



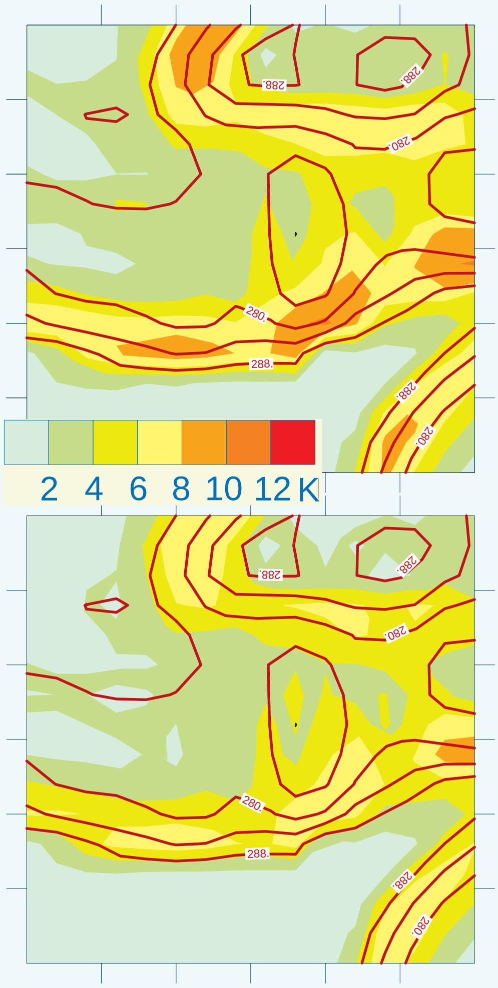


Figure SN1.8.2: *Assuming that the singular vector shown on Fig. SN1.8.1 has been properly sampled with good-quality, in-situ data, the study of Fischer et al. (1998) indicates that the actual impact of this data on the forecast uncertainty strongly depends on the assimilation technique employed once the data has been gathered. The top panel shows the impact of that data on the forecast error variance two days after the adaptive observation flight assuming a 3D-VAR-like system (isotropic covariance functions). It is the best use of an aircraft-like observing facility, but the impact is weaker than that of ships. The bottom panel shows the impact of the same data when flow dependent covariances are used, as cycling or long-period 4D-VAR system will have. In this case, even though no data is added after the "adaptive flight", the result is better than with ships constantly pouring information in. It appears possible that, providing the observation and assimilation problems are handled together, adaptive observation does have an impressive positive impact on ascertaining weather forecast.*

Operations in the Upstream Area were conducted with aircraft: a Learjet and, for some time, two C-130s, all three equipped for GPS dropsounding. The backbone facilities in the Midstream area were instrumented ships. Up to four ships with GPS radiosounding capabilities were available. Two of them also had a profiler radar and instruments developed for flux measurements. One also had a cloud radar. In the Multiscale Sampling Area, the platforms were a C-130, used primarily to drop sondes, and two other turboprop aircraft with airborne Doppler radars (see Section 1.7). The three aircraft were also able to perform *in situ* microphysical measurements and carried a number of remote-sensing instruments.

Finally, all three areas could be re-inforced with dropsoundings from a long-range, high-flying Gulfstream IV jet recently purchased by NOAA. In the course of the project, it was found that an efficient way of employing the Gulfstream was to send it from Shannon to St John's slightly in advance of a cyclone forming, by a relatively direct route and doing few measurements only. In a second flight from St John's, the Gulfstream added its capabilities to those of the Lear or C-130 in the Far Upstream zone. Then a day or so later, on the return flight to Shannon, it collected measurements in the midstream area or between the ships and the Multiscale Sampling Area.

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, see Short Note 1.7). 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. Indeed the longitude of the ships was chosen to help ensure that these motions were of reasonable amplitude. Practical experience during FASTEX revealed that the idea was quite feasible: the predictability on this scale was good enough and the resulting displacements manageable in spite of difficult seas.

1.7 Observations of mature cyclones

It is worth going into finner details in the plans for sampling the mature cloud systems. Three long-range turboprop aircraft were to operate in the Multiscale Sampling Area and collect the data needed in order to complete the dynamical objectives and to study the various aspects related to the cloud system. By decreasing order of range, these aircraft are the C-130 owned by the UK Meteorological Office (11 h endurance), one of the P3 operated by NOAA (9 h) and the Electra belonging to NCAR (7 h).

