Analysis of humidity, cloud and rain in the Met Office 3DVAR and 4DVAR systems: present and future

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1. Introduction

This paper describes some aspects of the assimilation of humidity, cloud and rain in the present and future Met Office 3D-Var and 4D-Var systems. Section 2 describes the basic operational NWP system and formulation of the new dynamics. Section 3 outlines aspects of the incremental variational assimilation relevant to the assimilation of moisture variables. This includes some characteristics of the humidity background errors and observations used. Section 4 discusses initialization and spin-up. Section 5 descibes developments in assimilation of humidity, cloud and precipitation including the formulation of the 4D-Var system and its properties, the use of cloud cover observations in 3D-Var and future moisture, cloud and precipitation data in 3D and 4D-Var. Section 6 discusses other issues related to improvements in assimilation of humidity, cloud and precipitation.

2. Basic NWP System

The Met Office operational NWP system uses grid point models and, since 29 March 1999, three dimensional incremental variational analysis (3D-Var) (Lorenc et al 2000). At the time of this workshop a new model formulation, referred to as the "new dynamics" (Cullen at al 1997), was undergoing parallel trials and was introduced operationally from 7 August 2002. The global model has 432x325 horizontal gridpoints and in the new dynamics 38 vertical levels (30 levels old dynamics) and a timestep of 20min. A limited area mesoscale model for a region surrounding the UK is also run with a resolution of 0.11deg and also changed to the new dynamics formulation on 7 August 2002. The incremental 3D-Var analysis is run at half the full horizontal resolution of the model (full resolution for new dynamics mesoscale model). A 4D-Var system is under-development and currently being tested in short trials at low resolution (96x73 gridpoints for analysis, 288x217 for the model) for the global model. The limited area version of the linear and adjoint models used in 4D-Var is still under-development.

The new dynamics is semi-implicit and semi-lagrangian with a 3Dsolver for pressure perturbations. It has Charney-Phillips staggering in the vertical i.e. potential temperature and humidity/cloud are staggered from winds and pressure. It has a hybrid-height terrain following co-ordinate and is non-hydrostatic. It includes full physics, in particular mass flux convection and a prognostic cloud scheme with separate advection of potential temperature, specific humidity, cloud liquid water and cloud ice but with rediagnosis each timestep of specific humidity and cloud liquid water from liquid water potential temperature and the sum of specific humidity and cloud liquid water, q_{tl}. The cloud scheme is basically the scheme of Wilson and Ballard 1999 but in its implementation in the old dynamics the advected variables were liquid water potential temperature, cloud ice and q_{tl}.

3. Outline of the incremental variational assimilation system

The control variables in the 3D and 4D-Var systems are horizontal spectral components of vertical empirical modes of increments of velocity potential, stream function, unbalanced pressure, and relative humidity; RH. There is currently no allowance for cloud water or ice in the control variables and transforms. RH' was chosen as the moisture control variable as RH has more uniform values with height than q. It is also perhaps better in near saturated conditions where RH is less correlated with temperature, despite errors being non-Gaussian. Previous studies in Lorenc et al 1996 on the use of radiosonde humidity observations in mid-latitudes found that assuming temperature and RH errors are uncorrelated rather than temperature and specific humidity errors reduced the cloud and precipitation spin-up during the forecast period by reducing the negative cloud and precipitation bias in the analysis. RH' is defined as

$$RH' = [q' - q\{\vartheta'\overline{\Pi}\frac{d\log e_s}{dT} + (\vartheta\overline{\Pi}\kappa\frac{d\log e_s}{dT} - 1)\frac{\overline{p'}}{p}\}]\frac{1}{q_s}$$

where the contribution of the pressure pertubations is currently ignored.

Background errors used are those derived from the so-called "NMC method" using T+48-T+24 forecast differences (Ingleby 2000). They use global vertical modes with zonally varying variances. Those used currently for any particular analysis are time interpolated between winter and summer statistics i.e. between those calculated using about 30 forecasts pairs per month for Jan 1999 and July 1998. From figure 1 it can be seen that background error variances for relative humidity peak in the extra-tropical mid-troposphere and are larger in the winter with values over 25% in northern and southern hemispheres in January and over 30% in southern hemisphere in July. However the variances are much more uniform that those for specific humidity, which vary over orders of magnitude between the surface and top of the model. From figure 2 it can be seen that the horizontal length scales for the relative humidity errors is much shorter than that for the mass ,and not shown, momentum fields. The statistics calculated using the new and old versions of the model are broadly similar.

