Quality Control and Assimilation of Radar Data — a Review

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1 Quality Control Issues

In the framework of the COST-717 action on 'Using Radar Information for Assimilation into Atmospheric Models' an up-to-date review has been made on processing techniques and limitations of radar reflectivity and wind data.

1.1 Introduction

The COST-717 action has a working group (No. 3) on 'Using Radar Information for Assimilation into Atmospheric Models'. As an initial part of its plan, the group is reviewing radar processing methods and previous attempts to assimilate radar data. The articles of Meischner et al. (1997), Serafin and Wilson (2000), and Fulton et al. (1998) give a detailed and recent overview of the abilities and limitations of the current generation of operational weather radars. In this article, an up-to-date overview of processing techniques and limitations of radar data is presented. Issues which are relevant to the assimilation of reflectivity and/or wind data into numerical weather prediction models have been stressed. The overview is divided into four sections, refering to the types of radar data relevant for assimilation purposes.

First, issues concerning the measurement of radar reflectivity, like calibration, attenuation and problems concerning radar echoes from non-hydrometeor targets objects are addressed. Then, the problem of estimating the on-ground rainfall from radar reflectivity data aloft is described, and the currently applied methods are reviewed. Thirdly, the extraction of wind information from Doppler radar and the problems due to aliasing and representativeness are described. Finally, the methods for the construction of wind profiles from radial wind measurements are discussed, and some verification results are highlighted.

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1.2 Reflectivity data

1.2.1 Radar equipment

For the extraction of quantitative information from a weather radar, it is essential that the radar equipment is accurately calibrated and perfectly stable. During operation of the weather radar, the receiver has to be calibrated on a regular basis and samples of background noise have to be taken almost continuously (Meischner et al., 1997; Serafin and Wilson, 2000; Manz et al., 2000). In this way, the repeatability of the system parameters during normal operation can be well within 0.2 dBZ, i.e. within 3% of the equivalent rain rate.

The absolute calibration of the radar equipment is more difficult. Koistinen et al. (1999) give a detailed description of their efforts to accurately calibrate the radars in the Nordrad network. Both extensive single-radar calibrations and comparisons between adjacent pairs of radars have been performed. Existing signal differences of 6-13 dB between Ericsson and Gematronik systems have been detected and partly corrected in this way.

With high-quality hardware and thorough calibration, it should be possible to keep the absolute calibration error of the radar equipment below 2 dB (30% of equivalent rain rate) (Joss and Waldvogel, 1990; Smith, 2001).

1.2.2 Attenuation and amplification

The radar antenna is normally positioned in a radome in order to protect it from rain and wind. The radome can affect, however, the radar beam in several ways: via absorption and phase shifting by the dry radome wal, via scattering from the radome joints, via the geometrical distribution of the radome joints, and via absorption by rain or snow on the radome (Manz et al., 1998). The absorption by the dry radome is typically a few tenths of a dB for a C-band radar, while for a wet radome values of up to 5 dB (100% of equivalent rain rate) for two-way transmission have been found (Manz et al., 1998; Germann, 1999). The geometrical distibution of the radome joints can have impact on the beam profile of the radar by for instance an increase of the sidelobes. Generally, no correction methods are applied for the radome influences apart from correcting for the losses caused by the dry radome.

On its way through the atmosphere, the radar beam encounters atmospheric gases, cloud droplets, and rain drops which may attenuate the radar beam by absorption and scattering of the radiation. For wavelengths between 3 and 10 cm, the attenuation by the atmospheric gases is only 0.008 dB/km (Collier, 1989) and the radiation is hardly effected by the presence of cloud droplets. The attenuation of X- and C-band radiation due to scattering from rain drops can be significant, i.e., up to 0.5 dB/km for C-band (Gorgucci et al., 1998). The typical attenuation of a C-band radar is $0.0044R^{0.17}$ dB/km with the rainfall rate R in mm/h (Joss and Waldvogel, 1990). The observed reflectivity in a certain range bin can be corrected for this attenuation by accumulation of the scattering losses in the preceeding range bins. Because of accumulation of measurements errors, the corrected reflectivities, especially those at long ranges, can become unreliable.

