Use of potential vorticity in monitoring and improving numerical analyses and simulations of severe winter storms in Western Europe.

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Abstract

Despite the large improvements of numerical weather prediction models (NWP) during the last decades, including more advanced data assimilation methods that allow extensive use of satellite data, such models still occasionally produce forecast failures. Though these forecast errors are rare, they tend to involve cases of rapid cyclogenesis that cause dangerous weather.

This investigation deals with a method that allows the human forecaster to improve the numerical analyses and forecasts in cases of imminent strong cyclogenesis.

The combined use of potential vorticity (PV) fields in the numerical analyses and information retrieved from Meteosat water vapor (WV) images reveals analysis errors early in the stage of strong cyclogenesis. It is demonstrated that manual correction of the PV fields in the analysis according to information retrieved from the WV images can improve the short range forecasts of rapid cyclogenesis substantially. This is achieved by performing inversion of the corrected PV fields. By this method a new, dynamically consistent analysis is produced, from which a numerical resimulation is carried out. It is further demonstrated that singular vectors constitute an additional important tool in this process, by allowing PV corrections to be performed in sensitive regions. This procedure makes it possible to determine the likely 3-dimensional structure of the required PV modifications. The beneficial effects by this method may have some limitations in cases of downstream developments.

List of papers

Paper 1: Sunde,J., Røsting,B., Breivik,L.A., Midtbø,K.H. and Ulstad,C. 1994: Operational monitoring and forecasting of mesoscale weather phenomena in ocean regions surrounding Norway. Meteorol. Appl., 1: 237-245

Paper 2: Røsting,B., Sunde,J. and Midtbø,K.H. 1996: Monitoring of NWP models by use of satellite data. Meteorol. Appl., 3: 331-340

Paper 3: Røsting, B., Kristjánsson, J. E. and Sunde,J 2003: The sensitivity of numerical simulations to initial modifications of potential vorticity – a case-study. Q.J.R.Meteorol.Soc.,129, 2697-2718

Paper 4: Skeie, R.B., Kristjánsson, J. E., Ólafsson, H. and Røsting, B. 2006: Dynamical processes related to cyclone development near Greenland. Meteorologische Zeitschrift, Vol.15, No.2, 147-156

Paper 5: Røsting, B. and Kristjánsson, J. E. 2006: Improving simulations of severe winter storms by initial modification of potential vorticity in sensitive regions. Q.J.R.Meteorol.Soc., 132, 2625-2652

Paper 6: Røsting, B. and Kristjánsson, J. E. 2008: A successful resimulation of the 7-8 January 2005 winter storm through initial potential vorticity modification in sensitive regions. Tellus, 60A, 604-619

Contents

1 Background and purpose of the investigation

1.1 Methods to improve the initial state of numerical weather prediction models and simulations

One of the key issues of scientific research in the field of numerical weather prediction (NWP) is the improvement of the initial state, that is, the numerical analysis. The atmosphere is frequently referred to as a chaotic system, where small errors in the NWP analysis may grow into large errors in even the short range simulation, such as 24-48 hours. Forecasts in the medium range, that is between 2 and 10 days, are more likely than short range forecasts to be affected by such analysis errors. Though serious forecast errors in the short range are comparatively rare with the state of art NWP models, they still occur, and when they do they tend to involve forecasts of rapid cyclogenesis that represents hazards to human life and damages to infrastructure.

In such serious albeit few cases of forecast failure there is a need for the human forecaster to intervene manually by correcting the numerical analysis. Because the corrections may have to be large and also yield a new analysis that has to be dynamically consistent (balanced), this is not a straightforward procedure. However, such an analysis can be obtained by applying potential vorticity (PV) thinking and rerunning the numerical model bypassing data assimilation routines.

The main reasons for NWP forecast errors are model errors, sparsity of observations and the way observations are assimilated in the model analysis:

(1) Because the equations have been discretised, model errors occur due to truncation, and there may be errors related to parameterization as well as inadequate representation of topography. However, these problems are becoming smaller by the introduction of models with higher spatial resolution, also containing improved physical parameterizations, and high resolution nonhydrostatic models.

Model errors can, to some extent, be accounted for by the operational forecaster, basing the decisions on experience as well as results from objective verifications.

(2) The model assimilation routine will reject observations that contain obvious errors or deviate too much from the guess field (a 6 hour forecast valid at the new analysis time). Due to sparsity of observations or if erroneous ob-

servations have previously been accepted, the guess-field may contain errors and new good observations may be rejected [1]. This is still a problem encountered in data assimilation, despite the increasing quality in assimilation achieved by 3 - Dimensional Variational data assimilation technique (3D-Var) and particularly 4D-Var (e.g. Rabier et al 2000, Bouttier and Kelly 2001). In cases of rapid cyclogenesis, particularly on a smaller scale, 3D-Var may produce a degraded analysis despite good observations and good background (first guess) field. This is due to temporal interpolation of good observations departing from the observation time by 1-2 hours. This problem is, however, to a large extent coped with by 4D-Var.