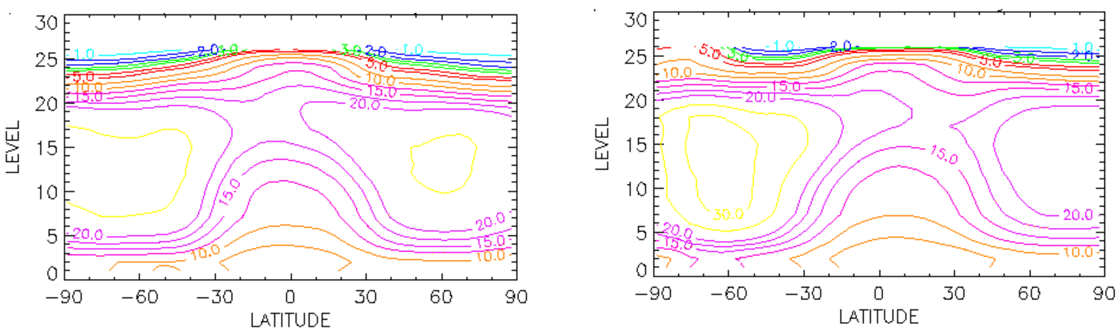

Figure 1 Implied background errors variances of relative humidity % calculated for old dynamics model with 30 vertical levels. Level 5 is the top of the boundary layer, level 11 is about 500hPa, level 19 is about 250hPa and level 15 is about 100hPa. On left are those calculated for January 1999 and on the right for July 1998

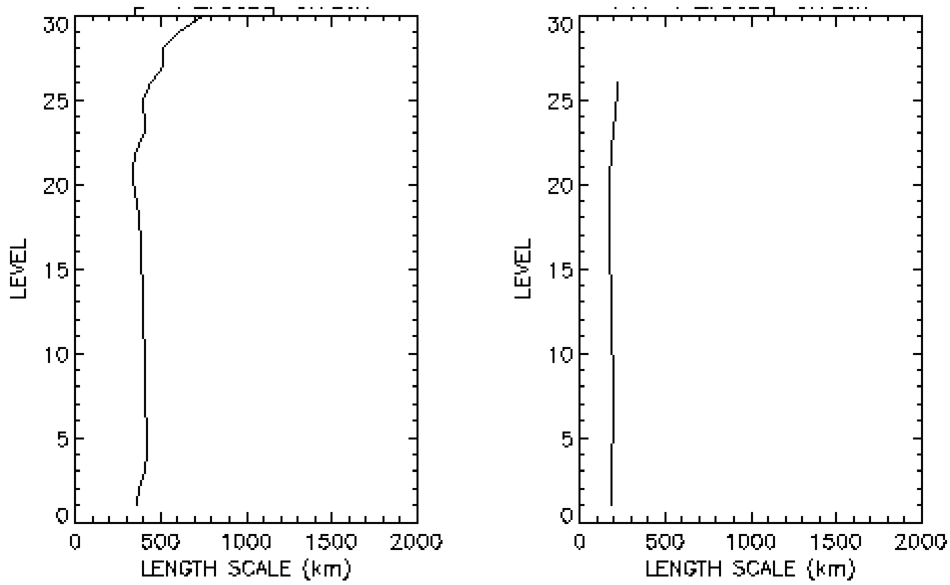

Figure 2 On left is the horizontal length scale for the unbalanced pressure and on the right the length scale for the relative humidity.

The humidity observations currently used operationally in the global and mesoscale models are shown in table 1.

Global	Mesoscale
Radiosonde layer average RH with bias correction Assumed error per level from surface to top 3x10,11,12,33x13%	radiosonde layer average RH with bias correction assumed error per level 8-13%
ATOVS radiances - AMSU-B with low weight -HIRS	Screen humidity as RH (error 6.2-8%) and visibility
Bogus data	nudging of RH vertical profiles derived from cloud cover
	latent heat nudging for use of precipitation analysis

Table 1 Humidity observations used operationally in global and mesoscale models

It can be seen that there is very little humidity data used, especially in the global model. The mesoscale model is used for detailed prediction of weather elements such as cloud, rain and visibility so there is greater emphasis on the humidity analysis. More information on the mesoscale assimilation can be found in Macpherson 2000 and references.