The intensity of the radar beam is not only attenuated by propagation through the atmosphere, it can also be enhanced in a particular direction, mostly above water surfaces, by "microwave ducts" or specular reflection from the surface. A microwave duct is a region where the radiation is trapped between two layers due to gradients in the refractive index. Ducts may for instance form above oceans and seas through evaporation of water or through large-scale subsidence (Brooks et al., 1999). When the lower part of a low-elevation radar beam is reflected from a water surface and the two sub-beams are recombined at longer ranges, interference effects can enhance the local radiation intensities with up to 3 dB (Zhenhua, 1985). Both the ducting and the specular reflection of the radar beam result in an overestimation of the reflectivity.

1.2.3 Range effects

The atmospheric volume sampled by the radar beam grows with the range distance from the radar location. The transversal dimensions of a range bin typically changes from few meters close to the radar up to about 1.5 kilometers at about 100 km from the radar.

These considerations imply that a meteorological phenomenon can be over-sampled close to the radar and under-sampled in other part of the domain. A large number of different techniques are available to reproject the radar data from the original geometry to a more useful gridded structure (nearest neighbor, maximum value, box averaging, objective weighted analysis). These techniques are, in principle, equally good, each of them with different characteristics and range of applications. Henja and Michelson (1999) discuss this topic from an operational oriented point of view, and they present an implementation scheme in their paper.

1.2.4 Clutter

The radar measurements can be contaminated by echoes due to for instance normal propagation ("permanent") and anomalous propagation ("anaprop") clutter, chaff, birds, insects, or refractive-index gradients. Clutter caused by reflection of radiation from mountains (orography) or large buildings (occultation) is commonly referred to as normal propagation clutter, while clutter caused by refraction of the radar beam from temperature and/or moisture gradients and subsequent reflection from land (sea) surface is referred to as anomalous propagation (sea) clutter. There is no definite answer on how to remove clutter yet, the preferred method depends strongly on the dominant type of clutter to be removed and therefore on local conditions at the radar site, like the orography or the proximity of a sea. Clutter removal algorithms that are currently in use are based on for instance clutter maps, radial Doppler velocities, signal statistics, or geostationary satellite data.

The clutter map, which is frequently employed in non-Doppler radar systems and which is updated during dry weather situations, can be used to eliminate normal propagation clutter to a large extent (Newsome, 1992; Meischner et al., 1997). Using the radial velocities as obtained from Doppler radar and filtering of signals having non-zero velocity only, both normal and anomalous propagation clutter can be suppressed to a large extent (Keeler and Passarelli, 1990; Koistinen, 1996; Seltmann, 2000). Archibald

(2000) has investigated the performance of the Doppler-based clutter removal techniques in the weather radar network of the UK and has found that roughly 80% of the clutter is removed. Kessinger and VanAndel (2001) have found that the WSR-88D Doppler-based clutter detection algorithm removes about 55% of the clutter and that it fasely removes about 7% of the rain. Wessels and Beekhuis (1997) have demonstrated that the Rayleigh fluctations of precipitation signal and the relative stability of clutter signal can be used to flag clutter-contaminated pixels in a reliable way. They have found that clutter over land is removed almost completely (98%), while sea clutter is partly removed (40%). The Doppler-based methods also have difficulties in removing sea clutter (Archibald, 2000).

Finally, overlays of radar rainfall maps with cloud maps obtained from IR images of a geostationary satellite, e.g. Meteosat, can be used to flag radar pixels with clutter (Pamment and Conway, 1997). The Meteosat-Second-Generation satellite which is to be launched in the near future should enhance the performance of this kind of clutter-removal algorithms considerably. Often a single method to discriminate between precipitation and clutter cannot do the whole job, and several different methods are combined using a decision tree or a statistical method to improve the performance (Lee et al., 1995; Pamment and Conway, 1997).

Not only reflections from land or sea surfaces give clutter, but also aluminum flakes (chaff) used by military to distract enemy radars, groups of birds, swarms of insects, and refractive-index gradients. The echo reflectivities observed by the WSR-88D S-band radars from swarms of insects can in the warm season be between -5 to 20 dBZ and that from birds during heavy migration events can even be up to 30-35 dBZ (Serafin and Wilson, 2000; Gauthreaux and Belser, 1998; Riley, 1999). Wilson et al. (1994) show examples of clear-air return from C-band radars at several locations and during various meteorological situations, and they have observed reflectivity values between -5 and 30 dBZ.

