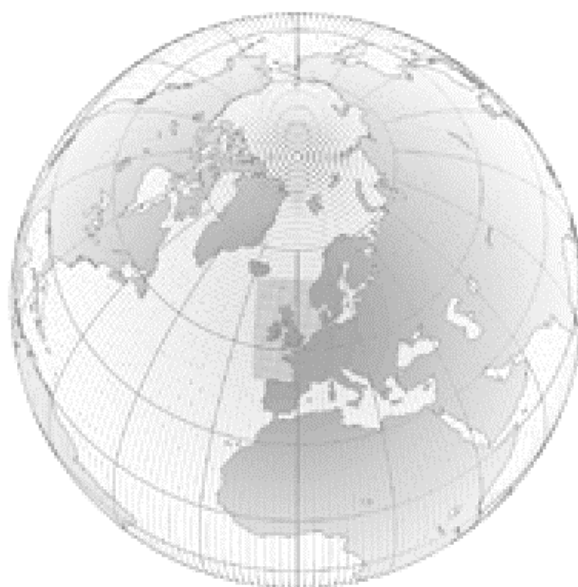


# Numerical Weather Prediction

An Error Breeding System for the Met Office 'New Dynamics'



Forecasting Research Technical Report No. 413

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A decorative wavy line that starts on the left, dips down, rises to a peak, and then dips down again towards the right.

# An Error Breeding System for the Met Office New Dynamics

Adrian Semple

27<sup>th</sup> November 2002

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## 1. Project Background & Aims

An Errors of the Day project was first initiated at the Met Office in July 1997, with the system ready for low resolution trials in Summer 1999 (VSDP 26, VTDP7, DADP2, DADP5). An assessment of the system on the Unified Model forecasts showed that the overall impact of the system was neutral, but with some notable positive impacts identified through individual storm forecast case studies (NWP Technical Report No 357, June 2001).

This project aims to develop a new error breeding system to work in association with the Met Office's new non-hydrological formulation of the Unified Model (the 'New Dynamics').

## 2. Theoretical Motivation

### 2.1 Limitations in the determination of the initial model state

A model analysis is the best possible estimate of the state of the atmosphere (i) within the confines of current data processing & modelling technology and (ii) within the limitations of determining the state of a chaotic system.

The errors in an analysis are minimised by the former – the efficient use of data assimilation techniques that produce a statistical combination of current observations and a background state. The background state for the analysis is provided by a 6 hour forecast which is itself a good representation of the current state of the atmosphere due to the model's property of acting as a transporter of information from data rich areas to data poor areas. However, the chaotic flow regime of the atmosphere imposes a limiting factor that dictates how good a forecast can be relative to reality: chaotic structures in the initial atmospheric state mean that small errors in the representation of the analysis can grow rapidly in model forecasts so that the skill of a forecast can decrease to zero within a couple of weeks.

The small errors that are present at the start of every analysis cycle can therefore have a huge effect on the skill of the forecast depending on the location, degree and intensity of the error structures. Errors in unstable areas of the atmospheric model may cause poor forecasts at short (less than a day) run times. Errors in more stable regimes can have effects at much longer run times due to the transportation of that error to an unstable region days or weeks later.

### 2.2 Error 'breeding' in a conventional analysis cycle

Toth and Kalnay (1993, 1997) considered a conventional analysis cycle from the point of view of error growth within it. During an analysis cycle, observations are combined with a background field to produce an analysis. For an error to have an impact on a model forecast, it must be organised so that it projects onto an unstable mode of the atmosphere and grows rapidly. Errors due to observations are random because they largely originate from independent instruments that are often randomly located across the globe.

In contrast, the repeated use of a short-period forecast as a background field for the analysis has the effect of organising errors so that they develop and project onto unstable model states. The origins of errors in the background field are rooted in the previous analysis cycles:

- i) a lack of complete data coverage during previous analysis cycles,
- ii) observational errors during previous analysis cycles,
- iii) approximations in analysis techniques during previous cycles.

The assimilation process is such that where observations are used, the observations reduce the error due to the background field so that the analysis should be closer to reality than the background field. However, because the errors in the background field are organised, the component of the error present in an analysis due to the background field is a source of rapidly growing errors. At every analysis cycle, the error is reduced again by the introduction of new observations, but rapidly grows in the short period forecast run from it so that the error is large again in the next background field. If a background error is such that it occupies a data sparse region of the globe, then it may not be reduced at all due to the absence of observational data. In this case, the error will be permitted to rapidly develop for at least a further analysis cycle or else until observations coincide with the error so that it may be reduced.

As growing errors will project onto baroclinically unstable modes where the errors and the unstable modes coincide, fast error growth in a model forecast (and therefore the background field) is highly dependent on the atmospheric flow. This means that both the shape and magnitude of the error field associated with a background state will vary from day to day as the synoptic pattern changes.

In 3D-VAR, the background error covariance matrix is calculated via the 'NMC' method in which the differential is calculated between the T+48 and T+24 forecast fields, and then averaged over a two week period in order to achieve sufficient statistics. The main drawback with this method however, is that the

averaging process washes out the synoptic variability (and therefore the fast growing errors) that occurs on a daily basis. This effectively means that the background error covariances are assumed to be constant in time and do not vary from day to day.

A more effective data assimilation system should contain a detailed knowledge of the fast growing, synoptically dependent error structures. This of course is not possible, as we have no a priori knowledge of the error pattern in the background, so a suitable method for the estimation of background error covariances is therefore required.

### 3. Ensemble Forecasting and Error Breeding

#### 3.1 Ensemble Forecasting

The motivation behind the development of ensemble forecasting techniques acknowledges the chaos inherent in any atmospheric state. Specifically, because of chaos, small perturbations applied to the initial state can have disproportionate and unpredictable effects so that the trajectory of the resulting forecast differs wildly from the trajectory of the forecast in the absence of the perturbation.

Ensemble forecasting systems therefore operate by perturbing the control analysis with small perturbations, running forecasts from the perturbed analyses and observing the resulting spread of the forecast trajectory. The probability distribution of the forecasts is then indicative of the reliability of both the initial analysis and of any particular forecast. Essentially, the ensemble forecast technique probes how sensitive the model analysis of that particular atmospheric state is to analysis errors by representing the errors as perturbations, and then disclosing their effect on the resulting forecasts.

#### 3.2 The Conventional Analysis Cycle – a Perturbation Forecast

Toth and Kalnay (1993, 1997) likened the conventional analysis cycle with that of running a perturbation forecast model of the atmosphere. In their analogy, the true state of the atmosphere is represented by the analysis, and the analysis error is represented by the perturbation applied to that state of the atmosphere. The deviation of the short-period forecast from the atmosphere is a result of the rapid growth of the errors present in the analysis that are primarily there due to the background field.

An ensemble forecast system with period of 6 hours (so as to mirror the generation of the background field), running alongside a conventional analysis cycle can be used to identify regions in the background field for the next analysis cycle which are unstable with respect to small perturbations. These unstable regions are the locations in which rapidly growing background errors would lurk and can therefore be used as an indication of background error.

Iyengar et al. (1996) verified that the spread of the NCEP ensemble system, with short-period forecasts, correlated well with the magnitude and spread of errors of the background field.

#### 3.3 The Error Breeding System (EBS)

Random perturbations applied to a model analysis provide a new analysis that is indiscriminately perturbed by varying (random) degrees. However, as discussed earlier, random perturbations are unlikely to project along the few very unstable states in the model atmosphere so that the difference between the control and perturbed short-period forecasts will not be so great (slow-growing random perturbations will grow into dynamically unstable modes in longer-term (~days/weeks) forecasts). In this case, the random perturbations will do little to disclose the very unstable states in the model atmosphere where fast growing errors lurk. In order to effectively sample the uncertainty in the initial background field then, one must apply perturbations to the background which are similar in magnitude and structure to the actual errors.

To achieve this, Toth and Kalnay adapted the NCEP ensemble forecasting system to produce the Error Breeding System (EBS). In the EBS, the output of one cycle is used as the input to the next cycle. The result is that the ensemble output from a cycle of the EBS discloses the unstable states that are present within the background field of the next analysis cycle, and the next analysis cycle is then perturbed in these regions.

A schematic of the EBS is illustrated in Figure 1. The cycle is started by adding and subtracting random perturbations to a control analysis, A1. This produces two analyses A1(+) (generated from the analysis which has had the random perturbations added to it) and A1(-) (generated from the analysis which has had the random perturbations subtracted from it). Two short period (6 hour) forecasts (F1(+) and F1(-)) are ran from each of these analyses.

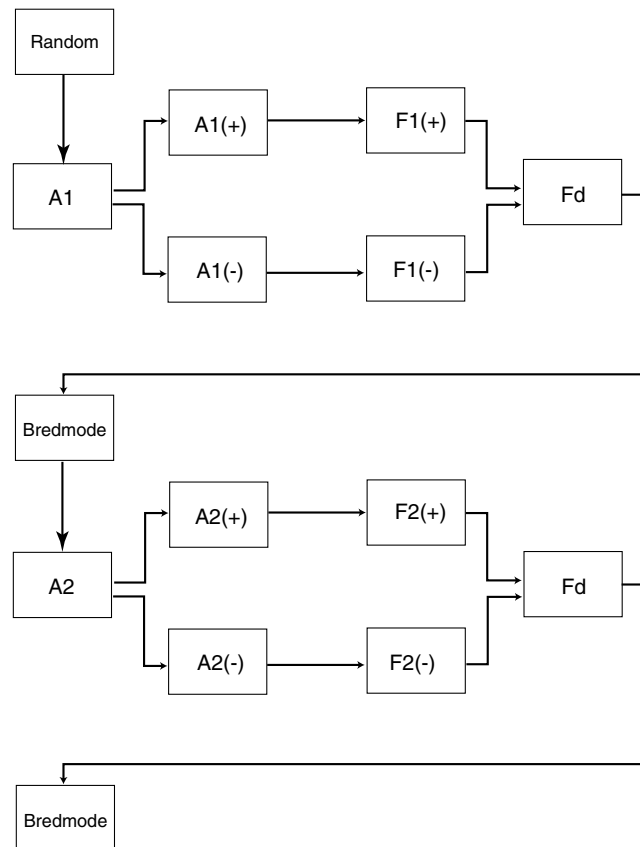


Figure 1. Schematic of the Error Breeding System. The labels are referred to in the text.

The next stage of the error breeding system takes a difference of the two forecasts (Fd). Fd cannot be used directly to perturb the analysis of the next cycle as the forecast differences will be too large for analysis perturbations. Fd is therefore reduced by a rescaling back to the magnitude of the original perturbations. These rescaled forecast differences have been termed the 'Bredmode' having been bred from the preceding cycle(s) of the EBS.

### 3.4 Coupled EBS and VAR System

The normal operation of 3D-VAR involves the use of background error covariance information in order to define a region of influence for each observation being assimilated. As discussed in Sec. 2.2, current background error covariances estimated via the NMC method are only representative of climatic structures and so will fail to optimally extend observational data away from the point at which the observation has been taken.

The forecast difference dump (Fd) generated by the EBS, qualitatively represents the spread of the error breeding ensemble. Fd therefore identifies the regions in the control analysis of the present cycle that are unstable to small perturbations - and are therefore sensitive to small errors - and regions of the background field in which the analysis errors will have grown. Fd may therefore be used as a proxy for the synoptically-dependent, rapidly-growing component of the background error covariances.

In 3D-VAR, the minimisation of the cost function is achieved by a statistical minimisation of the state which best fits the observations and background field and with observational extent dictated by the background error covariances. For a coupled EBS and 3D VAR system, the observational extent is given additional degrees of freedom which are dictated by the Fd pattern. This means that observations are given variable weighting in 3 dimensions depending on the local bredmode activity. An observation being assimilated in the centre of a bredmode for example, would have its influence extended to occupy the bredmode volume because this region of the background field is one where analysis errors in the previous cycle will have caused larger errors in the current background field. It is therefore appropriate that given any new observation in the current analysis cycle, that the analysis should be weighted closer to the observation rather than the background field.

## 4. Developing the ND EBS

### 4.1 Introduction

In developing an error breeding system for the ND, problems were encountered that forced modifications to the way in which the ND EBS operated relative to the OD EBS. This section discusses some of those problems and explains the investigations and the solutions that were developed to overcome them.

### 4.2 Initial Random Perturbation Generation

In normal operation, the EBS uses perturbations from the previous cycle for the perturbations to the current cycle. However, to start the EBS suitable random perturbations must be used. In the OD EBS, random perturbations were supplied from a random number generator. However, it was found that forecasts from analyses perturbed with random numbers generated in this way caused imbalances that caused the UM5.2 model to crash in its early timesteps. This section documents the research that was carried out that enabled suitable random perturbations to be found.

#### 4.2.1 Purely random perturbations

Random perturbations were generated by new code as part of the 'AlterData' utility of VarProg\_UMFileUtils via the 'EBSRandom' option. EBSRandom operates by generating a random field that possesses the same standard deviation as the newly-generated uninitialised analysis. An argument supplied to EBSRandom allows the magnitude of the perturbations to then be scaled to vary their impact: an argument of 10.0 will generate a perturbation size ~ a full field value. Generally therefore, arguments of 0.1 or less (resulting in perturbations ~ 1% full field value) are selected for initial perturbations for the EBS. Only those fields specified in Sec. 5.4 are operated on.



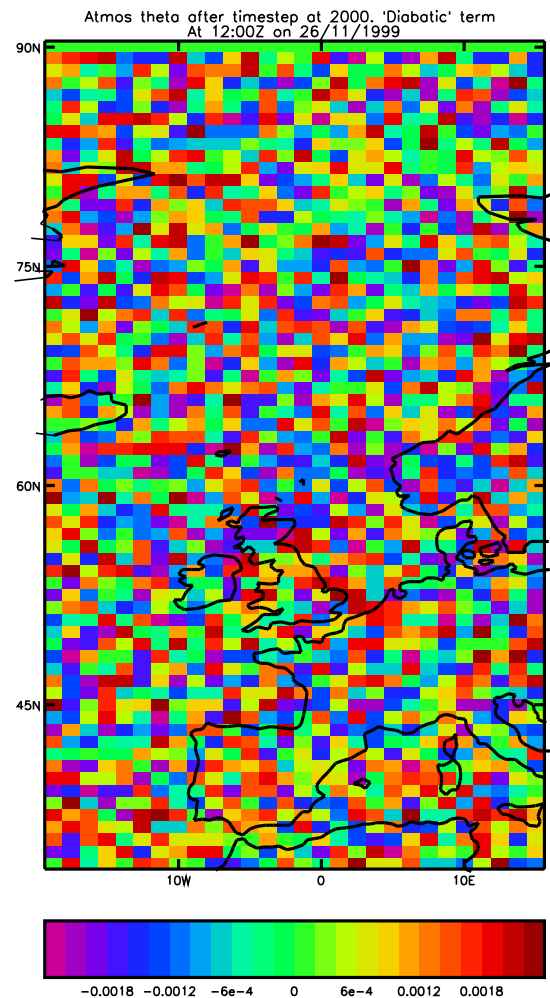


Figure 2 An example of a random field generated for initial perturbations for the Error Breeding Cycle. The field shown is theta on model level 10. Full field values are  $\sim 300\text{K}$ . Weighting argument for EBSRandom was 0.0001.