The use of ATOVS radiances has been tested in the mesoscale model and the use of SSM/I TCWV(total column water vapour) and latent heat nudging of tropical convective rainfall derived from meteosat imagery has been tested in the global model. However initial trials showed limited benefit and some local problems, e.g. excessive convection at the start of forecasts in the tropics from use of SSM/I TCWV data, therefore work on them has been delayed until other developments have been completed eg introduction of new formulation model.

In the minimization the model predictionsof the observations, y, are calculated for the observation penalty terms using a combination of high resolution non-linear forecast fields interpolated in time (from 3 hourly output) and space to the observation time and location, c_x, and low resolution increments interpolated in space to the observation location, c'_x. In 3D-Var the increments are those valid for the analysis time and in 4D-Var they are those from the closest linear model timestep to the observation time. The observation operators, H_{ob}, are either fully non-linear (as currently used in the mesoscale model for all iterations) or linearized. In the global model the nonlinear version of the observation operator is used every 10th iteration i.e. $y = H_{ob}(c_x^+)$ where $c_x^+ = c_x + c'_x$ but an incremental/linear operator is used at all other iterations i.e.

$$y = H_{ob}(c_x^{+old}) + \frac{\partial H_{ob}(c_x^{+old})}{\partial c_x}(c_x^{+new} - c_x^{+old})$$

The ability to update the observation operators non-linearly without the need for an outerloop non-linear model forecast run is useful for dealing with nonlinear observations such as radiance and visibility.

4. Initialization and Spin-up

The time evolution of precipitation and cloud cover in forecasts has been investigated (Christophe Accadia) to see if there are any problems in initialization indicating inconsistencies between analysis increments and the model formulation. If 3D-Var analysis increments are just added to the forecast background field at analysis time it is found that excessive convection is produced in the first timestep and then probably too little for the next hour or so compared to the background forecast. see figure 3. The excessive convection is occuring in the topics mainly over Malaysia, Indonesia and the Philippines.

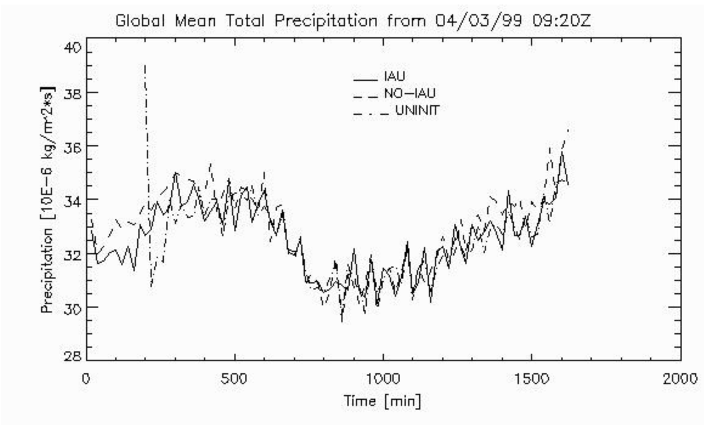

Figure 3 Evolution of global mean total precipitation rate from T-3 to T+24 for 12UTC 4/3/1999 forecast. Dashed-line is background(ie previous forecast), dash-dot line is with no initialization and solid line is with IAU.

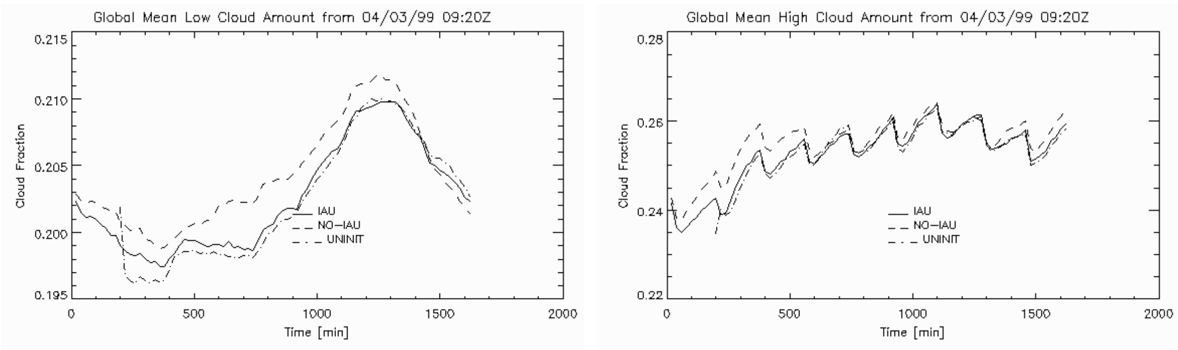

Figure 4 As figure 3 but evolution of global mean low cloud amount on left and high cloud amount on right