1.3 Rainfall intensity

For assimilation of radar data using latent-heat-nudging schemes and for input of radar data in hydrological models, the reflectivity values as observed at a certain range and height have to be converted to rainfall rates at ground level. This conversion introduces errors in the resulting rainfall map because of the variability of the Z-R relationship, bright band effects, vertical reflectivity profile, incomplete beam filling, etc.. Joss and Germann (2000) have given an extensive overview of the problems and solutions when applying qualitative and quantitative information from weather radar. The variability of the Z-R relationship originates from differences in the droplet-spectrum which depends on precipitation situation and climatologic circumstances. Many different Z-R relationships can be encountered in literature (Collier, 1989), but $Z = 200R^{1.6}$ is widely accepted.

Operational radar-based rainfall estimation generally uses correction for the vertical profile of reflectivity (including bright band effects) and adjustment to gauge accumulations (Joss and Lee, 1995; Harrison et al., 2000). Even after these corrections, the mean difference between radar-based rainfall estimates and gauge accumulations will typically still be a factor of two . Representativeness errors make up, however, a significant part of this difference (Harrison et al., 2000).

1.3.1 Vertical Profile of Reflectivity

Nowadays, possible gradients in the vertical reflectivity profile are believed to be the major source of observed differences between radar measurements and rain gauges (Koistinen, 1986; Joss and Lee, 1995; Anagnostou and Krajewski, 1999). Possible causes of strong vertical reflectivity gradients are interaction between droplets, updrafts and downdrafts, evaporation and accretion of drops under the cloud base, and melting precipitation (bright band). As a result, the observed reflectivity will depend on the beam-height due to strong reflectivity enhancement at the melting layer (bright band), reflectivity reduction when the radar beam samples the snow region, and nondetection at far ranges where the radar beam overshoots the cloud tops (Anagnostou and Krajewski, 1999).

The bright band with its vertical extent of less than 300 meter is only a disturbing factor at short ranges (<65 km) where the radar beam is narrow enough to resolve it. Methods for correction of the bright band enhancement use, for instance, NWP output (height of melting layer) (Harrison et al., 2000) or identification of the bright band in the vertical profile of reflectivity.

Several algorithms for conversion of radar volume data to rainfall maps that use vertical reflectivity profile correction have been developed (Joss and Lee, 1995; Fulton et al., 1998; Anagnostou and Krajewski, 1999). Generally, averaged vertical reflectivity profiles, which are obtained from high-quality and high-resolution data at short ranges, are used to extrapolate a reflectivity measured at a certain range and height to a corrected on-ground rainfall intensity. A comprehensive review on current vertical profile of reflectivity correction methods is given by Gibson (2001).

1.3.2 Gauge adjustment

To keep the radar rainfall estimates as accurate as possible, several operational radar systems are adjusted using rain gauge measurements on a regular basis. The precipitation processing system (PPS) of WSR-88D, which is used to produce radar-derived rainfall products, has the capability to adjust the radar rainfall estimates to hourly rain gauge accumulations (Fulton et al., 1998). In the UK, the radar data are adjusted to rain gauge accumulations on a monthly basis (Harrison et al., 2000). The Swiss radar-derived precipitation estimates are adjusted using longer-term radar-rain gauge analyses, averaged over one month to a year (Joss and Lee, 1995). Kitchen and Blackall (1992) have recognized that adjustment methods using hourly rain gauge accumulations can introduce representativeness errors due to small scale structures present in the rainfall field. In addition, differences in timing and location can occur between the precipitation observed at high-altitude by radar and that by the on-ground rain gauges. These errors can be significant, i.e., up to 150 % for the representativeness errors, and have to be separated from possible biases in the radar rainfall estimation using long-term averages or "mean-field" bias adjustments (Fulton et al., 1998). Several different techniques for adjustment of radar rainfall estimates to rain gauge accumulations are currently employed (Borga and Tonelli, 2000; Michelson and Koistinen, 2000; Gibson, 2000; Gabella and Amitai, 2000; Harrison et al., 2000).

1.4 Radial winds

A Doppler radar uses electromagnetic waves to investigate atmospheric properties: the amplitude of waves are used to estimate the reflectivity and the phase of the waves are used to estimate the radial wind. The radial velocity of scattering particles is determined from their observed phase difference between successive radar pulses.