The forecaster can "intervene" in the model analysis in the following ways:

(i) By "forcing" the assimilation system to accept new and presumably good observations, an improvement of the numerical analysis and subsequent forecasts could be achieved, provided that the observations are located in sensitive regions. This procedure also involves previously rejected observations, that have been judged to be correct.

(ii) By subjective evaluation of the model quality against the observations, including satellite imagery, which requires the use of conceptual models. This procedure allows the 3-dimensional structure of model errors to be identified in a subjective, albeit qualitative, way. The numerical analysis which presents the closest agreement with observations, e.g. in terms of fronts and upper level PV anomalies, is often chosen as the "best" model analysis of the day.

It is, however, difficult to choose the "best" model in this way, most likely because the important observations are located in sensitive regions of the atmosphere, not necessarily easily identified by conceptual models and satellite images.

(iii) Bogus observations can be inserted in the analysis. As an example we may consider a case of errors in the upper level PV field. Such errors are identified by comparing the upper level PV fields with features observed in water vapour satellite images as explained below in subsection 1.2. A model sounding can be transferred from the region of the original PV anomaly to the new and correct position. This procedure is performed for several positions, and a new analysis with corrected PV field is produced. However, if there are too few bogus points, this technique is rendered less efficient (Mansfield 1996). The data assimilation process is also likely to smooth out the new

[1]Good observations may also be rejected due to inadequate spatial resolution, e.g observations located close to each other in a strong frontal region.

PV fields. In our investigations, rather than using the bogus method, PV is inverted after the corrections, yielding new height and wind fields. These wind fields, together with relative humidity (RH) fields, constitute the new analysis.

In order to get more insight into processes leading to cyclogenesis whereby NWP models and forecasting techniques can be improved, several observational campaigns have been carried out, e.g. Fronts and Atlantic Storm Track Experiment (FASTEX) (Joly et al 1999) and most recently campaigns associated with The Observing system Research and Predictability Experiment (THORPEX, available on the web), the latter partly focusing on higher latitudes. An important part of these campaigns has dealt with the task of adding new observations, i.e. dropsondes, in sensitive regions of the atmosphere. New data in the sensitive regions are expected to have the greatest impact in a specific region (i.e. containing the cyclone) at a specific time ahead. Hence such additional observations are referred to as targeted observations. The locations of the sensitive regions are determined by methods described below. Though to date many evaluations of results from THORPEX remain to be done, there is an impression from campaigns within THORPEX and previous campaigns that the benefits from targeted techniques are limited. The reason seems to be that the data from dropsondes are not fully accepted by the assimilation routines (e.g. Petersen and Thorpe 2007).

The salient point in the above considerations is the occasional need to improve the NWP analysis in sensitive regions and this is also the main motivation for the research described in this work.

There are several approaches to improving the initial state of NWP simulations:

(1) The Ensemble Transform Kalman Filtering technique (ETKF) (Bishop et al 2001, Szunyogh et al 2001, Majumdar et al 2002, Petersen et al 2007).
(2) The singular vector (SV) technique (Buizza and Palmer 1995, Buizza and Montani 1999, Montani et al 1999, Kalnay 2003).
(3) Manual modification of PV according to information in water vapour (WV) images. We refer to this method as the PV-WV method (e.g. Mansfield 1996, Santurette and Georgiev 2005).

There are other methods as well, such as the breeding method (e.g. Kalnay 2003) and a method adopting adjoint methods (Hello et al 2000).

The method described by Hello et al is strongly related to the targeted SV technique. One determines a region (denoted by e.g. A) where the forecast is considered to be uncertain. This is done by comparing several previous NWP forecasts valid for the same time, yielding the region containing large discrepancies of surface pressure. An objective function, i.e. mean sea-level pressure in region A is defined. The gradient of this function at initial time is then computed by using the adjoint of a simplified version of the model (lower resolution and simplified physics). In this way the sensitive region where changes of surface pressure will affect region A is determined. The initial gradient is rescaled into a perturbation, a correction of the initial surface pressure according to observations is then carried out, and a model rerun is performed (Hello et al 2000, Hello and Arbogast 2004).

(i) The ETKF method is based on determining regions (target regions) where new observations will lead to the largest reduction in forecast error covariance within a specific area, the verification area, at a specific forecast time. This method is particularly designed for adopting additional observations, such as dropsondes from airplanes in the target areas. These observations are expected to improve the forecast in the verification region. As mentioned above, a number of flight campaigns have been performed, during which this method has been adopted, most recently in the campaigns within THORPEX.