The C-130, as the two others, is very well equipped for all kinds of in-situ measurements, including microphysics and turbulence. However, it has been employed in FASTEX primarily to drop arrays of GPS sondes developed by VAISALA. The key instruments on the P3 are its lower-fuselage C-band radar, a scatterometer and several radiometers as well as a tail X-band Doppler radar, including a dual beam option. On the Electra, the main instrument is the ASTRAIA/ELDORA X-band dual beam Doppler radar. It has been developed jointly by NCAR/RSF and by the CNRS-CETP group in France.

The sonde deployment strategy for the C-130 is such as to obtain regularly spaced vertical profiles relative to the whole wave cyclone, from front to rear (with respect

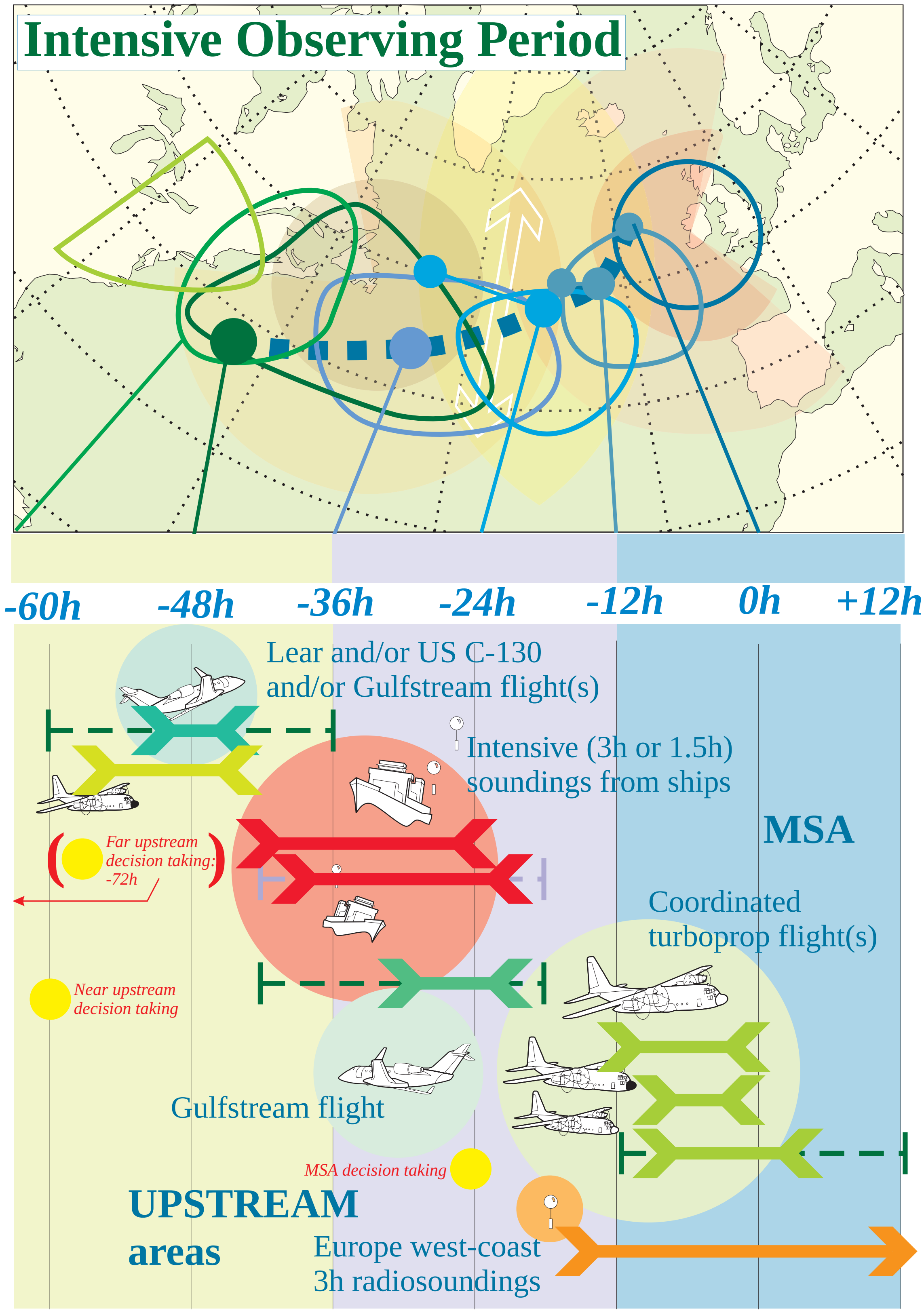


Figure 1.9: *Timelines and locations of the events composing a FASTEX IOP. The heavy arrows are proportional to the time of the flights (solid), the period of intensive soundings from ships (dash-dotted), the period of 3-hourly soundings from the UK, Ireland and France (dashed). Note the lapse of time taken into account between the cyclogenesis timeline and the Universal Time clock that determines some of the activities (the upstream flights, for example). The important decisions may have to be taken 12 h earlier than shown when they imply a shift from day to night actions.*

