

North Atlantic ultra high frequency variability

An introductory survey

By FRANCK AYRAULT, FRANÇOIS LALAURETTE*, ALAIN JOLY and CÉCILE LOO, *Météo France, Centre National de Recherches Météorologiques, 42, av. G. Coriolis, F-31057 Toulouse-Cedex, France*

(Manuscript received 8 September 1994; in final form 24 February 1995)

ABSTRACT

This study attempts to depict east Atlantic cyclones specificity using ECMWF 1984–1994 cold season analyses. Due to the strong low frequency variability in this area, a climatology of transient events has to take the “background” weather regime into account. North Atlantic weather regimes have therefore been recovered through cluster analysis techniques. An objective criterion defining the occurrence of subsynoptic cyclones is then designed. It uses the high frequency signature of vorticity. The events thus retained include frontal waves, cold air cyclogenesis and other small scale developments. The preferred location of these events is found to be quite distinct from the classical storm-tracks. They appear downstream and slightly south of them, reaching the north-western part of Europe during Zonal weather regimes, and a zone centred some 500 km north of the Azores during Greenland Anticyclone regimes. In order to gain some idea of the various types of subsynoptic cyclones captured by the criterion, a one-point selection of cases was performed and the resulting vorticity fields were partitioned by a cluster analysis. Two types of waves out of three clusters are documented. A Type 1 is shown to be a modified baroclinic development, with reduced scale and features well accounted for by recent theoretical work on frontal waves. A Type 2 composite, with its typical warm front, is more difficult to set into an existing theoretical framework. It seems connected to the presence of an actively diffluent background flow.

1. Introduction

An objective picture of large-scale cyclones has been available now for more than 10 years, built from detailed climatological studies (Blackmon et al., 1984b; Wallace et al., 1988). Although the dynamical origin of these events may still be a matter of some controversy, their preferred location (“storm-tracks”), structure, phase speed and even their interaction with low frequency weather regimes (Robertson and Metz, 1990) has been deduced from careful inspection of the atmospheric signals in the 2–6 days time spectral window.

A puzzling result from all these climatological studies is that they locate Europe quite at the end,

if not completely out of the Atlantic “storm-track”. This part of the world is however far from being free of meteorological perturbations, as is daily experienced by operational forecasters (Beugin and Rochard, 1991). This high level of the weather variability gave the Bergen school of meteorology a strong incitement at organising existing data in a coherent way. A large number of case studies underline the frequent occurrence of sub-synoptic and meso- α scale cyclones over Western Europe. If some of them can simply be related to the anomalous eastward penetration of the jet stream (Eastern Atlantic teleconnection pattern, Wallace and Gutzler, 1981), other ones clearly involve processes that are not typical of primary cyclones. They may include polar lows (Businger, 1985), frontal waves (Joly and Thorpe, 1990), or even “bombs” like the Great Storm of October 1987

* Corresponding author.

(Hoskins and Berrisford, 1988; Jarraud et al., 1989).

The fact that these phenomena are not accounted for by objective climatological studies is likely to be related both to (1) the fairly crude time-space resolution of the daily analysis operationally produced by the weather services, (2) the necessity of carefully depicting the "background" flow on which European cyclones develop, as this flow undergoes a very important intra-seasonal variability (the so-called weather regimes: Vautard (1990)). A misleading use of time-averaged datasets is probably responsible for the fact that the Norwegian Bergen school concepts of frontal instability were abandoned for a long time before being recently reactivated. A simple but effective partition of the background flow using classical statistical techniques (spectral filtering and cluster analysis) will be introduced in this study to avoid these problems.

More fundamentally, the theoretical concepts that have proven useful to interpret the 2–6 days variability are all more or less related to a modal description of baroclinic instability. Recent advances have been made that tend to question both the normal modes and the baroclinic instability concepts as the exclusive frameworks pertaining to extra-tropical dynamics. Farrell (1989a) has shown that extra-tropical developments can reach deepening rates much larger than predicted by unstable normal modes, while Farrell and Ioannou (1993) proved that the stochastic forcing of a *stable* (from a normal mode point of view) basic state baroclinic flow could lead to quite realistic vertical profiles of geopotential variability and meridional heat fluxes. On the other hand, recent frontal instability studies have shown that these sub-synoptic scale instabilities have a significant barotropic character, in the energy sense (Moore and Peltier, 1987; Schär and Davies, 1990; Joly and Thorpe, 1990) which is quite at variance from the classical description of primary cyclogenesis. These concepts offer new frameworks into which the interpretation of some results (some of them being included in the present paper) fit more naturally.

The improvement in quality now achieved for more than ten years in the global datasets issued from numerical weather forecast analyses (Shaw et al., 1987) gives another incentive for revisiting the mid-latitude cold season climatology. Even

though the exciting ECMWF project of a 10-year homogeneous reanalysis was not carried through at the time of this study, the operational 4-daily analyses are easily available for the period going from 1984 up to present time. We are not aware of any climatology taking advantage of this 6-h time-sampling which allows small scale cyclones to be more easily tracked in time.

It is the existence of both improved datasets and of new theoretical ideas about mid-latitudes dynamics that was felt to be a challenging opportunity to fill the gap between existing large scale climatological studies and the way "weather" is perceived on the European side of the Atlantic. The present study is a preliminary attempt to take up this challenge, and should be seen as a first step in a long-term scientific effort that includes a major field experiment (the Fronts and Atlantic Storm-Track EXperiment, FASTEX). The dataset and the basic data processing are described in Section 2, while weather regimes for this dataset are identified in Section 3. A tentative climatology of the events that fulfil a very simple criterion for sub-synoptic cyclones is exhibited in Section 4, while a first composite-like study of such events occurring at a given location is conducted in Section 5. Preliminary conclusions and perspectives are drawn in Section 6.

2. The dataset

2.1. Contents

Data come from the operational initialised analyses produced by ECMWF from 16 October 1984 to 15 April 1994. Only the 6 "cold season" months ranging from 16 October to 15 April were kept, as cyclones mostly occur during this period. This 6 months interval was preferred to the 3 months winter period used in some previous studies (Wallace and Gutzler, 1981 or Blackmon et al., 1984a; Vautard, 1990 used 5-month cold seasons) both to augment the number of cyclones cases and to avoid "boundary" effects in the low frequency variability treatment (Section 3).

The geographical domain selected extends from 90°W to 16.5°E, and 19.5° to 72°N, thus encompassing North-Atlantic, the eastern border of the North-American continent and Western Europe. The analyses were sampled on a 1.5° × 1.5° latitude/longitude grid. The operational analysis was

run with a T106 spectral representation up to 17 September 1991, and a T213 representation from then to now. This means that the shortest waves the *guess field* could represent up to the 1990–1991 cold season had a 380 km wavelength. This value is itself an overestimation of the true dataset resolution, due to the poor *observations* coverage over the Atlantic. The vertical sampling was made on 10 pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150 and 100 hPa). The retrieved fields are geopotential, temperature, humidity, 3 wind components and the vertical component of vorticity. This latter field is redundant with the wind field, but it is a key parameter for a cyclones climatology. Advantage was therefore taken from the fact that vorticity is one of ECMWF model historical variables, and thus no further numerical noise was introduced as would have been the case if it had been retrieved from the wind components using finite differences.

2.2. Homogeneity tests and spectral analysis

As this dataset does not come from the major reanalysis effort currently undertaken at ECMWF, it could be objected that it makes little sense to blend data coming from such different sources as the 1986 analysis scheme using T106L16 *guess fields*, and the 1993 one using T213L31 model. Several changes have been made both in the physical package of the forecast model used in the data assimilation cycle, in the observations (coverage, quality, type), and in the way these observations are handled by the analysis. The most important change in the analysis scheme occurred in September 1991, when both the horizontal and vertical resolution of the model were doubled. The homogeneity of the time series must therefore be questioned. A Kolmogorov–Smirnov statistical test (Smirnov, 1939) is employed. The test compared 1985–1991 and 1991–1993 time series (warm seasons excluded) of 1000 hPa geopotential for each grid point. About 10% among the grid points are found to have these two time series non-homogeneous at 95% of confidence. It is found moreover that this percentage is the same when the test is applied to the 1985–1988 and 1988–1991 time series, despite the fact that no major change in the model resolution occurred between these periods. This is an indication that the year-to-year climatic variability is still the dominant signal, and

that the analysis changes may be seen as marginal in front of it.

An important part of the treatment made in subsequent sections relies on time scale considerations. Part of the signal may be thought to be associated with the diurnal cycle. This was found to be the case only for the low level continental data, the signature being much reduced for oceanic locations on which we have most interest in this study. Another, unexpected, semi-diurnal signal (the smallest Fourier component for a 4-daily time serie) was however found. Tidal waves exist in the atmosphere with maximum amplitude in the tropics (Chapman and Lindzen, 1970). They may be spuriously excited by the analysis process, e.g., by data biases differing from an heliosynchronous satellite to another (P. Courtier, private communication). Such large scale signatures have however no chance to interfere with the subsynoptic phenomena that are highlighted by this study. The only specific treatment that was finally applied to the data before applying the Fourier filters was to remove from each cold season the 1-year best fitted sinus signal. The Fourier filters used in this study are a low pass (beyond 10 days), band pass or high frequency (2–6 days) and ultra-high frequency (less than 36 h).

3. Weather regimes

3.1. Motivations

An important step in climatological studies was taken some 15 years ago when the low frequency variability of the atmosphere was revealed by Wallace and Gutzler (1981) quickly after that Charney and De Vore (1979) suggested that several quasi-stationary atmospheric regimes could exist. Over the Atlantic, most of the 2–6 day variability is located by climatological studies on the Western side, while most of the slow (>10 days) variability is found on the Central and Eastern parts (Blackmon et al., 1984a, their Fig. 2). Our study is focused on highly transient (<2 days) variability over Western Europe; the palette of “weather regimes” that occur there will be seen to a very good approximation as a palette of *basic states* with contrasting properties.

Following Hoskins et al. (1983), the most convincing results associating firm statistical evidence of persistent large scale patterns to a dynamical

interpretation in term of their maintenance through eddy forcings have been published by Vautard et al. (1988), Vautard and Legras (1988), Vautard (1990) (V90 hereafter). We refer to these for a comprehensive description of the concept of "weather regime": it will not be revisited here. The key idea is worth recalling though: a regime is essentially a dynamically equilibrated pattern, which may therefore correspond to quasi-steady, persistent weather. These regimes will be extracted in order to ensure that the background flow on which the highly transient events evolve is realistic, and is not merely the result of averaging an heterogeneous sample. In that sense the identification of weather regimes in our study is only a step in the data processing, but it is felt to be a crucial one for the interpretation of further results.

3.2. The identification technique

Following V90, regime identification is based on the 700 hPa geopotential fields. As the large scale slow variability is our concern here, only one (12 GMT) of the four-daily analyses was processed using one-fourth of the geographical points ($3^\circ \times 3^\circ$ grid spacing). A Fourier treatment was applied first in order to retain only the low frequency part of the signal (beyond 10 days). A principal component analysis (PCA hereafter) was then performed in order to further compress the information in the subspace of the first 5 principal eigenvectors which represent 79% of the total low frequency variability.

The weather regimes are then identified as the preferred locations in which the large scale atmosphere stays in this subspace. A cluster identification algorithm is used (Hartigan and Wong, 1979). Such algorithms exhibit a prescribed number of clusters using an iterative procedure whose sensitivity to the initial estimation of the cluster centres (seeding) may be important, depending on the processed dataset (see Cheng and Wallace, 1993 for a comprehensive study of wintertime climatology using cluster analysis, or Legras et al., 1987 for an application to weather regimes). For the cluster algorithm, the distance between two geopotential fields is defined as the Euclidean distance in the 5-PCA subspace. If no projection was made to this subspace, this distance would be exactly equivalent to the spatial-average of the squared difference of the fields.