(ii) The SV method is based on running a linearized version of the NWP model forward in time, out to a specific time referred to as the optimization time, normally 48 hours, then the adjoint of the linearized model operator is used, which amounts to running the tangent linear model backwards to the initial time. After repeating this process several times (using the Lanczos algorithm) the SVs and their associated singular values are determined. The SVs and singular values express the directions in phase space and growth rate of the SVs respectively. SVs are ranked according to their growth rate, hence SV number 1 denotes the most unstable direction in phase space, SV number 2 the second most unstable direction and so on. Maximum amplitude of the SVs is achieved at opimization time. Beyond this time the SV development is non-linear. SVs form an orthonormal base in phase space, hence any flow perturbation can be expressed as a combination of the SVs. The fastest growing SVs indicate sensitive regions, as referred to above. The SVs used in our research are based on the energy norm.

Like the ETKF method, additional observations in regions highlighted as sensitive by the leading SVs are expected to have a large beneficial impact on the numerical simulations.

(iii) The PV-WV method is based on the strong connection between features in WV images and upper level PV fields in dynamically active regions (Appenzeller and Davies, 1992). The WV image is based on the strong absorption of thermal (infrared) radiation in the WV bands at 6.2-6.7μm [2]. Dry air allows radiation from lower and normally warmer parts of the troposphere (but generally levels above 800hPa) to reach the satellite. Such regions appear dark in the WV image.

1.2 Corrections of NWP analyses and improved simulations by manually performed PV modifications

For completeness we now describe briefly the connection between the PV field and dark and bright regions observed in WV images.

Figure 1 shows the WV image at 06 UTC, 13 March 2007, with PV on the 320 K isentropic surface superimposed. The PV fields are retrieved from a 6 hours simulation by the Norwegian HiRLAM, valid at the same time. PV is given in PV units (1PVU = $10^{-6} m^2 s^{-1} K kg^{-1}$).

Dry and PV-rich stratospheric air forms dynamically active cyclonic PV anomalies that trigger cyclogenesis. During cyclogenesis the dry intrusion becomes an integral part of the development, bringing the dry and high-PV stratospheric air close to the developing cyclone. Because this dry air is associated with large values of PV, there is a strong correspondence between the dark features in the image and high values of PV in dynamically active regions, e.g. feature A in Figure 1 (Weldon and Holmes 1991, Browning 1997).

The cyclonic upper level PV anomaly at D in figure 1, partly corresponding to a dark region in the image, is possibly a precursor to cyclogenesis, at this stage of development inducing a new wave on the trailing cold front to the east of D, as observed by the enhanced bright feature at E. During cyclogenesis a darkening of the dark feature at D due to dynamically induced subsidence is expected.

In the humid and cloudy regions, only radiation from the upper and cold levels of the tropsphere can reach the satellite. Hence such regions appear

[2] For lower level moist features the 7.3μm band is useful.

as whitish or bright regions in the WV image. The brightest (coldest) WV features are associated with thermal radiation from high level cloud tops. Since the troposphere generally contains low values of PV [3], there is a strong corrrespondence between the bright features in the WV images and low values of PV, an example being the regions at C and E in Figure 1.

In regions that are not dynamically active, such as cut-off cyclones, the pattern of grey shades and bright regions is almost reversed. Positive upper level PV anomalies are associated with a mixture of dark and bright shades, this is due to extensive convection taking place in the cold air below the upper level cyclonic PV anomaly, regions B and E in Figure 1. In the regions surrounding the cut off cyclone there is often subsidence creating dry and warm air causing dark features in the WV image, not related to high PV values (e.g. Santurette and Georgiev 2005). This is observed in Figure 1 as the dark regions at F, G and H.

By comparing PV fields in NWP analyses or forecasts with the tell tale features inferred from the WV images in dynamically active regions it is possible to detect errors in the numerical PV fields. Such an error may exist in region D, where the cyclonic PV anomaly partly covers a whitish feature in the image. However, this feature may represent mid-tropospheric moisture while the PV distribution at the tropopause level is correctly analysed or simulated by the numerical model. For a proper confirmation of a possible mismatch between the PV field and the WV features in a case like the one at D in Figure 1, an inspection of cross sections of the RH fields or use of pseudo WV images is required. Pseudo WV images are obtained through a radiation transfer algorithm that adopts model calculated temperature and humidity profiles (e.g. Santurette and Georgiev 2005).

If errors in the PV fields are identified, manual corrections of the PV fields are performed, followed by inversion which yields geopotential height, winds and temperature (Davis 1992). These fields, and the RH fields (which may also be modified initially), comprise a new analysis which is dynamically consistent (balanced). Then a numerical rerun, based on the new analysis is carried out. This procedure has yielded substantially improved numerical forecasts in several case studies (e.g. Demirtas and Thorpe 1999, Hello and Arbogast 2004)

The numerical reruns performed in this research were performed by the

[3]Exceptions are of course low level positive PV anomalies created by diabatic heating during cyclogenesis.

