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An assessment of using dropsonde data in numerical weather prediction

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An assessment of using dropsonde data in Numerical Weather Prediction

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Abstract

In this paper the use of wind and temperature profiles from dropsonde observations in the analysis and forecast has been studied in different contexts. Dropsondes have been deployed in three measurement campaigns: FASTEX (February 97), NORPEX (February 98) and the Tropical Cyclone campaign (summer 1998). In FASTEX and NORPEX dropsondes were released in sensitivity areas where errors in the initial state are fast-growing, in order to monitor data-sparse areas where storms are generated and evolve. The impact study results show a reduction of the 2-day forecast error over the forecast verification areas: west coast of North America for the NORPEX and west of England (over the North Atlantic) for the FASTEX measurement missions. Moreover, a positive impact has been found over the North Atlantic and Europe (FASTEX) and Europe and the Northern Hemisphere (NORPEX) in the medium range forecast. In the Tropical Cyclone campaign, deployed dropsonde observations in the hurricane region have been found to improve the analyzed structure of the tropical cyclones and to give a better forecast in terms of track and mean wind speed of the hurricane.

1. Introduction

In the last three years, data campaigns have been carried out to observe atmosphere circulations in traditionally data-sparse regions. Rapidly developing oceanic cyclones like frontal cyclones which form at the eastern end of the Atlantic storm-track are sometimes difficult to forecast. Moreover, the lack of an adequate observational system over the North Pacific can result in fast growing analysis error, specially in downstream motion conditions. In January and February 97, a meteorological measurement campaign, the Fronts and Atlantic Storm Track Experiments (FASTEX) was run in order to monitor data-sparse areas where storms are generated and evolve. The general opinion is that good forecasts of these storms would require more accurate initial conditions. For this reason FASTEX provided targeted observations from aircraft in the west and mid-Atlantic, that is, in sensitivity regions where errors in the initial state are fast-growing. Different approaches were tested in order to indicate these crucial regions on the forecast cyclone development (*Langland and Rohaly*, 1996; *Bishop and Toth*, 1996; *Buizza and Montani*, 1999) and some debate remains over the more suitable strategy to be used and the expected forecast improvement with respect to the cost of deploying dropsondes.

Another observational data experiment was realized in mid-January and February 98, the North Pacific Experiment (NORPEX) by the NOAA and U.S. Air Force aircraft. As for FASTEX, the primary purpose of the campaign was to test adaptive observing strategies by collecting data in areas most sensitive to develop forecast errors for meteorological features such as a land-falling cyclone or its associated front. The research flights were planned to collect this data with the goal of improving 1-3 day forecasts over the west coast of the U.S.. The two techniques used were the ensemble transform technique (*Bishop and Toth*,1996) by NCEP and the adjoint sensitivity analysis by NRL based on the singular vector computation (*Langland and Rohaly*, 1996). The targeted observations were used in real time in many meteorological centres.

In summer 98 another observational campaign took place, the Tropical Cyclones 98 by NOAA and NASA flight missions. The 1998 season will be remembered as being one of the deadliest in history and for having the strongest October hurricane on record. The goal of the mission was to deploy dropsonde observations in the area of tropical cyclones in order to better detect the evolution. A better knowledge of hurricane evolution can save human life and property from damage. This paper concentrates on the use of dropsondes observations in NWP and assesses the impact on the analyses and forecasts. In section 2 a description of the dropsonde data and the model used is given. Section 3 describes the experiments performed and the results obtained. Conclusions are drawn in section 4.

2. Observations and model

Dropsonde observations from different campaigns were obtained in several flight missions. In FASTEX six aircraft were involved (NOAA, US Air Force, UKMO and NCAR) in dropping two sets of sondes: high and low resolution data. The latter were processed according to WMO specifications in standard and significant levels. The total number of dropsonde launches was 1300 providing measurements of wind, temperature and humidity. Some inconsistencies were found in the humidity values to discourage their use in analyses (*Jaubert et al.*, 1999).

During the 27 days of the NORPEX experiment, 38 NOAA and 2 US Air Force aircraft released almost 700 dropsondes over the northeastern Pacific. The dropsondes provide vertical profiles of temperature, wind, humidity and pressure from the aircraft level (300-400 hPa) to the surface. The horizontal separation varied from 100 to 250 km. All the observations were distributed in real time via GTS to some meteorological centres.

A 4D-Var assimilation system (*Rabier et al.*, 1999, *Mahfouf and Rabier*, 1999) has been used for studying the dropsondes' impact in the assimilation. The assimilation system ran high-resolution model T319 on a linear grid and 31 vertical levels with full physics parametrization for comparing the observations with the atmospheric state (as part of the cost function) and a lower resolution model is used with simplified physics (*Mahfouf*, 1999) to minimize the cost function. The resolution used for the minimization was either T63 (operational at ECMWF) for FASTEX and NORPEX campaign or T106 for the Tropical Cyclone campaign. Hereafter the assimilation model using higher resolution for the cost function minimization is indicated as 4DVarT106 whilst 4DVarT63 indicates the lower resolution minimization.

In all the experiments performed using dropsondes, only the wind and temperature measurements have been assimilated and the instrument error assigned to them was unchanged with respect to the radiosonde observations. A different tuning for the dropsonde quality control has been set up with respect to the one performed on the radiosondes. The quality control in the operational 4D-Var assimilation scheme is performed in two steps: first, a background quality control is done for all the variables that are intended to be used in the assimilation. The background departure $y\text{-}H(x_b)$ is the difference between the observed value y and the model value x_b interpolated to the observation location by the H operator. The square of normalized background departure is considered too large when it exceeds its expected variance $1+\sigma_o^2/\sigma_b^2$ (σ_o and σ_b are the observation and the model error, respectively) by more than a predefined multiple (*Järvinen and Undén*, 1997). This multiple ranges from 8 (probably correct) to 20 (incorrect observation). A second check takes place during the iterative solution of the variational analysis scheme (*Andersson and Järvinen*, 1999). All the data used are quality-controlled simultaneously and the weight of each observation decreases when the gross error probability increases. The probability density function (pdf) for a single observation is expressed as

$$P^{QC} = (1-A)N + AF \tag{1}$$

where A is a prior probability of a gross error and 1-A is the probability of not having gross error. N and F are the Gaussian and a "flat" rectangular distribution, respectively. If a-priori, no gross error occur (A=0), the pdf is a Gaussian and the observational cost function is a quadratic form (*Lorenc*, 1986). Thus the uniform distribution F, in (1), has the role of a contaminating (or gross error) pdf. In general it can be shown (*Andersson and Järvinen*, 1999) that the observational cost function $J_o \propto -\ln p^{QC}$ has a gradient

$$\nabla_x J_o^{QC} = \nabla_x J_o^N W^{QC} \tag{2}$$

where weights W^{QC}=(1-P) represent the a-posteriori probability of gross error P. Rejections occur gradually as less weight is given to the more controversial observations with respect to the analysis (when $P \rightarrow 0$, $W^{QC} \rightarrow 1$). The rejection limit for wind measurements from dropsonde reports has been made a function of latitude. Wind observations on a tropical band are less rejected than in midlatitude band as explained in section 3.