It was found in developmental stages that random numbers in polar rows caused the ND UM to crash in the microphysics during the third timestep. It was therefore necessary to set the polar row increments to zero in the random field prior to file generation.

Random perturbations were initially generated on the full N144 gridscale (shown in Figure 2) and scaled so that their impact was small. Initial runs of the EBS did not show any significant development in the storm track regions. The magnitude of the random perturbations were then gradually increased and some development was observed in the storm track regions indicating that the EBS was working to some degree. However, the appearance of these bredmodes were distinctly 'blocky' and they did not grow horizontally sufficiently to represent useful bredmodes.

An additional problem was that the magnitude of the bredmode structures were  $\sim 10\%$  the desired magnitude if they were to be of the order of NMC errors. The magnitude of bredmodes are designed to spin-up over a period of  $\sim 7$  days, however, and the EBS was monitored over this period. The result was that the bredmode magnitude saturated  $\sim 10\%$  level and did not show any signs of increasing. The only option therefore was to try and increase the magnitude of the initial random perturbations.

On increasing the impact of the initial random perturbations further, the EBS T+6 forecasts would crash in the first timestep of the first cycle. This was investigated thoroughly and it was concluded that the ND was unable to rectify the noise introduced into the initial analyses by the addition and subtraction of the random perturbations.

This problem was not encountered in the trials of the 'Old Dynamics' EBS.

#### 4.2.2 Purely random perturbations with size > gridlength

It was considered possible that the random perturbations on the gridscale as discussed above were too fine for the EBS to develop any consistent forecast differences over a reasonable spin-up period. Additionally, the gridscale perturbations were unsuitable for EBS initial perturbations as it was impossible to increase their magnitude to achieve a suitable magnitude of bredmode development.

New code was written for the random perturbation routine in VarProg\_UMFileUtils that allowed the user to specify the size of the random perturbations in terms of number of gridpoints. The idea was that this would provide more consistent perturbations for the model to develop and that this would allow their impact to be increased beyond that achievable with gridscale perturbations.

Figure 3 shows the bredmode structure (pressure on rho level 1) after 7 days spin-up of the EBS. The 'blocky' structures evident in the field are characteristic of those observed in the previous trial for random perturbations generated on the gridscale. These bredmode structures would be unsuitable for 3D-VAR as their influence both horizontally and vertically (not shown) is too restricted and would more likely have a detrimental effect on the extent of the observation being assimilated.

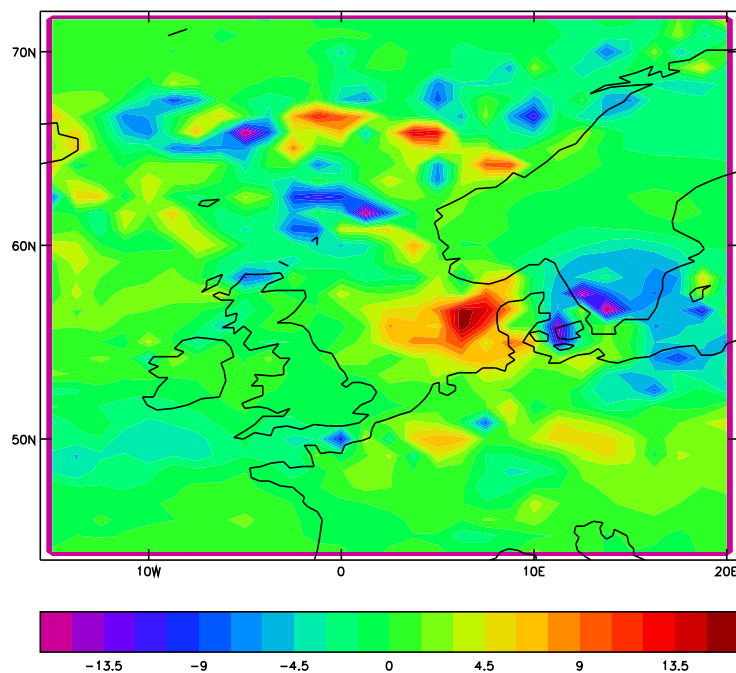


Figure 3 Bredmode structure - pressure on Rho levels, level 1 after 7 days spin-up. The 'blocky' structures evident to the north of the UK are characteristic of that observed across the global domain. By this time, the growth of the bredmodes as measured by the KE norm, had saturated indicating that no further growth was expected.

Further trials with generating random perturbations by this method showed that the degree to which the impact of the perturbations could be increased without the model crashing was insufficient to develop bredmodes with a magnitude of NMC errors.

#### 4.2.3 Increasing Diffusion in the EBS forecast

A characteristic of the New Dynamics is that the model fields are not 'smoothed' as much as those in the Old Dynamics. Along with the fact that the OD EBS was ran at climate resolution, this may have resulted in the OD EBS not being prone to the blocky nature encountered here. One way in which the degree of smoothing can be increased in the ND is by increasing the horizontal diffusion in the model.

Although the model was successfully ran with increased horizontal diffusion, the degree to which the diffusion could be increased without the model becoming unstable was relatively small. The result was that the increased diffusion achieved was insufficient to produce the desired effect of larger horizontal bredmode structures.

#### 4.2.4 ‘Balanced’ random perturbations

It was postulated that the ‘pure’ random perturbations discussed above could be causing the model to crash because of the imbalance that they introduced into the model analyses (perhaps the ND is less tolerant of imbalance than the OD).

NCEP produce random perturbations for their EBS by the subtraction of two randomly chosen analyses from their archives (Toth, private communication). It was thought that this may overcome the problem of the ND model crashing due to instability problems because random perturbations produced in this way should be largely in balance, whilst those produced in the ‘pure’ random way will (by definition) be imbalanced.

This was performed from two suitable files and the result is shown in Figure 4. Although completely different in structure to the ‘pure’ random perturbations of Figure 2, the actual structures within the initial perturbations is largely irrelevant as the random modes will diminish over a period ~7 days as the EBS cycles.

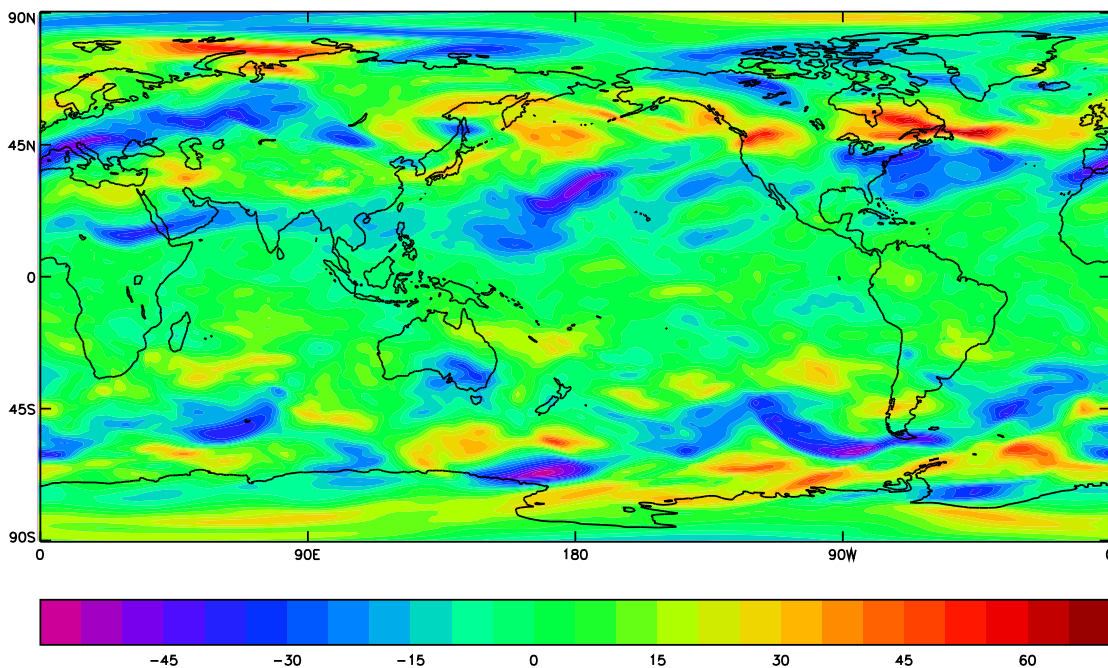


Figure 4 Initial random perturbations, u wind component, level 19. These perturbations have been generated by the subtraction of a random T+6 field from the start T+6 field of the trial.

These random perturbations were used with a small scaling factor so that again their impact could be controlled (the field above was scaled by 0.001). The EBS was observed to cycle successfully, with significant development in the storm track regions, but again the ‘blocky’ nature of the bredmodes meant that they would be unsuitable for the purpose of data assimilation.

The impact of the initial random perturbations were then increased successfully beyond that achieved with the ‘pure’ random perturbations (by scaling the above field by 0.1). The results after one day spin-up showed a promising increase in the horizontal extent of the bredmodes so that they occupied a larger area.

After 10 days spin up of the EBS, although the horizontal extent of the bredmodes had increased significantly, the ‘blocky’ nature of the bredmodes returned. The use of ‘balanced’ random perturbations had successfully solved the problem of being able to increase the magnitude of the perturbations to a suitable level but had not entirely reduced the ‘blocky’ characteristics of earlier runs.

#### 4.3 Smoothing of the forecast difference fields

The effect of a single cycle of the EBS on the balanced random perturbations shown in Figure 4 is shown in Figure 5(a). The structures already show significant noise and it is likely that such fields will rapidly become unsuitable as perturbations for the following cycle thus resulting in the blocky bredmode structures observed thus far.

To overcome this problem, a smoothing routine was written and incorporated in 'AlterData' as part of VarProg\_UMFileUtils. This smoothing routine works by calculating a running average across a 3 x 3 grid and setting the middle gridpoint to the average value. The process is repeated globally. The smoothing is applied to the forecast difference file generated as the difference between the two perturbed forecasts at each stage of the EBS. This smoothed forecast difference file is used together with the bredmode from the previous cycle (and used as analysis perturbations for this cycle) in the rescaling procedure to produce a bredmode for the current cycle (the rescaling is therefore calculated by the ratio of two smoothed fields).

Figure 5(b) shows the effect of the smoothing routine on the generation of the first bredmode in the current trial. It is clear that the smoothing routine is successful in producing a realistically coherent field with reduced noise and does not appear to destroy the overall bredmode pattern.

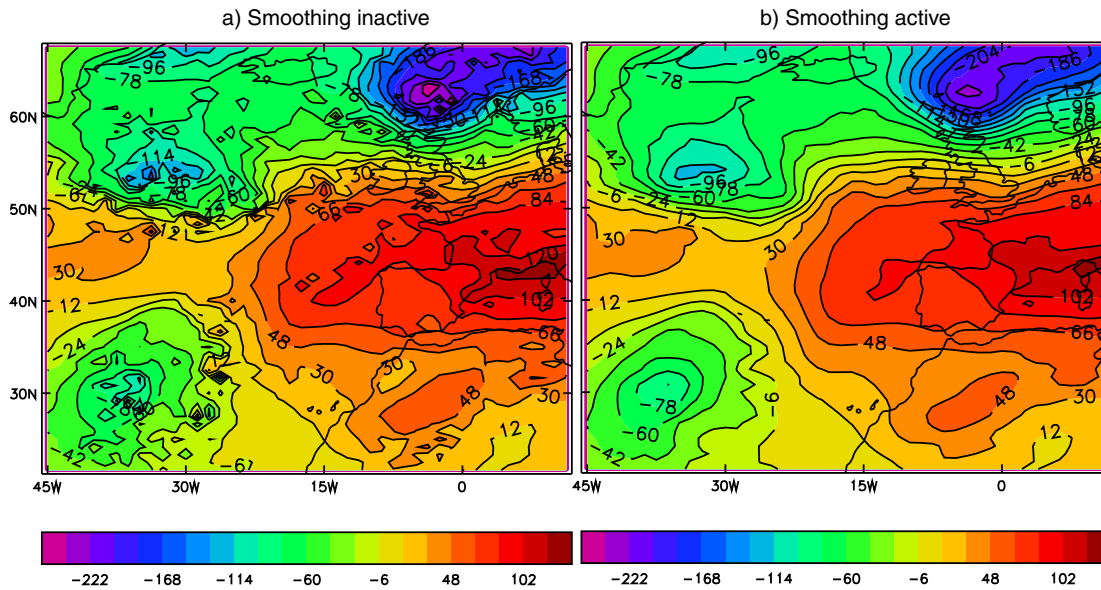


Figure 5 The effect of the smoothing routine on the bredmode generation. This bredmode (p on RHO level 1) was generated after a single cycle of the EBS (6 hours). The EBS was initiated with the perturbations shown in Figure 4. (a) Generated from a raw forecast difference field. (b) Generated from a smoothed forecast difference field.

The evolution of the bredmodes over six cycles is shown in Figure 6. At the top of the figure, the effect of the smoothing on the random perturbations are shown. By cycle 2 there are already signs of the blocky nature discussed above where the smoothing is inactive. With active smoothing the structures show more uniformity. Cycle 3 shows that with no smoothing the bredmodes have already broken down into small high intensity boxes, usually not more than 1 or 2 gridpoints across. In contrast, with smoothing active, coherent structures are visible.