High Resolution Limited Area Model (HiRLAM) [4], and they were carried out without data assimilation. This allows for large modifications in the analysis as such modifications might otherwise have been rejected by the assimilation routine.

The introduction of the DIgital ANAlysis system (DIANA) at the Norwegian Meteorological Institute (NMI) allows PV fields, superimposed on the WV image at analysis time, to be modified interactively. The inversion of the modified PV fields and the numerical reruns can be carried out in real time.

In order to ensure that the three dimensional structure of the modified PV field covers sensitive regions, the PV-WV method has in this investigation been combined with information from the fastest growing SVs (Browning et al 2000, Røsting et al 2003, Røsting and Kristjánsson 2006, 2008, Manders et al 2007).

There are no clear indications that one of the targeting techniques, ETKF or the use of SVs, generally performs better than the other (e.g.Majumdar et al 2002). The ETKF method is designed for additional targeted observations, i.e. dropsondes from airplanes. SVs are available from The European Center for Medium and long range Weather Forecasting (ECMWF) (ECMWF Newsletter 1999), and they frequently highlight baroclinic regions as sensitive. In our research PV fields are modified rather than adding new observations in sensitive regions. Thus targeted SVs are adopted in our investigations as an additional tool in PV modification.

Manual modification of the PV field is done at the risk of introducing errors in the analysis, hence causing a further degradation of the analysis. We believe that this risk is significantly reduced by addressing the following items:

(i) Forecasters have gained knowledge about the typical PV distribution associated with strong cyclogenesis through the combined use of conceptual models and the PV structure observed in successful NWP simulations. This knowledge yields firm support for analysing the PV field in cases of analysis errors, including errors in low level PV anomalies.

(ii) Though it is obvious that the region where rapid cyclogenesis occurs is sensitive to changes of the flow, targeted SVs constitute an important tool for identifying such regions, particularly for modification of low level PV

[4] The model was identical to the operational model, but was run for a smaller region.

anomalies. The locations of low level PV anomalies are difficult to determine from WV images alone.

Besides the successful resimulations based on the PV-WV method, including SV information, an additional motivation leading to the present investigations was to study the influence of selected PV anomalies on the cyclone development. Increased insight of the dynamics of strong cyclogenesis can be achieved through such application of PV thinking.

Clearly the development of PV anomalies associated with cyclogenesis is affected by upstream (and occasionally downstream) flow structures, confirmed by studying trajectories originating in upstream PV anomalies. Air parcels starting in PV anomalies at the rear of the cyclones descend almost adiabatically, nearly conserving their PV, and they constitute the dry intrusion (Appenzeller and Davies 1992, Browning 1997). An example is provided in Paper 6 described below. Hence local PV corrections will most likely improve the simulation of the flow on larger scales as well, as indicated by the trajectories calculated and presented in Paper 6. Such an impact from far upstream features of the flow also explains the structure of the SVs, which at upper levels often shows a widespread signal, while the SVs tend to be geographically confined at lower levels. On the other hand, the case dealt with in Paper 3 demonstrated that PV modification may have a detrimental effect on the simulation of other developing cyclones close to the one subject to modification.

We now briefly describe the papers provided below.

2 Papers

2.1 Paper 1

This paper deals with the monitoring and description of mesoscale weather patterns surrounding Norway. The phenomena of interest are polar lows and associated fronts forming in low level baroclinic zones separating the arctic air mass from the modified polar air mass. The northern frontal system described in this paper may appropriately be referred to as the arctic front, and a Bear Island polar low develops associated with it. The cross section through the frontal zone resembles a classical cross section through the polar front, but the dynamical tropopause in this case drops to 500-600 hPa levels.

The development of these systems is described by PV thinking, highlighting the redistribution of PV due to diabatic heating. By this process low level cyclonic PV anomalies is created below the diabatic heating maximum, while PV is reduced above the diabatic heating maximum. Low level PV anomalies contribute to the strong winds often experienced south and west of strong cyclones, while local reduction of upper level PV tends to create enhanced upper level PV gradients and hence stronger upper level PV advection.

2.2 Paper 2

This paper describes monitoring of NWP models by using satellite data. Two particularly interesting polar lows are investigated. One at Bear Island was triggered by a polar front cyclone approaching from the southeast, while in the other case an upper level positive PV anomaly (or upper level short wave trough) triggered a polar low on a strong convergence zone stretching from Svalbard southward across the Norwegian Sea. This development was not caught by the operational numerical model at the time. The satellite image clearly showed the convergence zone and indications of the upper level trough, the latter inferred by the presence of a comma cloud associated with a region with maximum upper level PV advection. These features were observed before the onset of the polar low development. The location and propagation of the upper level trough were well forecast by the model, as observed in the satellite images. Hence combined use of the satellite images and model output was essential for a successful forecast of the polar low development.