to cyclone motion). Sondes were to be dropped from heights varying from 6 to 8 km, depending on aircraft weight and air traffic constraints. In winter, this should just enable to catch the tropopause in the dry slot in the rear part. Because, by definition, the radar aircraft will not be able to collect significant data in this dynamically very interesting part of the cyclone, it will be important that the C-130 reaches this part relatively rapidly and samples it properly. For a large system, it may exceptionally share this task with the Gulfstream-IV. This strategy will be applied to all systems

Short Note 1.9:
Prototype IOP scenario

by A. Joly

The first characteristic of a FASTEX Intensive Observing Period is its duration. Facilities will be activated in turn during two to three days. Then, some warning lead time must be added to this. Given the very reason that led to set-up FASTEX (the uncertainties of west coast cyclone forecasting in the 36h–96h range), one can immediately see the importance of forecast experience, of the diversity of forecast products as well as the difficulty of the early decisions.

The second characteristic of FASTEX IOPs is that a new one is likely to begin while the previous one is fully buoying up. This is a direct consequence of the rapid chaining of events that is apparent in Fig. 1.4. This actually happened in several occasions during FASTEX: see the dates in Part 3.

The event that decides of the startup of an IOP is the extreme likeliness that a mature cyclone will go through the Multiscale Sampling Area 3 to 3.5 days after. We call the time when the cylones reaches the MSA $D0$. The extra 12 h are needed when there is a shift from flights to be conducted during the day to flights during the night. Note that the management of the ships (that are shared with other programmes) requires that their locations are changed depending on the 5-days evolution.

A summary of the sequence of events is then as follows (Fig. 1.9):

- $D-3.5$–$D-3$: Draft IOP schedule, tracking the various structures likely to be involved in the cyclogenesis. Start running the algorithms finding the locations for adaptive observations. A 24 h notice for a $D-2$ upstream flight may be issued. Some of the ships location may be adjusted so that they can take part to the IOP.
- $D-2.5$–$D-2$: Updated IOP schedule. Notices to ship crews taking part to the IOP are issued, as well as to aircraft crews for a near upstream flight. Final targets for objective flights are determined enterely from a forecast (typically, a 60 h forecast of the mature cyclone, with the target location being itself a 24 h or 36 h forecast.)

  Far upstream flights dealing with low level features could already happen at that stage.
- $D-1.5$–$D-1$: Upstream IOP. Intensive soundings from ships and upstream flights take place. The flights are monitored and may therefore be adjusted in real time (provided a satellite communication link is available). At the same time, the planning for the MSA IOP enters a critical stage: the air space booking NOTAM is issued, the crews are alerted. The ground radiosounding stations involved in the IOP in the UK, Ireland and France are alerted.
- $D-0.5$–$D0$: Benefiting from the upstream measurements, the short-range forecast are used to prepare the final flight plans. The MSA flights begin. A number of ground radiosounding station launch sondes every 3 h.
- $D0$–$D{+}0.5$: MSA flights are executed and also monitored from the ground. The intensive radiosounding period continues. When the flights are completed, a first debriefing takes place.

  There may be the possibility to extend an IOP with a further flight of the C-130 later on the same system.

A new weather system of interest may develop within 24 or 36 h of the previous one: this means that from $D-2$ of the IOP described above onwards, the schedule of the new IOP overlaps the current ones and two series of tasks have to be conducted in parallel.

