Four-dimensional variational analyses of FASTEX situations using special observations

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SUMMARY

This paper focuses on Intensive Observation Period 17 of the Fronts and Atlantic Storm-Track EXperiment (FASTEX); the FASTEX special soundings obtained during that period are added to the conventional dataset and assimilated with a 4-dimensional variational (4D-Var) scheme under development at Météo-France. Results show a consistent use of the high density FASTEX ship soundings by the 4D-Var formulation and an improvement brought by this new scheme over 3D-Var when using only the vertical profiles synchronous with synoptic time. The application of the 4D-Var analysis to dropsondes launched by a system-relative flight designed by the Joint Centre for Mesoscale Meteorology also produces a fine-scale description of sub-structures of the mature system.

KEYWORDS: Data Assimilation  FASTEX  Field experiment  Mesoscale observations

1. INTRODUCTION

One of the main objectives of the Fronts and Atlantic Storm-Track EXperiment (FASTEX) was to improve the description of the complete life-cycle of a number of cyclones in the Northern Atlantic Ocean (Joly et al. 1997). In this data-sparse area a unique observation network was maintained over nearly two months between 5 January and 27 February 1997 (Joly et al. 1999). Observations notably included a large number of additional vertical profiles not only from land-based sounding sites or ships, but also provided by dropsondes launched by aircraft. Some of the dropsondes launched along a flight segment designed to sample some particular features of a developing or mature cyclone can be vertically and horizontally interpolated in a vertical cross-section. Such an approach has, for example, already been applied by Thorpe and Clough (1991), and Browning et al. (1995) in order to present the mesoscale structures of a number of cyclones observed during FRONTS 87 and FRONTS 92 experiments. Other authors, like Shapiro and Hastings (1973) or Keyser and Shapiro (1986), also used temporal vertical cross-sections with profiles from a single site, in order to recover lower and upper structures associated with fronts. Another approach is to add such particular data collected during an experiment to the conventional dataset, and to use an assimilation scheme in order to recover the complete 3-dimensional (3D) structures associated with the observed cyclones. This strategy has for example been followed by Browning et al. (1996), using the UK Meteorological Office (UKMO) assimilation scheme with FRONTS 92 dropsondes.

Our objective is to perform a similar complete analysis of the FASTEX cases, or at least of a number of them, since these 3D composite views of the observed systems are required for diagnostic studies, model initialization and also to estimate the impact of adaptive observations made during FASTEX (Bergot 1999). Because during FASTEX the different vertical profiles were disseminated in TEMP format on the Global Telecommunications System (GTS), some national weather services were able to include them in their operational analyses in real time. This has been

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done, for example, at Météo-France, in order to improve the quality of the short-range forecasts and consequently to ease the control of the operations during the field phase of the FASTEX project. However, this first set of analyses produced by the French meteorological service cannot be considered as a final set for various reasons. The first is that, due to some inevitable problems, some observations have not been transmitted in real time; in order to get the maximum number of FASTEX data, there is a need to take these observations from the FASTEX database (Jaubert et al. 1999). It is essential to get them from this central site to be sure that they are in their validated form. Another reason to carry out a new analysis of the FASTEX data is that Météo-France has moved from an Optimal-Interpolation (OI) based analysis scheme, operational during the experiment, to a variational formulation (Thépaut et al. 1998); this presents some substantial improvements, mainly related to the absence of data selection, a source of noise in the OI formulation, and to a better forecast-error covariances description. A new step can be included with a 4D-variational (4D-Var) formulation, which is similar to the 3D-Var scheme but includes the use of the forecast model itself in the assimilation process. This 4D-Var analysis tool is now under development at Météo-France, and its present formulation is described by Janisková et al. (1999).

The aim of this paper is to present an application of the 4D-Var assimilation scheme to the cyclone observed during the Intensive Observation Period 17 (IOP17), using the whole set of FASTEX soundings collected during this IOP. In the following section, we first describe this FASTEX observation dataset, and some features of the evolution of the system. The 4D-Var set-up and the methodology followed in this study are presented in section 3. Subsequently analyses are presented and discussed in section 4, and final conclusions and perspectives are given in section 5.