The simulations of two extratropical cyclones, one successful simulation and one containing large errors, are described by comparing the model PV fields and the features observed in the WV images. In the case with large forecast errors the mismatch between the features observed in the WV images and the model PV fields is particularly distinct.

2.3 Paper 3

In this paper a study of the forecast failure of the Christmas storm of 1997, affecting the British Isles, was performed. By PV modification according to the features observed in the WV images, followed by inversion of the modified PV fields, a new analysis was obtained. The numerical simulation based on the new initial state improved the simulated development and track of the cyclone substantially. As an additional tool in PV modification, SVs were introduced to indicate sensitive regions. The SVs contributed to determining the three dimensional structure of the required modifications, i.e. the levels that were sensitive to changes in the PV field.

In the wake of the first cyclone a deepening second cyclone moved rapidly eastward from Newfoundland to Ireland. The modified numerical rerun failed to simulate the second cyclone properly. By enhancing the upper level PV anomaly associated with the second cyclone, the simulation was improved in terms of the cyclone track, but the forecast central pressure of the second cyclone failed to reach the observed by $\sim$ 10 hPa. These investigations suggested that in cases with two (or more) developing cyclones, PV modification may improve the simulation of one wave, but at the same time have a detrimental effect on another wave which is closing in on the first one.

Possible downstream effects arising from the PV modifications are also discussed. It is concluded that though local PV modifications may lead to substantially improved numerical simulations of strong cyclogenesis, they are performed at the risk of introducing errors in the analysis. Such errors will propagate downstream, and may become detrimental to the simulation.

2.4 Paper 4

This paper describes a case of rapid cyclogenesis east of Greenland on 20-21 September 2003. The part of this paper which applies PV thinking focuses on the interaction between the upper level PV anomaly and the incipient low at the east coast of Greenland. This incipient low may be described as a lee cyclone associated with a low level positive PV anomaly at the east coast and a low level positive temperature anomaly over parts of Greenland. During the early hours of 20 September 2003 a strong upper level positive PV anomaly moved southeast across Greenland. The contribution from these PV anomalies to the cyclogenesis is studied using PV inversion. The strongest contribution to the rapid deepening of the cyclone was due to the upper level positive PV anomaly.

2.5 Paper 5

In this paper the numerical PV fields, WV images and the initial SVs were applied to the French Christmas storms of 1999, which were very poorly forecast by the operational (short range) numerical models. The same methodics was applied to a case of rapid cyclogenesis affecting the British Isles, the North Sea and southern Norway. This cyclogenesis was captured by the operational HiRLAM model, though deepening and propagation speed were underestimated. PV modification according to WV information and SV signal resulted in a substantial improvement of the simulations.

Several methods to improve the initial state in general were discussed. Some of the limitations of the PV inversion technique were discussed as well, and the subject of the stucture of SVs was expanded on.

2.6 Paper 6

The paper mainly focuses on the severe winter storm (referred to as Gudrun) affecting the North Sea and southern Scandinavia on 07-08 January 2005. This exceptionally strong cyclone was not well forecast by the Norwegian HiRLAM initiated at 12 UTC on 7 January 2005. PV fields were modified by the same methods as used in the previous papers, and the new simulation turned out to be a substantial improvement over the operational simulation at 12 UTC. One of the reasons to select this case for study was that it was a "new" case, with the most recent assimilation routine available (i.e. 3D-Var).

The role of moisture is elaborated on. It appears that the NWP simulation is very insensitive to the initial moisture distribution, hence modification of the initial relative humidity fields had a very small effect on the simulation.

The structure of SVs is further expanded on as well, and it is proposed that SV dynamics is consistent with PV thinking.

It is demonstrated that the region of strongest signal for SV1 and SV2 is important for the development. Enhanced PV in this region has a pronounced impact on the cyclone development, though there was no indication in the WV image that the region was dynamically active at the initial time. Trajectories starting within the most sensitive region (at upper levels) at 18 UTC end up within the strong upper level PV anomaly associated with the cyclone at peak intensity 18 hours later. This result suggests that short range ensemble forecasts can be produced by perturbing PV in the sensitive regions and then through inversion and model rerun create ensemble members.

The downstream effect, and its possible limiting beneficial effect on local PV modification is discussed. It is stated that more experiments with cases of downstream developments have to be carried out in order to reach a firm conclusion.

3 An example of PV modification in a sensitive region

We have in the present investigation claimed that SVs constitute an important tool in PV modification, mainly in determining the 3-dimensional structure of the PV corrections and location of low level PV anomalies. Our results indicate that SVs are very useful for this purpose. Nevertheless, it is felt that a more systematic study of the use of SVs in forecasting is called for.