Without initialization for this forecast, large-scale precipitation, low and medium cloud cover decrease sharply over the first hour before increasing again and following the trends in the background forecasts and high cloud amounts start low and increase sharply over the first hour, see figure 4. Currently initialization is performed using the IAU (incremental analyis update), see Lorenc et al 2000, whereby the forecast is run adding a fraction of the increments over a period of 6 hours centred on the analysis time. It can be seen from figure 3 and 4 that cloud cover is reduced once the information from the latest observations is introduced and the impact lasts for about 6 hours for high cloud and 20 hours for low cloud. Statistics and verification over a large number of forecasts are required to indicate whether this indicates an inconsistency between the model and the observations or a problem in the assimilation, e.g. due to the lack of consistent cloud water/ice increments.

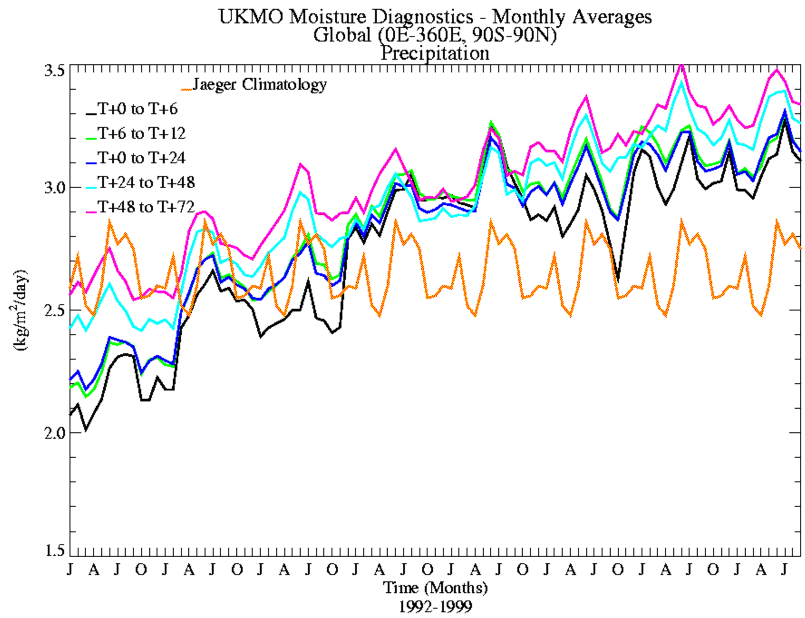

Figure 5 Evolution of monthly averages of global precipitation/day for different forecast periods from the operational Met Office model from January 1992 to September 1999 compared to Jaeger climatology

Long term statistics on the spin-up of precipitation with forecast period have been produced by Sean Milton at the Met Office and these can be seen in figure 5. Apart from a period from November 1994 to November 1996 there is considerable spin-up of global precipitation with forecast period. There is also a long–term trend of increasing precipitation compared with the Jaeger climatology. In January 1992 the model was under-predicting precipitation in the first 2 days of the forecast compared to climatology but from November 1995 onwards it was producing more than climatology at all forecast ranges. Changes in characteristics of the spin-up and amounts can apparently be linked to model and assimilation changes. The increase in March 1993 coincides with a change in diffusion of specific humidity from first to second order $(\nabla^2 \text{ to } \nabla^4)$. The increase above climatological amounts in November 1994 and reduction in spin-up coincided with revisions to the moisture assimilation, in particular introduction of bias correction of sonde relative humidity and analysis of relative humidity rather than specific humidity. In January 1995 a change was made to switch off horizntal diffusion over steep orography. In November 1996 assimilation of 1DVAR TOVS retrievals, including moisture, rather than NESDIS retrievals was introduced and this appears to coincide with reintroduction of spin-up in the precipitation forecasts. 3D-Var was introduced in March 1999 along with AMSU 1D-Var retrievals but there is no apparent change in the precipitation forecasts at that time – a longer time series is required to see if the spin-up has actually been reduced slightly by increasing the precipitation bias from climatology in the early period forecasts.