3. Experiments and results

3.1 Tropical cyclone campaign

Some experiments have been performed in order to investigate the impact of dropsonde observations in the analysis and forecast The first experiment performed is during the Tropical Cyclone campaign in summer 98. The ECMWF received through the GTS network a set of observations taken by NASA and NOAA (US Air Force reconnaissance flight) missions by releasing dropsondes mainly on tropical cyclone areas. The 1998 season was a very active season with 14 named tropical storms of which 10 became hurricanes. The tropical depression that was to become Danielle formed early on August 24 about 700 miles west of the Cape Verde islands. Tropical storm status was reached later that day. Moving west-northwestward, Danielle rapidly strengthened into a hurricane and reached the first of several peak intensities near 105 mph while centred about 1040 miles east of the Leeward islands. For the next several days the hurricane continued west-northwestward gradually slowing in forward speed. Danielle turned northwestward and northward on August 30-31, passing well east of the Bahamas. It then turned northeastward at increasing forward speed passing about 230 miles northwest of Bermuda early on the 2nd September and the wind briefly reached tropical storm force. Danielle lost tropical characteristcs about 260 miles east southeast of Cape Race late on the 3rd September. Because of the very fast evolution into an hurricane (few hours), the ECMWF analysis was not able to resolve the tropical cyclone in its early stage. On the contrary, the hurricane Bonnie (980819-980830) was well resolved by the analysis because it slowly strengthened into a hurricane over 3 days. In Fig 1 are shown the dropsondes observations received at ECMWF between the 24th of August and the 3rd of September 98. Only one third of the total dropsondes is in the area of Danielle's track (red dots); one third is following the tropical cyclone Bonnie (blue dots) whose track evolution is shown for the same period (0824-0309). The remaining dropsondes are in the Mexico Gulf where the tropical storm Charley was taking place (21-24 august). Unfortunately, there was not information to be used in the early stage of Danielle (24-27 august) and the first significant dropsondes, that is, near the cyclone core, were released on the 29 of August.

In Table 1 the experiments performed to assess the impact of the use of wind and temperature information from dropsondes in tropical cyclones are shown.

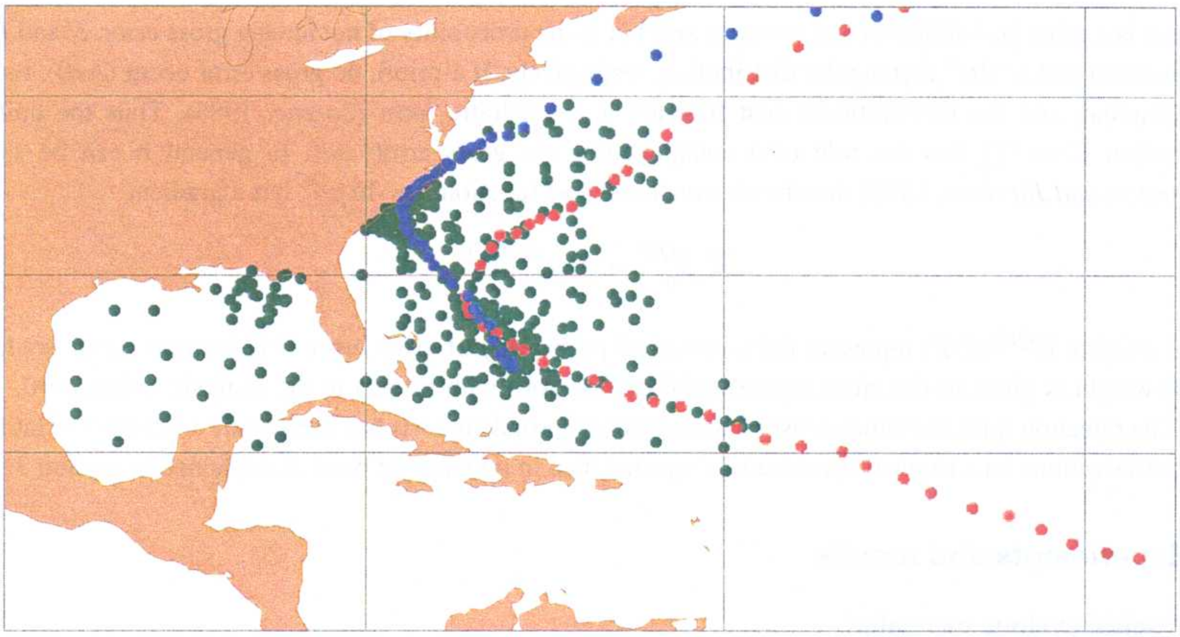


Figure 1: Dropsondes location received at ECMWF from 980824 to 980903 (green dot). Valid at the same time, Danielle (red dots) and Bonnie track (blue dots) are overlaid to the observations

Experiment	Data used	Model
CONTRTC	ECMWF oper suite	4DVarT106
DROPTC	Control add TC dropsondes	4DVarT106
DROPQC	Control add TC dropsondes	4DVarT106 different Q C for dropsonde

Table 1: Analysis experiments performed during the tropical cyclone campaign

The CONTRTC experiment contains all data used operationally at ECMWF (August 98) whilst in DROPTC all the dropsondes have been added to the ones used in CONTRTC. In DROPTC the dropsondes are quality-controlled as radiosonde observations (*Järvinen and Undén*, 1997; *Andersson and Järvinen*, 1999); the experiment DROPQC uses the same observations as DROPTC but dropsondes have a more relaxed quality control than in the operational suite. For wind observations taken in very intense storm, like for dropsondes released in the core of hurricanes, the background quality control was very active by rejecting almost all the observations in the cyclone centre and releasing only the ones at the edges. In DROPQC the background quality control is not performed and all the dropsondes can be assimilated. In fact, the threshold value at which rejections occur (rejection limit) has been increased by a factor 100 for all wind dropsonde observations, i.e. effectively switched off.

Fig 2 shows the histograms of analysis wind speed departure from dropsonde wind observations for the period 19980830-19980902, when the prior probability of gross error is tuned at $A=10^{-3}$ (DROPTC (a)) and $A=10^{-10}$ (DROPQC (b)), respectively. Thin outlines show the non-rejected data and filled outlines show the rejected ones. The first value of A was suggested by Andersson and Järvinen (1999) from a study of historical radiosonde wind observations database. In both figures the used observations are symmetrically shaped. Of course, rejections occur more frequently for larger A, while the effect of decreasing A concentrates rejections on the right tail of the distribution, avoiding the peak on moderately high analysis departures ($\sim 12 ms^{-1}$). Fig 2b shows the rejection limit shifted to $19 ms^{-1}$. The latter feature seems particularly appropriate to control intense weather phenomena like tropical cyclone development. The use of more wind observations in the hurricane area improves the analysis and in the cyclone area a more realistic vertical temperature field structure is depicted. Fig 3 shows a cross section of the perturbed temperature ($T'=T-T_{mean}$) valid on the 980830 at 00UTC, for CONTRTC (Fig 3a), DROPTC (Fig 3b) and DROPQC (Fig 3c), respectively. The cyclone core position is 25.5N -71W. The mean temperature has been subtracted from each corresponding temperature field and the vertical variation of this temperature depicts the analyzed hurricane structure. Fig 3c clearly shows a warmer core at 300 hPa (solid line) propagating towards the surface (900 hPa). DROPTC displays (Fig 3b) a less warm core and to a less extent than in DROPQC (Fig 3c). The poorest representation of a vertical temperature field (*Frank*, 1977) is given by CONTRTC (Fig 3a) where dropsonde wind observations are not used at all. The vertical structure of the vorticity fields evidences a closed low-level cyclonic circulation at 900 hPa for the experiment DROPQC (not shown). The 10-day forecast cyclone track has been computed for CONTRTC, DROPTC and DROPQC, respectively. Fig 4 shows the best observed track in yellow and the 10-day forecast tracks starting the 30/08, 31/08, 01/09 and the 02/09 at 12 UTC in green, blue, red and black, respectively. The track computation method is based on the low-level wind field (Fiorino, personal communication) and the best observed track combines all the information available. In DROPQC (Fig 4b) all the tracks are better forecast than in CONTRTC (Fig 4a) when compared with the observed one. The only exception is day 7 and 8 from the forecast started on the 30 august at 12 UTC. DROPQC performance in forecast track is also better comparing with DROPTC (not shown). Table 2 shows the observed and forecast mean wind speed (in knots) for Danielle at the analysis time (980830 at 12 UTC) and for the following 24,48,72 hour forecast for the three experiments.