Below, we present a case of a successful NWP simulation, initiated at 00 UTC 10 January 2006. We want to investigate if SVs properly highlight the sensitive regions in this particular case study, by applying combined use of PV modification and SV information. SVs were calculated as for the cases described in papers 3, 5 and 6 and sensitive regions indicated by SVs 1-5, but with emphasis on SV 1 and 2. Several experiments were performed where PV in the analysis at 00 UTC 10 January was modified in sensitive and non-sensitive regions. Inversion of the modified PV fields yielded new analyses from which reruns were conducted. The simulations were carried out using a version of the Norwegian HiRLAM with 20 km horizontal resolution and 40 vertical model levels. The integration region was smaller than in the operational model (Figure 2 in paper 5). It turned out that PV modifications in sensitive regions had a large impact on the simulation, while PV modifications in non-sensitive regions had generally small effects. Results from one of these experiments, which is now described, are shown in figures 2-4.

The presence of a lee cyclone at the east coast of Greenland may strongly influence the development of North Atlantic cyclones tracking northeast between Iceland and Scotland (Petersen et al 2003) and across Iceland and the Norwegian Sea (Skeie et al 2006). Figure 2 shows the subjective analysis valid at 12 UTC on 11 January 2006. This winter storm was the strongest that winter season over the Norwegian Sea. Figure 3 shows the leading initial SVs (SV1 and SV2) at level 24 ($\sim$ 850 hPa), valid at 00 UTC 10 January, indicating the region at east Greenland and over the North Atlantic at 55°N, $15 - 30$°W as strongly sensitive at lower levels. This means that analysis errors as well as new observations there are likely to have a large impact on the numerical simulation of the winter storm. The SVs are targeted, with an optimization time of 24 hours. They are calculated to reach maximum amplitude at optimization time within the verification region confined within the latitude/longitude lines defined by 75°N, 40°W as the northwest corner and 55°N, 20°E as the southeast corner. Low level PV in the sensitive region at the eastern coast of Greenland was enhanced between 1000 and 800 hPa (Figure 4(a)). PV is then inverted to yield geopotential heights and winds. The modifications are tuned to yield height fields that are more consistent with observations in the region Iceland-Greenland, as the model analysed surface pressure in that region was slightly too high. The effect from the PV inversion weakens with height but at 500 hPa there is still a lower geopotential height than in the control run (the simulation based on the analysis obtained by inverting the original PV fields, not shown).

By this procedure a new analysis is obtained, from which a numerical rerun is carried out. This rerun is referred to as the EXP run. Figure 4(a) shows the difference between the modified PV fields and the original ones, at 00 UTC 10 January, given in PV units. Figure 4(b) shows the difference between surface pressure in the EXP simulation and in the control run, valid at 12 UTC 11 January. The new simulation was an improvement over the control run in that the cyclone was deeper than in the control simulation and located further north, consistently with the subjective analysis. The reduction in upper level geopotential height may have contributed to stronger upper level vorticity advection further north than in the control run, interacting with the cyclone, hence causing a stronger deepening and a faster propagation speed of the winter storm.

In another experiment low level PV was enhanced in the sensitive region at lower levels, between 1000 and 800 hPa, over the North Atlantic, at 55°N, $15-30$°W. A new simulation based on these modifications yielded a large improvement over the control simulation (not shown).

The findings in this case study confirm that the leading SVs are very useful in highlighting sensitive regions where local PV modifications in the analysis have large impact on the new simulations.

Nearly optimal 3-dimensional corrections of the PV fields should be obtained by observing the following items:

(1) Upper level PV anomalies are corrected according to WV information. The actual 3-dimensional modification is determined by the sensitive regions, e.g. if the 500 hPa level in the region of interest is sensitive according to the

fastest growing SVs, the upper level PV correction is extended to the 500 hPa level.

(2) As locations of low level diabatically produced PV anomalies are difficult to infer from satellite imagery, SV information is particularly important for modification of such PV features.

The procedure involving SV information is performed subject to the condition that the SVs target the true sensitive regions. If the targeting fails PV is modified according to the WV information and knowledge of conceptual models.

SVs are calculated using the tangent linear operator and its adjoint, that is a linearized model along the non-linear trajectory, i.e. the NWP forecast itself. If the NWP simulation contains large errors, they may have a detrimental effect on the SVs. The tangent linear model also contains simplified physics and the SVs are designed to describe rapid, albeit linear, growth. In our investigations we have studied rapid cyclogenesis that certainly is a highly non-linear process. The diabatic contribution in such cases is furthermore very large. All these factors may suggest that SVs give inaccurate targeting in some cases.