1.4.1 Aliasing

Because a Doppler radar uses phase differences to determine the radial velocity, there is a maximum velocity that can be determined unambiguously. This maximum velocity is called the Nyquist velocity and it can be expressed as:

$$V_{Nyquist} = \frac{\mathrm{PRF} \cdot \lambda}{4} \tag{1}$$

where PRF is the Pulse Repetition Frequency of the radar pulses and λ is the wavelength of the radar (5 cm for C-band). The timelag between two successive radar pulses, and thus the PRF, also determines the maximum range that can be resolved unambiguously. This leads to the fundamental equation for the maximum (Nyquist) range and maximum velocity of a Doppler radar:

$$R_{Nyquist} \cdot V_{Nyquist} = \frac{c \cdot \lambda}{8} \tag{2}$$

where c is the speed of light. For measurements with a Doppler radar, a trade-off, therefore, has to be made between the maximum velocity and the maximum range. For a typical C-band weather radar and a maximum range of 150 km, a maximum velocity of only 12 m/s is obtained. Velocities higher than the maximum velocity will be folded back into the fundamental Nyquist interval (aliasing). The measured radial velocity, V_m , is, therefore, related to the true velocity by:

$$V_{true} = V_m + 2 \cdot n \cdot V_{Nyquist} \tag{3}$$

where n is an unknown integer called Nyquist number.

Velocity aliasing can usually be identified in radar images by detecting abrupt velocity changes of about $2 \cdot V_{Nyquist}$ between neighboring measurements. In this case, the basic assumption is that the true wind field is sufficiently smooth and regular; this is true for the greater part of the weather situations with the exception of mesocyclones, tornado vortices or highly sheared environments. The basic de-aliasing methods are based on local statistics (Ray and Ziegler, 1977; Bargen and Brown, 1980; Leise, 1981; Mohr and Miller, 1983; Miller et al., 1986) or on local continuity (Eilts and Smith, 1990; Liang et al., 1997). Both methods need a starting point, and therefore they are not capable of de-aliasing isolated areas of radar data without additional information on the environmental wind.

This information could, for instance, be provided as a profile from a nearby sounding or from a NWP model. Radar wind data can be de-aliased in a straight-forward manner by always taking the Nyquist number that results in the smallest deviation from a given wind profile (Doviak and Zrinc, 1993). More sophisticated de-aliasing techniques based on, for instance, two or more-dimensional variational methods have been developed (Merritt, 1984; Boren et al., 1986; Bergen and Albers, 1988; Desrochers, 1989; Jing and Wiener, 1993; Wüest et al., 2000).

Aliasing problems can largely be circumvented by applying different measurement techniques, like dual-PRF or staggered PRT (Pulse Repetition Time). Many operational Doppler radars in Europe have the capability of using the dual-PRF technique. During a dual-PRF measurement, radial winds are measured with alternating high and low PRFs. By combining the measured velocities at low and high PRF, the maximum unambiguous velocity can be extended by about a factor of three (Doviak and Zrinc, 1993). The dual-PRF has the disadvantage that measurements performed at slightly different times or locations are combined which can lead to representativeness errors. This problem is solved by the staggered PRT technique in which two radar pulse frequencies are transmitted simultaneously by alternating the timelag between pulses (Keeler et al., 1999; Sachidananda and Zrnić, 2000). Currently, the majority of the operational Doppler radars is not capable of running at staggered PRT, but this probably will change in the near future.

1.4.2 Representativeness

Radial wind measurements, just as reflectivity measurements, can heavily be effected by normal or anomalous propagation clutter. Clutter signal can be suppressed from the reflectivity and radial wind data to a large extent by reducing the echo power around zero radial velocity using discrete filtering techniques in time or frequency domain. All operational Doppler radars apply this kind of filtering before the radial velocity is determined. Sachidananda and Zrnić (2000) recently introduced a new technique for clutter suppression and radial wind estimation based on staggered PRT. For a complete discussion on the problem of the bias introduced in the radar wind spectrum due to the clutter and clutter-suppression algorithms, the reader is referred to Seltmann (2000).