2. Presentation of the FASTEX IOP17

In this paper, we focus on the cyclone associated with IOP17, which occurred between 17 and 20 February and showed one of the strongest deepening rates observed in FASTEX. It has also been one of the best documented cases of the experiment. This case has already been studied by Cammas et al. (1999) who especially investigated the triggering phase, related to an upper-level potential-vorticity (PV) trough moving over a lower baroclinic zone, and the rôle of the diabatic processes in the explosive deepening during the first development phase of the low. Using a manipulation of initial conditions through PV, Arbogast and Joly (1998) have also shown the importance of a low-level precursor in this IOP, related to the presence of a pre-existing continental surface low over the USA.

Here we will rather concentrate on the mature stage of the system, and investigate the ability of the FASTEX observing network and of the assimilation scheme to recover some realistic structures of the developed cyclone.

Figure 1 indicates the set of soundings performed during IOP17, by land-based upper-air stations, FASTEX ships, Automated Shipboard Aerological Programme (ASAP) ships and aircraft-launched dropsondes. Land-based upper-air stations all around the North Atlantic basin performed soundings at 0600 UTC and 1800 UTC and a number of UK, French, and Irish stations also made soundings at 0300 UTC, 0900 UTC, 1500 UTC and 2100 UTC, from 0000 UTC 19 February until 0000 UTC 20 February, during the mature stage of the system. From Fig. 1, it also appears that three of the FASTEX ships, namely the Aëgir, Suroit and Victor Bugaev, performed radio-soundings at 1.5 h intervals from 0900 UTC 18 February to 1200 UTC 19 February. The fourth
FASTEX ship, the US research vessel Knorr, was taking part during this period in a parallel experiment in the Labrador Sea.

Figure 2 presents the composite water-vapour image at 1800 UTC 18 February, superimposed on the mean-sea-level pressure field taken from the French operational analysis. This shows that the three FASTEX ships were quite well located with respect to the low. Two ASAP ships, with World Meteorological Organisation station identifiers OXTS2 and V2EZ, also performed additional soundings at 0600 UTC and 1800 UTC during that period, the ship V2EZ also being located close to the system. By that time, the cyclone had developed a cloud band associated with the cold front and a well formed cloud head above the surface low. The system was also sampled by a National Oceanic and Atmospheric Administration (NOAA) Gulfstream-IV flight from St John's to Shannon, between 1541 UTC and 2134 UTC 18 February launching 54 dropsondes. Around 1800 UTC this aircraft passed just above the French Sturoit vessel.

Twelve hours later, at 0600 UTC 19 February (Fig. 3), the low was even deeper and the cloud head was associated with a back-bent warm front and a dry zone entering between this back-bent front and the cold front. Around that time, the UKMO C-130 aircraft performed a flight, from 0327 UTC to 1109 UTC 19 February launching 44 dropsondes, in order to observe the mesoscale structures within this region. This flight, designed by the Joint Centre for Mesoscale Meteorology, presents a good example of complex but successful system-relative flight tracks defined to get an optimal sampling of a relatively small region. This flight was combined with that of a NOAA P3, with meteorological Doppler radar on board, to get a fine-scale description of precipitation and winds (Moine and Roux 1998).
3. 4D-VAR SETTING AND EXPERIMENT DESIGN

A description of the incremental 4D-Var formulation developed at Météo-France is given by Janisková et al. (1999). These authors have used two FASTEX situations to quantify the impact of different types of tuning related to this new analysis scheme. In the present paper, we will rather focus on the way some particular FASTEX datasets are used by this analysis scheme. In the light of the tests presented by Janisková et al. (1999), the incremental 4D-Var setting will here be fixed equal to the tuning criteria that gave sensible results. In all the following 4D-Var experiments, we use three updates of the trajectory; the reduced set of simplified physics, presented by Janisková et al. (1999), is activated only in the last minimization of the cost function specified in this variational procedure. Up to 70 iterations are used for the whole analysis, with 25 adiabatic interactions in the first two minimizations and 20 iterations with the reduced simplified physical parametrizations in the last minimization. This parametrization set includes the computation of vertical turbulent diffusion, orographic gravity waves and stratiform precipitation but excludes radiation and deep convection. A 6-hour assimilation period is used, centred on synoptic times, with a surface analysis carried out at the end of the filtered variational analysis of the upper fields.