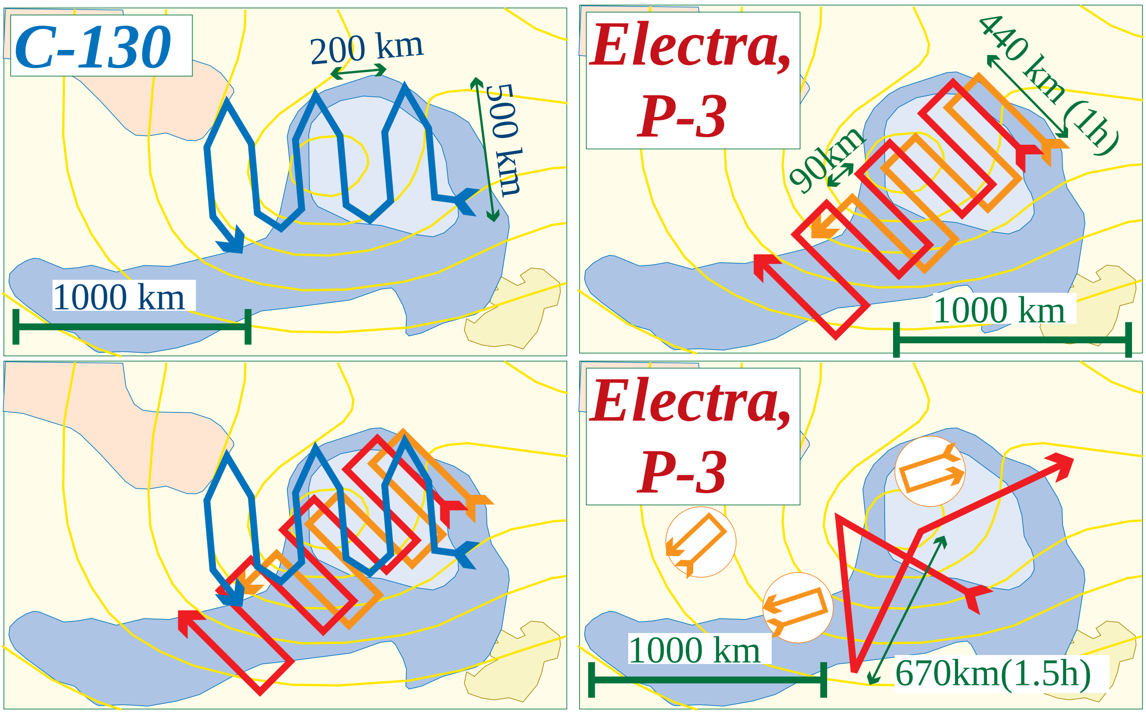


Figure 1.10: *Schematics of system-relative flight patterns to be employed by the turboprop aircraft in the MSA. The flight tracks are overlayed on the a composite structure for a second generation cyclone re-derived from automatic tracking and automatic classification of trajectories. The solid lines are surface pressure and the shaded areas are the vertical velocity at 700 mbar. The top-left panel shows the UKMO C-130 pattern going towards the clear air, low tropopause, components of the cyclone. This pattern is to be performed on all cases. Two other panels show the two main alternatives for the NCAR Electra (orange track) and NOAA P-3 (red track). The top right panel shows the so-called "lawnmower pattern" from which an overall observation of the ascent zone could be derived. The bottom right panel shows the overall exploration of the wave by the P-3 while circles mark possible areas where the Electra could performed a truly mesoscale sampling of rainbands and other structures (mesoscale investigation). The bottom left panel shows the full systematic survey pattern by overlaying the three aircraft tracks. These patterns are the result of the discussions within the MSA flight planning group. (Backround composite frontal wave: after F. Ayrault, Météo-France.)*

and will provide a cyclone-wide description of the thermal and wind fields as well as water vapour. This will be achieved by flying a series of 4 to 6 legs, about 500 km long, aiming at the dry slot following the cloud head. The sonde will be dropped about every 100 km. Relative to the system, legs should be spaced by about 100 or 200 km, depending on the scale of the cyclone.

Embedded within this systematic survey of the FASTEX cyclones that will provide a unique, multi-purpose documentation of their overall and internal structure, the Doppler aircraft were deployed according to two basic strategies. The first one reproduces, within the cloud system, the kind of systematic, regular survey proposed for the C-130. The P-3 and the Electra will fly parallel legs, so that the Doppler coverage of the two aircraft joins but does not overlap. The dual beam technique that permits recovery of the full wind vector from a single aircraft allows this new