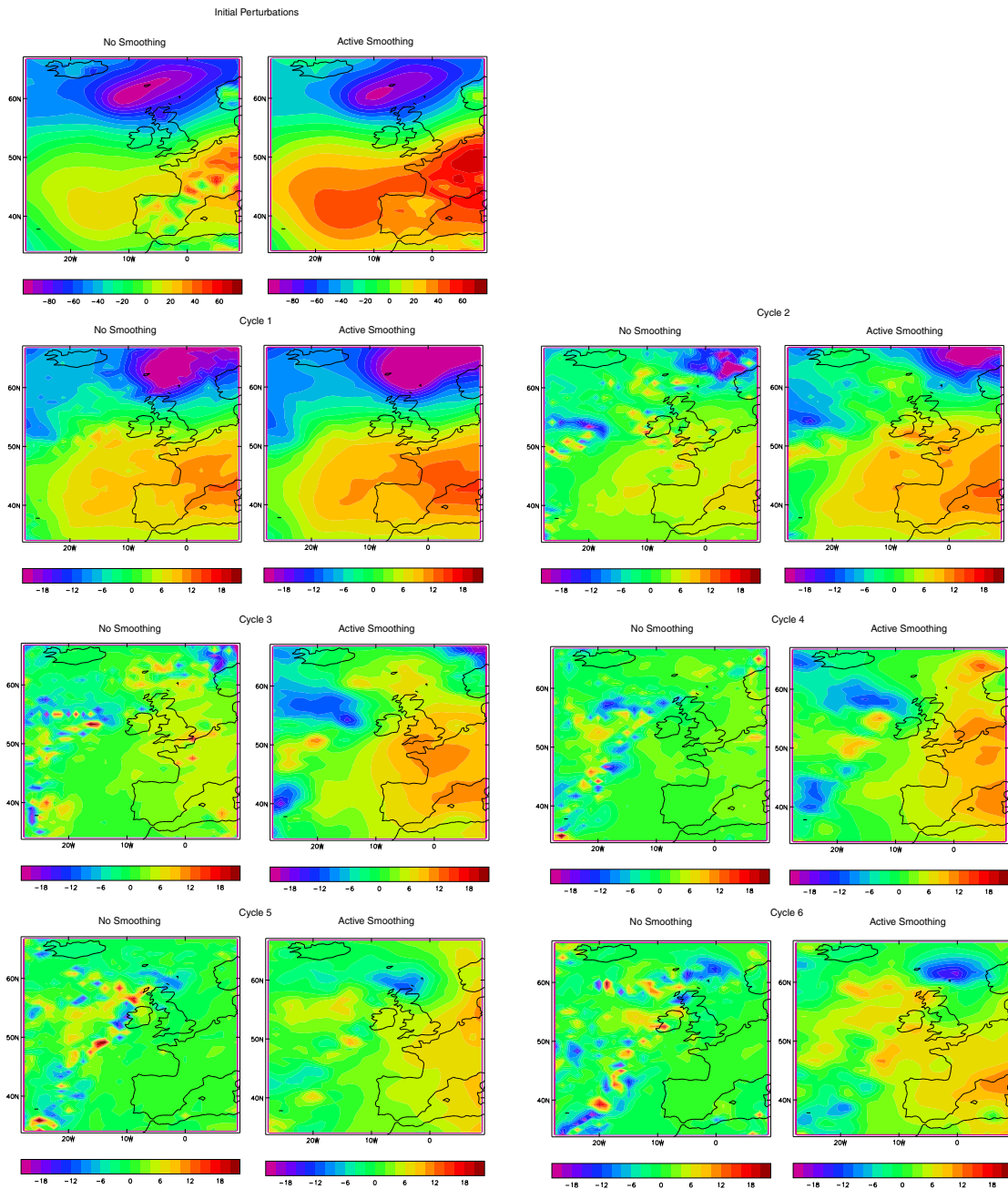


Figure 6 The effect of the smoothing routine over the first 6 cycles of the EBS. At the top are the initial perturbations that are applied to the start dump. Each pair of figures then compares the subsequent evolution of the EBS with smoothing active and inactive.

The importance of this is that each of these fields will be used as the perturbations to the next breeding cycle. The fields with the small gridpoint bredmodes never develop much beyond these structures even when left spinning-up for over 10 days. With active smoothing structures are observed to grow and diminish in both horizontal intensity and in magnitude. An example of this can be observed as the negative (blue) bredmode structure approaches the UK from the west in cycle 2, diminishes in cycle 4 and 5 and then re-intensifies in cycle 6.

#### 4.4 Summary

Two main changes have been incorporated into the ND EBS that were not part of the OD EBS process:

- (i) random perturbations are generated by the subtraction of two randomly chosen analyses so that the perturbations are balanced.

- (ii) A 3x3 gridpoint smoothing is applied to the forecast difference field in order to reduce the noise and produce a bredmode that maintains the development of the most unstable modes during the cycling of the EBS.

It will be shown in Section 6 that the bredmode structures resulting from these techniques are meteorologically sound and are not the product of the smoothing technique nor of the random perturbation generation method.

## 5. The ‘New Dynamics’ Error Breeding System

### 5.1 Suite details

The UM version used in both the EBS trial and Control trial is the current operational version of the ‘New Dynamics’ : UM 5.2 G4.10.

- UM5.2 G4.10 Dec 99 Control trial – sbgga.
- UM5.2 G4.10 Dec 99 EBS trial – sbgge.

The trial period chosen for the assessment of the EBS was 26 November – 30 December 1999. This period was chosen to be consistent with that ran for the OD EBS on which extensive assessment was carried out (Semple, 2001). This was to enable direct comparisons between the performance of the ND system relative to the OD system.

In producing a UM 5.2 G4.10 suite for the trials the current operational versions of the OPS and VAR were initially chosen. However, it was found that the OPS would crash in ATOVS pre-processing suggesting that the current version of the OPS was incompatible with Nov 1999 data. A slightly earlier version of the OPS was used to remedy this problem: there is not expected to be any impact on the performance of the UM from this earlier versions.

- UM – UM5.2 G4.10
- VAR – Stable version 18 (1.4.1)
- OPS – Stable version 11 (1.2)

The differences between the EBS trial and the control trial are merely the extra tasks required to run the EBS and the addition of the EBS dump into the VAR analysis task after a suitable spin-up period.

### 5.2 Resolutions of the Components

The UM, VAR and EBS are all coded on the ‘New Dynamics’ Arakawa-C / C-P grid with 38 levels. For trial purposes both the UM and VAR are ran at the same horizontal resolution of 288x217.

The OD EBS trial was ran at a horizontal resolution of 96x73. Due to unresolved problems with the ND routine to reconfigure from 288x217 to 96x73, the decision was taken to run the ND EBS at the higher resolution of 288x217. These problems have now been rectified, and it should be now possible to run the EBS at a lower resolution if required.

This means that the UM, VAR and EBS are all operating at the same resolution, without the requirement for reconfigurations.

### 5.3 System Architecture

The Architecture of the coupled UM/VAR/EBS system is shown in Figure 7, which shows one complete analysis/EBS cycle. Files attributable to a specific system have been given the same symbols: UM – yellow boxes, VAR – green ovals, EBS – blue boxes.

The stages of an EBS/VAR coupled system may be described as follows (moving from top left to bottom right).



# UM 'New Dynamics' + 3D VAR + EBS

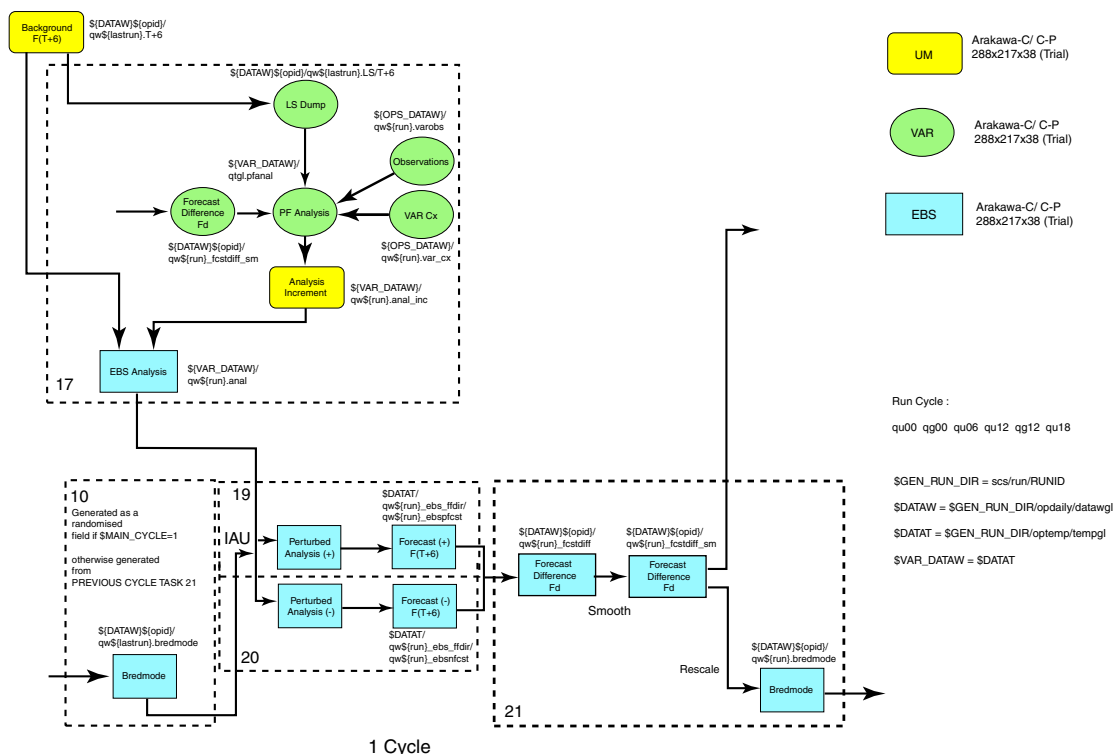


Figure 7. The EBS and its interface with VAR and the UM in an operational system. Files ‘attributable’ to the UM, VAR and EBS are shown as yellow boxes, green ovals and blue boxes respectively. Dashed boxes split the system up into constituent tasks (numbered) of the Suite Control System (SCS). Filenames of the components as used in the trial are specified above each symbol. Note that all components in the trial are at the same resolution.

1. A UM Background field is reconfigured to VAR resolution to produce the LS (Linearisation State) Dump.
2. VAR operates on the LSDump, Observations, model values at the observation points (VAR Cx), and EBS Dump (the forecast difference file) to achieve the PF Analysis state.
3. Operationally, the PF Analysis is reconfigured to UM resolution to produce the Analysis Increment dump (although this not necessary in the trials as all components are ran at the same resolution).
4. The analysis increments and the background are added together to produce an uninitialised analysis.
5. If the EBS is to be ran at a different resolution than the UM, the uninitialised analysis is reconfigured to EBS resolution to produce the EBS analysis (not necessary in the current trials).
6. If the first cycle of the EBS, a random field is generated. This provides an initial bredmode file to act as perturbations to the EBS. Otherwise the bredmode is the output of the previous EBS cycle (see 10)
7. The bredmode is added to and subtracted from the EBS Analysis via the Incremental Analysis Update (IAU). This provides a (virtual) pair of perturbed analyses from which a pair of T+6 forecasts are ran (to mirror the generation of the background field for VAR). Note that the IAU is used in dummy mode – all increments are added at the same time.
8. A forecast difference is calculated Fd, and then smoothed. This is used as input to VAR for the next analysis cycle.
9. In the EBS, a difference is computed between the two forecast fields, Fd.
10. Rescaling is performed to reduce the forecast differences down to the chosen magnitude (the bredmode). This provides the perturbations for the next cycle of the EBS.

In the early cycles of the EBS the bredmodes will be dominated by the random perturbations introduced to start cycle 1. However, after approximately 40 or 50 cycles (10 days+) the random modes are replaced by the most rapidly growing modes which are indicative of synoptically dependent background errors.

## 5.4 EBS Fields

To avoid unnecessarily large model dumps, bredmode perturbations are created for the ND prognostic variables only :



Model Variable	Stash Code
U	2
V	3
Theta	4
Specific Humidity	10
W	150
Density*R*R	253
Pressure at RHO levels	407

Note that a ND model dump contains Exner (stash code 255) as it's pressure variable, but this must be converted to pressure at rho levels (stash code 407) before use by the IAU as this pressure variable is used by VAR. Pressure at rho is converted back to exner at the end of the VAR cycle to be used by the UM.

## 5.5 Initial Random Perturbations

In full operational mode, the Error Breeding System works by using perturbations generated from the previous EBS cycle so as to efficiently 'target' the correct regions with appropriate perturbation sizes. For the first cycle of the EBS, we have no knowledge of the rapidly growing background errors so that random perturbations must be used.

Random perturbations in the EBS trial were generated by the method for developing 'balanced' random perturbations described in Sec. 4.2.4.

## 5.6 Perturbed Analyses

The above description of the EBS discusses the creation of perturbed analyses from which forecasts are ran. However, it should be noted that the ND EBS does not create these files explicitly. Instead, the Incremental Analysis Update (IAU) has been used in a dummy-mode to add and subtract the bredmode to the EBS (uninitialised) analysis. In the mode used here, the bredmode is added to the analysis all at once at the start of the IAU period – rather than over a 6 hour period as in the mode of the IAU in the analysis cycle.

The advantages of using the IAU to do this rather than using a utility to simply add the bredmode to the analysis are that the IAU has in-built consistency checks to prevent spurious model values that may otherwise occur when two files are added together. This should therefore reduce the chances of model failure and make the EBS more robust.

## 5.7 The Rescaling Process

As discussed above, a rescaling of the forecast differences is required so that the bredmode perturbations are of a suitable size with which to perturb the ensemble analyses. In the ND EBS, the rescaling factor is calculated via the same method as that employed in the OD EBS (Barker, 1997).

The idea is that during an EBS cycle, analysis perturbations will grow so as to produce forecast differences of a size that are of the order of magnitude of NMC errors and are therefore suitable for use within VAR. To produce the analysis perturbations for the following cycle, these forecast differences are reduced so that they will grow again and produce new forecast differences again of a suitable size.

The rescaling process used in the ND EBS is shown schematically in Figure 8, in which the first 5 cycles of an error breeding cycle are shown. The Rescaling factor is a product of two factors:

- 1) Growth rate factor. The forecast differences are reduced by the growth rate at each stage. This is designed so that, assuming a growth rate is constant in two successive cycles, the forecast differences produced at the end of cycle  $n$  will be reduced back to the size of the original perturbations of cycle  $n$ . These will then grow in cycle  $n+1$  to be of the same size as the forecast differences in cycle  $n$ . In this way, the forecast difference sizes are restricted from growing out of control in successive cycles.