	00	24	48	72
OBS	74.00	76.25	73.33	67.50
CONTRTC	32.90	18.38	21.93	16.30
DROPTC	35.40	18.10	26.00	15.00
DROPQC	37.30	27.43	25.60	19.55

Table 2: Analyzed and forecast hurricane mean wind speed

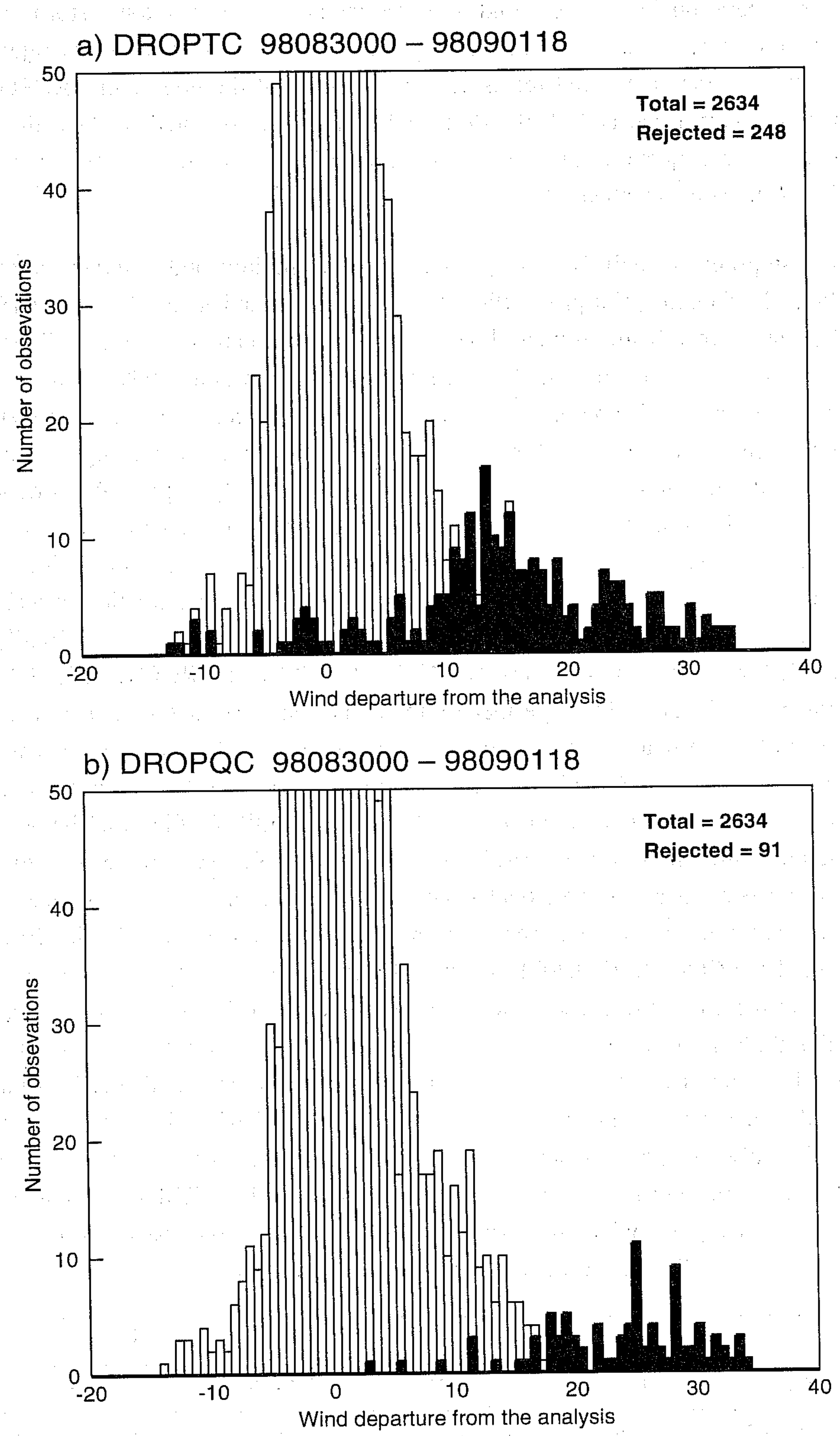


Figure 2: Histograms of departures from the analysis for dropsonde wind data showing rejections before (a) and after (b) the Var Quality Control revision. The thin outlines are no-rejected data and filled outlines are rejected data