It should be noted that the Jaeger climatology is probably an underestimate compared to more recent estimates such as GPCP (global precipitation climatology project - combined gauge and satellite estimates). This puts the global mean precipitation at around 3 mm/day, so the model is still probably excessive compared to this, particularly at later forecast ranges.

During the period from 1992 to the end of 1997 the gradual drift in increasing precipitation has been accompanied by a drift in the T+72-T+0 RH at 500 hPa. From a largely positive difference in 1992 to 1993 the difference was reduced and became largely negative, especially in the tropics once the 1D-Var TOVS humidity was introduced in November 1996. Analysis of results for the period 1999 onwards has just started but seem to indicate that there is now a spin-down in precipitation in the first 12-18hours of the forecast. Over the period T+ 0 to T+72 the spin-up seems to be dependent on season or forecast as on some occasions there is a slight spin-down in precipitation.

5. Developments in assimilation of humidity, cloud and precipitation

5.1. Development of 4D-Var

The incremental 4D-Var system aims to find low resolution increments by running multiple ‘outerloops’ at high resolution with the full nonlinear model to refine the fit to the observations and to update the linearization state. The evolution of low resolution increments is predicted with a linear perturbation forecast (PF) model and these are added to interpolated high resolution fields to update the prediction of observed values. The gradients for the descent algorithm come from the adjoint of the PF model and the observation operators. The minimization is achieved by iterating at low resolution (inner loop) to obtain updated increments and interpolation to high resolution.

The PF model is a linearization of the full model (new dynamics) with some small terms omitted and it will eventually have its own linear physics. Although the formulation is based on the new dynamics the PF model is not constrained to be tangent linear to any particular model. Lorenc (personal communication) believes that what is actually required is a linear model that will predict the evolution of finite perturbations with respect to a basic state and is a good approximation to the evolution of those perturbations in the non-linear model. This may require undesirable features of an exact tangent linear model to be filtered out, eg unrealistic growth due to lack of feed-backs in the linear dynamics or physics. It may also be required to simulate area average properties rather than gridpoint values due to differences in resolution and to allow better treatment of cloud and precipitation observations. This approach potentially allows more flexibility in formulation and allows cost saving approximations. It also avoids problems with linearizing the semi-Lagrangian interpolation and the solver for the elliptic equation.

Most of the adjoint model is coded explicitly using the transpose of the PF model code (automatic adjoint method). Originally the elliptic equation in the adjoint model was derived from the equations in the adjoint of the discrete PF model (Amos Lawless). Recently it has been found that even that stage can be coded as the transpose of the forward code (James Beck).

The PF model variables are perturbations of wind components (u’, v’ and w’), potential temperature, pressure and density, with just one moisture variable. This is a reduced set of prognostic variables compared to the nonlinear model as the PF model currently just has passive advection of one moisture variable rather than specific humidity, cloud liquid water, cloud ice plus diagnosis of cloud fraction. The single moisture variable can be considered as either specific humidity or total water increments. At present the linearization state is just specific humidity so that the increments are formally specific humidity but there is no removal of supersaturation. Once the linearization state is changed to total water (specific humidity plus ice and liquid water) from the nonlinear model, the PF model variable can be regarded as total water increments. At present the only physics included in the PF model is constant coefficient vertical mixing of momentum increments (Tim Payne). Others will be added as required e.g. removal of supersaturation (or formation of increments to precipitation and cloud), vertical mixing of heat and moisture increments and increments to convective fluxes of heat, moisture and momentum.

Example of new dynamics equations

$$\frac{Du}{Dt} - fv + f_2 w + \frac{wu}{r} - \frac{uv\tan\phi}{r} + \frac{c_p \vartheta_v}{r\cos\phi}\left[\frac{\partial\Pi}{\partial\lambda} - \frac{\partial\Pi}{\partial r}\frac{\partial r}{\partial\lambda}\right] = S^u$$

$$\frac{Dq_v}{Dt} = s^{q_v}, \frac{Dq_l}{Dt} = S^{q_l}, \frac{Dq_i}{Dt} = S^{q_i}$$