At the start of the error breeding cycle, in which the initial perturbations are random, the perturbed model states will grow in various directions and only a small fraction will target the most unstable (and

rapidly growing) modes. In successive cycles however, the random modes die out, and the targetting of the most unstable modes increases. This means that in the early cycles of the EBS the growth rate in successive cycles will increase so that the size of the initial perturbations for the following cycle will grow. However, as the targetting improves and the randomness declines, the growth rate will saturate and become relatively constant thus maintaining the size of the forecast differences in successive cycles.

2) Targetting Factor. The forecast differences are normalised and multiplied by a target factor. The growth rate factor alone is sufficient to maintain the magnitude of forecast differences but it does not allow the size of the forecast differences to be easily specified. This additional factor normalises the forecast differences to 1.0 so that the multiplication by the target factor results in forecast differences of a specified size.

The size of the forecast quantities referred to in the rescaling procedure are determined by the choice of a suitable norm. The ND EBS code allows the choice of any model field to be chosen as this norm via it's specification in the namelist, from which the RMS is calculated. In both the OD and ND EBS the zonal kinetic energy at ~500 hPa has been chosen as the norm. The calculation of this norm therefore uses the  $u$  field on level 19. The specifics of the process are then:

- i) The area weighted RMS zonal KE of a chosen horizontal field in  $F_d$  is calculated in a series of specified latitudinal bands. By default the three latitudinal bands  $-90$  to  $-30$ ,  $-30$  to  $+30$ , and  $+30$  to  $+90$  degrees are selected but others may be specified in a namelist. The area weighting consists of a  $\cos(\text{latitude})$  factor.
- ii) The area weighted KE within the latitudinal bands is calculated for the bredmode created from the previous cycle of the EBS.
- iii) A ratio of the two KEs is calculated to provide a rescaling factor  $R$  which is a function of latitude (or equivalently model row number).
- iv) The Rescaling factor within each of the latitudinal bands is likely to vary considerably. In order to avoid large discontinuities at band boundaries, a 5-point average is performed to the rescaling factor which smoothes the rescaling factors across the band boundaries.
- v) The forecast difference field of the current cycle is multiplied by  $R$  to produce a bredmode used as perturbations for the next cycle.

The result of the KE norm calculation on a typical bredmode file (taken from towards the end of a month's trial) is shown in Figure 9. The solid curve is an indication that the zonal KE is a good choice for the rescaling norm. The activity and predominance of the northern and southern hemispheres over the tropics is borne out well by the curve which is due to the developmental activity in the storm track regions. The southern hemisphere peak is also narrower and taller than the corresponding region in the northern hemisphere. This is due to the landmasses in the northern hemisphere breaking up the jet streams into more regions of activity – whereas in the southern hemisphere the jet stream is more continuous where the surface is predominantly ocean.

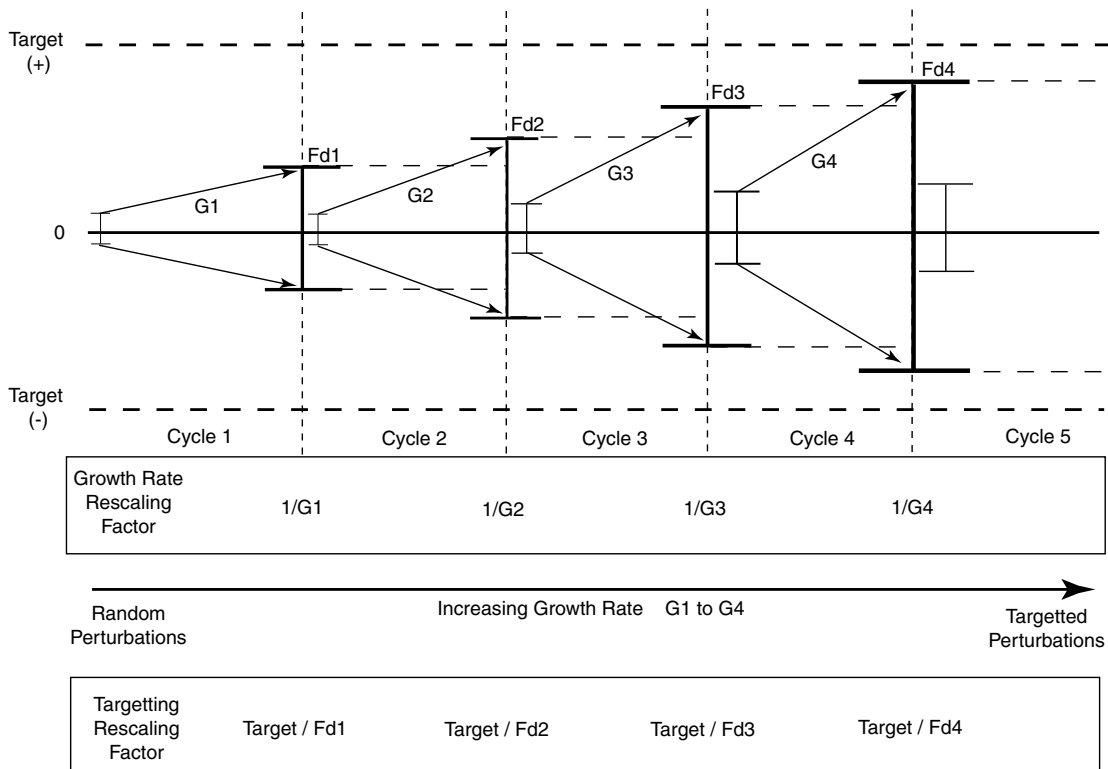


Figure 8 The Rescaling process in the ND EBS is a product of two functions: (i) A factor that reduces the forecast differences back to the size of the original analysis perturbations and (ii) a factor that forces the forecast differences to be of the specified target size.

In this case, the default three latitude bands (NH, Tropics, SH) has been chosen to calculate the average Zonal KE. The result is shown by the large dashed lines. The curves show that there may be some advantage to the error breeding system in dividing the northern and southern hemispheres into two further latitude bands – this is particularly true for the southern hemisphere which is not as broad as the northern. The effect of the 5-point averaging to remove the sharp discontinuities at the boundaries is evident on the dashed curve.

The Growth rate of the perturbations may then be calculated from the ratio of the KE norms for the bredmode from the previous cycle (i.e. used as perturbations in the current cycle) and the forecast differences of the current cycle. The stability of the growth rate at the end of each 6 hour cycle is shown in Figure 10. The figure shows that all perturbations are observed to grow (Growth rate > 1.0 ) and that the relative behaviour is similar to that observed for the OD EBS (Barker, 1997). In common to the OD EBS, the tropics is observed to generally have the lowest average growth rate, and ~1.0. Barker suggests that this is because of the highly nonlinear physical processes (such as convection) that dominate the growth at low latitudes. Whereas these nonlinear processes would have a relatively high growth rate for infinitesimally small perturbations, bredmode perturbations have been bred to be of the synoptic scale, thus making growth limited in the Tropics.

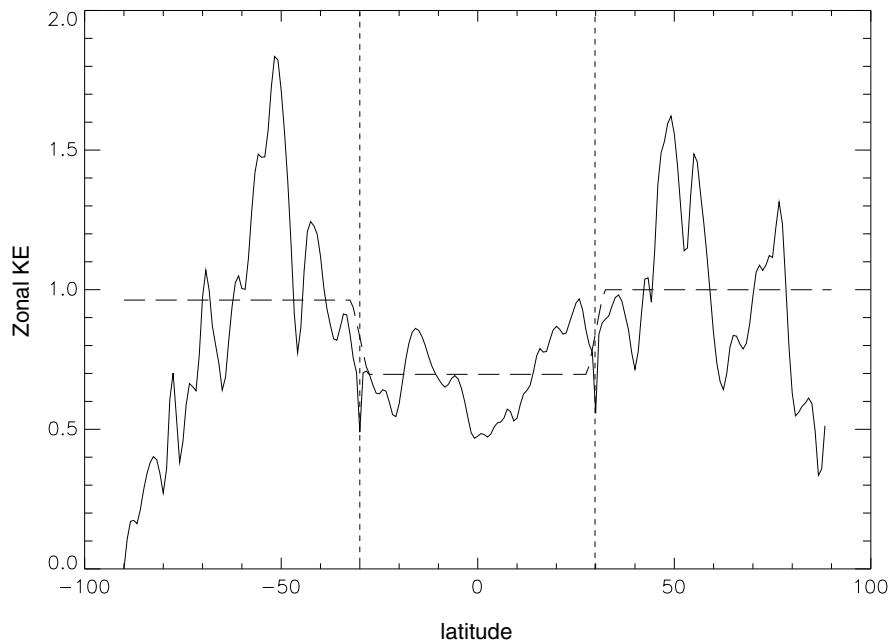


Figure 9 Zonal KE norm of a bredmode calculated on level 19. The solid curve shows the calculation of the norm across each model row, showing the characteristic peaks of KE in the northern and southern hemisphere storm track regions. The large dashed curve shows the mean of the KE in the pre-defined latitude bands indicated as vertical small dashed lines. The effect of 5-point averaging across the mean may be seen at the boundaries between the latitude bands, where the sharp discontinuities are reduced.

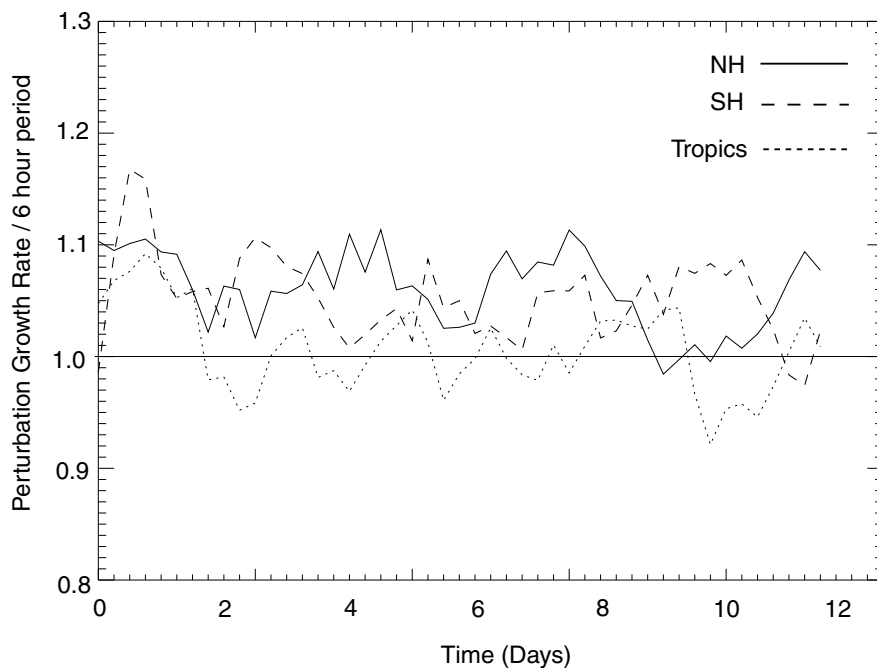


Figure 10 Growth Rate (KE norm) of (half) the forecast differences per 6 hours during the first 12 days of a trial. The growth rate of the perturbations is both positive (showing that the perturbations grow throughout the period) and stable, indicating the success of the targeting method.

With the growth rate stabilised and  $> 1.0$ , the effect of the targeting of the perturbations so that they grow to a specified size is shown in Figure 11. In this case, the targeting has been specified for the KEnorm as  $NH = 1.0$ ,  $SH = 1.0$ ,  $Tropics = 0.7$ . These values have been chosen to reflect the size of NMC errors that one would expect for the appropriate region. The figure shows that the rescaling technique successfully reproduces the targeted values to within  $\sim 10\%$ .

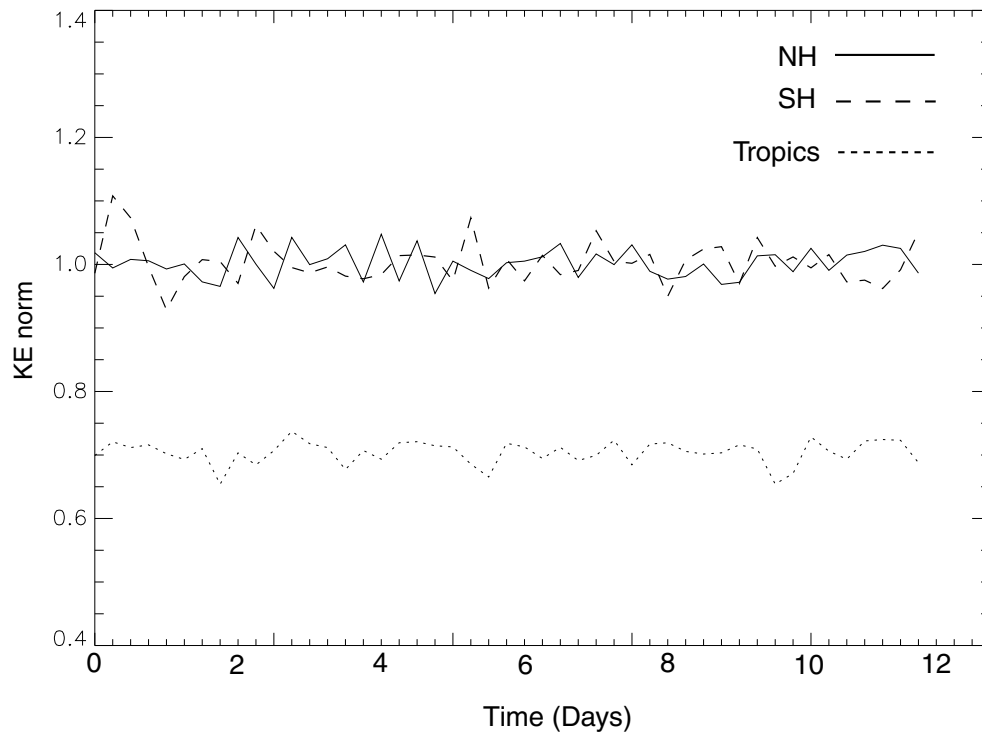


Figure 11 KE norm (model level 19) of (half) the forecast differences as a function of time during the first 10 days of a trial. Each norm has been successfully targeted to it's specified value (NH:1.0, SH:1.0, Tropics:0.7).