3.3. Results and sensitivity tests

To keep close to the four "quasi-stationary" patterns identified by V90 from long climatological series over the Atlantic, the number of clusters is set to four. Several initial seeds were tested: they have shown the robustness of the results to this arbitrary initialisation. In order to

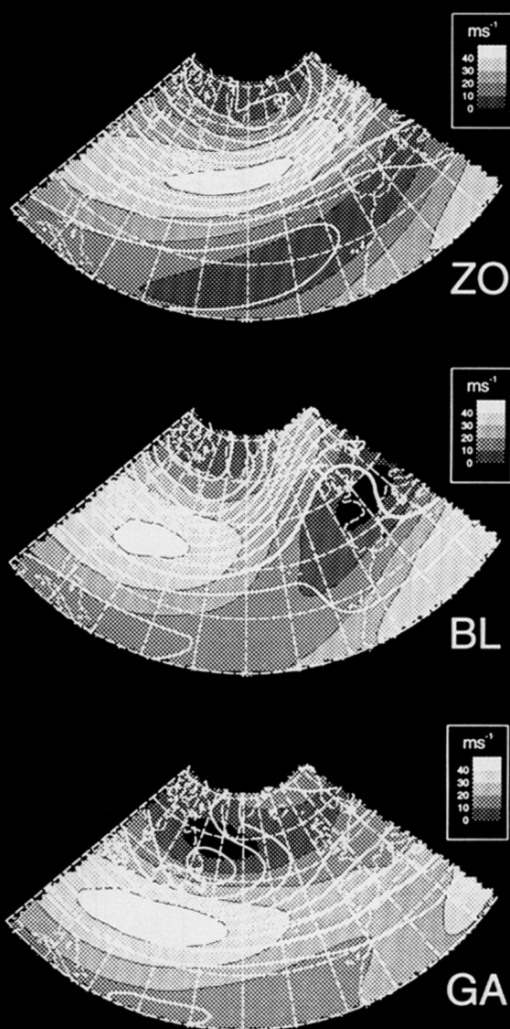


Fig. 1. Mean 700-hPa height every 50 m (black lines, heavy line is 3000-m) and 300-hPa zonal wind (shading), respectively for (ZO) Zonal (BL) Blocking (GA) Greenland anticyclone regime. Note the anomalous eastward 300-hPa flow (white shading) over France (Blocking) and the Labrador Sea (Greenland anticyclone).

reinforce the homogeneity of the regimes, the dates preceding or following a cluster change were rejected: the regimes introduced here are lasting for at least 3 days, among which the first and last days are never used. Some quantities summarising the result of the cluster analysis together with a calendar of cluster events are given in the Appendix (Section 8).

The 700-hPa geopotential mean fields for the first three clusters (Fig. 1) are in agreement with V90 (his Fig. 3). The most contrasting regimes are the Zonal and Blocking regimes: they are similar to the “high”- and “low”-index regimes already identified by Charney and De Vore (1979) in a highly idealised atmospheric model. The Zonal regime corresponds to a maximum eastward penetration of the zonal jet, whereas the Blocking regime corresponds to an anomaly leading to 300-hPa easterlies over France, the westerly jet being confined to the eastern coast of the USA. The Greenland anticyclone regime is again well captured, with 300-hPa easterlies over the Labrador sea, and a westerly jet moved southward by reference to its Zonal regime position. Another feature apparent from our results is the well-known existence of an African subtropical jet whose strength and northward extend are maximised during the Blocking regime.

The agreement between our results and the Atlantic ridge regime of V90 is by contrast not so obvious, as the ridge is here quite evanescent (not shown). This feature was already found by Legras et al. (1987), and is at least partly due to differences in the spatial and temporal windows. It is not a major caveat for our study, as this regime is probably not associated with the most active perturbations.

3.4. Weather regimes dependence of some dynamical parameters

3.4.1. Background flow. Weather regime dependence was usually sought using univariate dataset, with only 500- or 700-hPa geopotential height time series. Various parameters and levels being available in the ECMWF dataset, the opportunity of depicting more precisely the background flow on which most transient perturbations develop (the Zonal regime) is taken here.

This regime is characterised by high static stabilities over North America (Fig. 2), a feature that was already stressed by Whitaker and

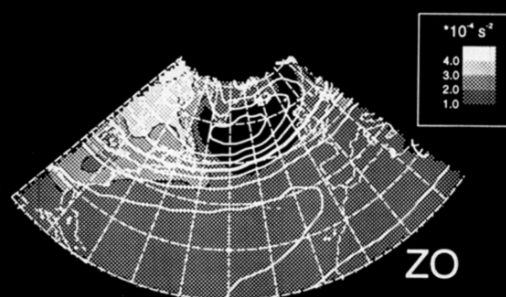


Fig. 2. Zonal regime mean 1000–850-hPa squared Brünt-Väisälä frequency (shading) and 300-hPa potential vorticity (contours 0.5 PVU, 1 PVU = $10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$; the 2-PVU contour is highlighted).

Barcilon (1992) as a characteristic of the background flow that has important consequences on its dynamical stability. The pattern they highlighted as a paradigm of an eastern American low level cyclogenetic configuration (a highly contrasted continent/ocean low-level stability) is best recovered during the Greenland anticyclone regime (not shown). The well-marked North-South dipole over the eastern Atlantic during the Zonal regime (with squared frequencies that are halved along 20°W between 35°N to 55°N) was less expected. Low static stability is associated with maximum high level potential vorticity (Fig. 2). Following Eady (1949), simple scalings of the cyclogenesis wavelength and growth rates are $1.25\pi NH/f$ and $0.3 U_z f/N$ respectively (N denotes the Brünt-Väisälä frequency, f the Coriolis parameter, U_z the large-scale vertical wind shear, and H the tropopause height). We may therefore anticipate that this low static stability/low tropopause (high 300-hPa PV) area is conducive to small scale cyclogenesis by coupling of the lower and upper troposphere (Hoskins et al., 1985).

The background flows depicted here have probably much more to do with the large scale flows in which the extratropical cyclones are embedded than the commonly used monthly climatology. Of some interest for theoreticians may be the confirmation of the robustness of the “uniform PV” hypothesis in the light of these new background data. This hypothesis that is often made for the sake of simplicity in idealised models, especially semi-geostrophic ones (Hoskins and West, 1979 and others), is found to hold in the “slowly varying” northern Atlantic troposphere

where the PV is found to be 0.4 ± 0.1 PVU (not shown).

An important feature of European weather is the occurrence of well-marked fronts over scales that may often be much beyond those of cyclones. The frontogenesis process has been known for a long time to be initiated by the deformation action of the wind on the thermal field (Bjerknes et al., 1934, their Fig. 130, p. 767; Miller, 1948). More recently, it was also found to be a key parameter to explain where and when frontal instability (which is a potential source of subsynoptic cyclones) is likely to occur (Bishop and Thorpe, 1994).

Our dataset shows the "background" frontogenetic areas to lie mostly near the North-American coast, the Eastern Atlantic area being mostly frontolytic (the Zonal regime signature is shown on Fig. 3). This is a striking confirmation that the background flow cannot by itself explain the creation of fronts over Europe, and that the baroclinic wave part of the frontogenetic signal that is here filtered out is of crucial importance (Mudrick, 1974; Hoskins and West, 1979; Lalaurette et al., 1994). The Greenland anticyclone regime is an exception, with a frontogenetic, diffluent flow over the north-west of the British Isles during Greenland anticyclone regime (not shown).

3.4.2. Synoptic scale (2–6 days) transients. Before turning to subsynoptic cyclones to which the present study is dedicated, advantage is taken of identification of the weather regimes to shed

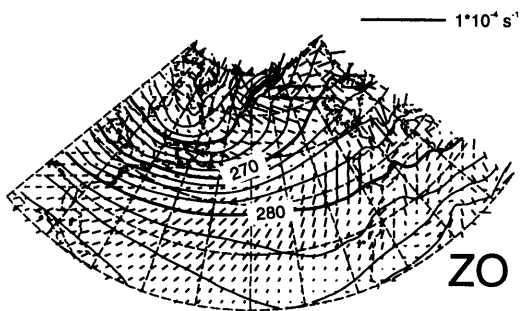


Fig. 3. Zonal regime mean 850-hPa temperature (contours 2.5 K) and amplitude dependent dilatation axes of the wind field. The forcing on frontal zones is frontogenetic when this axis is more or less parallel to the isotherms, it is frontolytic when the dilatation axis is roughly parallel to the gradient. Large deformation values near Greenland and the Alps are associated with orographic effects.

new light on our knowledge of the large scale extra-tropical cyclone climatology. As the differences between the latter phenomena and eastern Atlantic events are stressed in this study, basic results about the synoptic scale cyclones must be recovered from the data employed here. Moreover, this part of the study is intended as a validation of the data processing through a comparison with published results on the subject.

"Storm-tracks" are usually identified from the 2–6 days low- or mid-tropospheric geopotential variance (Hoskins et al., 1983; Blackmon et al., 1984a; Wallace et al., 1988). The geopotential have been rescaled by $\sin \varphi_0 / \sin \varphi$, where φ is the latitude and φ_0 is an arbitrary latitude taken equal to 45° N. This is to display geopotential values that are not affected by the Coriolis effect, and may be seen as streamfunctions (see Wallace et al., 1988). The storm-tracks identified in this way in our dataset are in quite good agreement with the previous studies, with a location slightly displaced to the north-east of the zonal jet (not shown). However a very large sensitivity to the weather regime is found, the 2–6 days variance being strongly correlated with the eastern part of the jet: if Blocking regimes are associated with the largest amount of 2–6 days variance over north-eastern America, the Zonal and Greenland-anticyclone regimes are more likely to affect northern and southern Europe respectively (Fig. 4). The latter pattern even exhibits an almost continuous crest of high values from America to the Mediterranean sea, which might be related to the somewhat smooth transition from the American to the African jet occurring during this regime. Note that each regime-related stormtrack extends over a larger area and to the north-east of the mean storm-track: this is a beneficial effect of the separation into regimes and the subsequent reduction of the low-frequency variability within each of them in the north-east Atlantic ocean. It should be stressed however that the European 2–6 day standard deviation never exhibits the values beyond $500 \text{ m}^2 \text{ s}^{-2}$ that are characteristic of the storm-track: the combination of weather regime dependence and of the 2–6 day period band-pass filter are therefore not sufficient to account for the European weather variability.

The extended form of Eliassen-Palm fluxes or *E*-vectors have been computed from the 2–6 days time spectral window of our dataset, for each of the

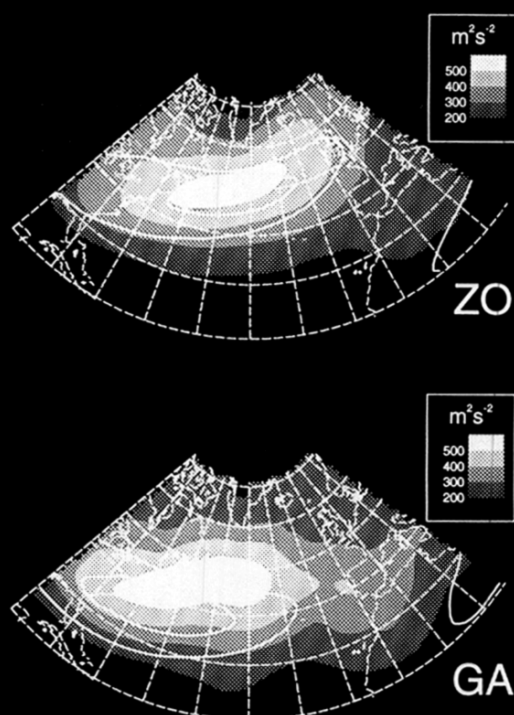


Fig. 4. 2–6 days 700-hPa standard deviation of the rescaled geopotential for (ZO) zonal and (GA) Greenland anticyclone regime (shading). The corresponding 300-hPa mean zonal winds from Fig. 1 are recalled (black lines are 30 m s^{-1} and 40 m s^{-1}).