Table 1.4: *Time table of the FASTEX project*

Dec 1991	"Proposition pour une expérience FRONTS 9x" document
Apr 1992	FRONTS 92 pilot experiment by the British JCMM
Jan 1993	The project begins at Météo-France, Research Dept
Sum 1993	The project becomes FRONTS 97, a joint CNRS and Météo-France programme
End 1993	British scientists from JCMM (Reading) join in the project and US scientists are also involved in early discussions
Feb 1994	FRONTS 97 becomes FASTEX, a new acronym for a higher level of international cooperation
Jui 1994	FASTEX Day in Bergen, presentations and discussions in order to enlarge the project group
Mar 1995	The main project groups begin their actions in Silver Spring, Maryland Emergence of the adaptative observation theme
Oct 1995	2nd plenary meetings near Oslo
Dec 1995	COAST Experiment: test of MSA-like flight plans in the Pacific Ocean
Jan 1996	Pre-FASTEX: real size simulation of the FASTEX operations centre in Toulouse and Bracknell
May 1996	3rd plenary meetings in Boulder, Colorado
Sum 1996	The Data Base development begins
Sep 1996	RMS and AMS Mesoscale Conference in Reading 4th plenary meetings
Dec 1996	Set-up and first test actions of the Operations Centre in Shannon
Jan 1997	The FASTEX field phase begins; unfavorable period
Feb 1997	Very favorable period; end of the FASTEX field phase
Mar 1997	The Data Base is opened to all scientists on the INTERNET
Nov 1997	First results submitted or published, e.g. in *Compte-Rendus de l'Académie des Sciences* (origin of Low 41, by Ph. Arbogast, see Short Note mininviop.)
Apr 1998	The first results are presented and discussed (EGS Annual Conference in Nice and FASTEX workshop in Toulouse)
Sum 1998	Most participating groups submit publications to the *Quarterly Journal* special issue.

approach. The aircraft are separated by about 100 km (the Doppler range being about 50 km on each side) and, as above, the leg length are about 500 km across the system, perpendicular to its motion. At regular interval along these legs (about every 120 km), complete 360°turns were executed, providing a kind a vertical conical scan similar to a ground-based VAD (results are shown in Part 5). This type of scanning allows for the unambiguous recovery of the terminal falling velocity of the reflecting droplets. This is an important microphysical information. It is also needed for inverting the vertical velocity of the air from the Doppler signals. This strategy is called the "lawnmower" pattern. This is a highly coordinated multi-aircraft plan. The Electra will fly at a height of 3 km, the P3 at 1.5 km.

This systematic survey allows a truly multiscale sampling of the structure of the cloud system. The end products depend on the way the signals are filtered and inverted. In the spirit of studying the overall wave dynamics, including cyclone-wide vertical motion, the overall distribution of microphysical fields, etc, a well suited technique is the MANDOP programme (Scialom and Lemaitre, 1990, Dou *et al.*, 1996). This algorithm is designed to recover the 3D wind field on a relatively large scale regular grid, as well as its main derivatives: see Part 6 for results in FASTEX. This wind field and the reflectivity can be used as input to other techniques that will provide thermodynamical and microphysical distributions. The same scans resampled in a different way can also provide information on the mesoscale substructures.

However, the mesoscale substructures and in particular, their own life cycles, could also be investigated mostly with the second flight strategy, called the "phenomena investigation" pattern. The flights were coordinated in a different way. The P3 takes off about an hour earlier than the Electra and enters the system at the same time as the C-130 begins its survey. The P3, however, performs in the meantime an X-like pattern covering the cloud head and frontal systems within 3 to 4 hours (1 to 1.5 h per leg) and centered on the position of the minimum pressure. The idea is to derive a map of the precipitating structures present in the cyclone using the lower fuselage radar. Based on this information, the Electra is directed towards mesoscale substructures of interest. These can be cold frontal rainbands, cloud head or warm frontal rainbands or convective structures in the cold air. Rainbands can be studied in two possible ways. A front relative pattern gives an idea of along-front variability and enable to follow several rainbands, sampling them at two different times at least, as the same portion of front is covered from both sides in turn. A band-relative pattern enable the use of the highest rate sampling capabilities of ASTRAIA/ELDORA and give access to the internal structure of the band. The objectives here are to derive life-cycles of mesoscale features and frontal eveolution on the mesoscale. The retrieving techniques and the kind of results that can be obtained are shown by Wakimoto *et al.* (1992) in an explosive extreme cyclone. What is the activity on these scale in the generally much weaker FASTEX cyclones and their contribution to the overall budgets is one of the challenging questions of FASTEX.

Figure 1.10 provides an idea of these flight strategies shown on the objective composite of one type of frontal wave derived from Ayrault (1995). The P3 and the Electra will be based at Shannon (Ireland). The C-130 will be in Lyneham, in England, about 50 minutes flight away from Shannon. The entire low level airspace to be sampled by these flights will be blocked about 24 h in advance. Resources have been determined in order to allow the observation of 10 cases.

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 schedule during which all these ideas were discussed and prepared is shown by Table 1.4.

Acknowledgments.

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