## 5.8 Other Notes

Because of the way that the forecast difference dumps are generated, the fixed length header information may not correspond to the look-up header information (the verification time and the data time are the same in the fixed length header, but should actually be six hours apart because they are the product of two six hour forecasts – this is correct in the look-up header). This is not a bug.

However, AnalysePF has a routine 'CheckHeaders' that verifies that the headers of the files to be used are suitable for the current model run time – this checks the fixed length header and not the look-up header. CheckHeaders therefore fails because the verification time is six hours previous to the current model run time.

To get around this problem, it was necessary to comment out the 'CheckHeaders' call in AnalysePF in the section that initialises the forecast difference file (Section 8.0 : 'Initialize error-mode state EM if EOTD\_Modes=.TRUE.').

## 6. Meteorological Assessment of the ND EBS

### 6.1 Introduction

Structures within the forecast differences highlight the differing evolution of two forecasts that have been ran from two analyses perturbed in opposite directions by the same magnitude. These differences will only occur where the evolution of the forecast from the analysis state is sensitive to the perturbations applied to the analysis, and the most sensitive regions within an analysis will be those that are developing and unstable. The result is that the forecast differences should correspond to developmental regions such as areas of cyclogenesis and frontolysis. This identification of developing/unstable model states is boosted by the error breeding method as the perturbations from the previous cycle are used to target those for the next cycle.

Meteorologically this is sound, as the targeting of a model state which is declining in its development will merely make it less susceptible to the perturbation, the forecast difference will diminish, and the bredmode structure will die. Alternatively, even the smallest forecast difference developed in the location of a new region of instability will be used to target the same region again, and the bredmode structure will grow. This process of a 'birth', 'lifetime' and 'death' for a bredmode structure is observed routinely in the error breeding products.

This section discusses the results of the EBS in terms of its meteorological context, and verifies that the error breeding system is developing the 'correct' (unstable) states. It is important to stress that the physical significance of the error breeding products is the same whether one considers the forecast differences themselves or alternatively the bredmodes, as these are just rescaled versions of the same fields.

### 6.2 Surface Development

Diagnostics indicative of surface development are a useful tool in assessing the operation of the error breeding system. In particular, a pressure variable on model level 1 is an integrated quantity that efficiently represents the overall characteristics of the bredmodes. Figure 12 shows the pressure on rho level 1 forecast difference field after 7 days spin-up from the start of the EBS (after which time random perturbations have diminished).

The figure shows that the forecast difference structures largely occupy the mid-latitude storm track regions. These structures are therefore consistent with the EBS identifying the developmental regions. Animations of these structures also confirm that the structures advect along from west to east with a similar propagation speed to the synoptic pattern, further suggesting their synoptic dependence. Animations also show that the structures change in size and intensity over a varying period of a few days to over a week. This growth and decay is probably linked to the growth and decay of the developmental regions.

Figure 13 shows the north Atlantic and Europe area of the same field, now overlaid with contours of 500hPa gph. The important features here are that the bredmode structures occupy the main developmental areas of the upper trough pattern due to the geostrophic departure at changes in curvature and pressure gradient. For example, a strong jet exists zonally across the north eastern Atlantic with jet entrance south of Greenland and jet exit south of Scandinavia. At both locations there is significant bredmode activity as shown by high positive and negative values in these locations (note again that there is no meteorological significance of the sign of the bredmode structure).

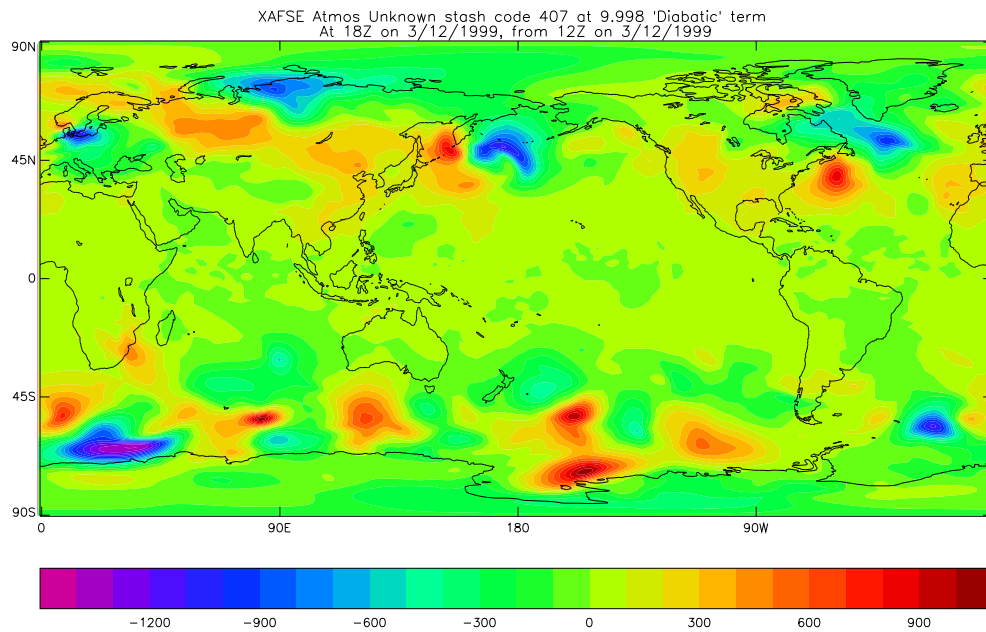


Figure 12 Pressure on Rho level 1, forecast difference file. The structures are observed to occupy the mid-latitude storm track regions and advect with a propagation velocity similar to that of the synoptic pattern. Field verifying at 18z 3/12/99.

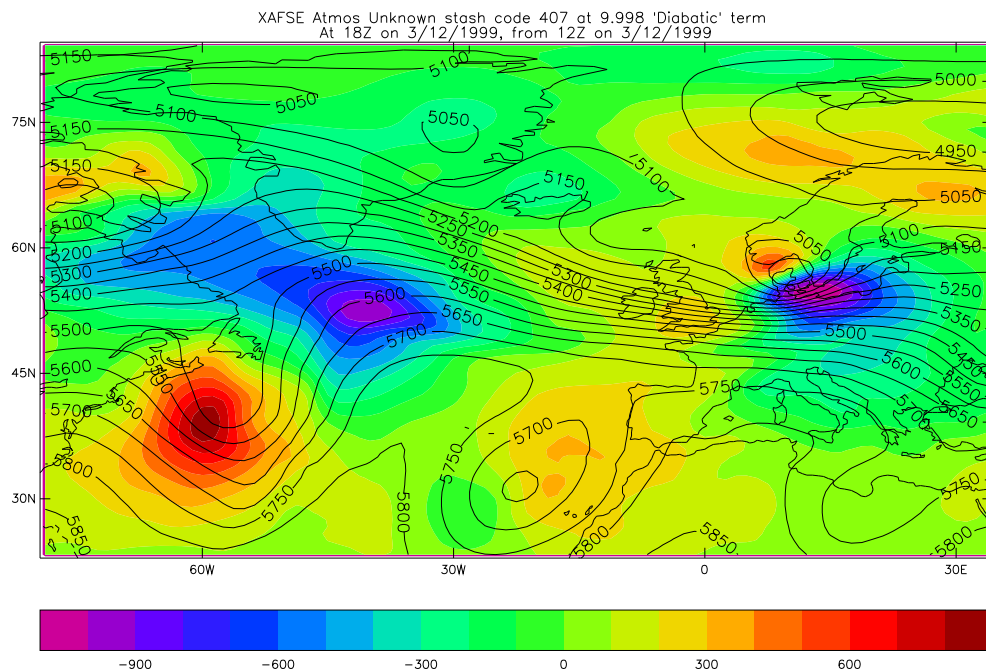


Figure 13 Pressure on Rho Level 1 forecast difference file, overlaid with contours of 500 hPa gph (control analysis). Field verifying at 18z 3/12/99.

Figure 14 shows the forecast difference field for theta on model level 15. Associated with the zonal trough is a cold front that extends from west to east across the Atlantic, and towards the low centre over Scandinavia. At this level, there is a large elongated structure just south of Iceland, and another to the east

of the UK. These structures represent the uncertainty on the position of the frontal surface, given the sensitivity of the initial analysis to the perturbations. A cross section through the line AB is shown in Figure 15. The slope of the forecast difference structure in this figure is effectively representing the sloping surface of the cold front, and the uncertainty in the surface's position.

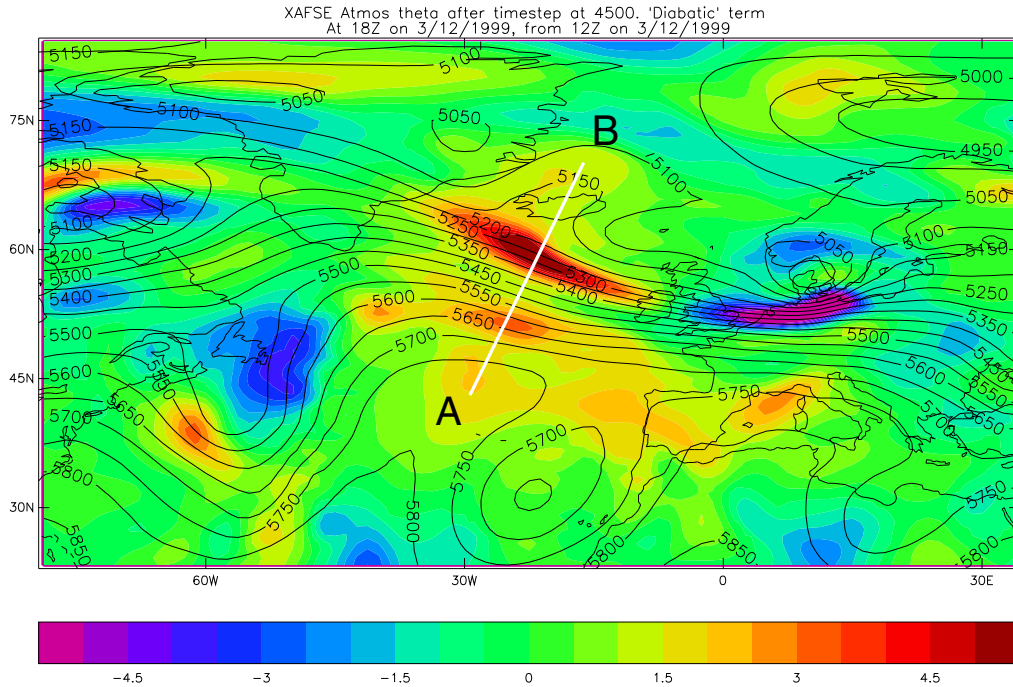


Figure 14 Theta on level 15 (~600 hPa) forecast difference, with contours of 500 hPa gph (control analysis). Field verifying at 18z 3/12/99.

Upper level jets are also strongly associated with development regions and it is instructive to consider the behaviour of the EBS within this context. Figure 16 shows the forecast difference field for the u component on model level 18 over the North Atlantic region. Overlaid on the colour field are the contours of the u component from the control analysis at 500hPa gph. The forecast difference structures are observed to occur largely where the strongest gradients are. These reflect the uncertainty in the position of the jet at the time, given the sensitivity of the initial analysis to the perturbations. Note in particular the large relative uncertainty at the jet core head where the most significant dynamic development will be occurring.

A cross section through the line AB is shown in Figure 17. The contours of the jet core have been overlaid onto the figure to show its vertical extent. It is clear that the vertical extent of the forecast difference correlates well with vertical extent of the jet core.



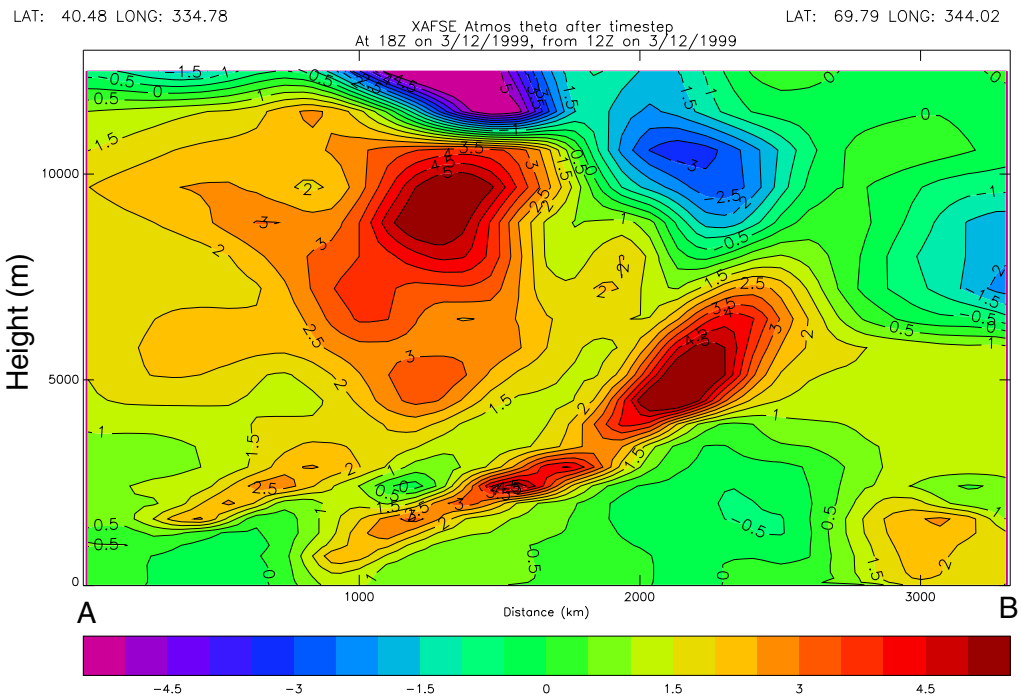


Figure 15 Cross Section through the line AB for theta forecast difference. Field verifying at 18z 3/12/99.