equivalent PF model equations

$$\frac{Du'}{Dt} + u'\bullet\nabla u - fv' - \frac{u'v\tan\phi}{r} - \frac{uv'\tan\phi}{r} + \frac{c_p\vartheta'}{r\cos\phi}\left[\frac{\partial\Pi}{\partial\lambda} - \frac{\partial\Pi}{\partial r}\frac{\partial r}{\partial\lambda}\right] + \frac{c_p\vartheta}{r\cos\phi}\left[\frac{\partial\Pi'}{\partial\lambda} - \frac{\partial\Pi'}{\partial r}\frac{\partial r}{\partial\lambda}\right] = S^{u'}_{friction}$$

$$\frac{Dq'}{Dt} + u'\bullet\nabla q_v = 0$$

Prototype 4D-Var suites have been set-up (Mark Dubal). These have outerloops with non-linear model resolution 288x216 and analysis resolution at 96x73 or 216x163 or 2 outerloops with analysis resolution increasing from 96x73 to 216x163 in the second loop. They have a time window of T-3 to T+3 with observations used at nearest timestep and processed as for 3D-Var with high resolution, time interpolated 3 hourly forecast fields for use in the innovation. The low resolution trajectory, interpolated from the high resolution forecast, is available every timestep. Initialization was originally with the IAU T-6 to T+0 for the single outerloop and the PF digital filter for multiple outerloop. The PF digital filter (digital filtering of the increments using the PF model (Adam Clayton)) will become the standard initialization in 3D-VAR so 4D-Var suites have now been set up with this.

5.2. Comparison of relative humidity background errors in 3D-Var and 4D-Var

As well as extracting extra information from the time evolution of observations, 4D-Var also introduces flow dependent structure functions, apart from at the the start of the time window, which should improve the treatment of humidity in the analysis. The impact of the horizontal and vertical structure of the background error covariances for humidity in the Met Office systems can be illustrated by maps and cross-sections of specific humidity increments resulting from a single relative humidity increment. We look at the effect in an active area to the south of a surface low centre, see figure 6, just ahead of an upper level jet at 7.5deg E, 45degN. An observation increment of 1% above the background value at level 10 (near the top of the boundary layer) at 12UTC (centre of the observation time window of 6 hours) on 26th December 1999 is analysed in both the 3D-var and 4D-Var systems.

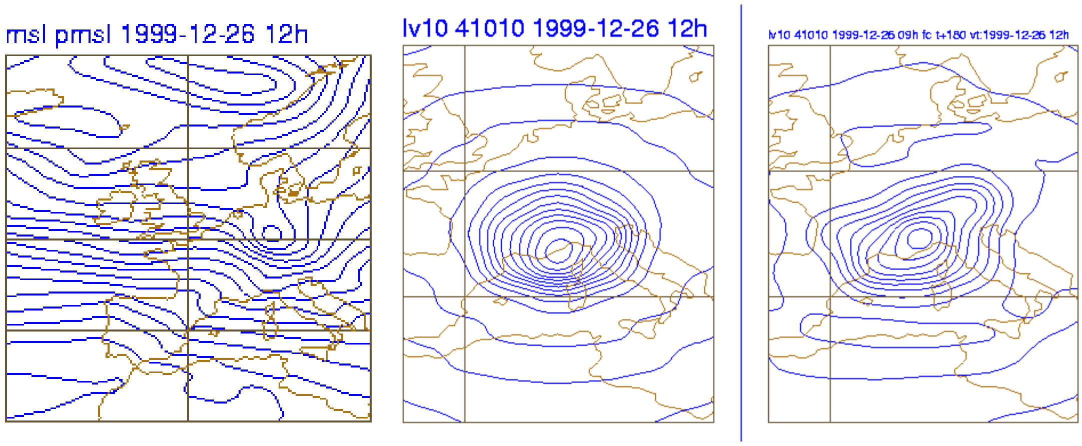

Figure 6 Comparison of Increments of specific humidity at level 10 at 12 UTC 26 th December 1999 (Map on left is the operational analysis mean sea level pressure). The map in the centre is the 3D-Var analysis and that on the right are the increments from the PF model 3 hours into the time window of 4D-Var at the end of the minimization.

It can be seen that 4D-Var has introduced a flow dependence to the analysis increments at 12UTC which are spread over about 15 degs longitude and 5 levels either side of the observation level in both systems.