a

b

c

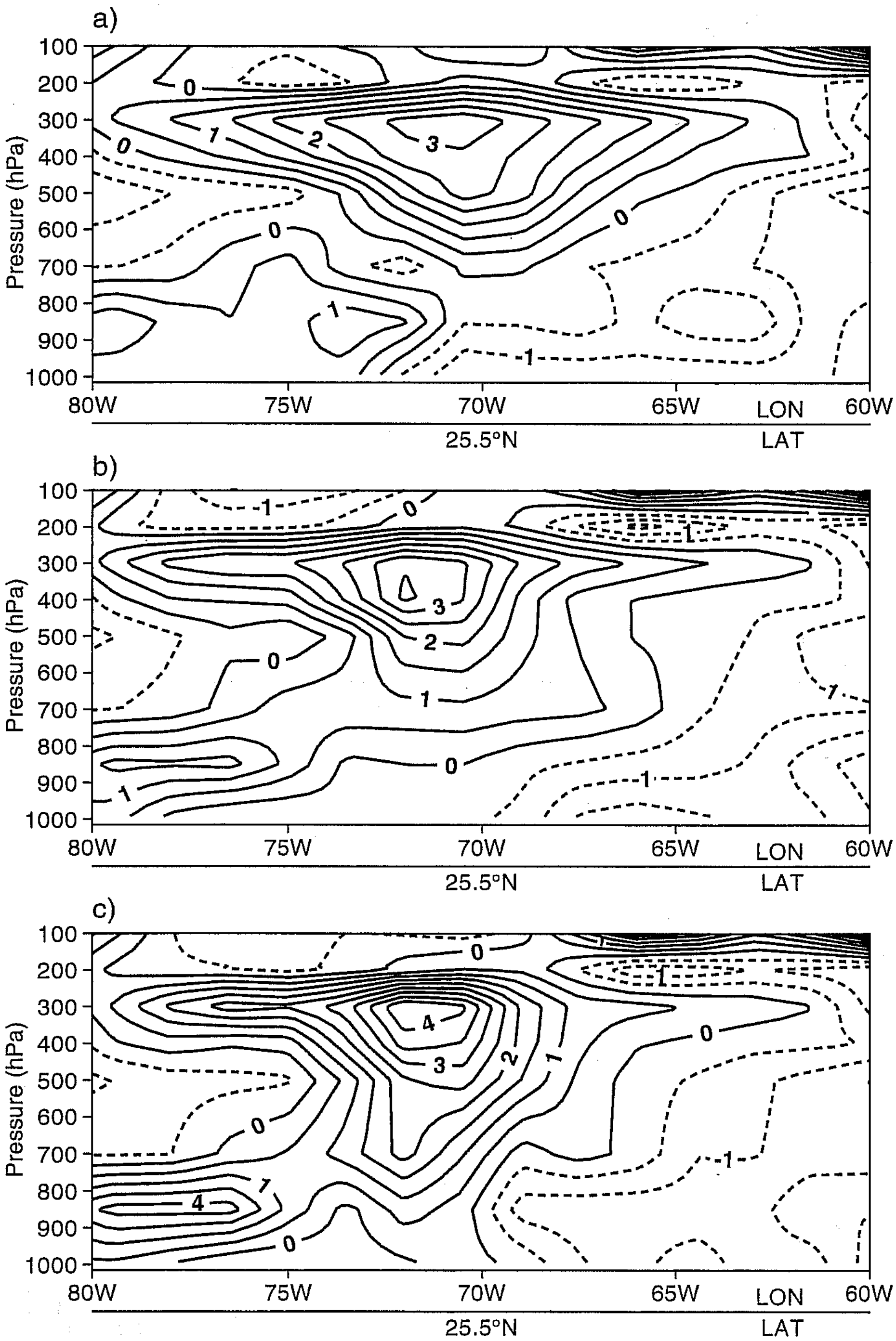
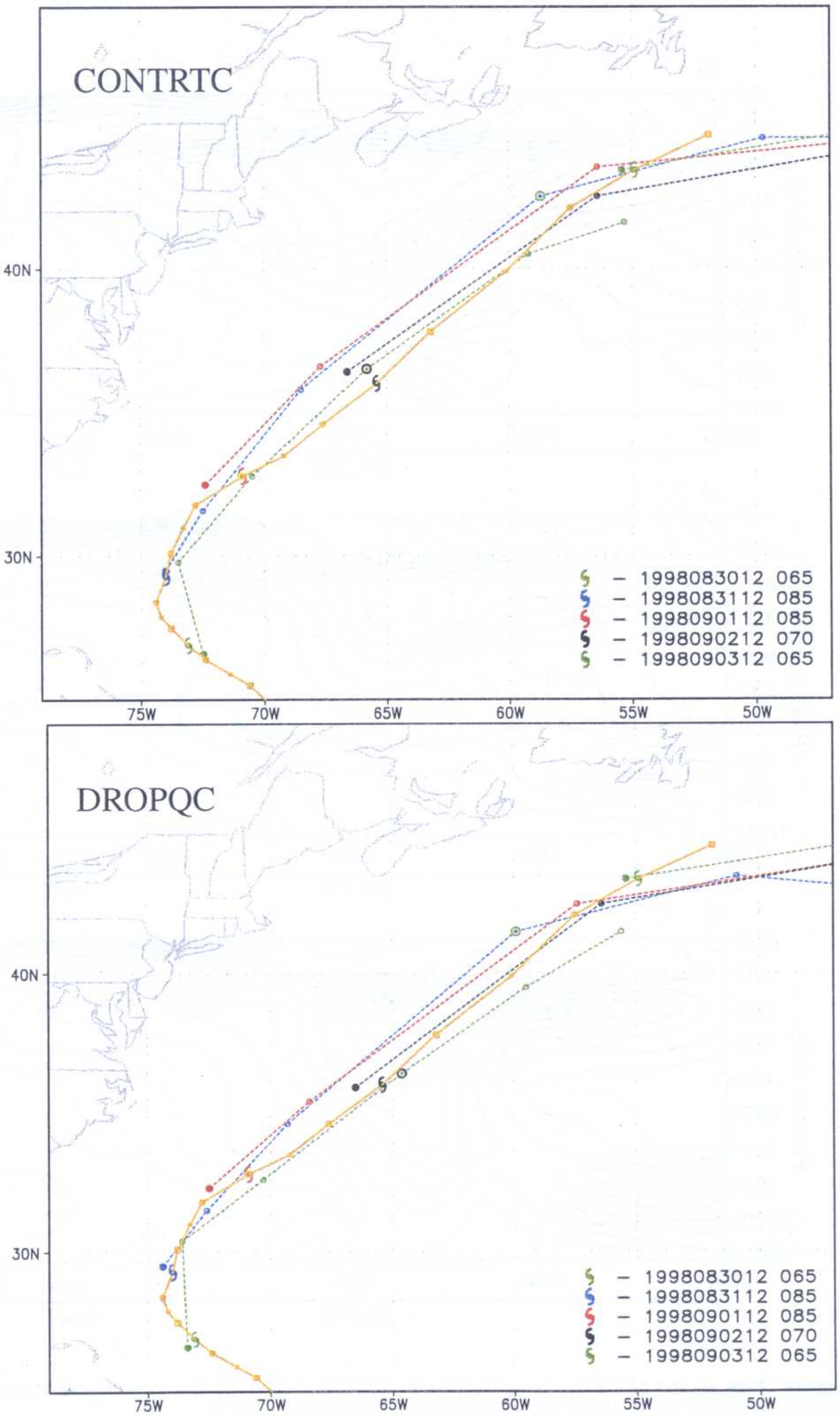


Figure 3: Temperature cross section of the hurricane Danielle for 980830 at 00 UTC. The temperature field is $T'=T-T_{mean}$ for the experiment CONTRTC (a), DROPTC (b) and DROPQC (c). The contour interval is 0.5 C.



a

b

Figure 4: Forecast cyclone track for CONTRTC (a) and DROPQC (b). Observed track is yellow. The forecast track starting the 30/08, 31/08, 01/09, 02/09 and 03/09 at 12UTC is in green, blue, red, black and green, respectively

DROPQC shows higher mean wind speed with respect to CONTRTC and DROPTC but still too small when compared to the observed mean wind speed. The forecast impact of DROPQC and DROPTC with respect to CONTRTC has been tested over a two week period and the results in terms of geopotential and wind anomaly correlation are neutral. All the experiments have been verified against radiosondes observations and own analysis (not shown). The assimilation of dropsondes over tropical cyclones improves the quality of the analysis and the forecast by giving a better representation of the hurricanes in terms of wind speed and cyclone track. When more dropsondes are assimilated by relaxing the quality control for this type of observations the internal structure of the tropical cyclone results are much more realistic and benefits are obtained in the following forecast. The analysis will tend to filter the small-scale information from the dropsonde data in a way more appropriate for mid-latitude storms. Local changes to the B-matrix (*Derber and Bouttier*, 1998) in the vicinity of the storm are required to improve the use of the data.

3.2 NORPEX campaign

Two analysis experiments have been set up for an assessment of the impact of these extra sources of information on the analysis and forecast. A control experiment (CONTRNX) has been generated using all the observations operationally used at ECMWF. DROPNX experiment assimilates NORPEX dropsonde observations in addition to the ones used in CONTRNX. The experiments resolution is 4DVarT63. The impact of assimilating wind and temperature profiles from dropsonde observations has been examined over the period 980202-980222. These observations were mainly released at 00 UTC and the targeting areas were provided equal by NCEP and NRL. In DROPNX the quality control for wind observations has been relaxed by increasing the background control threshold by a factor 2 (1 is the operational rejection limit). In the subsequent quality control, during the minimization procedure, the probability of gross error A has been decreased ($A=10^{-10}$) allowing more dropsondes to be assimilated. Table 3 shows the percentage of rejections as in the operational assimilation system (Operation) and after the new calibration. BgQC and VarQC are the background and the variational check, respectively.

	BgQC	VarQC
Operation	1.6%	1.5%
DROPNX	0.6%	0.5%

Table 3: Percentage of rejections

In general, the percentage of rejection is small in both cases, DROPNX reduces rejections by a factor ≅ 3. The analysis differences due to dropsondes data between the two experiment is shows in Fig 5. For the period 980202-980222 the root mean square (rms) differences of analyzed 500 hPa geopotential height between DROPNX and CONTRNX at 00 UTC displays an area with changes up to 20 m due to the assimilation of dropsondes. Differences in the analyses propagated downstream and after 12 hour forecast a new location is found approaching the west coast of the US as it can be seen in Fig 6 where, for the same period are shown the rms of 12-hour forecast differences of the 500 hPa height. One of NORPEX campaign goals was to reduce the 48 hour forecast error over a certain forecast verification area (FVA) (*Langland et al*, 1999). During the winter of 97-98 heavy precipitation occurred over parts of California, probably associated with maximum intensity of El Niño towards the end of January. The typical weather response was strong wind at jet level and storms releasing a large amount of rain over the California coast. Therefore, a primary goal was to improve the short range forecast error in these regions reducing then the risk of damage to people and property. All the targeting techniques used in NORPEX specify a FVA located 30-60N, 100-130W and the dropsondes were released in the sensitivity regions affecting the 2-day forecast in the FVA. Fig 7 shows the 48-hour rms forecast error differences between CONTRNX and DROPNX for the 500 hPa geopotential height and for the period 980202-980222. The green line marks the FVA, the yellow shaded contours indicate larger forecast error in CONTRNX than in DROPNX and blue contours smaller ones.