3 more active weather regimes (not shown). They confirm previous statements about the shape and propagation of transient events at this scale, together with their forcing on the background flow (Hoskins et al., 1983; Robertson and Metz, 1990).

3.4.3. Ultra-high frequency contribution. The full time resolution of ECMWF analysis is now exploited with a study of periods smaller than 1.5 days, hereafter the ultra-high frequency (UHF) variability. This seems the most natural way to call the unexplored frequency band, the 2–6 days window being known as the high frequency band (or “short time scales”, Blackmon et al., 1984a). The 6-h sampling of the dataset enables us to approach the 0.5–1.5 days variability. Fig. 5 shows that it actually contains a significant part of the atmospheric variability* (peak values in this 1-day

window are roughly 30% of those in the 4-day high-frequency band). The key result here is not limited to the level of geopotential variance existing at this scale. It is just as important to note that the geographical location of the UHF variance is distinct from its synoptic counterpart, with a maximum clearly lying downstream. This is not a clue that specific *waves* or *instabilities* are associated with these time scales. Frontogenesis for example is a good candidate to account for this highly transient variability at the end of the storm-tracks, in locations where baroclinic waves have reached a mature stage with highly frontogenetic configurations embedded within them (Hoskins and West, 1979).

The 850-hPa *E*-vectors associated with these band-pass transients diverge over the British isles and northern Europe during zonal and Greenland anticyclone regimes respectively (Fig. 5). This is

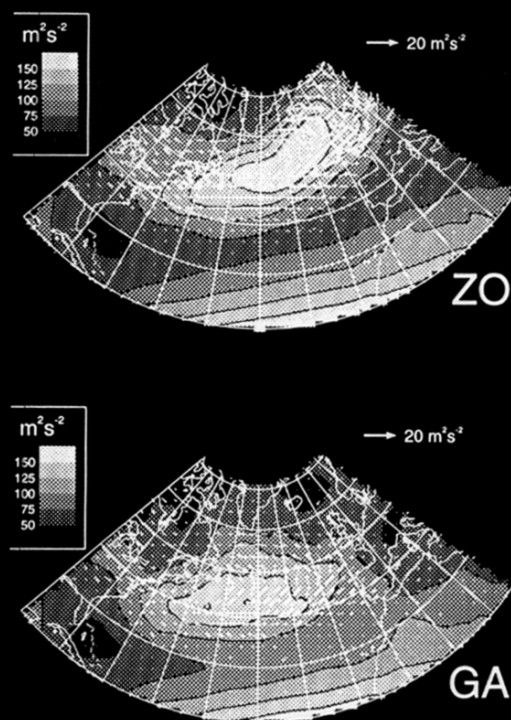


Fig. 5. 850-hPa UHF standard deviation of the rescaled geopotential and *E*-vectors for (ZO) zonal and (GA) Greenland anticyclone regimes. Even if the values are smaller than for the band-pass (Fig. 4), such a variability being associated with small scale events is liable to produce significant winds.

* The strong values south of 30°N are associated with the semi-diurnal tidal signal discussed in Subsection 2.2.

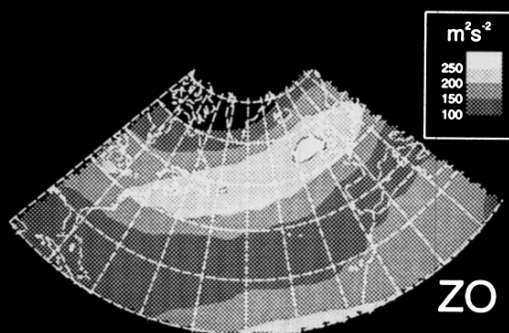


Fig. 6. Zonal regime UHF 300-hPa standard deviation of the rescaled geopotential.

indicative of a barotropic reinforcement of the background flow by the transients, and of a global predominance on these maps of frontogenesis processes creating strong low level jets. The interpretation of E at such levels is however complicated by the influence of baroclinic processes. Of interest is also the high level of 300-hPa geopotential variance associated with these time scales (Fig. 6). Such anomalies are likely to be sometimes associated with rapidly moving deep stratospheric intrusions. These have been shown by Thorncroft and Hoskins (1990), in an idealised baroclinic wave life cycle experiment, to be a possible source of frontal cyclones.

4. A crude, objective criterion for highly transient cyclones

4.1. The necessity of going beyond spectral filtering

One might expect that once weather regimes have been identified, subsynoptic cyclones should be isolated by considering the ultra high frequency time window. Examination of the filtered vorticity fields soon reveals however that even once the primary cyclones are filtered out, an important part of the high-pass signal is associated with frontogenesis. This is the case, for example, on the 22 February 1991 1800 GMT when both a mature cyclone "P" and a frontal wave "S" occurred (Fig. 7). While the latter is almost unaffected, the core of the former is removed by the spectral treatment, but the vorticity signature of the bent-back "F" front West of Scotland is retained. This important frontal signature appears to be systematic.

Eastern Atlantic low level baroclinity for example was found to have most of its signature in the 0.5–2 days time window (not shown). If applied to the UHF part of the time series, the usual statistical techniques are thus likely to blend fronts and subsynoptic cyclones signatures.

A full composite analysis is however beyond the scope of this study, and is postponed to future work (a first step in this direction is made however in Section 5). For the preliminary climatology of subsynoptic cyclone events over the northern Atlantic, the following very simple criterion was defined. A subsynoptic cyclone is expected each time and at each point meeting the two following conditions:

- (1) a local maximum in the vorticity field exceeds 0.5 times the Coriolis parameter;
- (2) more than 50% of this relative vorticity comes from the UHF part of the signal (more than 1.5 day^{-1}).

It should be stressed however that such a criterion cannot aim at cleanly identifying frontal cyclones, even if these events should be retained by the criterion (see Fig. 7, where the "S" frontal wave can be seen to fulfill it). It is expected rather that most of the primary cyclones and the frontogenesis will be filtered out, the remaining events being small scale developments of various kinds as will be shown later.

4.2. A first step towards quantifying the frequency and location of subsynoptic cyclones

The relevance of the above-stated definition was tested by an indepth analysis of an event filled 7-day period (4–10 January 1991). For this "Zonal regime" period, the results of objective application of the definition were compared to the "subjective" analysis of forecasters using both model output, surface data and satellite pictures. The case of the 7–8 January cold air cyclone that was successfully selected by the criterion is used here to illustrate the events of interest to this work. The satellite infra-red imagery revealed a poorly organised cloud cluster reaching Cornwall at 18 GMT on the 7th, in the cold air behind the decaying cold front extending from Sweden to Portugal (not shown). 6 hours later, a small scale vortex signature can be seen on the infra-red picture (Fig. 8a). The ECMWF analysis depicts this small scale event with a much clearer signature in the vorticity field

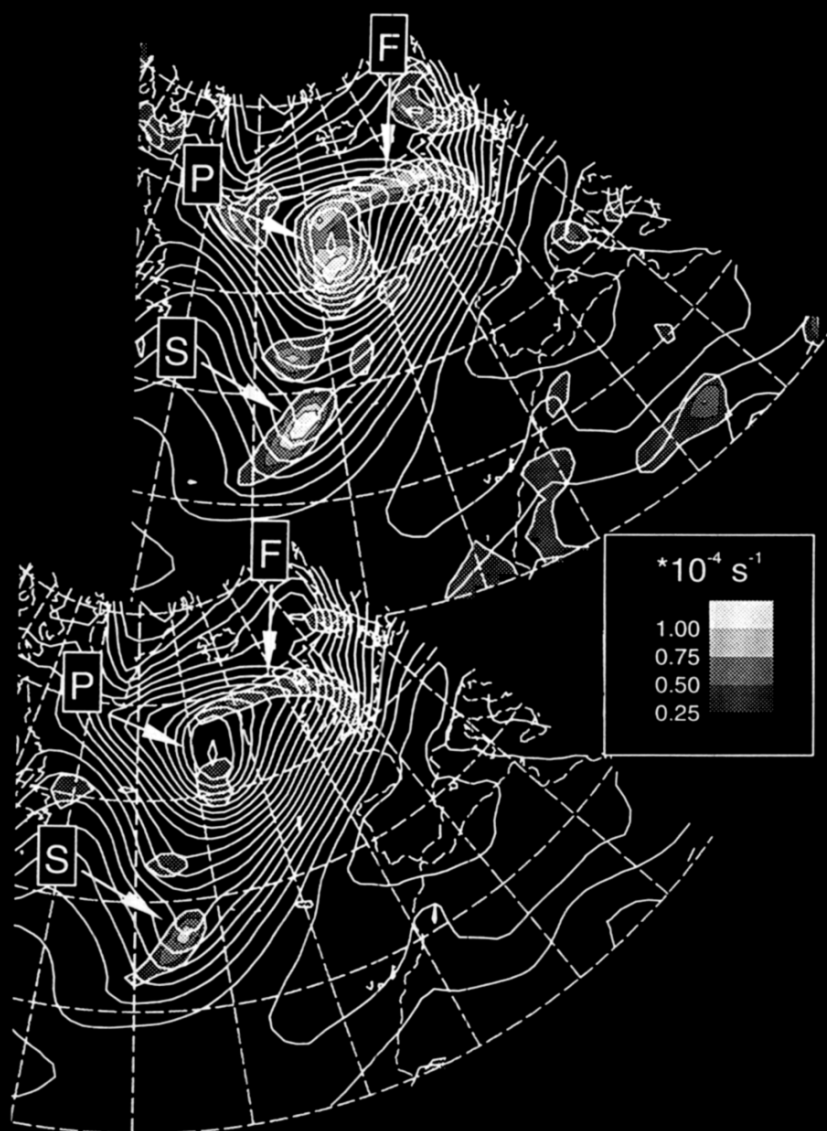


Fig. 7. 1800 GMT 22 February 1991: 1000-hPa height (contours 25 m) with the total (upper panel) and UHF (lower panel) part of the 850-hPa vorticity field (shading every $0.25f$).

than in the pressure field (Fig. 8b). This system corresponds to relatively strong winds and localized rainfall activity (Fig. 8c).

From this 7-day comparison between ECMWF analyses, satellite imagery and "subjective" operational analyses, our criterion was found to have a positive bias (more cases of false alerts than of

undetected events) but the overall picture was found to be realistic enough for an extensive use of the criterion on the 9-cold season sample to be attempted.