On the other hand current NWP analyses and short range forecasts rarely fail to simulate properly the large scale flow, in which the individual cyclones are embedded. For that reason we believe that the leading SVs still tend to highlight true sensitive regions in cases with local analysis errors. This is probably the reason that SVs turned out to be useful in the cases studied in our investigations (e.g. the winter storm Gudrun).

4 Future Directions

The results obtained by the PV-WV method supported by the use of targeted SVs have been quite promising. The studies have, however, been performed after they took place and the experiments were carried out with the benefit of hindsight. Hence it is necessary to perform more real time experiments.

(1) As a part of the current preparations at NMI for implementing a more active and organized monitoring of the performance of the operational NWP models, real time tests of the PV - WV method have been carried out in test periods. Though the cases of identified analysis errors were few and the

errors small, some results indicated slight improvements over the operational simulations, while no modifications were detrimental to the forecast [5].

(2) In order to further compare the PV fields from the NWP analysis with the features in WV images, pseudo water vapour (PWV) images are now available as an additional tool. PWV images are calculated by a radiation transfer model, using fields of temperature, humidity and clouds from the NWP model. This new product (in use for some time at e.g. the meteorological institute in The Netherlands, KNMI) will most likely constitute an efficient additional tool in identifying errors in numerical output.

(3) It is expected that the use of the PV-WV method will be automated. This will take place within the framework of data assimilation methods.

Ongoing research on PV modification introduced in 3D-Var is currently taking place as well. A PV term is introduced in the cost function from which a modified NWP analysis is prepared (Verkley at al 2005). This work has yielded promising results.

An approach containing an automatic tracking algorithm linking PV anomalies and dark regions in WV images (also adopting pseudo WV images) has been developed by Y.Michel and F.Bouttier (Michel and Bouttier 2006) at Meteo France. The method is still under development and suggests further applications in data assimilation, notably in 4D-Var.

(4) In spite of automation as a likely and necessary step forward, the need for human intervention by PV modification is not rendered superflous by the development of automatic methods, e.g. 4D-Var. It may be necessary to retain the PV-WV method for dealing with cases of dangerous weather developments, i.e. rapid cyclogenesis, because the NWP models, including assimilation routines, will never become "perfect".

The PV-WV method is also highly useful for training purposes, by which insight into dynamically complex cases (i.e. cyclogenesis) can be gained.

[5] Future real time experiments involve solving some technical problems currently related to running the required routines at the super-computer at NTNU in Trondheim.

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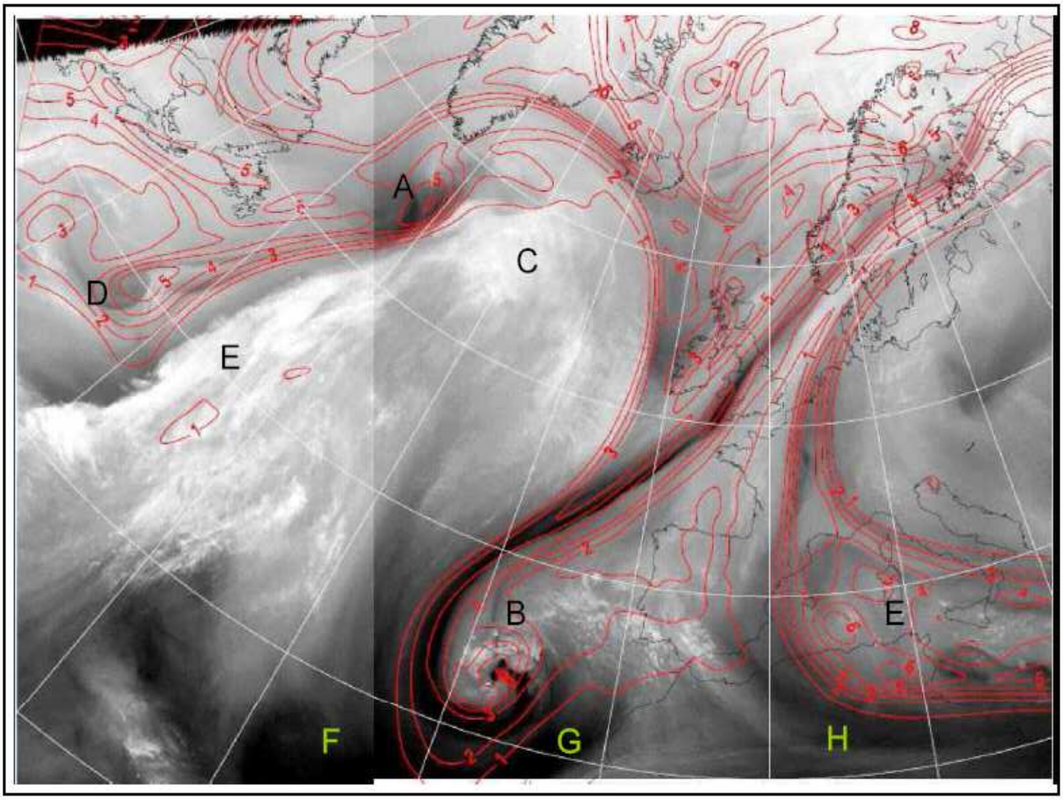