The ARPEGE French forecast model (Courtier et al. 1991) is used to give the trajectory. This spectral model is based on a stretched geometry (Schmidt 1977; Courtier
and Geleyn 1988). In these experiments, the model is used with a T95 spectral truncation on the stretched sphere and a stretching factor of 3.5, that provides roughly $L = 180$ km resolution near Newfoundland and $L = 70$ km resolution near Ireland, using the $L = (4\pi)^{1/2} a / (N + 1)$ formula proposed by Laprise (1992), where $N$ stands for the spectral resolution and $a$ for the earth’s radius. On the other hand, the successive minimizations around the different trajectories with this stretched model, are performed using a non-stretched tangent linear model and its adjoint with $N = 63$ spectral truncation, corresponding to a uniform $L = 370$ km resolution, again using the previous formula. In the vertical, both the model for the trajectory and the tangent linear model for the inner minimizations are used with the same 27 $\eta$-levels.

In this paper, a particular point of interest is to use the largest possible number of vertical soundings carried out during FASTEX. In the study performed by Janisková et al. (1999), only a subset of these soundings has been taken into account. This is due to the fact that this first set of 4D-Var analyses was based on operational observation files, built in real time during FASTEX, and including the profiles synchronous with synoptic analysis times corresponding to the intermittent OI scheme operational during this period. In particular, these files only contain the FASTEX ship soundings closest to the four analysis times per day and the dropsondes launched in a $+/–$ 30 min time window around these synoptic times.

Here, most of the soundings found in the FASTEX database are used. However, for some flights, such as the NOAA Gulfstream-IV flight, providing dropsondes with
a very high horizontal density (down to 20–30 km apart), a selection has been made, since some preliminary tests with FRONTS 92 dropsondes (Browning et al. 1995) and an incremental 3D-Var scheme showed that a problem of representativeness error could occur with too coarse an analysis increment (Desrozier et al. 1997).

All the FASTEX vertical profiles are also available in the central archive with a very high vertical resolution. However for the time being, only the TEMP format versions of these profiles have been used, because of the much coarser vertical resolution of the analysis compared to the high-resolution FASTEX soundings. An intermediate way to handle these high-resolution profiles would be to compute averaged profiles that would compare better with their model equivalents in the vertical.

One of the advantages of using 4D-Var is to enable the use of the observations at their true dates and times. This is particularly important, since it allows the use, not only of all the vertical profiles performed with a high frequency by the FASTEX ships, but also dropsondes from long duration flights, with launch time departures of up to 3 hours from the main synoptic time. For the profiles performed by land-based sites or by ships, the duration of the balloon ascent can be as long as 1.5 hours; this could theoretically be taken into account in the 4D-Var formalism but has been neglected in this preliminary study, as well as the true position of the balloon during the ascent and the temporal error correlations.

4. 4D/3D-Var analyses

(a) Analyses at 1800 UTC 18 February 1997

In this section, we investigate the impact of the FASTEX data on the final analyses, and also the rôle of the assimilation scheme used to produce these analyses. In order to document these points, different analyses are presented for 1800 UTC 18 February, at the time when FASTEX ships started their intensive soundings (Fig. 1) and corresponding also to the mid-flight time of the NOAA Gulfstream-IV flight from St. John’s to Shannon (Figs. 1 and 2). All these analyses are carried out with the same background, provided by a preliminary incremental 3D-Var assimilation using the operational observation files as in Janısková et al. (1999). This 3D-Var configuration is also the same as in the study by these authors; compared to the 4D-Var formulation it uses an analysis increment with an identical T63 spectral resolution but omits the model integration. The consequence is that the structure functions are static and, unlike 4D-Var, do not depend on the meteorological situation.