The frequency of occurrence of subsynoptic cyclones, as defined by our criterion, during Zonal and Greenland anticyclone regimes is depicted in

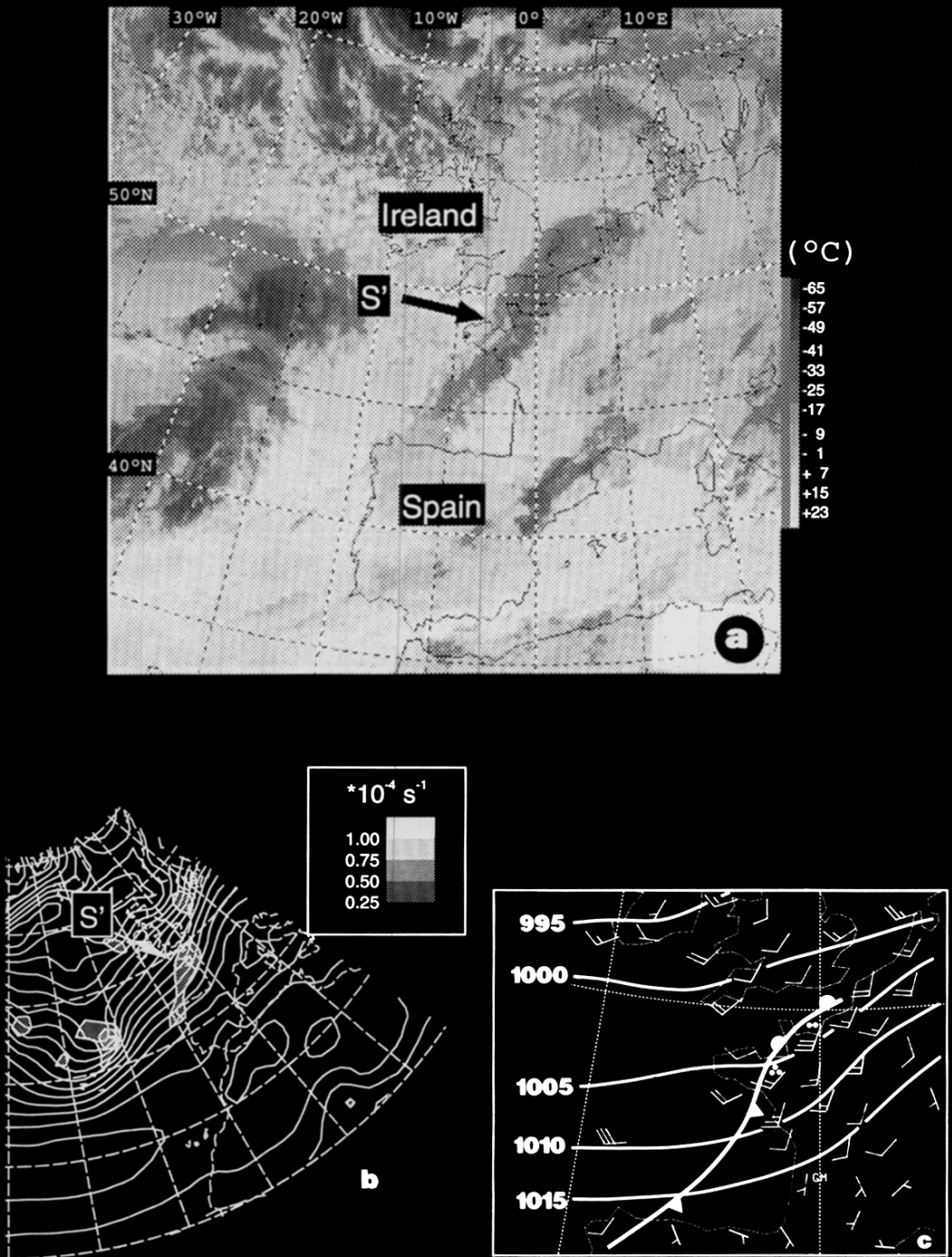


Fig. 8. 0000 GMT 8 January 1991 (a) Meteosat Infra-Red picture, (b) 1000-hPa height and UHF part of the 850-hPa vorticity field (plotting as in Fig. 7), (c) surface data and forecasters "real time" analysis.

Fig. 9. The difference in location between synoptic and subsynoptic cyclones is obvious there, the latter lying further east and slightly south of the former storm tracks. The difference in location with the UHF variance maxima of Fig. 5 should also be noted. The Zonal regime subsynoptic cyclone track is particularly illuminating: only the very end of the maximum high-frequency variability area is found associated with significant

subsynoptic cyclone occurrence. This fits the picture of these cyclones as phenomena having preferred location roughly corresponding to an area where primary cyclones have reached their decay stage. Such a signature can also be found during the Greenland-anticyclone, but not during the Blocking regime. The presence of a significant secondary maximum south of Sicily during Greenland anticyclone regime should be pointed out: the fact that our criterion picks out Mediterranean cyclones is a sign of its ability at identifying such small scale phenomena.

These maps, although based on a crude approach, should however be stressed as showing the first objective statement of the fundamental, qualitative difference between synoptic and subsynoptic scale cyclones. If eastern Atlantic and Europe appear to be barely affected by the former phenomena, the latter are on the contrary most likely occurring in these area, at least during perturbed (Zonal and Greenland anticyclone) regimes.

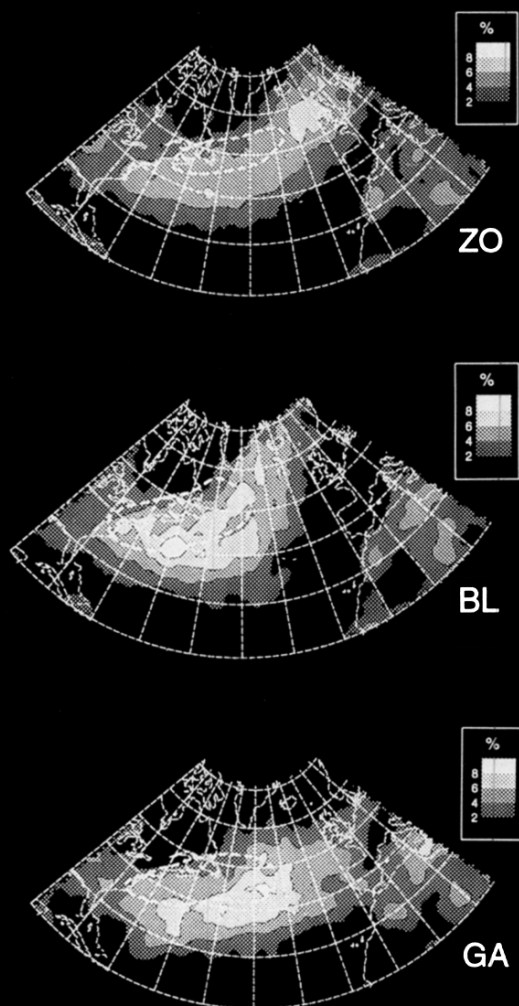


Fig. 9. Geographical distribution of the number of subsynoptic cyclones. It is expressed as a % of the total number of analyses in respectively (ZO) Zonal (BL) Blocking (GA) Greenland anticyclone regime time series. Contours recall the $500 \text{ m}^2 \text{ s}^{-2}$ contour from Fig. 4 (the synoptic "storm-tracks").

5. Composite scenarios: preliminary results

5.1. Methodology

It is easy to see from cases as different as the frontal wave of 22 February 1991 (Fig. 7) and the cold air cyclones of 7 January 1991 (Fig. 8) that "subsynoptic cyclones" is a generic term that embodies weather systems having very different life cycles. It seems likely that these differences reflect diverse origins or/and dynamical processes. Any statistical summary of the maps sampled using the criterion defined in the previous section may turn out to be irrelevant as long as the set of cases is treated as a whole. In this section, a detailed analysis of the events captured by the criterion at a particular location is attempted. Various aspects of proto-composites of these cyclones are documented and an interpretation is proposed at the end.

The method employed to reach this goal may belong to one of the following two. The first method is to take maximum advantage of the present "state-of-the-art" in the field of subsynoptic scale development theories, and try to identify subsets of the sample of subsynoptic cyclones that could be accounted for by one of

these idealized models. In the present study, however, the choice is definitely in favour of a second, purely "morphological" method. It avoids the use of any preconceived dynamical picture of the cyclogenesis processes. This open-minded approach allows observed but possibly unexplained or even unexpected phenomena to be exhibited.

The method is now described. It consists of a cluster analysis of subsynoptic cyclone events occurring at a given point for a given (Zonal) weather regime. The chosen point is (51°N , 6°W), at the west tip of Cornwall, in the southern part of the "Zonal regime" subsynoptic storm-track. It was chosen because both frontal waves and subsynoptic cyclones are expected in this zone surrounded by Ireland, United Kingdom and France. Starting from the list of dates belonging to the Zonal regime, a subset of dates and times is compiled. They correspond to analyses meeting the cyclone criterion at the reference point or at the eight nearest grid-points. For each of these analyses, a 9×7 sub-grid centred on the same location is extracted. The field to be partitioned is the unfiltered vorticity at 850 hPa. Because of the smallness of the area used for the selection within the already reduced sample of zonal regime analyses, and also because only data from 8 cold seasons (1985 to 1992) are used, the number of cases amounts, in the end, to about 50. Therefore, a partition into only 3 clusters has been constructed.

A raw summary of the result of this procedure is shown by Fig. 10. The composite maps that appear in this figure, as well as all subsequent ones, show the straightforward average of all analyses belonging to one cluster. The figure shows the vorticity field on which the partition is essentially based and the low level equivalent potential temperature θ_e . The signature of the cyclones on this latter field is one of the clearest and will be used as a reference. The largest cluster is denoted hereafter Type 1: it is based on 23 cases. The next one in size, Type 2, has 17 cases. It is the most homogeneous class, as could be verified from the individual vorticity maps. The third cluster involves 14 cases only.

This third cluster suffers from being made up of very different looking, weak, individual events. It is dominated by their background, a rapid seclusion process occurring on a mature cyclone of synoptic

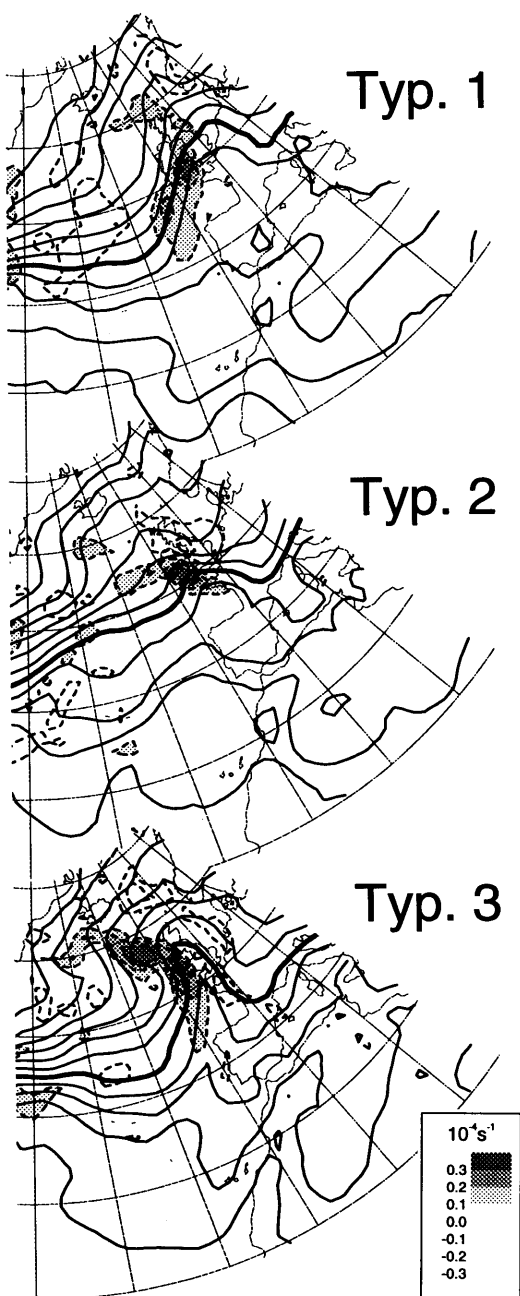


Fig. 10. Composite pictures deduced from the 3-cluster analysis of 850 hPa vorticity fields for the Zonal regime subsynoptic cyclones detected by (51°N , 6°W). 850-hPa θ_e (full contours every 3 K, 300-K is bold) and 1000-hPa high-pass ($\tau < 6$ days) vorticity fields (dotted contours every 10^{-5} s^{-1} , zero excluded; positive values beyond 10^{-5} s^{-1} are shaded).

scale. The composite picture only reflects its connection to a late stage of large scale cyclogenesis, blurring the subsynoptic events. For these reasons, it will not be discussed any more. The remainder of this section is dedicated to the Type 1 and Type 2 subsynoptic "European" cyclones.

5.2. Description of Type 1 and Type 2 cyclones

In order to try and characterize the Type 1 and Type 2 cyclones, several diagnostics are now presented. An important step in the identification process is to consider the time evolution of the systems. The fact that a signal can be seen in composite maps obtained prior to and after the system has crossed Cornwall is also a good test of the robustness of the approach, as these fields were not involved in the partitioning process.