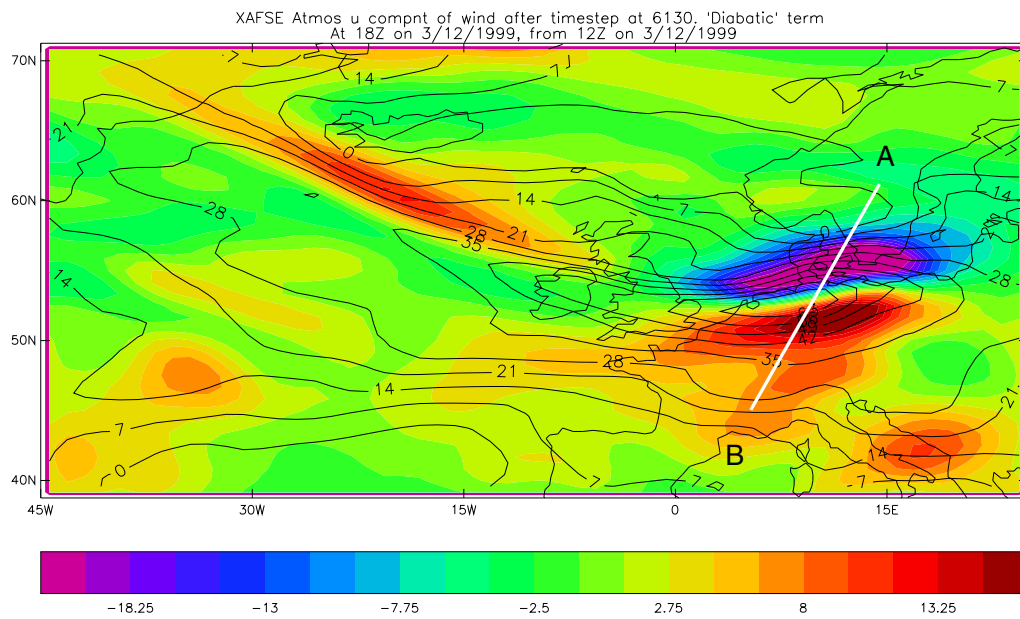


Figure 16 U wind component forecast difference, level 18 (~500 hPa), overlaid with contours of u component at 500hPa (control analysis). Field verifying at 18z 3/12/99.

LAT: 35.82 LONG: 7.63

XAFSE Atmos u compnt of wind after timestep  
At 18Z on 3/12/1999, from 12Z on 3/12/1999

LAT: 71.61 LONG: 15.66

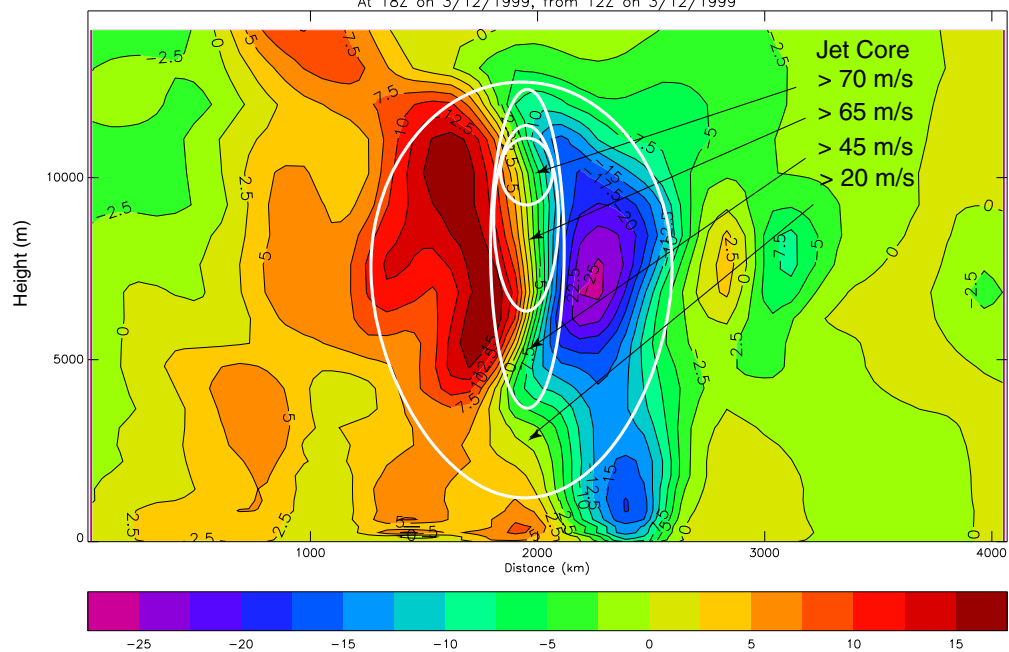


Figure 17 Cross section AB through u component of wind. Field verifying at 18z 3/12/99.

## 7. Trial Results & Discussion

This section discusses the verification of the trial results with some examples that typify the effect of the EBS on the model performance.

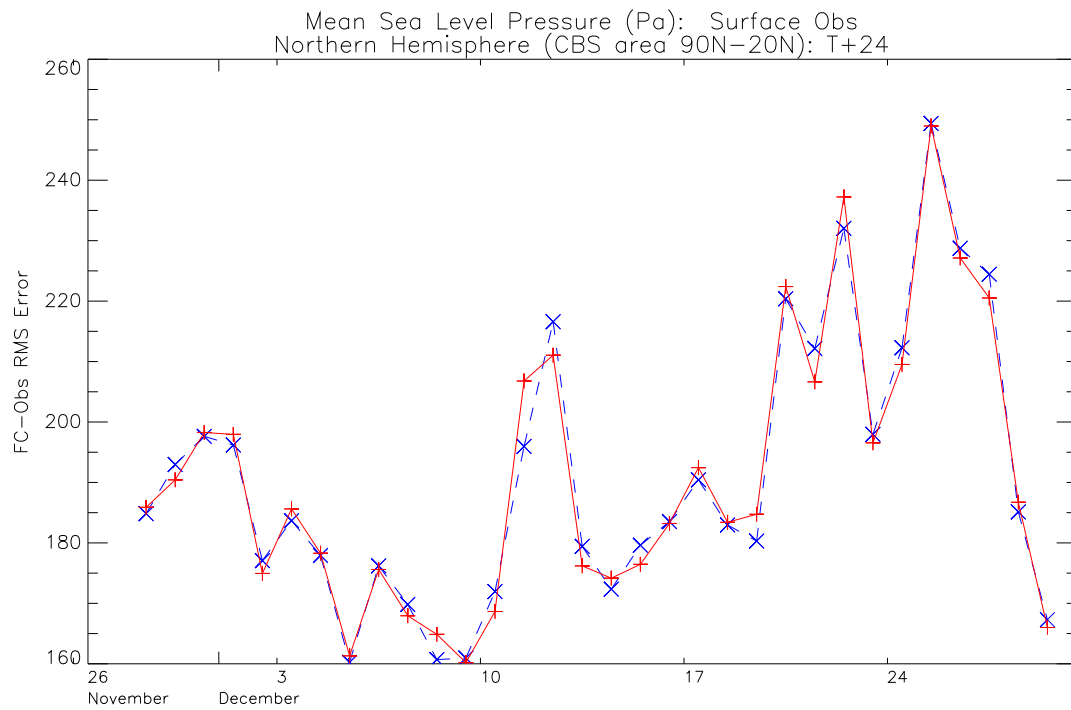
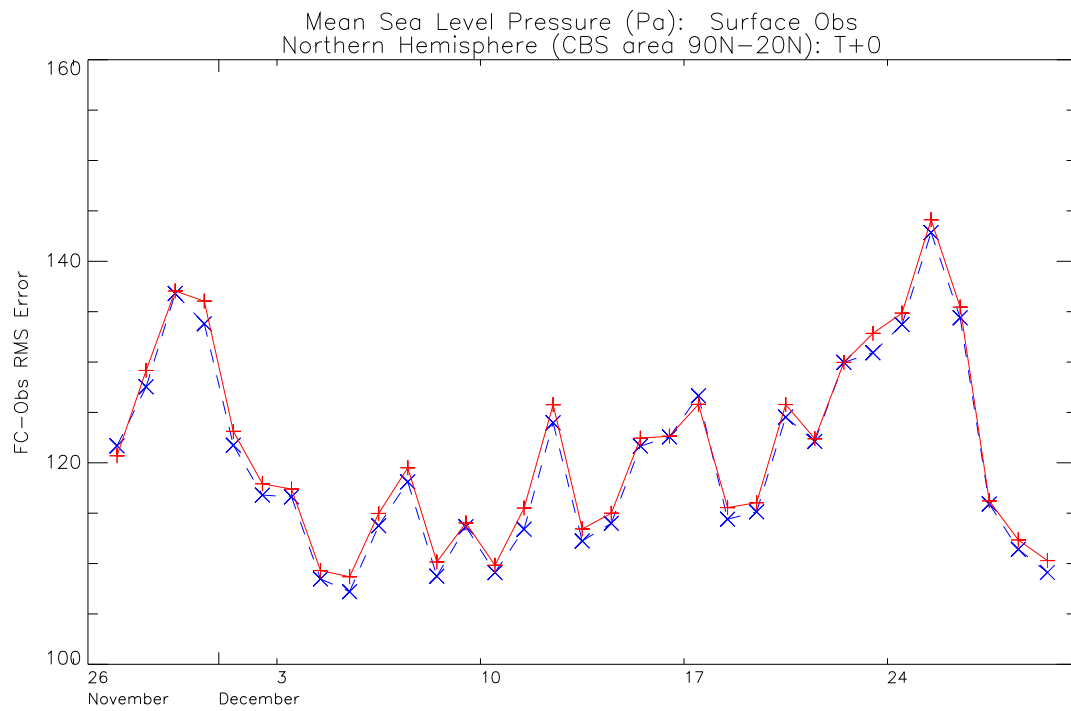
### 7.1 Verification Against Analyses and Surface Observations

The effect of the EBS on the data analysis appears to have a slightly positive effect when one compares the T+0 field with the surface observations. Figure 18 shows the T+0 verification for the northern hemisphere and shows that the RMS error for forecast-Observations has been reduced for the analysis with error breeding active. However, the lower panel shows the verification of the T+24 shows more mixed results, with only small positive and negative impacts during the trial period.

In general, the impact of the EBS on the longer period forecasts are mixed, whether one verifies against analyses, surface observations or sondes. This is true for the northern and southern hemispheres. Typical behaviour is shown in Figure 19 and Figure 20.

Figure 20 also shows the verification of the T+0 analysis against sonde observations for the northern hemisphere. These results are consistent with the verification against surface observations.

Cases: +— DLoC1 x— DLoE3



**Figure 18** Verification of trial results for T+0 and T+24 in the northern hemisphere against *surface observations* for the EBS(DIoE3). The result of the EBS appears to be slightly positive for the majority of the trial. The effect on the T+24 forecast is more mixed and is largely neutral.

Cases: +— DLoC1 x— DLoE3

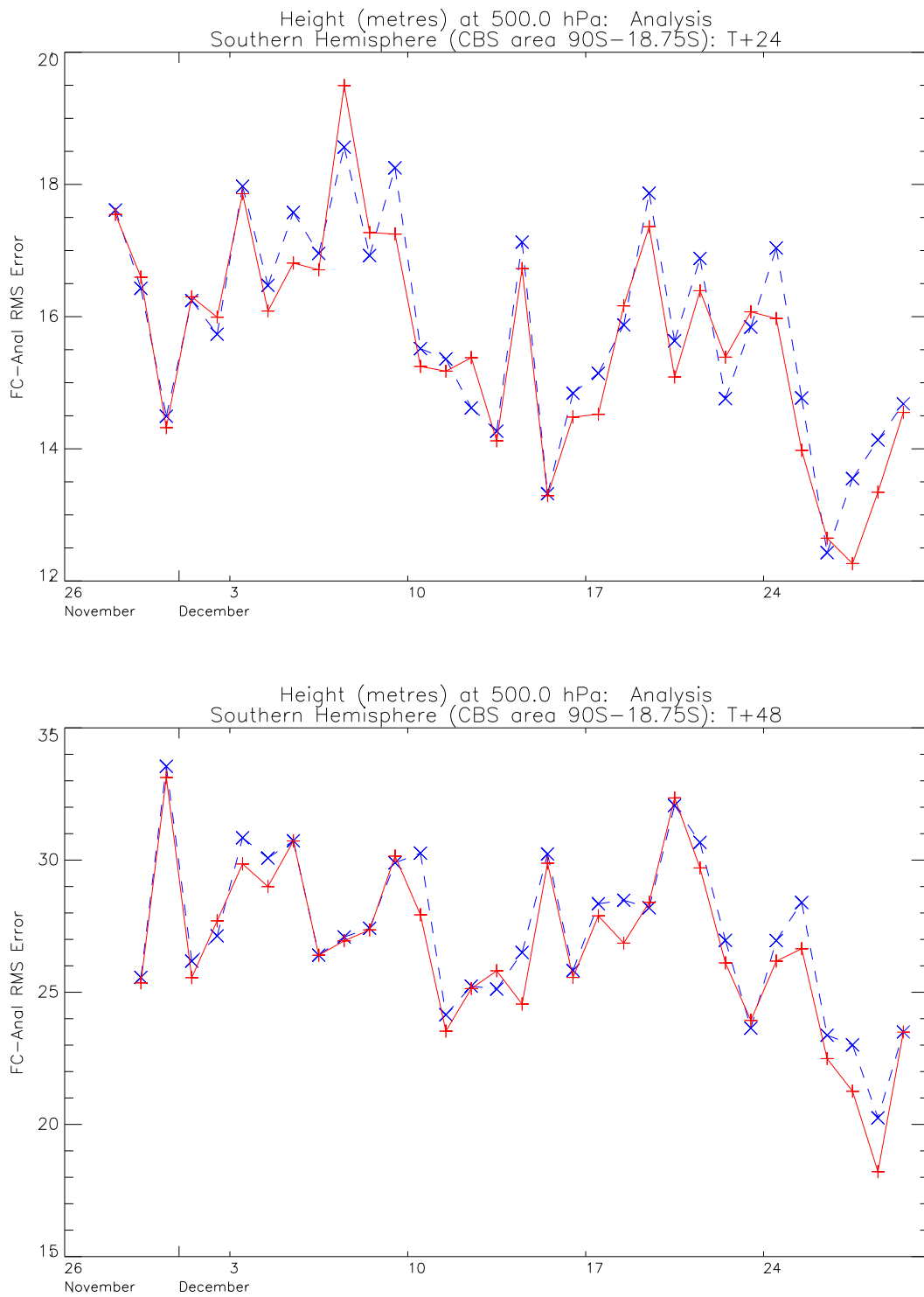


Figure 19 Verification of trial results for the southern hemisphere against *analyses*, T+24 and T+48. The results are mixed, but in these cases slightly negative across the trial period.