Figure 4(a) presents the structure of the jet at 250 hPa, as given by this background at 1800 UTC 18 February. At this time, the jet stream had split into two jet streaks (Cammas et al. 1999): the outflow jet (not shown in Fig. 4), and another one which will be referred to as the polar jet, with an entrance region near 40°N, 40°W and a maximum value of about 80 m s⁻¹. Three of the FASTEX vessels were at that time located along the 35°W meridian (from north to south, they were the Ägir, Surort and Victor Bugaev); the German ASAP V2EZ was also located close to the cyclonic side of the jet. A 4D-Var analysis using only the soundings associated with these ships was carried out (soundings from the FASTEX vessel Knorr and the Danish ASAP OXTS2 have also been included, but at that time their positions were far from this area of interest). One can observe that the resulting analysis for the wind velocity (Fig. 4(b)) is different from the background analysis: the jet streak structure of this polar jet is reinforced, with the maximum values around 80 m s⁻¹ pushed north-eastward. Also, this part of the jet is now more curved on its cyclonic side. The main point to be noted is that this characteristic curved flow appears to better fit the cyclonic curvature of the sharp edge of high altitude clouds found
along the jet axis (Fig. 2). A 4D-Var analysis based on the same background has also been produced using only the conventional data and excluding the previous FASTEX ship soundings. Figure 4(c) shows that the increase of cyclonic curvature of the polar jet brought by the FASTEX ships is also suggested when using only these conventional data. Finally, a 4D-Var analysis with both sets of data gives a representation of the jet very close to the one obtained with only the FASTEX ships (Fig. 4(d)).

Figure 4 also shows the structure of the PV field on the 310 K isentropic surface. According to what has been observed in the wind field, the analysis using only the FASTEX ship soundings (Fig. 4(b)) appears to differ more from the background representation (Fig. 4(a)) than the analysis using the conventional observations (Fig. 4(c)); the amplitude of the PV anomaly on the south-west part of the polar jet streak is increased; this is consistent with the above mentioned change of the jet structure in the south-west entrance region (near 41°N, 41°W). Note also, in the 4D-Var analyses with the FASTEX ship soundings (Fig. 4(b) and (d)), the characteristic tongue of high PV just north-east of the Suroit (46.1°N, 36.6°W), and the characteristic hammer-head shaped leading edge of the high-PV values associated with a descent of stratospheric or high-tropospheric dry air on the left flank of the jet axis (Browning 1990).

In order to evaluate the impact of the intensive soundings made by the FASTEX ships during this 6-hour assimilation period, a 3D-Var analysis has been produced at 1800 UTC, using only the FASTEX soundings closest to this synoptic time. The retrieved wind and PV analyses (Fig. 4(e)) differ far less from the background representations than the previous analyses obtained with 4D-Var and using all the profiles available in the 6-hour period. However, a 4D-Var analysis including only the same subset of FASTEX ship soundings (Fig. 4(f)) appears to be closer to the one obtained with all the profiles: the maximum values of the polar jet streak are moved north-eastward and the characteristic curvature of the jet entrance is suggested, with a reinforcement of the PV anomaly. This indicates a clear improvement of 4D-Var over 3D-Var for this case, that is likely to be related to the use of implicit dynamical structure functions by the 4D-Var formulation; isotropic and less realistic structure functions are used in the 3D-Var formulation (Thépaut et al. 1996).

From a dynamical point of view, the increase of the jet curvature found near 42°N, 42°W in the 4D-Var analyses (Figs. 4(b) and (d) particularly should be associated with a dipole of mid-tropospheric descent and ascent, due to ageostrophic motions along the jet flow, with confluence and diffluence areas located upstream and downstream of this flow inflection, respectively (Keyser and Shapiro 1986). The descending air, associated with this secondary circulation, should also reinforce the downward branch of the direct transverse ageostrophic circulation at the entrance of the jet streak axis (43°N, 38°W/52°N, 22°W).