Fig. 11 shows the evolution over 12 hours of θ_e , the 1000 hPa geopotential and the 700 hPa relative humidity for both types. A consistent time evolution is indeed apparent. Both cases reveal the prominent mark of a thermal wave. Type 1 cyclones can, at first sight, be singled out as having a strong cold front that re-inforces the original frontal zone. Type 2 cyclones have a more apparent warm front. The pressure field, on the other hand, is barely disturbed and shows only a very weak signature. The pressure signature at the reference (0 h) time of is about 3 hPa for both types. This is a remarkable result, even allowing for the effects of averaging. A maximum of relative humidity clearly escorts the thermal and pressure systems, showing also the vertical consistency of the approach. It is of interest to note that the maximum of Type 1 is already quite significant prior to the reference time and does not amplify. The one of Type 2, on the other hand, can barely be seen at -6 h and extends rapidly over the warm-front-like feature typical of this type of cyclone.

It is sometimes difficult to separate the cyclones from their environment. A more focused picture of scales, phases and, at 0 h, amplitudes, is obtained by looking at time-filtered fields. The UHF part of the θ_e field (not shown) is useful to recover the parent front in the Type 1 case. At the reference time, the anomaly is a positive 2.5 K egg-shaped spot, its axis extends from the Channel entrance to the centre of the North Sea with its small tip over Cornwall. The characteristic length or "diameter" is of the order of 1000 km, or, assuming the ter-

minology to be appropriate, the "wavelength" is about 2000 km. When the UHF θ_e anomaly is removed from the total field, revealing the environmental flow, a clear frontal signature remains: the cold frontal gradient of Fig. 11b is only slightly smoothed. The same exercise performed on the Type 2 system has a more dramatic effect as it removes the characteristic warm wedge and leaves a quite broad zonal baroclinic zone. The amplitude of the UHF anomaly is the same as that of Type 1, but it is more elongated meridionally. The meridional scale, parallel to the environmental thermal gradient, still is 1000 km. The zonal scale is about 500 km. Type 1 and Type 2 positive anomalies are followed by a negative one of smaller amplitude. Finally, it is worth noticing that the warm anomaly of Type 1 is very well collocated with the maximum of relative humidity. In Type 2 systems, on the other hand, the maximum of relative humidity is shifted ahead of the warm maximum. This remark has energetical implications if the relative humidity field is viewed as a time-integrated vertical velocity.

A number of questions concerning some specific aspects of the composite cyclones are now examined in turn. The choice of questions is guided by the most common features referred to in, for example, case studies of cyclogenesis. To begin with, the long-standing problem of the presence and time-history of an upper-level forcing of these cyclones is examined.

The question of the existence of an upper-level component is addressed using potential vorticity. Time filtered parts of the potential vorticity field are plotted on the 300 hPa surface. Although the use of a pressure surface somewhat weakens the results as anomalies may cross it, the absence of the interpolation to a θ surface is meant as a reminder that the vertical resolution is limited. Two parts of the potential vorticity distribution have been examined: the UHF component (shaded on Fig. 12) and the 2-180 days part (not shown). The latter represents the synoptic and larger-scale contributions with the mean component removed.

As clearly shown by the figure, there is, in both types, a definite upper-level UHF component. Furthermore, it can easily be traced over the 12-h sequence covered by the figure. During this sequence, the upper-air maximum is located distinctly upstream of the 850 hPa thermal anomaly.

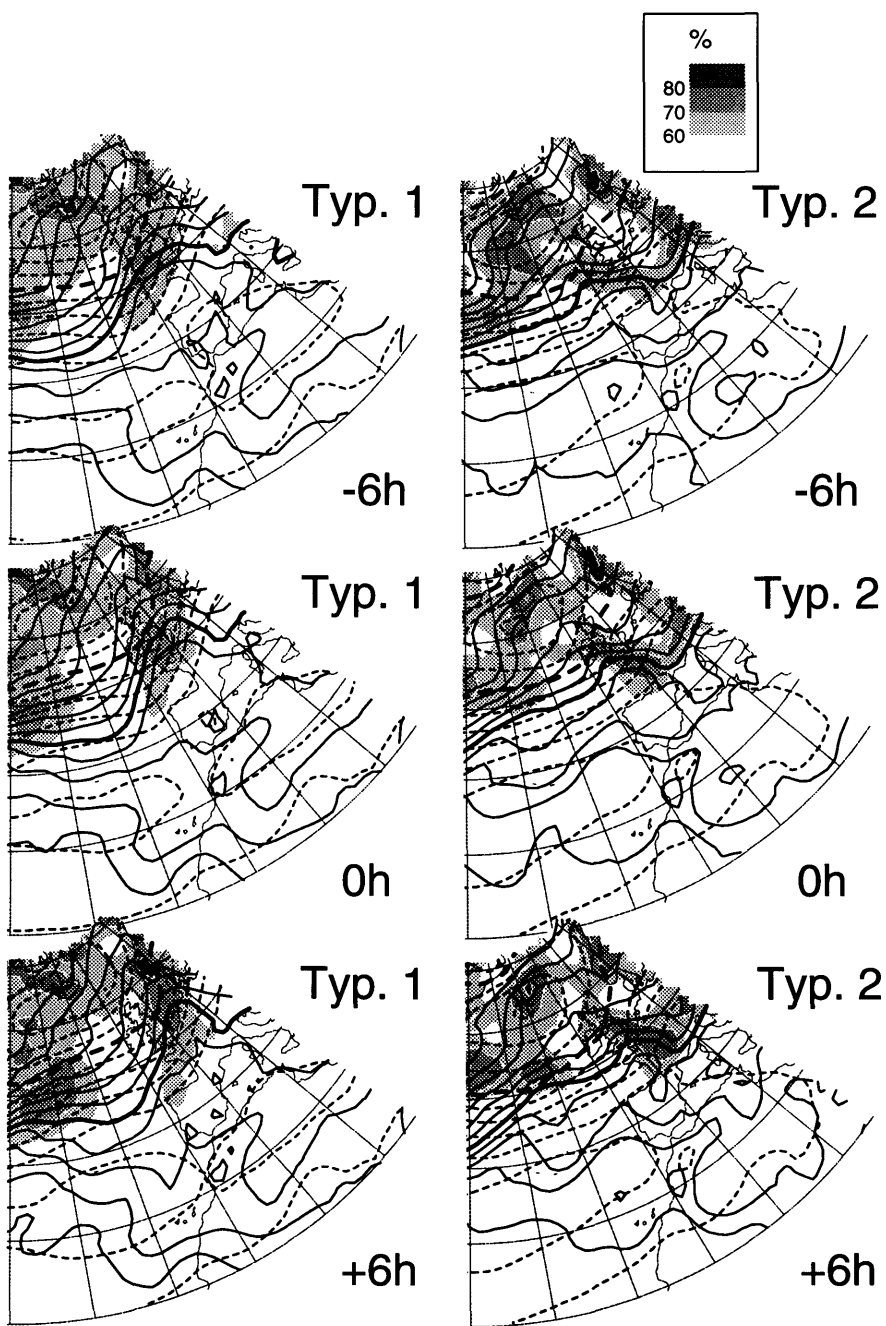


Fig. 11. Composite pictures deduced from the cluster analysis of 850 hPa vorticity fields for the Zonal regime sub-synoptic cyclones detected by (51°N, 6°W). 850-hPa θ_e (full contours every 3 K, 300-K is bold), 1000-hPa height (dashed contours, zero is bold) and 700-hPa humidity (shading beyond 60%). Time (-6, 0 and +6 h) refer to the date at which the events reached (51°N, 6°W).

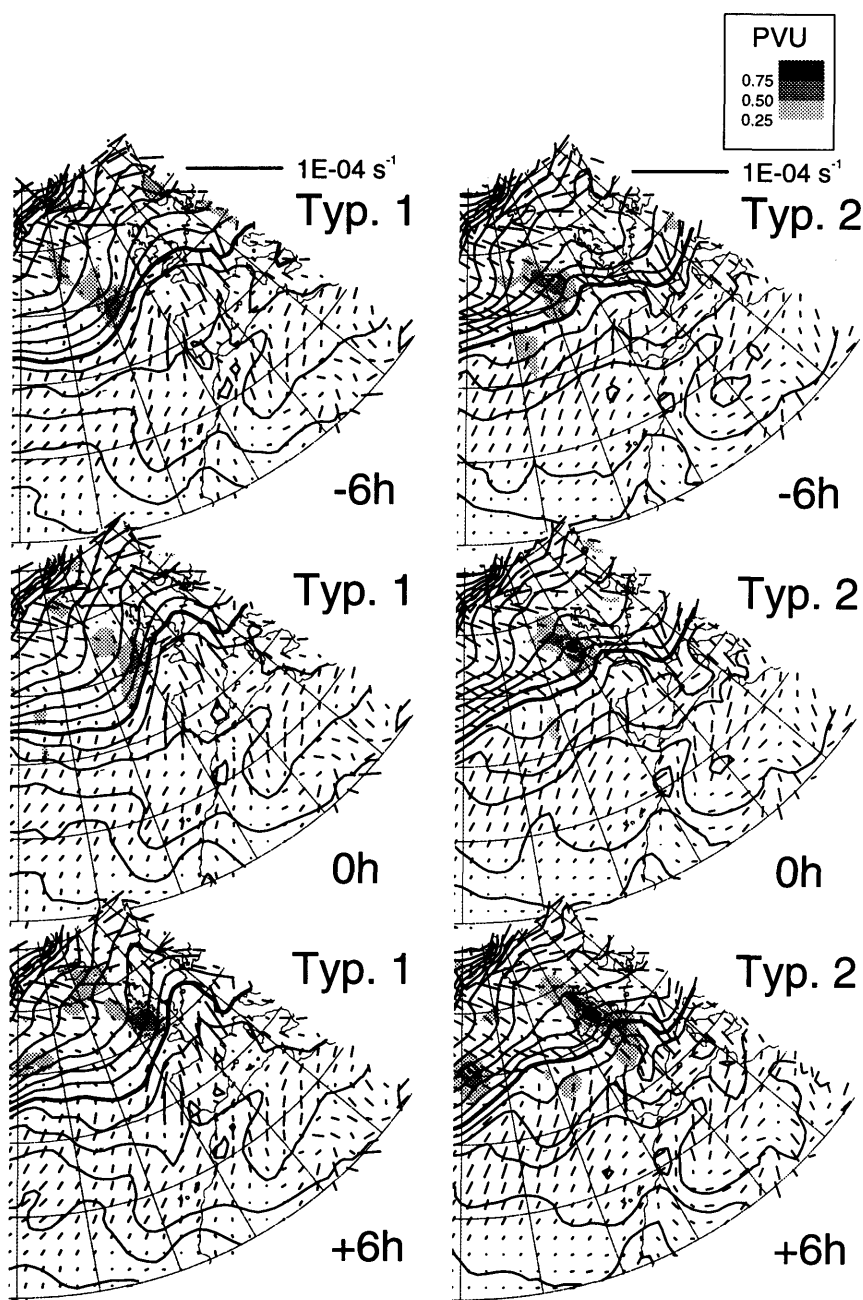


Fig. 12. Composite pictures deduced from the cluster analysis of 850 hPa vorticity fields for the Zonal regime sub-synoptic cyclones detected by (51°N , 6°W). 850-hPa θ_e (full contours every 3 K, 300-K is bold), 300-hPa UHF potential vorticity positive anomaly (shading every 0.25 PVU) and 850-hPa low-pass ($\tau > 2$ days) amplitude dependent dilatation axes. The forcing on frontal zones is frontogenetic when this axis is more or less parallel to the isolines of θ_e , it is frontolytic when the dilatation axis is roughly parallel to the gradient. Time (-6 , 0 and $+6$ h) refer to the date at which the events reached (51°N , 6°W).