Cases: +— DLoC1 x— DLoE3

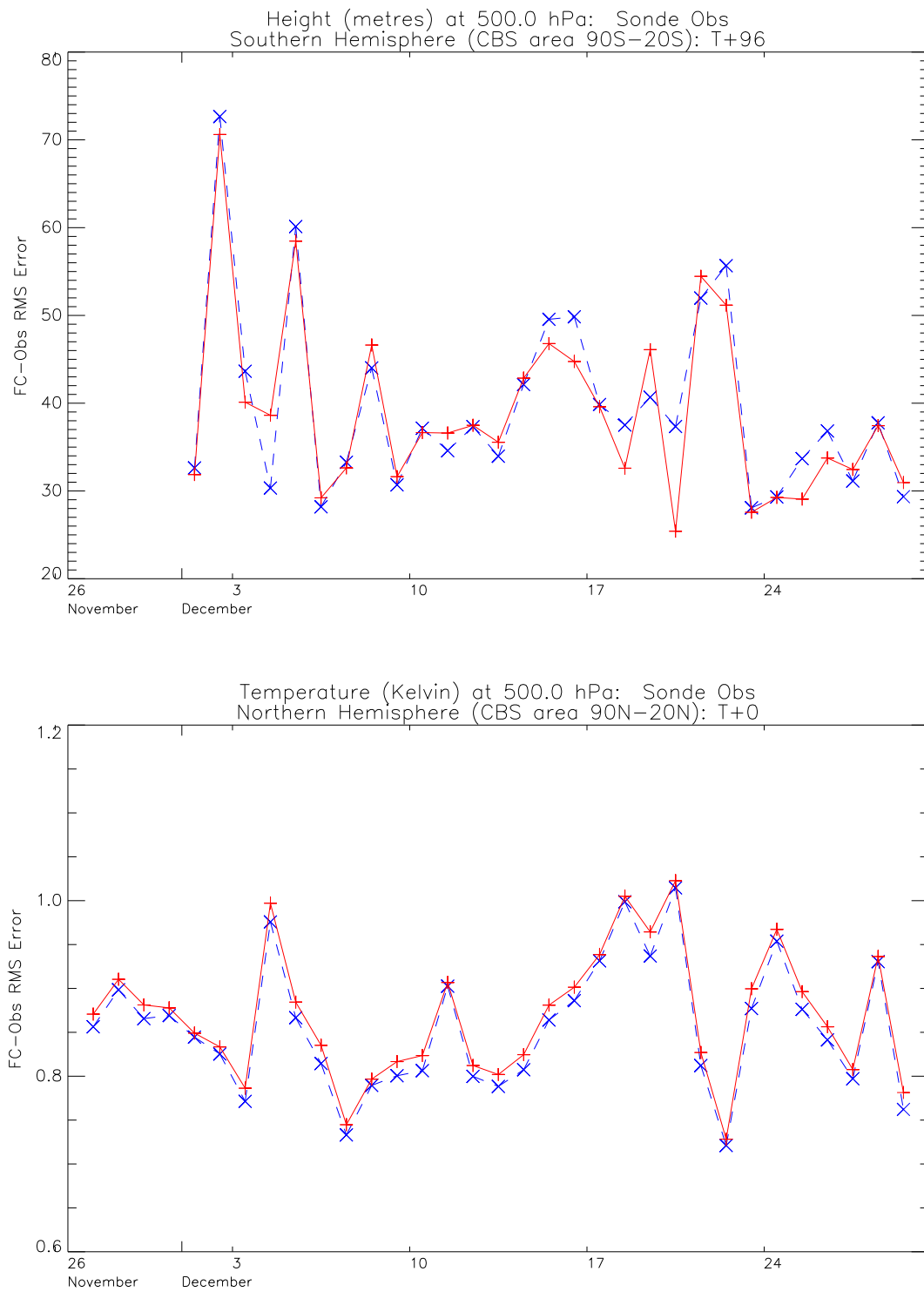


Figure 20 Verification results against *Sonde obs*, Southern hemisphere T+96 and Northern Hemisphere T+0. The mixed results for the southern hemisphere longer period forecast are mixed. The T+0 verification for the northern hemisphere shows a small yet consistent improvement.

The overall verifying statistics for the trial relative to the control trial were:

Total Weighted Mean Skill (total weight = 100)

Control Case = 86.106

Test Case = 85.960

Test - Control = -0.146

Estimated Analysis Based Global Index

(36 Month, normalised to March 2000)

Control Case = 114.521

Test Case = 113.926

Test - Control = -0.595 (-0.520 %)

These results suggest that the impact of the EBS is marginally negative. However, they should be taken into context with the discussion in the following sections.

## 7.2 Typical Effects on the Meteorological Fields.

The verification results of the previous section are a useful way in which to give an overall indication of the effect of the EBS on Var and the forecasts ran from the analyses. This section shows the effect on one case study: a T+144 forecast verifying at 12z 11/12/99. The case study illustrates the magnitude of the maximum changes that have been observed using the ND EBS with Var.

Figure 21 shows the mean sea level pressure field for the verifying control analysis. A cyclone is situated over the eastern coast of Canada. To the east of Newfoundland, a small anticyclone exists. The difference fields between the control analysis and the control forecast, and the control analysis and the EBS forecast (i.e. the forecast in which the EBS has been used to modify Var) is also shown in the figure. For the control forecast, large differences exist over the Canadian coast – the pattern is indicative of both an intensity and Positional error for the cyclone. There are also large differences over Iceland extending to the south.

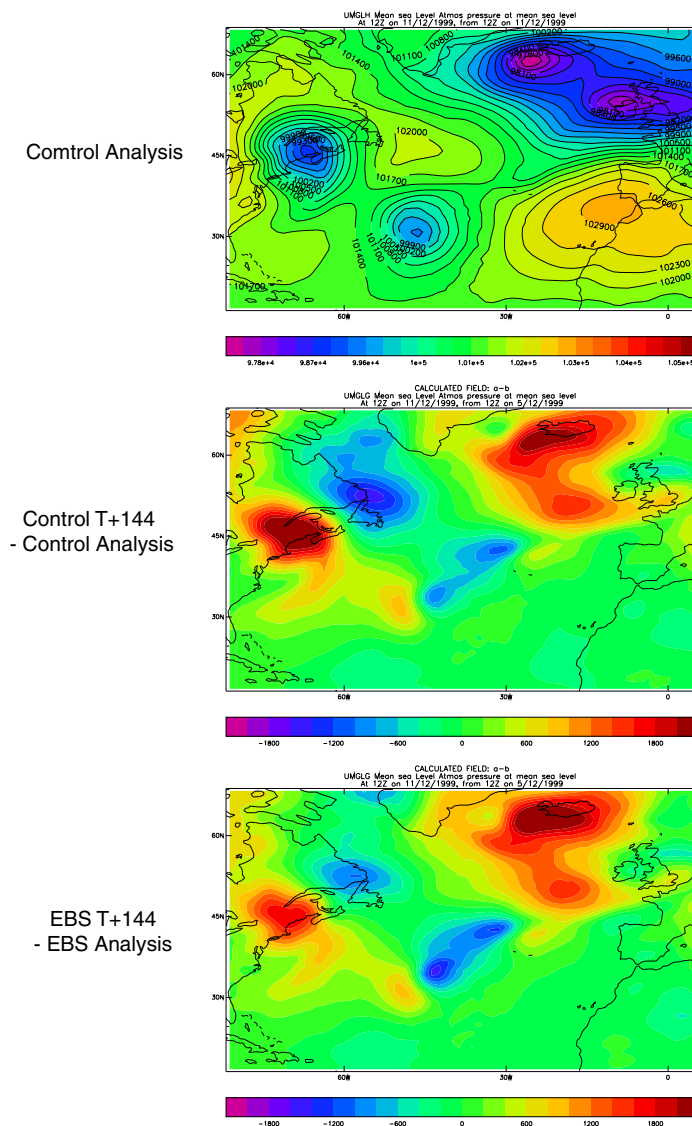
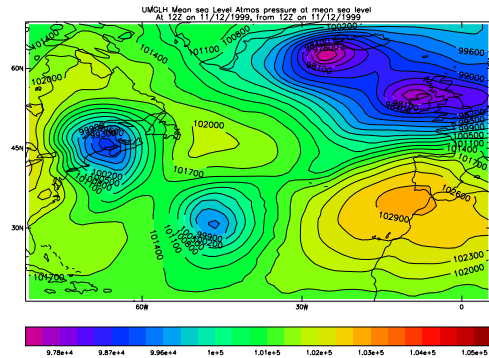


Figure 21 MSLP T+144 forecast. The EBS has reduced the magnitude of the error for the cyclone situated in the west of the North Atlantic.

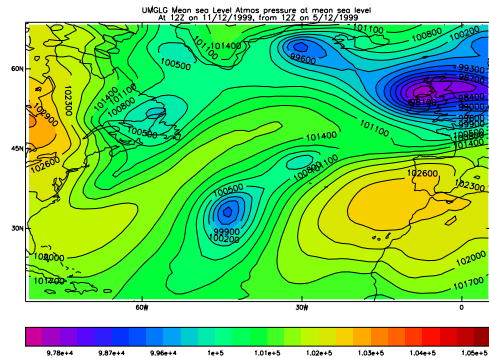
The lower panel indicates that there has been a substantial reduction in the error associated with the cyclone over the coast of Canada. However, small increases in the magnitude of the errors occur in mid-Atlantic and over Iceland – although perhaps the magnitude of the error has been reduced slightly over the southern UK.



Control Analysis



Control T+144



EBS T+144

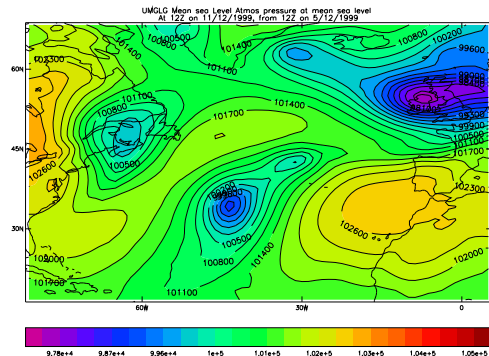
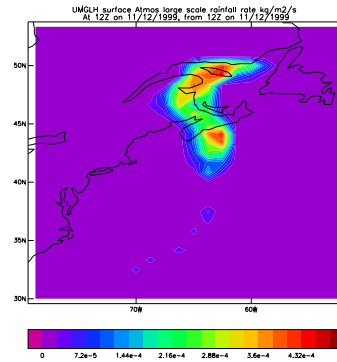


Figure 22 MSLP T+144. The EBS is observed to improve both the intensity (increasing depth) and position (further to the SW) of the low under study. Small negative effects are observed on other lows in the domain.

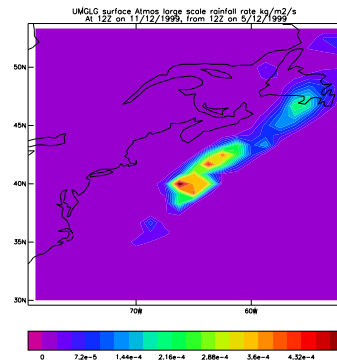
The reason for these error changes may be observed in Figure 22. The cyclone over the coast of Canada has been both correctly intensified and moved further to the south west in the EBS forecast. There are signs that the anticyclone to the east of Canada is better developed in the EBS forecast – it is merely a weak ridge in the control forecast, but has been correctly intensified and extended in the EBS forecast. The cyclone in the mid-Atlantic has been deepened too much relative to the control analysis however. The origin of the error changes over Iceland can be seen to be an incorrect weakening of the cyclone over Iceland relative to the control analysis.

The cyclone over eastern Canada is however, the greatest magnitude of modification in this domain. Figure 23 shows the large scale precipitation rate associated with this cyclone. The distribution of rainfall is significantly better in the EBS forecast; the control forecast has the distribution too elongated and over the sea – whereas the EBS forecast correctly predicts the rain to be more concentrated and aligned North-South.

Control Analysis



Control T+144



EBS T+144

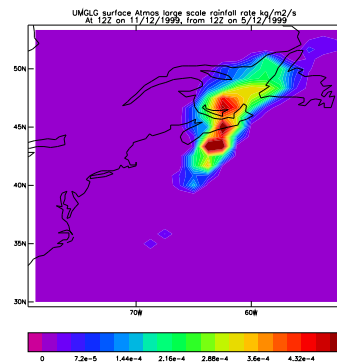
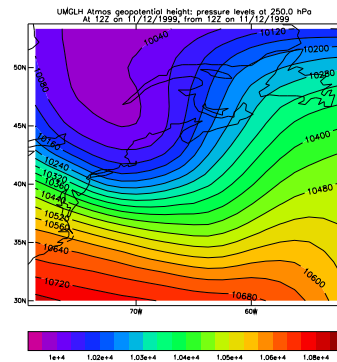


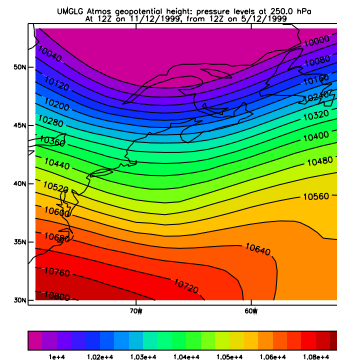
Figure 23 Large Scale Precipitation Rate. The effect of the EBS on the forecast is to move the distribution further north and into a more meridionally orientated alignment. This agrees better with the verifying analysis.

Figure 24 shows the upper trough distribution for the control analysis, and Control and EBS T+144 forecasts. The EBS forecast has correctly intensified the curvature of the upper trough pattern relative to the control analysis. This shows that the modifications to the model atmosphere are relatively large in this area and extend throughout the atmosphere.

Control Analysis



Control T+144



EBS T+144

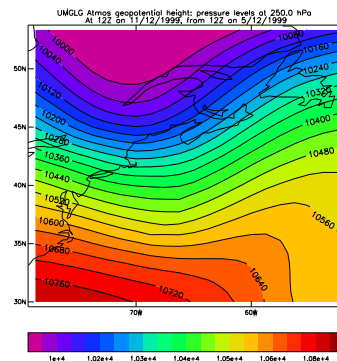


Figure 24 T+144 250hPa gph. The EBS has increased the curvature of the upper level trough relative to the control forecast.