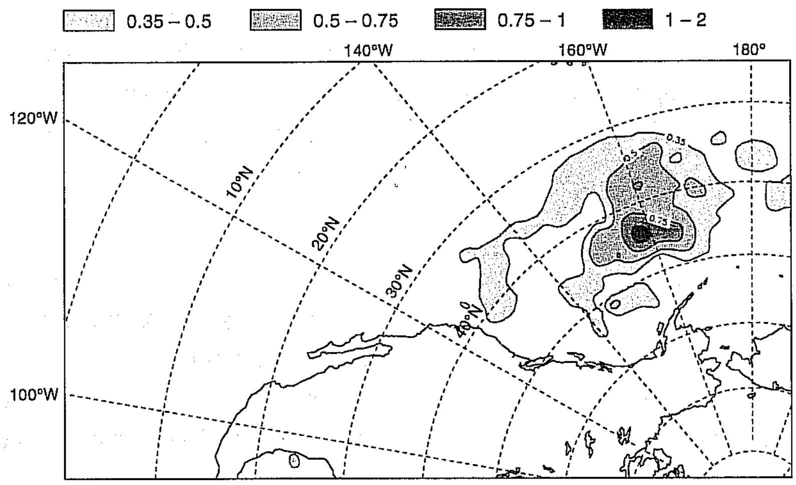


Figure 5: RMS of analysis differences at 500 hPa for geopotential field for the period 980202-980222 at 00 UTC between DROPNX and CONTRNX. Contours in dam.

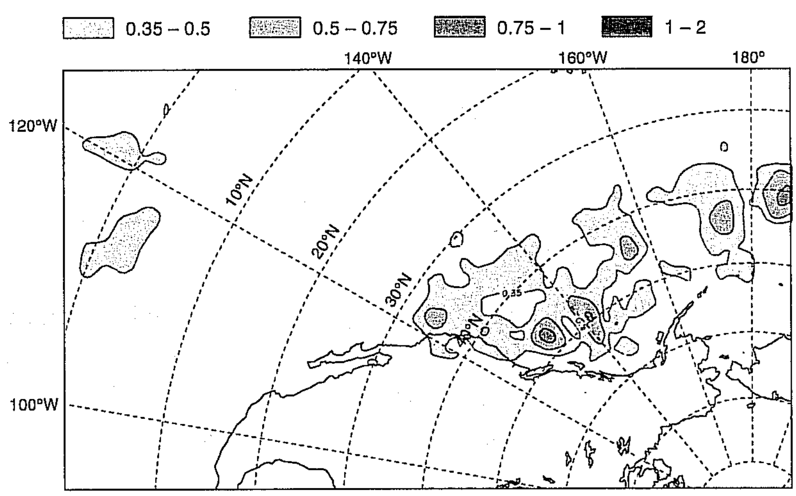


Figure 6: RMS 12-hour forecast differences at 500 hPa for geopotential field for the period 980202-980222 at 12 UTC between DROPNX and CONTRNX. Contours in dam.

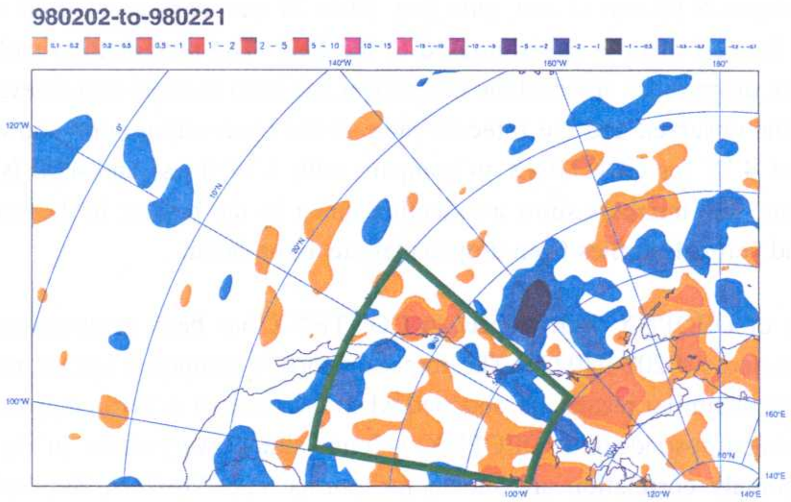


Figure 7: 48-hour RMS forecast error differences for the 500 hPa geopotential field for the period 980202-980222. Green line marks the FVA. Yellow shaded contour indicate larger error and blue smaller error in CONTRNX than DROPNX. Contour in dam.

In the FVA, DROPNX diminishes on average the 500 hPa height 48-hour forecast error up to 10m and the improvement is evident at every pressure level specially at the surface where the 48-hour forecast error of the mean sea level pressure field (mslp) has been decreased by up to 15m (not shown). However, a large area of deterioration appears outside the FVA (blue shaded contours in Fig 7). DROPNX produces in that region larger error than CONTRNX (10m). The cumulated precipitation over a 36 to 60 hour period from 980202 to 980220 has been verified against the observations in the FVA. The bias and the standard deviation of the difference between the forecast precipitation field and the observed value at the observation point are reduced when dropsondes are assimilated. On average the bias and the standard deviation decreases by a factor 0.95 in DROPNX with respect to CONTRNX. On the 20th of February at 00 UTC, one of the biggest NORPEX missions took place and 40 dropsondes were released north of Hawaii and west of Cape Mendocino. The western flight track was tasked by NRL, the eastern track by NCEP. Sondes were deployed on the anticyclonic shear side of the upper level jet, with a good definition of gradients across the lower tropospheric baroclinic zone (R.H. Langland personal communication). The analyzed differences of the 500 hPa geopotential height between DROPNX and CONTRNX shows an intensification of the front system when dropsondes are used (not shown): DROPNX is 22m deeper. In Fig 8 the cross section of the zonal wind component difference between DROPNX and CONTRNX clearly shows a stronger zonal wind from 700 to 200 hPa with a maximum difference of $10ms^{-1}$ at 500 hPa (solid line). A large impact from the dropsonde data on the 2-day forecast over the FVA (30N-60N, 100W-130W) is found. The 48 hour rms forecast error for mslp field is on average 5 m smaller in the FVA for DROPNX than for CONTRNX and for smaller regions near the coast, the error reduction is up to 30 m (not shown). The cumulated precipitation over 36-60 hours has been verified against observations. The forecast started on 980220 12 UTC is verified on the period 980222-980223 at 00 UTC and in the FVA. In Fig 9a,b the forecasted precipitation fields are shown for CONTRNX and DROPNX, respectively.

Areas in light grey depict 5-10 mm of rain, pale grey 10 to 20 mm, dark grey 20-50 mm and charcoal 50 to 100 mm; the mean forecast error is superimposed to the field. The precipitation path is similar in the two experiments but when dropsondes are used the mean error has been reduced almost everywhere (Fig 9b). The difference between the observed and the forecast value at the observation point shows a bias of 1.85 and a standard deviation of 4.78 for CONTRNX to compare with 1.73 (bias) and 4.08 (standard deviation) for DROPNX experiment. The numbers show a reduction either in the bias or in the standard deviation when temperature and wind vertical profiles from dropsondes are assimilated.

The forecast impact of DROPNX with respect to CONTRNX has been investigated in terms of anomaly correlation for the period 980202-980222. The forecast score is computed against radiosonde observations (mean over 20 cases) but similar results are obtained when the forecast is verified against the own analysis. A positive impact of using dropsonde data (DROPNX) is found almost everywhere. In Fig 10a,b the 500 and 200 hPa geopotential anomaly correlation are shown for Europe and Northern Hemisphere, respectively.The figures show a positive impact of dropsondes on the medium range forecast either in Europe (Fig 10a) or in the Northern Hemisphere (Fig 10b) and it is preserved on all vertical levels (not shown). In the Southern Hemisphere the impact is neutral when the verification is performed against the own analysis and slightly negative when it is done against the radiosonde observations (not shown), probably because of radiosonde sampling lack. Wind and temperature measurements from deployed target sondes during the NORPEX campaign have been shown to improve the analysis and the forecast. The 2-day forecast error in the FVA is always smaller when they are assimilated and an improvement on the medium range forecast over the Northern Hemisphere is found.