When, as for Type 1, the distinction from the front is difficult, the relative positions were determined using the θ_e anomaly. The scales of these upper-air anomalies have the same magnitude as at low level. They also have roughly the same orientation. The UHF anomaly of Type 2 keeps amplifying. Note that only the positive anomalies are shown. They are accompanied by negative anomalies of similar scales but slightly smaller amplitudes that do not show up on the figure for the sake of readability. These UHF anomalies are embedded, furthermore, in a much broader zone of larger-scale positive anomaly.

Therefore, in spite of their weak pressure signature, these subsynoptic cyclones do have an upper-level component at the same scale. These upper-level anomalies can, for both types, easily be followed at subsequent times for up to 24 h. A related question is whether these anomalies can be traced back in time: a positive answer would imply that these cyclogenesis events have independent upper-level precursors, fully reproducing scenarios well-known on the synoptic scale. The discussion below will pinpoint the fact that the composite maps beyond ± 6 h must be handled with great care. However, the bare fact stated plainly, is that the behaviour of the two types is, in this respect, quite different. It is easy to trace back trajectories of Type 1 upper-level and low-level components up to about 30° W, along the 50° N parallel and over the previous 18 h at least, with a consistent phase speed of about 20 m/s. That is not so with Type 2: beyond -6 h of the reference time, signals become very weak or vanish. This distinction pertains to both the upper-level potential vorticity anomaly and the low-level θ_e one.

Leaving the subject of upper-level dynamics, but keeping with potential vorticity, the 850 hPa potential vorticity has also been examined. A weak UHF positive anomaly accompanies the cyclone at the reference time. Otherwise, no clear signal can be determined, either at other times in the UHF pictures nor in the larger-scale part.

Another question of current interest in the study of cyclogenesis is the role that the background deformation field may play in it (Bishop, 1994). An estimate of the 850-hPa background deformation field, that is the deformation field applied by the synoptic and larger scales to the mesoscale flow, is constructed from low pass time filtered wind components. The cut-off is at 2 days: in other

words, the forcing due to synoptic scale baroclinic waves is included as well as that due to the regime. Type 1 and Type 2 cyclones appear, in this respect, to be fundamentally different from one another (Fig. 12). Type 1 cyclones develop in a deformation field that is frontogenetic (contracting θ_e surfaces) but essentially weak or even vanishing in the vicinity of the system. Type 2 cyclones, on the other hand, are collocated with a significant *frontolytic* background low-level deformation field. These distinctive features exist throughout the 12 h period shown. This, the authors believe, is one of the most significant result of the present investigation.

It is better, however, to postpone an interpretation until all the facts are given. The last aspect that has been documented, only partially though, is the energetical one. No detailed budget has been attempted. More simply, an estimate of the most often referred to sources of energy in cyclogenesis studies has been performed. They are, respectively, the baroclinic source of highly transient available potential energy A' (or the potential energy that can be deduced from the UHF part of the flow) and the barotropic source of highly transient kinetic energy K' :

$$\begin{aligned} \left(\frac{\partial A'}{\partial t} \right)_{\text{clin}} &= -u'\theta' \frac{\partial \bar{\theta}}{\partial x} - v'\theta' \frac{\partial \bar{\theta}}{\partial y}, \\ \left(\frac{\partial K'}{\partial t} \right)_{\text{trop}} &= -u'^2 \frac{\partial \bar{u}}{\partial x} - v'^2 \frac{\partial \bar{v}}{\partial y} \\ &\quad - u'v' \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right), \end{aligned} \quad (1)$$

where the prime (') denotes the UHF perturbations (< 1.5 days) and the overbar ($\bar{}$) is for the environment defined as the difference between the actual value and the UHF part: the environment includes the regime and the synoptic scale. (u, v) are the wind components and θ the potential temperature. A cartesian metric is shown here for simplicity; the proper spherical metric has been used in the actual computations of these terms. An important point to note is that these terms are meaningful in steady or weakly time-dependent environment. In time dependent flows, there may be other sources and some of them do not involve the perturbation variables (see below). Finally, it may be useful to recall that the baroclinic source is

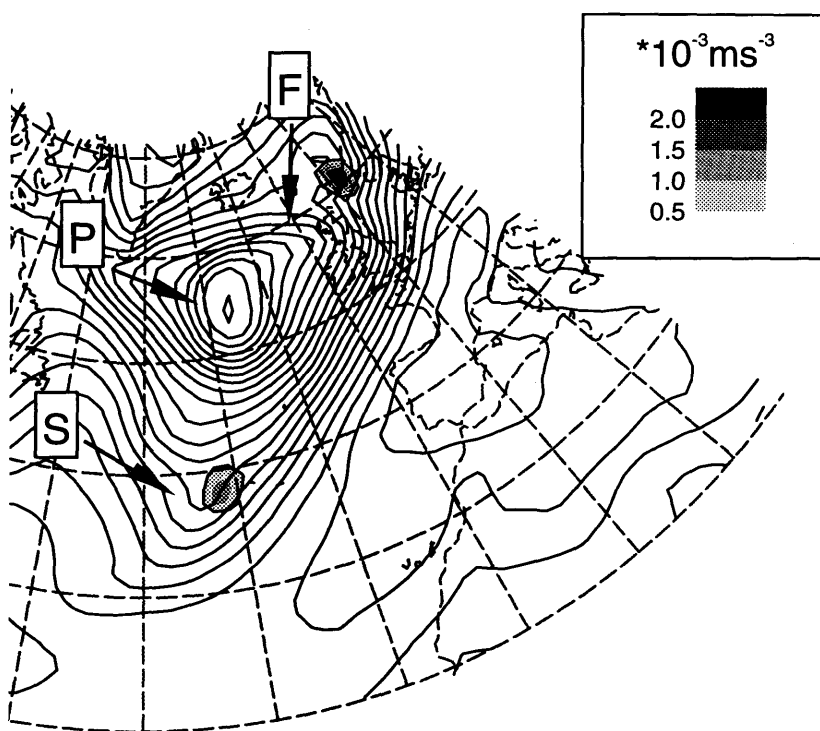


Fig. 13. 1800 GMT 22 February 1991, (frontal wave case, cf. Fig. 7): Positive 850-hPa $(\partial K'/\partial t)_{\text{trop}}$ (shading and dashed contours). Contours are the 1000-hPa height every 25 m.

effectively turned into wind if the internal conversion, involving vertical motions, is positive.

Local values of energy conversions have seldom been used in the past. As an example of their relevance, the barotropic contribution to the transient kinetic energy $(\partial K'/\partial t)_{\text{trop}}$ to a typical individual frontal wave case is illustrated in Fig. 13 for the already mentioned case of 22–23 February 1991. Despite the quite complex vorticity patterns on the Atlantic at these dates (cf. Fig. 7), the barotropic source term clearly goes with the frontal wave that develops on the front coming from southwest and reaching Ireland at 23 February 1991 18 GMT.

Composite maps of the $(\partial A'/\partial t)_{\text{clin}}$ and $(\partial K'/\partial t)_{\text{trop}}$ source terms at 850 hPa for the reference time are shown on Fig. 14. The baroclinic source term has also been examined at 400 hPa. Both types of subsynoptic cyclones indicate a dominant baroclinic source term in the low troposphere, reaching $7 \cdot 10^{-4} \text{ m}^2 \text{ s}^{-3}$. The scales and

shapes of these fields in the vicinity of the cyclones is very near to that of the UHF thermal anomaly. Otherwise, both types are different. Type 1 is the only one with a clearly positive barotropic contribution, with a maximum of $3 \cdot 10^{-4} \text{ m}^2 \text{ s}^{-3}$. Moreover, this characteristic is remarkably stable in time (not shown). It also gains energy from the upper-troposphere baroclinicity, the cyclone being embedded near the western boundary of a wide zone of positive conversion, not unlike the low-pass filtered ($\tau > 2$ days) anomaly of upper-air potential vorticity. Type 2 cyclones lose energy through the low level $(\partial K'/\partial t)_{\text{trop}}$ term, and they are also away from the weak synoptic scale-size upper-air baroclinic source term, located too far to the east.

The picture that emerges is that Type 1 is a mixed baroclinic/barotropic wave that takes advantage, as in a simple linear evolution, of both the frontal shear and baroclinicity. The importance of the baroclinic source underlines the effectiveness

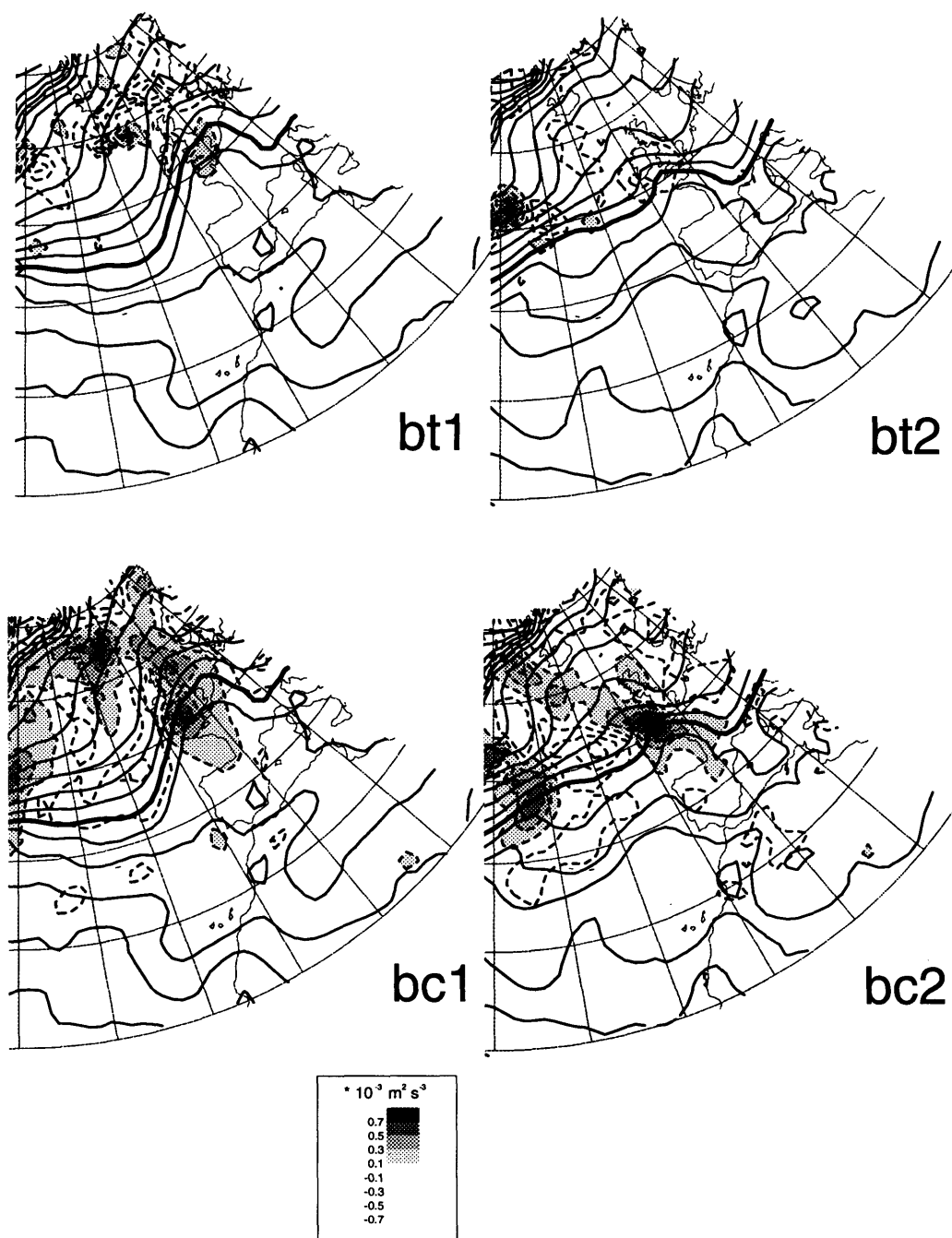


Fig. 14. Composite pictures deduced from the cluster analysis of 850 hPa vorticity fields for the Zonal regime sub-synoptic cyclones detected by $(51^\circ\text{N}, 6^\circ\text{W})$. 850-hPa θ_e (full contours every 3 K, 300-K is bold) together with $(\partial K'/\partial t)_{\text{trop}}$ (upper panels) and $(\partial A'/\partial t)_{\text{clin}}$ (lower panels) source terms (every $2 \times 10^{-4} \text{ m}^2 \text{ s}^{-3}$, positive areas are shaded) for Type 1 (left) and Type 2 (right) clusters.

of the coupling between the low and upper-troposphere components. Type 2 is predominantly baroclinic, although the low tropospheric part dominates. However, Type 2 cyclones most probably have another source, as the maximum $(\partial A'/\partial t)_{\text{clin}}$ is not much larger than for Type 1 and both types reach roughly the same amplitude. This is already shaping an interpretation.