The differences at low levels between the background field (Fig. 5(a)) and the 4D-Var analysis using only the FASTEX ship soundings (Fig. 5(b)) seem to be consistent with the above mentioned dynamical processes. These differences show a displacement and a reinforcement in the analysis of the downward velocities at 600 hPa, south-west of the PV-anomaly axis (38°N, 45°W), which is in agreement with the water-vapour image (Fig. 2). The expected increase of upward velocities east of the latter PV-anomaly axis is also found. One has to note that these likely dynamical modifications, due to ageostrophic adjustment, are a direct and positive consequence of the use of the temporal dimension in 4D-Var; the amplification of the downward and upward velocities found in the 4D-Var analysis cannot be observed in the corresponding 3D-Var analysis (Fig. 5(c)).
Figure 4.  (a) Background representation of wind speed at 1800 UTC 18 February and at 250 hPa (solid lines, contours every 5 m s\(^{-1}\) and only for values above 50 m s\(^{-1}\)), superimposed on the background representation of potential vorticity (PV) on the 310 K isentropic surface (dashed lines, contours every 1 PV unit \(10^{-4}\) K m\(^2\) s\(^{-1}\) kg\(^{-1}\)) and for values more than 1 PV unit; values between 1 and 3 PV units are shaded. (b) Corresponding 4D-Var analysis using only the soundings given by the FASTEX ships (circles with the symbol \(\times\) inside) and ASAP ships (circles with the symbol \(+\) inside); the thick dashed line corresponds to a part of the west–east segment of the Gulfstream IV flight from St John’s to Shannon and defines the location of the cross-sections shown in Fig. 8. (c) As (b) but for a 4D-Var analysis using only the conventional data. (d) As (b) but using both conventional data and FASTEX ship soundings. (e) As (b) but with a 3D-Var analysis and using only the soundings closest to the synoptic analysis time. (f) As (e) but with a 4D-Var analysis.
A striking point is also the appearance of a frontal wave, quite clear in the wet-bulb potential-temperature, $\theta_w$, field at 950 hPa, in the surface trough south-west of the main cyclone. This frontal wave can be observed in the measurements made by the Victor Bugaev (not shown) as mentioned in Cammas et al. (1999). The surface cyclogenesis associated with the frontal wave might be related to the reinforcement of ageostrophic vertical motions, inducing a coupling between an area of initially strong vorticity at low levels and the circulation associated with the upper PV anomaly shown in Fig. 4(b) (Hoskins et al. 1985). Note that the frontal wave is nearly absent in the 3D-Var analysis (Fig. 5(c)).

The high cadence FASTEX ship soundings performed in a meteorological active region actually make up an unique dataset. A way to investigate how 4D-Var handles this dataset is to look at what happens in time at a particular ship location. Figure 6(a) shows
the temporal evolution of the meridional component of the wind above the Suroit location (46.1°N, 36.6°W). The observations associated with the four soundings performed by this ship during the 6-hour assimilation period are analysed with a spline algorithm (Desroziers and Lafond 1993). In order to filter observation and representativeness errors, a smoothing is applied, the amplitude of this smoothing being determined by an objective cross-validation method (Wahba and Wendelberger 1980). This figure shows that the Suroit was very nicely located during this 6-hour period, since it sampled the jet structure with a characteristic sharp gradient on its cyclonic side. The equivalent background evaluations at the same time and location can also be interpolated using the previous spline algorithm, but with no additional smoothing in this case (Fig. 6(b)). The resulting cross-section presents large differences: the maximum value of the wind is lower and the cyclonic gradient is also less important, the whole upper-wind structure being too early in the background; the lower structure is also quite different, with too steep a slope in the gradient associated with the cold front. Figure 6(c) presents the corresponding vertical cross-section for the 4D-Var analysis with only the FASTEX ship soundings. This representation is much closer to the observed values: the cyclonic upper gradient of the wind is better described and the lower structure is also modified. Of course, the small details found in the observations are not retrieved, but one has to keep in mind that this incremental assimilation is only performed with a T63 tangent linear model.

The same vertical and temporal cross-sections at the Suroit location can be produced for the observation (Fig. 6(d)), background (Fig. 6(e)) and analysis (Fig. 6(f)) representations of relative humidity (RH). According to Cammas et al. (1999), the RH values less than 70% at 400 hPa and at 2100 UTC, found in Fig. 6(d) are associated with the upper-level dry-air intrusion on the cyclonic side of the jet stream. The values of RH less than 70% at 700 hPa and at 1600 UTC are related to the low-level part of this dry intrusion. The values of RH more than 80% below 400 hPa correspond with the above mentioned cloud-head structure associated with the system. Figure 6(e) shows that the humidity background cross-section is quite different from that observed: we especially note that according to the wind representation, the upper-level dry-air intrusion on the cyclonic side of the jet, is too early in the background description. This deviation between observation and background is, however, strikingly corrected in the final analysis (Fig. 6(f)): this latter upper-level dry-air intrusion is moved backward in time and the low-level dry intrusion is also suggested.