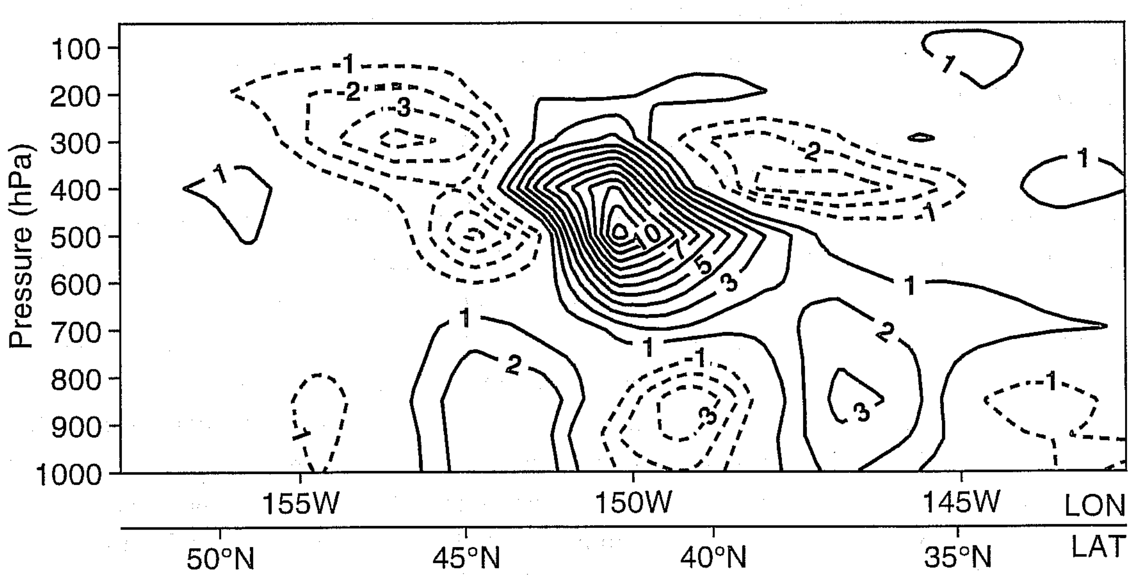
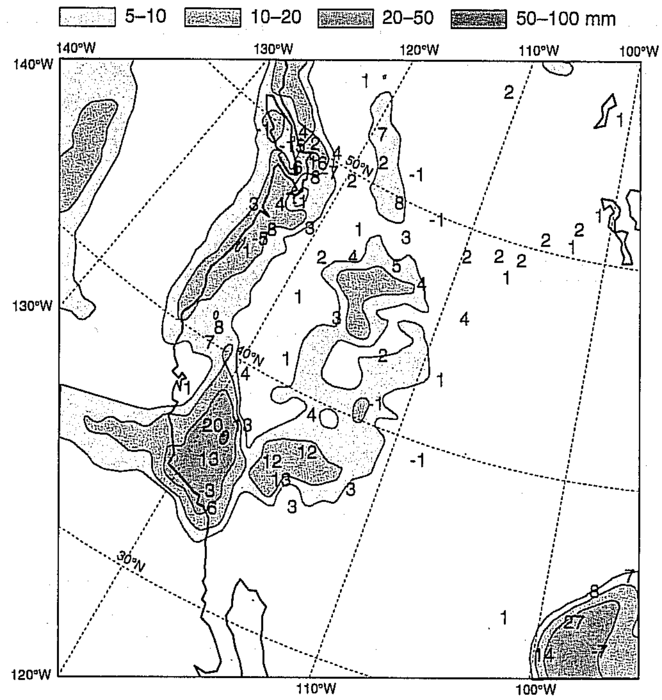


Figure 8: Cross section of u wind component differences between DROPNX and CONTRNX. Contours every 1 m/s.



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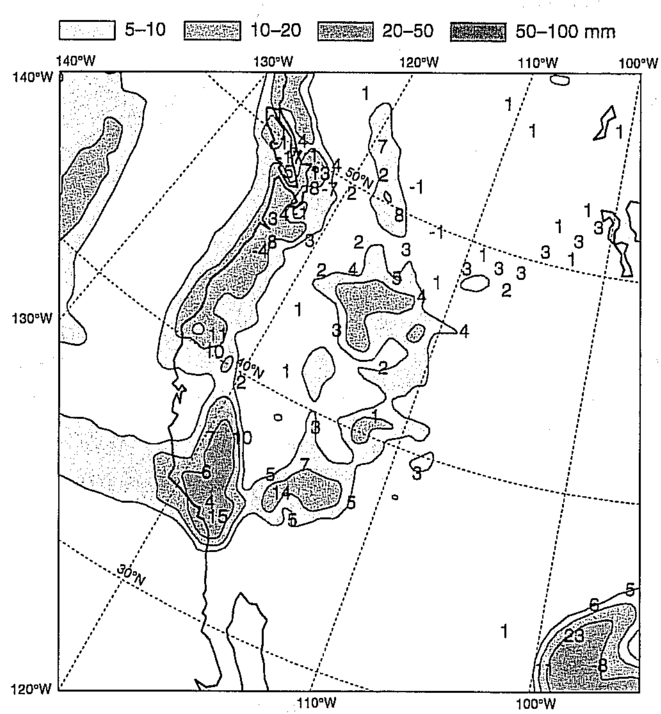

b

Figure 9: Cumulated forecast precipitation over 36-60 hours for the period 980222-980223 at 00 UTC for CONTRNX (a) and DROPNX (b). The precipitation fields are verified with the observations (superimposed number).

NORPEX mission also provided advanced and experimental wind data from GOES-9 and GMS-5 every 6 hour. These conventional satellite data has been used in a passive way for verification purposes. The departures to these observations are computed but not used in the assimilation. The rms differences in the u and v wind components with respect to the wind satellite data are computed for CONTRNX and DROPNX. DROPNX fits the satellite wind observations better than CONTRNX (not shown).

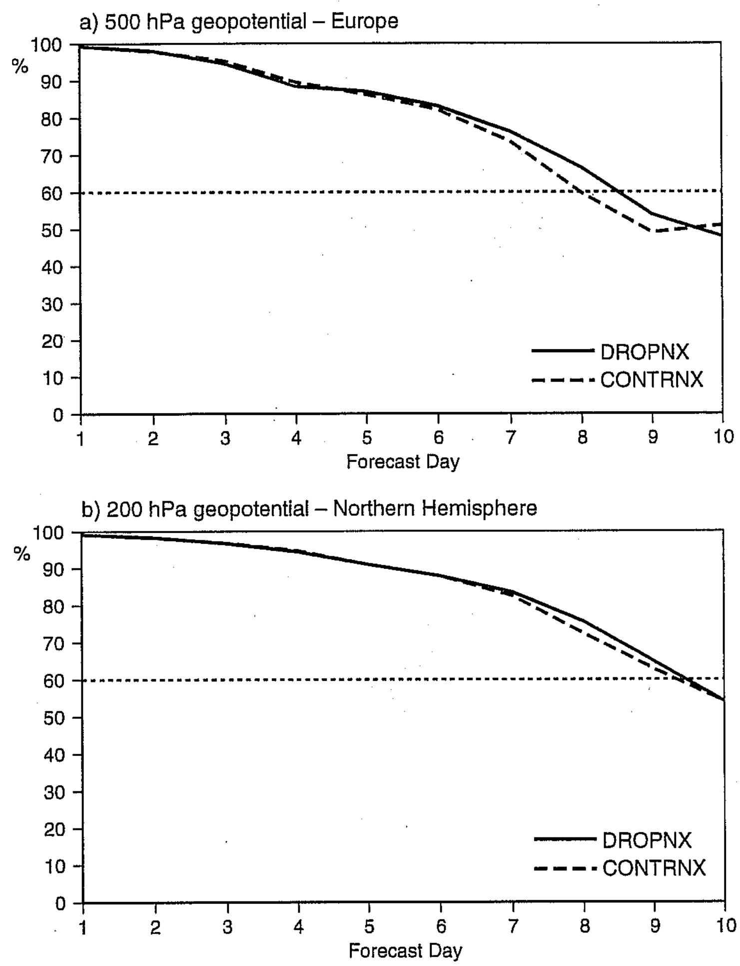

Figure 10: 500 hPa (a) and 200 hPa (b) geopotential anomaly correlation for Europe (a) and N.Hemisphere (b) verified against radiosonde observations. Mean over 20 cases.