5.3. Accuracy of PF Model - linearization errors

The ability of the linear PF model to predict the evolution of increments in the non-linear model can be assessed in a number of ways. Here we investigate the evolution of the damping error ie the ratio of the linear to the nonlinear increments. Errors in pressure are smallest. Errors in vertical velocity are largest due to absence of physical parametrizations (if both models are adiabatic the errors in vertical velocity are much smaller). The magnitude of increments in windspeed and potential temperature are reasonable apart from in the boundary layer levels. The linear model overpredicts the windspeed increments in the middle of the boundary layer but the inclusion of suface friction and simplified vertical diffusion with constant coefficient has removed errors in near suface windspeeds. However the lack of vertical mixing of heat means that errors in potential temperature increments increase towards the surface, see figure 7. The magnitude of increments in specific humdity are also reasonable in the PF model apart from a peak in errors around level 25. Increments are underpredicted after one timestep and overpredicted after 6 hours of forecast, see figure 7. By inspecting maps it is seen that the errors are concentrated in the area around Indonesia and the Phillipines.

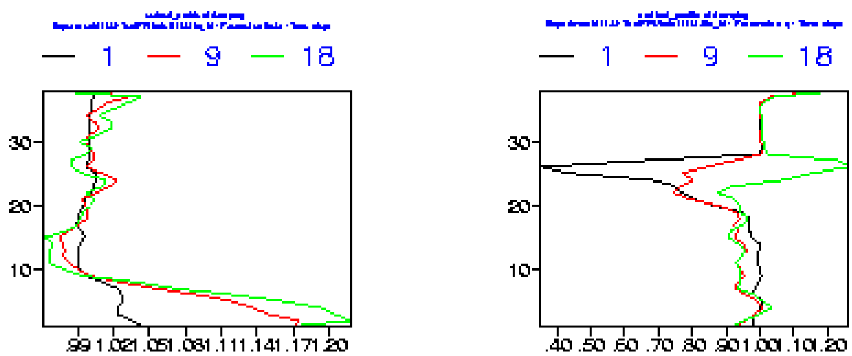

Figure 7. Evolution of damping error = global rms linear increment/global rms non-linear increment for 1,9 and 18 timesteps of 20mins for N144 resolution starting from 3D-Var analysis increments at 12 UTC 26 Decmeber 1999 left is potential temperature and right is specific humidity.

After one timestep the nonlinear model with incremented fields with no initialization produces excessive convection in that area which the linear model cannot represent due to the lack of linearized convection. By the end of the forecast period it is likely that the linear model is overpredicting the moisture increments due to the lack of linearized large scale precipitation scheme, to remove increments to supersaturation, and a representation of convection.

Adiabatic TL and adjoint models have been used successfully in 4D-Var as they can accurately describe the development stage of baroclinic waves in mid-latitudes. That needs surface friction and boundary layer mixing but how much more parametrization of sub-gridscale processes is needed to get useful results from 4D-Var? Despite the limitations of the current formulation of the PF model a short trial of 4D-Var for 2 weeks in December 1999 produced slightly improved forecast skill compared to that of 3D-Var for NWP index fields of mean sea level pressure, 500 hPa heights and 850 and 250 hPa winds. The rms errors for relative himidity against observations at 850,700 and 500hPa were generally slightly lower in the northern hemisphere and tropics but higher in the southern hemisphere.

However moist processes are needed to improve the dynamics in the tropics and extratropical storm tracks and also to enable use of cloud and precipitation observations. Linearization of the full physics is expensive, complicated and can produce spurious results due to missing feed-backs and it may also give response at wrong timescales and there are problems dealing with thresholds. We also want to be able to generate cloud and precipitation where there is none in the full linearization forecast, eg want to allow convection to begin for some finite perturbations. Therefore the aim is to develop simplified parametrizations that can account for these factors. Can we find simple schemes to predict precipitation and cloud? Ideally we want diagnostic relationships for cloud fraction, water, ice and humidity to limit the number of prognostic variables in the model to just the total water.

5.4. Future observations

Table 2 lists various observations providing information on humidity, cloud and precipitation which can be tested in the operational models over the coming years and where work has already started.