5.3. A tentative interpretation of the results

Before pursuing further the discussion and analysis of the results from the composite scenarios of subsynoptic cyclogenesis events, the limits of the approach must be clearly stated and kept in mind. Although this is (to the authors knowledge) the first objective composite study of frontal waves using post-war data, it is a crude local one. Its main objective is one of feasibility: to show that the weather at the end of the Atlantic stormtrack involves time and space scales that are different from those met off the East Coast of America, and that this difference is captured by ECMWF analyses.

The limitations of the present results are, for the most part, due to the small size of the samples, the absence of amplitude rescaling and the absence of any phase adjustment of the individual cases before compositing. These problems are now briefly discussed.

The number of cases (23 and 17) that made up Type 1 and Type 2 cyclones is not large, in spite of the number of analyses available. This is a direct consequence of the extremely local character of the selection process. In other words, many cyclogenesis cases on those scales are ignored. Some may help refining the picture of Type 1 and Type 2 waves, while others will enter new types. Cold air cyclogenesis events, for example, have been shown in the previous section to be selected by the criterion but they do not directly hit Cornwall during Zonal regime. The advantage, on the other hand, is that the dispersion of the life-cycles of the individual events making the composite should remain reasonable because the large-scale flow is quite similar (same regime) and the cyclones are effectively colocated at one moment.

The other problems come from the very direct averaging of the fields as they were analysed, without regard for the differences in phase and amplitude of the selected cases. One cannot rule out the possibility that, because of the absence of

amplitude checking, the composite are dominated by one or two cases and completely lose their statistical significance to become case studies. We have checked one variable, the vorticity field, and found that it was not controlled by a few high amplitude cases.

The absence of phase and location corrections makes any in-depth analysis of the life-cycle aspects of these composites fragile. A reduction of amplitude, going forward or backward in time from the 0 h reference, may reflect a dynamical mechanism but may just as well result from averaging fields with maximum anomalies in different locations. In other words, both prior to and after the reference time, the trajectories of individual events may diverge from the reference point and this implies a smoothing out of all features in time.

Because of these limitations, the interpretation that follows is only speculative and likely to be provisional. It is more than ever an incentive to dig further rather than a definite portrayal of subsynoptic scale cyclones.

Within these limits, the properties of the subsynoptic cyclones captured in this study can be summarized as follows: there are at least two distinct types of sub-synoptic scale cyclones. Both have a very weak pressure signature and a modest thermal anomaly amplitude (2.5 K). Their horizontal scale is larger than the often quoted 1000 km wavelength of frontal waves (Moore and Peltier, 1987; Joly and Thorpe, 1990; Schär and Davies, 1990): using only the reference anomalies, the nearest equivalent wavelength rather is 2000 km. At the reference time, they both possess an upper-air anomaly located upstream of the surface low.

The distinctive features of Type 1 cyclones are that they form along a well defined cold front that they reactivate and re-inforce with their own cold frontal system. Moist processes are active just above the maximum warm anomaly, indicative of positive internal energy conversion. Otherwise, they draw energy at least from the well known linear sources: baroclinic in both the low and upper troposphere and they also use the wind shear that goes along with the marked cold front. The potential vorticity anomaly and the low level θ_e anomaly can easily be traced back to at least 18 h prior to the reference time. This indicates that this kind of event has precursors. It is possible

that they are already coupled, but that does not necessarily imply phase locking.

Restricted to the time/space window of interest, this evolution is indicative of a baroclinic development type of evolution (as opposed to an instability) in the line of ideas from Sutcliffe (1947), Petterssen and Smebye (1971) and others. This process, however, is altered by the presence of the front. It occurs on a smaller scale than the Type B cyclogenesis presented in the latter reference and it has a low level barotropic contribution. The reduced scale can be accounted for in two ways: it can result from the moist processes, as shown by Emanuel et al. (1987) and confirmed for more complex moisture distribution by Fantini and Buzzi (1994). Another possibility is the interaction between the precursors and a frontal instability mechanism such as that examined by Schär and Davies (1990) and Joly and Thorpe (1990). This mechanism accounts for the possibility of having a significant barotropic contribution to the energy budget. The non-linear results derived from it (Malardel et al., 1993) explain the weak pressure signature, which is in fact a consequence of the reduced scale. The latter does not allow a strong enough coupling with upper-levels. This instability mechanism is effective provided the front is steady or subject only to shearing background deformation (Joly and Thorpe, 1991): it has been noticed that the background deformation is weak in the vicinity of the cyclone. The second requirement is the presence of a narrow low level potential vorticity anomaly. Apparently, it is absent from the composite. However, following ideas from Farrell (1984, 1989a), Joly (1995) has shown that the weak pressure signature of frontal waves and the possibility for them to use the frontal shear extends to non-modal linear development initiated by precursors, even for fronts deprived of the low level potential vorticity anomaly.

The present state of the theoretical knowledge of sub-synoptic cyclogenesis accounts therefore rather well for the extension of the baroclinic development paradigm that are necessary to account for Type 1 cyclones. None of these mechanism accounts, on its own, for the observed wave but no obvious contradiction arise from blending them. This favourable position between theory and a statistical set of observations does not seem to exist for Type 2 cyclones.

Type 2 cyclones form in a zone where the back-

ground baroclinity is weaker than around Type 1, and that is actually weakened by a frontolytic background deformation field. The cyclone features a noticeable active warm front, the ascent being located ahead of the warm anomaly. This configuration occurs in small scale cyclones in which the baroclinic conversion is weak, such as the modal frontal wave of Joly and Thorpe (1990). Indeed, although an upper-air potential vorticity anomaly is present, the baroclinic conversion is not efficient at this height. No energy is gained from the barotropic source and this goes along with the weakness of the larger scale shear: there is only little to be gained. In other words, apart from a certain amount of baroclinic input, the energy source of these waves is *not* a classical one. Another remarkable property of Type 2 cyclones is their apparently spontaneous formation beginning 12 h at most prior to the reference time. This may obviously result from the dispersion problem recalled above or from their location relative to the data distribution. The time-history of an actual event (reference time 1200 GMT 21 March 1989) confirmed, however, the difficulty of tracing precursors. This event was chosen for its proximity to the composite 850 hPa vorticity field. Its amplitude is also representative of the composite (it is not larger than that of other events).

Assuming this to be a true property of the Type 2 wave, it is proposed here that cyclones of this kind essentially develop from the action of the deformation within a relatively broad baroclinic zone. The interaction of fronts, deformation and cyclogenesis is a fully time-dependent problem, and so its detailed study has begun only recently. Joly and Thorpe (1991) have shown that pure shearing deformation had no direct effect on the stability properties of a front while allowing moist processes to fully influence the development of waves in a dramatic way. Bishop and Thorpe (1994) concentrated on stretching deformation. They studied the case of a frontogenetic deformation and showed that it was very efficient at *preventing* cyclone development. However, the reverse case is not studied. But it is known that, in principle, a deformation field can help the building of transient cyclones even in an otherwise stable environment (Farrell, 1989b). Furthermore, the corresponding linear problems lead to non-autonomous linear systems. As a consequence, time evolution equations of second order quan-

tities like energy are difficult to write and involve new terms: examples are given in Joly and Thorpe (1991). The effectiveness of the proposed mechanism has not been studied theoretically, but it does not contradict the evidence currently available.

This speculative reading of the results must be perceived as a source of impulse for further work in two directions. The first one is to set the proposed scenario on much firmer observational grounds. This goes along with developing the description and knowledge of both types and more precise documentation of other systems like cold air cyclones. This work is the direct extension of the one reported here. Simultaneously, it clearly means that the theoretical understanding of the appearance of coherent structures like cyclones in a baroclinic atmosphere subject to live deformation must be deepened and refined.

6. Summary and preliminary conclusions

This study reports the first results gathered in a long-term effort aimed at describing and understanding the statistical reality of the complex subsynoptic atmospheric variability over and about western European coasts. In this field, one is faced on the one hand with numerous reports and hearsay from forecasters describing cyclones that are difficult to fit into the standard model of baroclinic instability or development: the scales, the structures, the life-cycles appear to be different. These remarks are backed by a number of published case studies (Browning and Harrold, 1969; Browning and Roberts, 1994). On the other hand, existing theories of cyclogenesis have, recently, been extended towards smaller scales: a number of results are available and are waiting for a systematic validation. On these scales and locations, surprisingly little recent statistical evidence is available to update ideas that often date back to the early century. A proper validation can, in no way, rest on the current patchwork of observational results.

The motivation of the present work is, therefore, to try to bridge the gap between a wealth of recent theories formulated in terms of relatively new concepts or diagnostics, and the current state of the statistical description of atmospheric cyclogenesis that does not account for the variability met in the north-east Atlantic. The line of attack followed

here assumes that the high-resolution (both in space and time) of the last ten years of 4-daily analyses produced at ECMWF provide the best picture of the reality that is currently available. The idea was to extend, in a straightforward way, the time-separation techniques so successful on the synoptic scales.

The specificities of European weather, so often mentioned by forecasters in subjective terms however prevented such a direct extension. The work was therefore steered from pure time-series analysis to a blend of methodologies. From this, the following results were derived.

- The concept of weather regime is central to any statistical approach of European weather systems. The end of the North-Atlantic storm-track is characterized by a large *low-frequency* variability that must be reduced prior to any analysis of larger frequency phenomena. Following Vautard (1990), 4 regimes have been identified, and all subsequent results turn out to be strongly regime-dependent, at least by their preferred location.

- The 2–6 days window period was revisited, originally for validation purposes. In this respect, it was successful. The separation into regimes confirmed, moreover, that the “synoptic storm-track” may extend significantly further to the north-east than shown by pioneering studies. The precise orientation and location of this extension depends on the regime, and is erased when they are considered together.

- Original results have been obtained as the higher frequencies were approached, namely those corresponding to periods shorter than 1.5 days. The raw variances for this part of the spectrum are well organised. The structure shows, in particular, a well defined maximum extending directly from the end of the synoptic stormtrack. A signal also exists in other fields and *E*-vectors have been computed. They suggest that the dominant process is to loose kinetic energy to the lower frequency flow.

- A key turning point, however, follows from recognizing that the variability on these scales results from very different processes, the dominant one being probably the ultimate stages of frontogenesis within synoptic waves. Classical diagnostics, like lag-correlations, cannot be interpreted properly.

- In order to isolate subsynoptic cyclogenesis

events, a very simple criterion has been constructed and tested for an eventful one-week series of maps and satellite pictures. The criterion identifies low level vorticity maxima containing a predominantly ultra high-frequency signal. It is possible to construct climatological maps of occurrences of the events selected in this way. Their distribution is located to the south-east of the high frequency variance maxima. Another outcome of this definition is discussed below.