3.3 FASTEX campaign

FASTEX field phase has given the opportunity to assess the impact of targeted observations on the 1 to 2 day forecast skill of North Atlantic frontal cyclones. Previous studies during an intensive observation period (*Undén et al.*, 1997) have shown a positive impact in the forecast over Europe and North Atlantic from dropsonde data. In this investigation, the impact of dropsonde observations has been examined in one particular synotic situation. On the 22nd of February 12 UTC a cyclone started to develop south of Greenland and quickly deepened in the following 24 hours. The region of strong initial condition sensitivity was 45-58N, 30-55W according to the targeting strategies used: singular vector method (*Montani et al,* 1996; *Palmer et al.*

1997) and the gradient sensitivity (*Langland and Rohaly*, 1996; *Bergot et al.*, 1997). The FVA was located 48-63N, 30-15W. The main goal of this mission was to reduce the 24-hour error forecast in the FVA. Two experiments have been performed, a control experiment CONTRFX (4DVarT63) assimilating the observations operationally used at ECMWF (February 97) and DROPFX where wind and temperature profiles from dropsondes data were added. Fig 11 shows the 300 hPa geopotential height analysis differences between CONTRFX and DROPFX for the 970222 at 12 UTC. The geopotential differences (up to 30 m, solid line) cover the large sensitivity area where dropsonde observations have been released (open square in Fig 11). Dropsondes create a deeper geopotential field in the upper troposphere whilst in the lower levels near the surface the geopotential is deeper in CONTRFX. The cross section of the zonal wind component difference between the two experiments (Fig 12) shows an increase of vertical wind shear in the upper troposphere (solid line) due to the assimilation of wind and temperature measurements from dropsondes. In both experiments the cyclone quickly deepens in 24 hours from about 994 to 956 hPa, the resulting position at the surface was slightly different (not shown). The 24-hour rms forecast error differences between CONTRFX and DROPFX for the 500 hPa geopotential height show that the error is reduced almost everywhere in the FVA when dropsondes are assimilated (Fig 13). The FVA is drawn in green. In DROPFX the maximum error reduction is 30 m (west of Ireland).

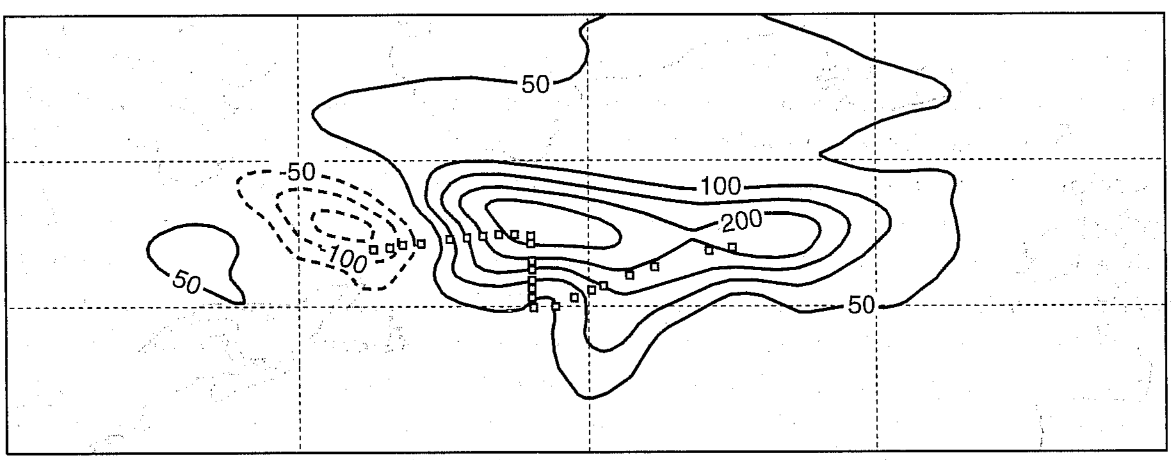

Figure 11: 300 hPa geopotential analysis differences between CONTRFX and DROPFX for 970222 at 12 UTC. Dropsondes location in open square. Contour interval every 50 m^2/s^2

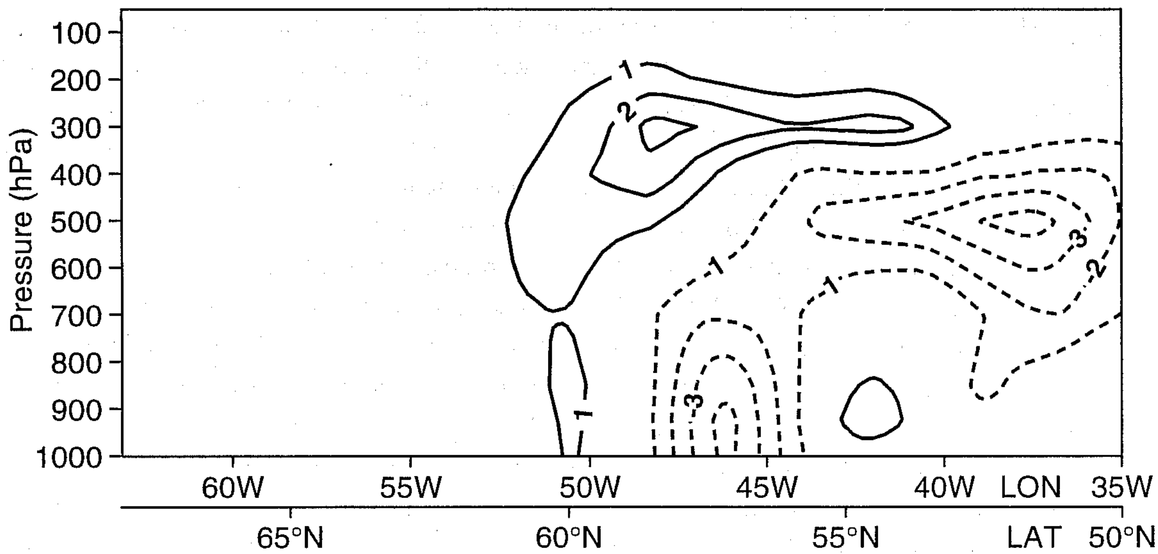

Figure 12: Cross section of the u wind component differences between CONTRFX and DROPFX for 970222 at 12 UTC. Contour interval is 1 m/s.