The comparison of the humidity field representations at 350 hPa, produced by the different experiments (Figs. 7) also shows that, as for the jet description, the differences in these representations are associated with the use of a 3D- or 4D-Var analysis scheme. Using the same subset of FASTEX ship soundings synchronous with synoptic time, 4D-Var produces a description of the humidity (Fig. 7(d)) that is much more in agreement with the vertical and temporal cross-section shown in Fig. 6(d) than the one obtained with 3D-Var (Fig. 7(c)). However, the use of the whole set of FASTEX soundings available during the 6-hour assimilation period still brings improvements to this description (Fig. 7(b)): the zone of strong humidity gradient associated with the clouds is pushed west of the Suroit location, in agreement with the vertical cross-section found in Fig. 6(f). This description of the humidity field also better fits the water-vapour image shown in Fig. 2.

As mentioned above, a NOAA Gulfstream-IV flight took place on 18 February between 1541 UTC and 2134 UTC and this flight passed over the Suroit around 1800 UTC. Figure 8(a) presents a vertical cross-section of the interpolated dropsonde observations
Figure 6. (a) Vertical and temporal cross-section of the meridional component of the wind (contours every 5 m s⁻¹), at the location of the Suroit (46.1°N, 36.5°W) and between 1500 UTC and 2100 UTC 18 February; the time runs from right to left and the data have been interpolated by a spline algorithm; (b) as (a) but for the background equivalent; (c) as (a) but for the 4D-Var analysis with only the FASTEX ship soundings; (d), (e) and (f) as (a), (b) and (c), respectively, but for relative humidity (contours every 10%).
of the meridional component of the wind along the first part of the west-east Gulfstream IV flight segment (see Fig. 4(b) for the position of this cross-section). This cross-section shows the lower part of the south-west to north-east polar jet portrayed in Fig. 4 with a strong gradient in its western part and suggests the two branches embedded in this polar jet streak (Cammas et al. 1999). As for the temporal cross-section at the Suroit location, the equivalent cross-section for the background (Fig. 8(b)) presents the same discrepancy with the previous observed one: the jet maximum is not properly located and the slope of the gradient at the lower levels is too steep in the background. The equivalent cross-section for the 4D-Var analysis using only the FASTEX ship soundings (Fig. 8(c)) shows a better agreement with the observations: the jet is moved westward and the slope of the lower gradient is decreased (but the western part of the polar jet is still not well described). The improved fit to observations which were not used in the analysis is a strong indication that the analysis is a better representation of the true state of the atmosphere. Note that the corresponding 3D-Var analysis presents a larger departure from observations (Fig. 8(d)).
(b) Analysis at 0600 UTC 19 February 1997

Starting from the same 3D-Var background used to produce the previous assimilation experiments centred on 1800 UTC 18 February, two 4D-Var analysis cycles have been performed from 1800 UTC 18 February to 0600 UTC 19 February, using different datasets. The first one used data normally available operationally, with the addition of soundings made during that period by the land-based sites around the Atlantic basin plus the profiles provided by the FASTEX and ASAP ships, (hereafter experiment A); the second experiment added dropsonde data from the NOAA Gulfstream IV and the UKMO C-130 during this time to the previous dataset (hereafter experiment B).