This case was chosen by subtracting the T+144 control and EBS forecast fields from each other and studying the area with the largest differences. Such differences occur in other regions of the model domain. These can be of a similar order of magnitude to those discussed here and can produce effects on model fields that are as significant as these. However, the more normal effects tend to be the slight modification of a pressure contour for example. These have been observed to be both positive and negative.

### 7.3 Pseudo Observation Tests

Pseudo single observation tests have been carried out using the EBS and Var. It was found that only small modifications to the single observation field were observed. The effect of the weight given to the alpha control variable term for the single observation had no noticeable impact. This is in contrast with trials with the OD EBS + Var in which much larger effects were observed.

However, the EBS mode information is certainly being used in Var – a difference field taken between the single Obs field with the EBS turned on and off results in the pattern of the EBS field supplied to Var.

We can therefore conclude that some information of the EBS is being used to modify the analysis increments – this can be seen from the single observations and the trial results – but it may be that the EBS information is not being used optimally. This is discussed further in the following sections.

### 7.4 VAR Operation

The three main terms within the cost function  $J$ , are the background term  $J_b$  (the departure of the state away from the background), the observation term  $J_o$  (the departure of the current state away from the observations), and the  $J_\alpha$  term which represents the forecast difference field. The effect of the EBS on VAR should be to allow an extra degree of freedom (given by the forecast difference) in the minimisation of the cost function by the  $J_\alpha$  term.

The performance of VAR in the use of the forecast difference information may be observed by the study of the variation of the  $J_o$  term during the trial. Figure 25 shows the distribution for both the EBS and control trials and for both the initial and final  $J_o$  values (i.e. at the start and end of the Var minimisation process). The graphs show that the EBS values are consistently lower than those of the control trials for both the initial and final  $J_o$  values. This suggests that the forecast difference information is correctly facilitating a better fitting of the observations, and this would be a desired effect of the EBS on Var.

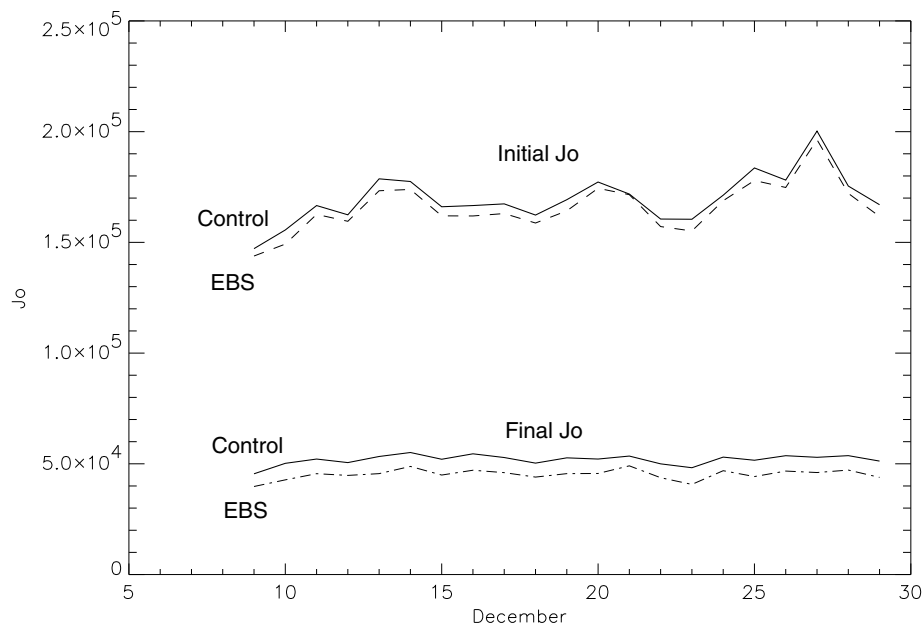


Figure 25 Initial and final  $J_o$  values for the Var minimisations during the trial, allowing for a long spin-up period of 14 days. The top curves show the control (solid) and EBS (dashed) initial values, whilst the lower curves show the control (solid) and EBS (dotted) final values. The EBS curves are consistently lower than the control suggesting a better fit of the observations in the analyses in the EBS trial.

The difference between the initial values of  $J_o$  for the EBS and Control are shown in Figure 26. This graph now includes the spin-up period and therefore includes the start of the trial (26<sup>th</sup> November). At the start of the spin-up period, the difference between the two trials is zero – and this should be the case because the initial  $J_o$  values should be identical at the start of the trial whether the EBS is active or not. However, the trial was set-up so that no forecast difference dump would be supplied to Var during a spin-up period of 7 days. In this period, the Var code automatically de-activates the use of the error breeding information and this has been verified. One should therefore expect that the difference between the two runs (EBS and control) should be zero, as the assimilation should be proceeding identically in both cases. Only after the spin-up period, when the forecast difference dump is supplied to Var will the alpha control variable code be activated, and a difference between the two values be expected. This difference between the two runs during the spin-up period is an unsolved problem at the time of writing.

A second concern with the operation of Var with the alpha control variable is the output values of  $J_\alpha$ . At each minimisation, the values of the three  $J$  terms are displayed. The output values of  $J_\alpha$  are displayed as zero throughout the minimisation of the entire trial. This is a puzzle since one would expect that this cannot be the case – it has been verified that the EBS output is modifying the analysis increments, the analyses and forecasts – and one would expect that this could only be due to the modification of the cost function.

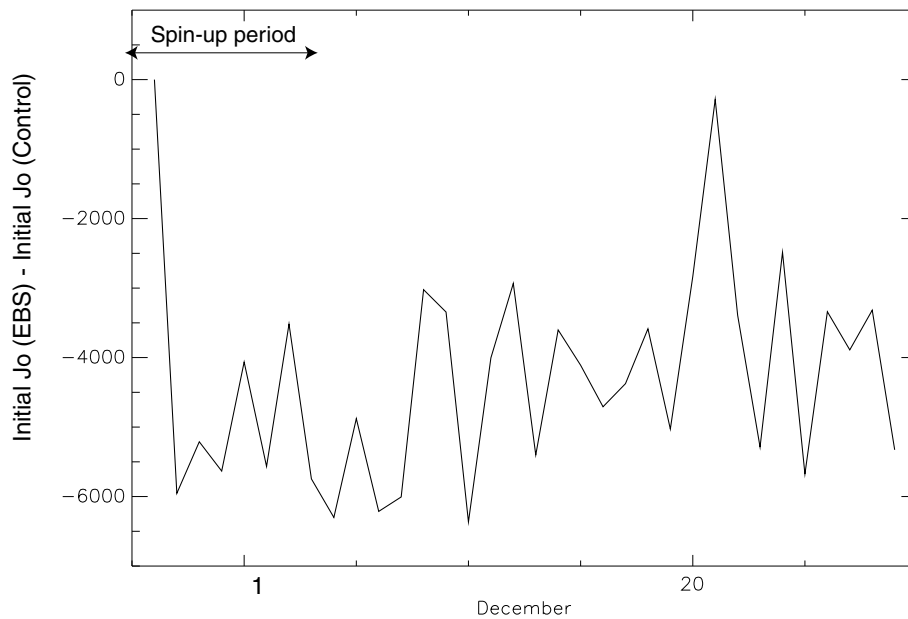


Figure 26 Initial Jo for the EBS – initial Jo for the control trial. The expected spin-up period, within which the modes are expected to be a result of the random perturbations is shown.

Figure 27 shows a schematic of the stages that are gone through in the Var code to achieve a minimisation of the cost function with the EOTD active. The scheme works by first transforming the perturbation forecast (PF) state to control variables. If the EOTD is inactive, Var calculates the contribution to the cost function for each of the J terms, minimises, and then transforms back to model space. With the EOTD active, the forecast difference field (or ‘error mode’ EM) is only transformed to parameter space. The contributions to the cost function are then calculated, and in the first iteration the alpha term is zero. Once the cost function is minimised, the EOTD is added (in parameter space) to the minimised state as a result of the cost function. This new state is then transformed back to model space.

The use of the EOTD structures in Var is a two part process then : the first involves a minimisation of the cost function to achieve the best fit to the three J terms, and the second involves perturbing the control variable state towards the EOTD state by adding the EM dump.

The evidence suggests that the EOTD is only operating at part capacity : it is possible that the minimisation of the cost function with the  $J\alpha$  term is ineffective (hence the zero values in the output), but that the perturbation of the control variables by alpha is effective (hence the modification of the analysis increments, analyses and forecasts observed in the trial). The relevant subroutine that appears to be at fault is the Var\_EmPenAndGrad routine that computes the alpha contribution to the EOTD penalty function. Specifically, the penalty is only calculated when working on the alpha section of the model state – and this never appears to be true. The reason for this is not known at the time of writing.

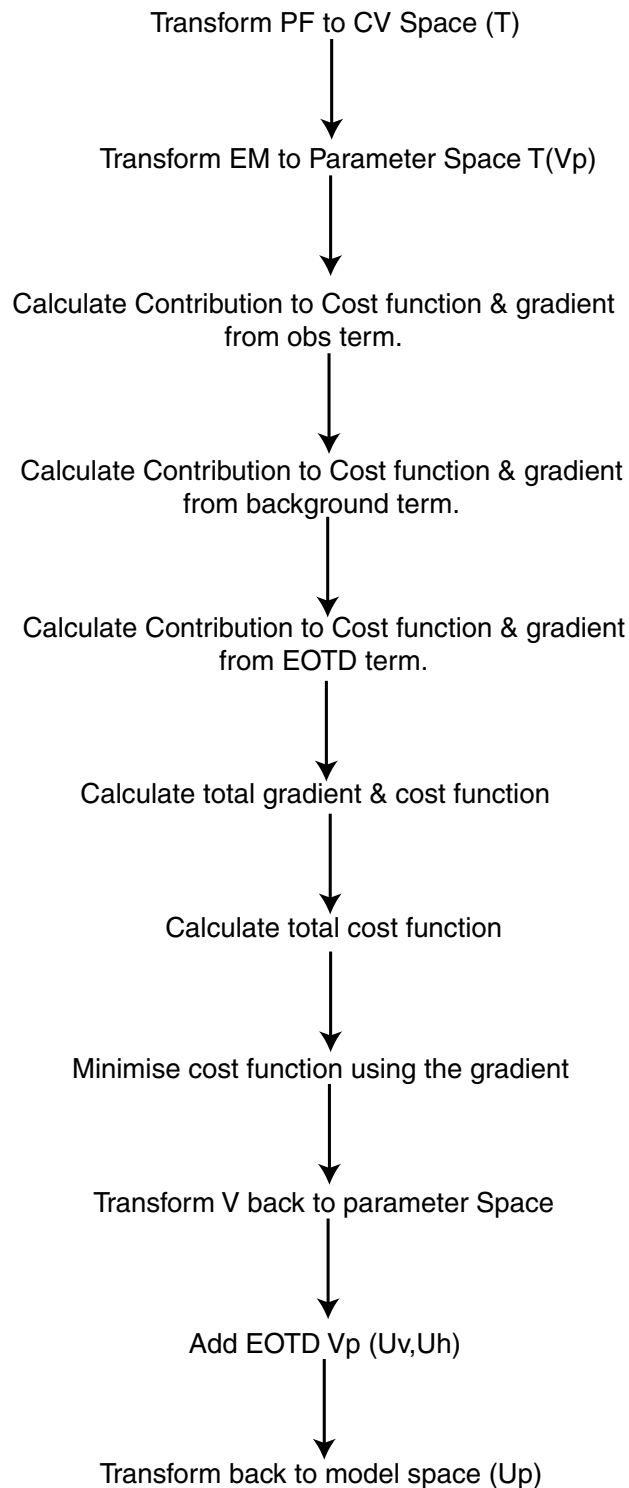


Figure 27 Stages to minimise the cost function with the EOTD active. The T and U transforms are indicated. V denotes the use of the variable in control variable (CV) space.

## 8. Conclusions & Recommendations

This report has shown that an Error Breeding System has been successfully developed for the New Dynamics. The EBS has been shown to be effective in 'breeding' the most unstable states that are meteorologically consistent with the dynamics of the system. It is also successful in the 'targeting' of the forecast differences to develop the forecast differences of a size suitable for the use within Var. This size can be specified by the user in a namelist – this makes the ND EBS flexible and suitable for other uses outside data assimilation.

The results of the trial indicate that the Var use of the EOTD data may not be optimal. It is thought that the minimisation of the cost function using the  $J\alpha$  term may be at fault; the error is thought to originate in the Var\_EmPenAndGrad routine of the Var code.

Despite these problems, there are positive signs that the ND EBS may have a positive impact on the data assimilation process. Individual case studies have shown that small positive and negative impacts in the meteorological fields are common. The impact of the current EOTD is greater at longer forecast ranges (T+72 and longer). Case studies have shown some significant changes to T+144 forecasts. These manifest themselves in relatively large changes in the position and intensity of cyclones or anticyclones; although it is true that both negative and positive impacts occur.

Based on the results documented in this report, the following recommendations can be made:

- Identify the source of the error within the EOTD Var code to allow the alpha control variable to be correctly utilised within AnalysePF.
- It is expected that the preconditioning test carried out by Barker (1999) will need to be carried out again. There are a number of parameters within the code that are highly sensitive, and it is anticipated that with the new model, higher resolution, and use of smoothing that these parameters are in likely need of change.
- Carry out a new trial to determine the performance of the EOTD within Var.

## 9. Acknowledgements

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## 10. References

Barker, D.M., The Specification And Use of Synoptically-Dependent Background Error Modes in 3Dvar Using Information From An Error Breeding Cycle, Poster Contribution, Quebec City WMO DA Conference, 7-11 June 1999.

Barker, D.M., VSDP25: A new background error variance prediction algorithm for the OPS/3DVAR system, August 1999.

Toth, Zoltan and Kalnay, Eugenia, , *Ensemble Forecasting at NMC: The Generation of Perturbations*, Bulletin of the American Meteorological Society Vol. 74, No. 12, December 1993

Toth, Zoltan and Kalnay, Eugenia, *Ensemble Forecasting at NCEP and the Breeding Method*, Monthly Weather Review, Vol. 125, 3297-3319, December 1997

Iyengar, G., Toth, Z., Kalnay, E. and Woollen, J., *Are the Bred Vectors Representative of analysis error?* , Preprints, 11<sup>th</sup> Conf. On Numerical Weather Prediction, Norfolk, VA, AMS., J64-J66, 1996