In a small area upstream inside the FVA, CONTRFX is performing better showing a smaller forecast error up to 10 m. Outside the FVA a region of larger forecast error in DROPFX can be spotted between Scandinavian and Island (20 m). Singular vectors can be used to compute the smallest initial perturbation, so-called pseudo-inverse initial perturbation (*Buizza et al.*,1997; *Gelaro et al.*, 1998 and *Buizza and Montani*, 1999) which can reduce the forecast error inside the FVA if added to the reference initial condition. The pseudo-inverse initial perturbation $\delta e(t_0)$ (*Buizza and Montani*, 1999) has been computed using the leading 10 singular vectors growing between the 22nd and the 23rd of February at T63L19 resolution. Table 1 lists the total energy norm (m^2s^{-2}) of the error of the 24 hour forecast started from the unperturbed analysis (CONTRFX reference), from the reference analysis perturbed by adding or subtracting $\delta e(t_0)$ and $2\delta e(t_0)$ and last from DROPFX. Results indicate that the forecast error reduction obtained using the dropsondes is very close to one obtained by adding to the reference analysis the pseudo-inverse initial perturbation multiplied by a factor 2. This scaling is probably needed to compensate for non-linear effects in the perturbation growth. From the period 970222 to 970228 the rms forecast error over 24 hours has been computed for CONTRFX and DROPFX. Results are shown in Fig 14 in terms of scatter plot at 1000 hPa for North Atlantic. Fig 14 shows that DROPFX is performing better in 3 cases out of 6 and for the other 3 cases the impact is neutral. Similar results are obtained for the other pressure levels. A slightly positive impact can be observed even over Europe (not shown) but is neutral everywhere else. The one case study for the FASTEX campaign shows an analysis improvement when dropsondes are used and a reduction of the 24 hour forecast error, mainly in the FVA. A positive impact is also shown in the short range forecast over North Atlantic and Europe.

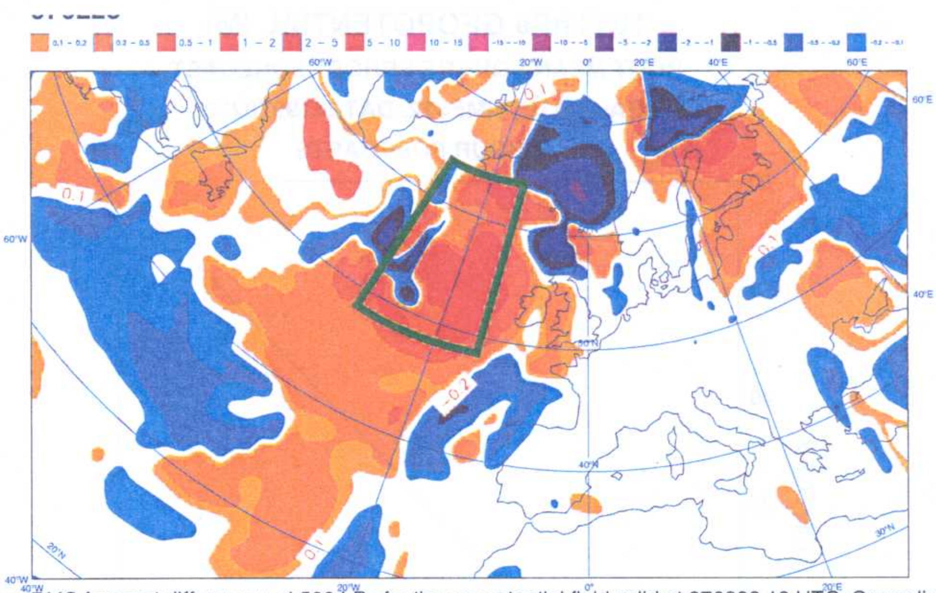

Figure 13: 24 hour RMS forecast differences at 500 hPa for the geopotential field valid at 970223 12 UTC. Green line is the FVA. Yellow shaded contour show larger error and blue smaller error in CONTRFX than DROPFX. Contour in dam.

Exps	For. error	For. err. variation
CONTRFX	92.63	0
DROPFX	83.78	-9.5%
CONTRFX-$\delta e(t_0)$	87.40	-5.6%
CONTRFX-2$\delta e(t_0)$	82.26	-11.2
CONTRFX+$\delta e(t_0)$	104.46	+12.7%
CONTRFX+2$\delta e(t_0)$	114.47	+23.5%

Table 4: Total energy norm of 24-hour forecast error

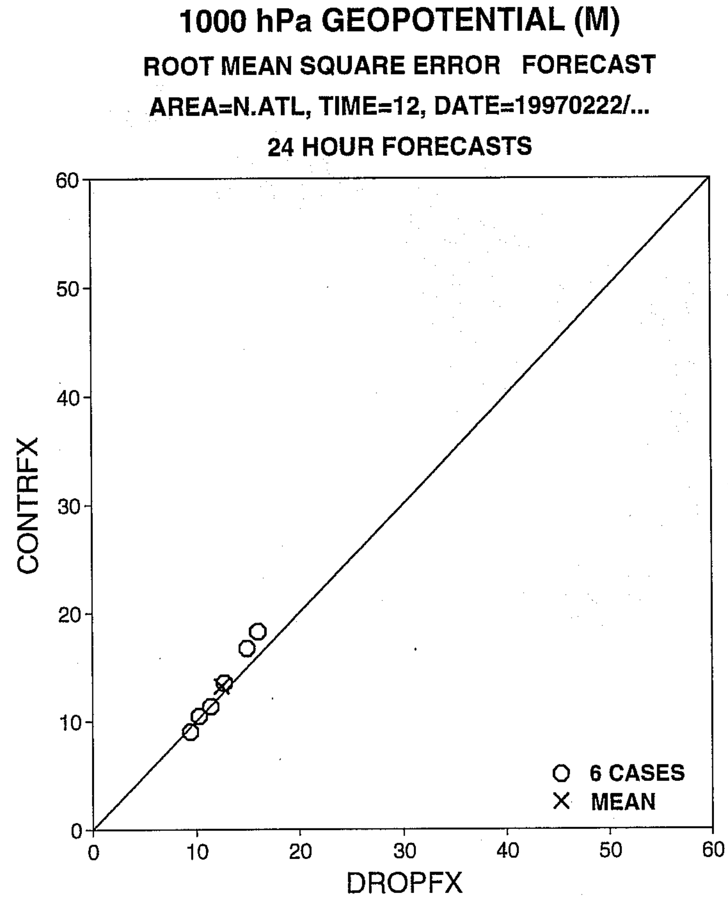

Figure 14: Scatter plot of 24 hour RMS forecast error at 1000 hPa for geopotential field for the period 970222-970228 for DROPFX versus CONTRFX

4. Conclusion

The use of wind and temperature profiles from dropsonde observations in the analysis and forecast has been studied in different contexts. Dropsondes can be released in areas where tropical storms are developing, helping to detect and follow the evolution of very strong meteorological features such as hurricanes. Moreover, dropsondes can be deployed in some mid-latitude regions that are considered to be of crucial importance for cyclone evolution. Dropsondes have been deployed recently in three measurement campaigns. In the Tropical Cyclone campaign (summer 1998), aircraft released the sondes in hurricane areas. These observations have been found to improve the analyzed structure of the tropical cyclones and to give better forecast in terms of track and mean wind speed of the hurricane. A more relaxed quality control for wind dropsonde observations has been shown to give better results in the analysis and the following forecast. Because the analysis tends to filter the small-scale information coming from the dropsonde data, local changes to the model error covariance matrix in the vicinity of the storm is expected to enable better use of such data.

Recently, some numerical weather prediction centres have organized campaigns for targeted observations in data-sparse regions. The main purpose was to improve the weather forecast skill in the short and medium range by improving the analysis in regions where errors are fast growing. The experiments performed for the FASTEX and NORPEX missions, have shown a positive impact of dropsonde data in the so-called forecast verification area. The 1-2 day error forecast has been reduced in FVA by assimilating wind and temperature observations from deployed sondes.

Moreover, a positive impact in the short and medium range forecast has been found over the North Atlantic and Europe (FASTEX) and Europe and the Northern Hemisphere (NORPEX). The results obtained are encouraging, although the benefit of assimilating dropsondes can be lessened in case of advanced geostationary satellite wind data are also assimilated in the same areas (NORPEX). In order to justify the high cost of additional in-situ observations, further experimentation is needed as a large amount of information is also provided by conventional satellite data. Some results also indicate that the forecast error reduction obtained using the dropsondes is very close to one obtained by adding to the analysis a factor of the pseudo-inverse initial perturbation (FASTEX). Again, the cost of using different strategies for improving the forecast skill has to be evaluated.

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