Figures 9(c) and (d) present the 4D-Var analysis at 0600 UTC 19 February resulting from experiment B, that is to say using all the FASTEX soundings, including the UKMO C-130 dropsondes, added to the operational dataset. As mentioned above, these dropsondes were launched during a long duration and system-relative flight which makes it difficult to use the corresponding observations in an intermittent analysis scheme with a unique analysis time, such as 3D-Var; the 4D-Var formulation simplifies the use of such asynchronous data. The background humidity field used for this assimilation depicts the global structure of the cloud head associated with the mature cyclone (Fig. 9(a)), with homogeneous values everywhere higher than 70% RH. On the other hand, the retrieved analysis (Fig. 9(c)) shows a clear tongue of dry air on the 310 K isentropic surface, just west of the UKMO C-130 flight. This is in better agreement with the composite water-vapour image at 0600 UTC 19 February (Fig. 3), which shows this darker and then dryer area on the western part of the flight. This dry-air intrusion, north of the main intrusion associated with the 'polar jet' is likely to be related to the subsidence zone at the entrance of the 'outflow jet' (Cammas et al. 1999). Moreover, the analysed PV
Figure 9. (a) Representation of relative humidity at 0600 UTC 19 February and on the 310 K isentropic surface (contours every 10%) for the background used in experiment B (see text) with all FASTEX observations; (b) as (a) but for potential vorticity (PV; contours every 0.5 PV units and between 1 and 4 PV units); (c) and (d) as (a) and (b), respectively, but for the corresponding representations given by the 4D-Var analysis B with all FASTEX observations; the different segments of the UKMO C-130 flight are also indicated, the dashed arrow corresponds to the cross-sections shown in Fig. 10; the dashed line AB indicates the location of the cross-sections presented in Fig. 11; (e) and (f) same as (a) and (b), respectively, but for the corresponding representations given by the 4D-Var analysis A (see text) with all FASTEX observations but without the dropsonde data.
Figure 10. (a) Vertical cross-section of relative humidity (contours every 10%) along the UKMO C-130 flight segment defined in Figs. 9(c) and 9(d); (b) as (a) but for the background equivalent; (c) as (a) but for the 4D-Var analysis B (see text) including all FASTEX observations; (d) as (c) but without the dropsondes launched along the last two segments of the flight (see Figs. 9(c) and 9(d); these two segments are plotted with a thinner line).

Field on the 310 K isentropic surface (Fig. 9(d)) also presents a characteristic tongue of higher values just west of the dropsonde flight segment, that suggests a downward and north-eastward dry-air intrusion (note that this potential anomaly is also missing in the corresponding background field seen in Fig. 9(b)). On the other hand, Figs. 9(e) and 9(f) present the corresponding representations of the humidity and PV fields for the 4D-Var experiment A, that is to say with no dropsonde data: they do not show the dry-air intrusion, which proves that the UKMO C-130 dropsondes contain essential information not found in other observations, and that this information is correctly treated by the 4D-Var scheme.
Figure 11. (a) Vertical cross-section along the dashed line AB in Fig. 9 of relative humidity in the 4D-Var analysis B (see text) including all FASTEX observations (contours every 10%); (b) as (a) but for vertical velocity (contours every 0.25 Pa s⁻¹; upward velocities dashed); (c) as (b) but for the corresponding background representation.
The comparison of the observation, background and analysis descriptions along one of UKMO C-130 flight segment (see Fig. 9(c) for its position) confirms the correct use of the dropsonde data by the 4D-Var analysis. In agreement with the previous horizontal views, the vertical cross-section through the background RH field (Fig. 10(b)) only presents very high values except in the lower levels. On the other hand, the vertical cross-section through the observations (Fig. 10(a)) shows a narrow and tilted dry-air intrusion with RH values everywhere less than 80%. The retrieved analysis cross-section (Fig. 10(c)) consistently depicts this dry-air intrusion with particularly good agreement in the slope of this tongue of dry air. However, the scale of this intrusion appears broader in the analysis than in the observations and the minimum values are also larger; one has again to keep in mind the coarse resolution of the analysis increment. Figure 10(d) shows a corresponding cross-section from the 4D-Var analysis obtained with the same set of data but excluding the dropsondes launched along the two last segments of the flight (see Fig. 9(c) for their locations; these two last segments are plotted with thinner line). These dropsondes have also sampled the dry-intrusion structure, but later in time. Figure 10(d) shows a poorer description of this structure, which proves that repeated observations of the same structure are quite beneficial in a 4D-Var scheme. It also implicitly indicates that a 3D-Var analysis, which can only use data synchronous with a single analysis time, would provide a less accurate description in such a case.