Global	**Mesoscale**
SSMI TCWV	ATOVS radiances
Latent heat nudging of tropical convective rainfall derived from meteosat imagery	
Cloudy ATOVS	3DVAR of RH derived from cloud cover profiles
SSMIS images	Ground-based GPS
Meteosat imagery/Wv	
Radio-occultation GPS	
AIRS	

Table 2 Sources of humidity and cloud information

In order to exploit information from cloudy radiances and cloud cover observations the Var control variables must be

extended to allow for cloud or it must be possible to derive relationships for increments to cloud cover, cloud liquid water and cloud ice from a limited set of control variables. It is likely to be difficult to derive error statistics for cloud fields and they are correlated with the specific humidity and temperature near saturation. Therefore rather than having additional control variables, adding to the cost of the minimization, it is hoped that the current humidity control variable can be extended to be total water and that diagnostic relationships can be used to separate the vapour,liquid and ice phases and to provide cloud cover increments.

Unfortunately the model cloud scheme is being extended to be even more prognostic in the future so that diagnostic relationships will have to be derived to approximate the prognostic results. At present relationships are being developed based on the Smith 1990 cloud scheme.

At present the mesoscale model includes information from a 3D cloud cover analysis (MOPS) by nudging in increments to relative humidity derived from cloud cover profiles (using the inverse of the Smith 1990 cloud scheme) outside the 3D-Var system. Increments from the 3D-Var analysis, the MOPS data and from latent heat nudging are all derived independently. Richard Renshaw has developed a method of including the MOPS cloud cover information within 3D-Var, again this is based on the Smith 1990 cloud scheme. In the nonlinear model, liquid water cloud and cloud fraction is diagnosed from total water and liquid water potential temperature using Smith 1990. Ice cloud is now prognostic, however we assume the scheme is still a good approximation for ice and mixed cloud . This can give an expression for cloud cover,C, in terms of RH (or total water and liquid/ice potential temperature) and critical RH. As there is currently no allowance for cloud water in VAR the relationship with RH is currently used. These relationships are very nonlinear and gradients are non-zero over only a small range of relative humidity. The errors in background RH are the same order as the range of RH over which clear to full cloud is obtained. Therefore the observed cloud cover profiles, after adjusting for model background convective cloud cover, which is not allowed to change in the analysis, are converted to relative humidity before use in the observation penalty function. The model observation operator also uses a first guess RH calculated from the model cloud cover using the same approximate C/RH relationship at cloudy grid-points but uses the model RH elsewhere. The observation penalty function is smoothed to cope with special cases for no or full cloud e.g. no cloud observed and none in model. This has been tested in the mesoscale model and was beneficial for cloud cover forecasts but had a slightly detrimental effect on other fields such as precipitation which may require changes to the scheme such as reduction of the weight given to the observations.

4D-Var provides the potential to extract dynamical information from a time sequence of satellite images of cloud top temperature or water vapour. It may be easier to use the tropical moisture data, such as SSM/I TCWV, in 4D-Var as the time evolution of precipitation may provide a constraint not available in 3D-Var and so remove the undesirable effects. However improved specification of background error correlations will be important in ensuring correct use of low vertical resolution humidity data such as radiances and TCWV. These will need to take into account geographical and synoptic variations and errors especially those related to boundary layer depth and tropopause height.

Work is also planned to allow direct use of precipitation observations derived from radar and satellite data, or use of the direct observations of radar reflectivity or precipitation contaminated radiances in 3D-Var and 4D-Var to replace the latent heat nudging.

6. Other Issues

Further work on the humidity control variables may be undertaken to see if correlations with temperature and vertical velocity can be found and removed. Work will also look at whether the humidity increments need to be constrained to limit the moisture fields to positive values and to remove supersaturation, there are currently no constraints until the model fields are updated. It should also be noted that RH is non-linear so there is a jump in the background penalty between outerloops in 4D-Var due to the change in the linearization state. Work is also planned to ensure that the initialization method copes with diabatic processes. Also in the current system only the specific humidity is updated and there is no attempt to provide consistent increments to the cloud fields. Before cloud increments are provided directly from the variational analysis, Martin Sharpe is testing methods of calculating consistent cloud fields, again using the Smith 1990 scheme. In order to fully exploit observations of cloud and precipitation changes are likely to be required to the non-linear model or the way it is used in the analysis. For instance figures 7 and 8 show unrealistic short timescale variations in precipitation rates and high cloud cover (the latter due to use of 3-hourly updating of the radiation) which need to be removed before comparing with instantaneous observations. Model biases also need to be removed to allow optimum use of the observations.

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