- The weather systems actually selected by this relatively objective but blind criterion have to be shaped more clearly. A detailed study of the events that occurred at one grid-point has been conducted by way of a further cluster analysis. The low level vorticity fields meeting the criterion at that point have been partitioned. Three clusters provide a reasonable separation of the cases, and two classes can be identified.

- A straightforward averaging of the maps belonging to these two types provides the first objective but very crude composite picture of these systems based on recent data. Type 1 is reminiscent of a downscale version of baroclinic development (Petterssen's type B), modified by the presence of a strong shear at the front and/or moist processes. Indeed, a number of features are as predicted by recent frontal instability theories, classical and generalized: the pressure signature is weak; part of the energy is derived from the basic flow kinetic reservoir with the help of the large shear; the waves are colocated with a weakness of the background deformation field; precursors exist

simultaneously at low and upper-levels in the most developmental system, the ones the analysis is the most likely to capture.

- A Type 2 composite has been shown to have somewhat different properties. Morphologically, these cyclones are dominated by their warm front. They develop in a broadening baroclinic zone in a somewhat spontaneous way: no clear precursors can be identified. They form in an area of frontolytic or diffluent deformation field, and it is proposed that this organization of the large scale wind field is instrumental in helping the emergence of the cyclone.

These are speculative conclusions as the analysis of the life-cycle aspects of the composites is hindered by the dispersion of the trajectories, as no relocation of the grids was attempted.

The complexity of European weather weakens its predictability. A field experiment dedicated to the kind of atmospheric phenomena studied statistically here has been proposed: FASTEX or Fronts and Atlantic Storm-Track Experiment. One of its objective is to measure the impact of a better description of the tropospheric flow over the Atlantic ocean on numerical weather prediction systems. One further result to be drawn from the present work is the feasibility of such a programme. The vorticity criterion defining a cyclogenesis-like event can be used to estimate the time distribution of these events in a given area. Several zones have been defined according to logistical reasons: they must be within reach of existing instrumented aircraft. An example, valid

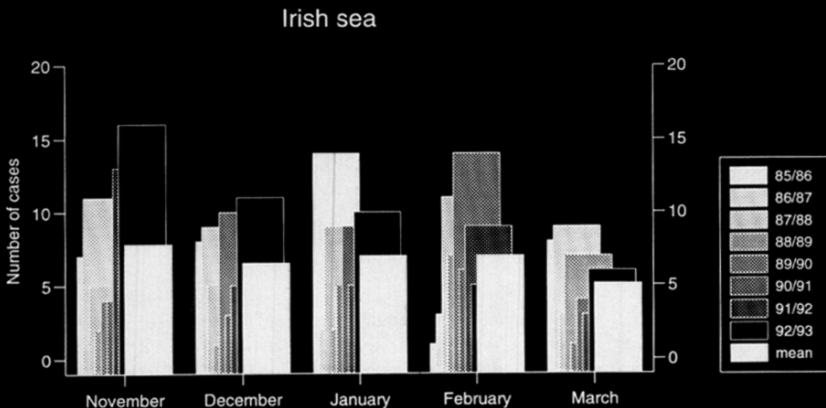


Fig. 15. Monthly distribution of subsynoptic cyclones cases detected in ECMWF analysis in the Irish sea area.

for the Irish sea area is shown in Fig. 15. In this area about 5 cases per month can reasonably be expected. There is, *on average*, only a weak month to month variability, allowing for an easier final choice of date between November and February. The objectives of FASTEX (to try to sample about 10 cases) appear tractable within a two month period. There is, however, a large variability, within a given year or year to year, corresponding to that of favourable regimes.

All our results are not better than the quality of the objective analyses from which they are derived. Apart from the excellent time and space resolution that is provided, the other advantages of using ECMWF analyses are the absence of missing data (time-series are complete as well as all fields) and the three-dimensional (at least) consistency. The drawbacks mostly result from the lack of low-tropospheric data over the ocean. As a consequence, the results shown here may reflect the behaviour of the guess-field rather than that of the real atmosphere. In the upper-troposphere, wind measurements from aircraft are abundant in this area and are known to be beneficial to the analysis (Kelly et al., 1993). The importance of this obvious drawback had to be measured in some way. Sample comparisons between low level small scale features in the vorticity and other fields and satellite images and hand-made charts suggest that all actual events are included, and very few are created by the model. In other words, ECMWF system slightly over-estimates the sub-synoptic activity.

Any improvement brought to the analysis system is an indirect contribution to the future evolution of the work presented here. The 10-year re-analysis project will provide a far better dataset than the one explored here. The FASTEX project will help to quantify the loss of information due to the oceanic gap in data coverage. It will also supply reference validation cases of the global ECMWF data assimilation system on the meso-scale.

These are long term endeavours. In the meantime, the way the statistical picture of cyclogenesis events is constructed must be improved. The preliminary work reported here suggests that only a full-scale composite approach can extract the information from the analyses. In order to take full advantage of the large sample potentially provided by ten or fifteen years of analyses, it has to be, to

a large extent, automated. This method also yields more objective results. Work along these lines is in progress.

7. Acknowledgements

The authors are indebted to Béatrice Pouponneau for her help in collecting and organizing ECMWF data. This work originates from many discussions with the Météo-France forecasters. Among them, Patrick Santurette and Raymond Beugin have to be singled out for their patient efforts at convincing the authors that everything is not already known about the subsynoptic scales over Europe!

8. Appendix

Weather regimes cluster analysis scores and resulting calendar

The cluster analysis yields a partition of the initial 1800 daily analysis into 4 clusters. The clusters cannot easily be displayed as they are located in a 5-dimension space (first 5 PCA components), so only a few characteristic figures qualifying the aggregation of the data are given here (Table 1). Well-marked clusters result in inter-cluster distances much bigger than intra-cluster ones. The ratio here is roughly 2. Somewhat surprisingly, the clusters that appear to be the most interpenetrated are the zonal and blocking ones. This occurs because, although these regimes are quite different over western Europe, they are rather similar over western Atlantic (cf. Fig. 1). To improve the separation between the clusters, the transition dates just before and after a regime change have been eliminated. They represent 22% of the total dates. The resulting distribution of the different regimes is in Table 2.

The weather regime chronology in the 10-years dataset is reported in Fig. 16. The very large year-to-year variability is a striking feature in the results. Some winters are subject to the perturbed Zonal regime over very long periods: 1989–1990 is an example of such an uncommon season (see Beugin and Rochard, 1991 for an exhaustive description of the most significative events during this period from the forecasters point of view). 1990–1991 is a contrasting example with Blocking events more numerous than Zonal ones.

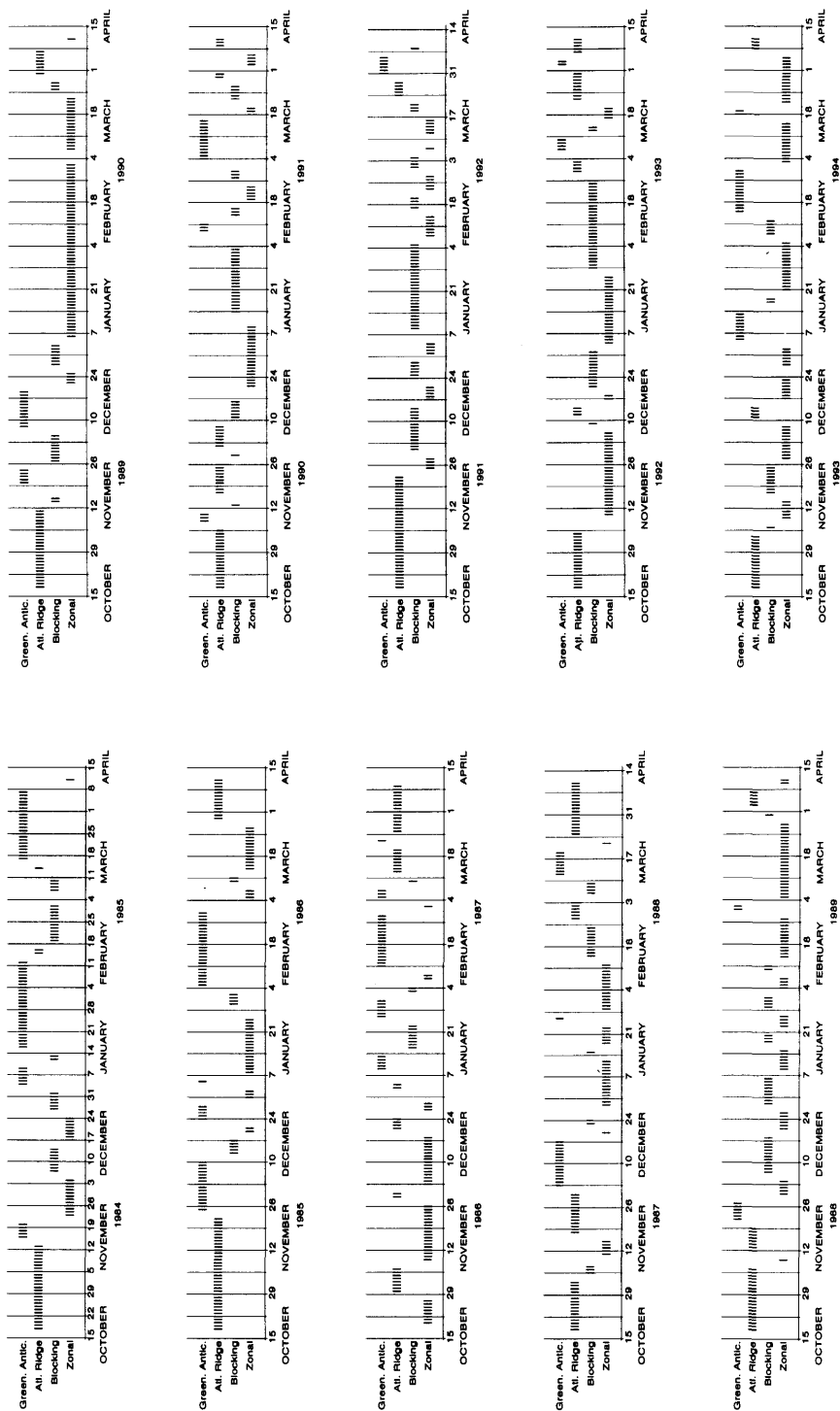


Fig. 16. Time representation of the weather regimes variations during the 10 cold seasons of our dataset (some “one-day” regimes exist because the first and last day of a regime are excluded: three-days regime are therefore reduced to one day).

Table 1. *Statistics of the cluster analysis*

Regime	Population		Distance from			
	number	(%)	zonal	blocking	Atlantic ridge	Greenland anticyclone
zonal	608	33.8	114*	179	272	286
blocking	394	21.9	179	116*	227	232
Atlantic ridge	490	27.2	272	227	127*	243
Greenland anticyclone	308	17.1	286	232	243	129*

The distances (units are arbitrary) are measured between the clusters centres of gravity, except for the values marked with an asterisk that are the mean distances between the different members of a given cluster.

Table 2. *Weather regimes populations when transition dates have been excluded*

Population	Zonal	Blocking	Atlantic ridge	Greenland anticyclone
number	488	289	383	244
(%)	27.1	16.1	21.3	13.6

Differences from Table 1 are due to the rejected cases; total %s are therefore not 100%.

Only winters 1984–1985 and 1985–1986 are common to V90's dataset and ours. The agreement between our results and Vautard's during the latter season is quite good for the well marked regimes (zonal, blocking and Greenland anticyclone, see V90 Appendix). It should be stressed that the

method used here differs from Vautard's in that every day is forced to belong to a regime (transitions were removed afterwards), while Vautard's regimes are identified as equilibrated periods (a given day may be "unequilibrated", and therefore not belong to any regime).

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