Figure 1

A dynamically active cyclonic PV anomaly is located at A. B and E are cyclonic PV anomalies associated with cut off lows. C is a region containing moist tropospheric air and high level clouds. D is a cyclonic PV anomaly, associated with incipient cyclogenesis.

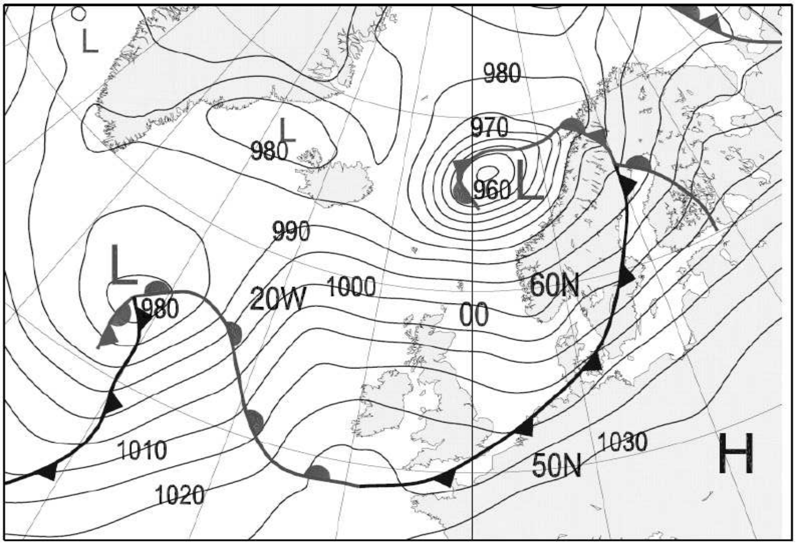

Figure 2

Subjective analysis valid at 12 UTC, 11 January 2006

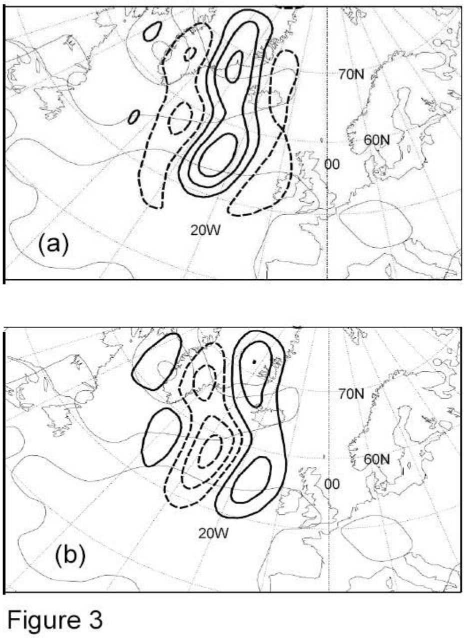

Figure 3

Initial SV1 (a) and SV2 (b) at level 24 (~850 hPa), valid at 00UTC 10 January 2006. Thick solid (dashed) contours for the SVs give positive (negativ) values with contour interval 0.004 PVU. Basic state PV in light contours with interval 0.5 PVU.

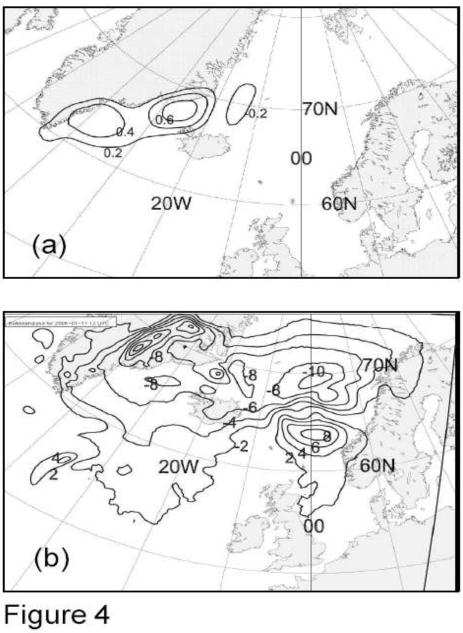

Figure 4

(a) Difference between modified PV and original PV (in PV-units) at 800 hPa, at 00 UTC 10 January 2006

(b) Difference in surface pressure between the EXP run and control run, valid at 12 UTC on 11 January 1006