The dry-intrusion description given by the analysis using the complete set of dropsondes is confirmed by the vertical cross-section presented in Fig. 11(a). This is located south-west of the UKMO C-130 flight in the dry zone appearing very clearly on the 310 K isentropic surface in Fig. 9(c) (the position of this cross-section is also indicated in this figure). Figure 11(b) also shows that this dry-air entrance is associated with clear downward vertical velocities in this area. Moreover, these downward vertical velocities are completely absent in the background representation (Fig. 11(c)), which proves that the whole correction to this background is dynamically consistent.

5. CONCLUSIONS

We have presented a case-study of the use of FASTEX additional soundings in the 4D-Var analysis formulation, including simplified and regular physical parametrizations described in the first part of this paper. The results are found to be encouraging, since this 4D-Var analysis scheme appears to handle the FASTEX dataset consistently. The 4D-Var formulation especially provides a natural and beneficial framework to deal with the high cadence soundings performed by the FASTEX ships: the background used in the variational procedure is modified according to the observations performed by the ships. Even with the same limited dataset of observations synchronous with synoptic time, 4D-Var provides a better analysis than 3D-Var.

There is also a clear impact from the FASTEX observations, containing information that is not present in the operational dataset. This is particularly evident in the case of the system-relative UKMO C-130 flight which brings essential information on the fine structures of humidity, and also of dynamical fields such as vertical velocity and PV.

This application of 4D-Var to the dense FASTEX network is also considered particularly promising, as these first analyses have been obtained with a low-resolution tangent linear model. However, comparison with the high-resolution FASTEX observations show that some sub-structures or regions of strong gradient are misrepresented in the analysis. This suggests that there is still scope to improve this preliminary set of analyses by increasing the resolution of the increments.
Another point of potential improvement is to increase the length of the assimilation period. According to what is known about 4D-Var, this should further improve the way the increments between observations and background are spread in space and time. Furthermore, an attractive idea is that analysis at a given time could be improved by FASTEX data available over a longer period, and distributed before as well as past the analysis time. This is also in agreement with the idea developed by a number of authors that an improvement could be expected from making the assimilation period longer in 4D-Var (Pires et al. 1996, for example). This test of 4D-Var with FASTEX data with an increased assimilation period of at least 12 hours will also be undertaken.

In this paper, the different analyses have been validated by comparison with an external source of information such as satellite images. Another kind of validation has also been proposed, that is by considering the proximity of the final analysis to FASTEX observations. This has been possible in regions where these observations were dense, as in vertical cross-sections sampled in time and space by ship soundings and by dropsondes. In another case, the way the analysis came closer to a FASTEX subset of observations deliberately withdrawn from the assimilation, such as a NOAA Gulfstream IV flight, has also been shown. This need of an objective procedure to estimate the quality of an analysis is obvious and crucial in the scope of the re-analysis project of a field experiment such as FASTEX. Furthermore, this objective procedure should be distinct from the simple evaluation in terms of score of the resulting short-range forecasts. With respect to that subject, the Generalized Cross Validation method proposed by Wahba et al. (1995) could provide such a criterion and its possible application in the framework of the 4D-Var analysis of FASTEX observations is planned to be investigated.

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REFERENCES

Courtier, P. and Geleyn, J.-P.

Courtier, P., Freydière, C., Geleyn, J.-F., Rabier, F. and Rochas, M.

Desroziers, G. and Lafore, J. P.

Desroziers, G., Nechad, B., Sadiki, W. and Thépaut, J.-N.

 Hoskins, B. J., McIntyre, M. E. and Robertson, A. W.

Janisková, M., Veersé, F., Thépaut, J.-N., Desroziers, G. and Pouponneau, B.

Jaubert, G., Pirio, C., Loehr, S. M., Petitpa, A. and Moore, J. A.


Keyser, D. and Shapiro, M. A.

Laprise, R.

Moine, M. P. and Roux, F.

Pires, C., Vautard, R. and Talagrand, O.
Schmidt, F.


1999 Overview of the field phase of the Fronds and Atlantic Storm-Track EXperiment (FASTEX) project. *Q. J. R. Meteorol. Soc.*, 125, 3131–3163