As noted before, non-hydrometeor targets such as insects and birds are detected by (Doppler) radar as well. While insects can provide an help in defining the boundary layer wind (Riley, 1999; Szturc et al., 2000; Venema et al., 2000), birds are mainly a problem for velocity retrieving algorithms (Koistinen, 2000). Erroneous wind data due to birds can be recognized by inconsistency of the wind data (Koistinen, 2000).

1.5 Wind profiles

Radial wind data is quite crude information that is not straight-forward to interpret, some further processing is required before it can be presented to users. Also for assimilation into NWP models, some further processing of radial wind data is required either via the extraction of a representative wind profile or via averaging of raw radial wind data to grid size of the model (super-observations).

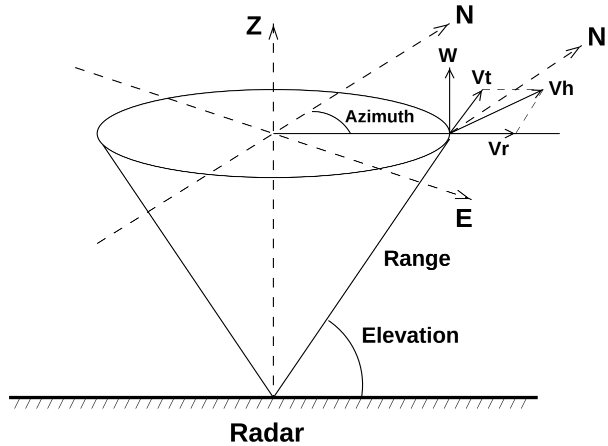

Figure 1: Radar geometry for measuring wind profiles.

Wind profiles can be obtained from single-site radar data under the assumption of a linear wind model. In this model the wind in the proximity of the radar (in origin) is expressed as:

$$U(x, y, z) = u_0 + x\frac{\partial u}{\partial x} + y\frac{\partial u}{\partial y} + (z - z_0)\frac{\partial u}{\partial z} \tag{4}$$

and likewise for $V(x, y, z)$ and $W(x, y, z)$. Using this linear wind field, the radial wind can be calculated as a function of range, azimuth, and elevation. For a uniform wind field this results in:

$$V_{radial} = u_0 \cos\theta \sin\phi + v_0 \cos\theta \cos\phi + w_0 \sin\theta \tag{5}$$

When Doppler radar data is displayed at constant range and elevation (θ), the radial wind as function of azimuth (ϕ) will have the form of a sine. The wind speed and direction can be determined from the amplitude and the phase of the sine, respectively. This technique is called Velocity-Azimuth Display (VAD), and it has been introduced by Lhermitte and Atlas (1961) and Browning and Wexler (1968).

Nowadays, (Doppler) radars are recording volume scans, i.e., reflectivity and radial wind data as a function of range, azimuth, and elevation. The radar geometry used to measure these volume scans is schematically shown in Figure 1. The range, azimuth, and elevation are indicated in the figure. From the volume scans, different VADs can be extracted as a function of height, and a wind profile at the radar site can thus be obtained. Extraction of the vertical air velocity (w_0) using the VAD technique is troubled by divergence of the local wind field. Improved versions of the VAD technique, for additional extraction of divergence and vertical velocity, are the Extended-VAD technique (Srivastava et al., 1986; Matejka and Srivastava, 1991) and the Concurred-Extended-VAD technique (Matejka, 1993).

Instead of processing, for each height, a single VAD or a series of VADs (EVAD, CEVAD), one can also process all available volume data in a certain height layer at once. This so-called Volume Velocity Processing technique (VVP) has been introduced by Waldteufel and Corbin (1979). Using equation 4 of the linear wind model, the radial wind can be calculated for all points within a layer centered at height z_0. Via a multi-dimensional and multi-parameter linear fit, the parameters of the linear wind field can be extracted. The VVP technique is typically applied to thin layers of data at successive heights to obtain a wind profile. An interesting comparison of divergence and vertical velocity obtained by EVAD, CEVAD and VVP techniques has been presented by Ciffelli et al. (1996). The results of these techniques were quite similar, although the VVP profiles often extended to greater heights. Unfortunately, no comparison of wind speed and direction was made.

Andersson (1998) has published a verification of VAD winds against radiosonde winds and HIRLAM winds. In this study the availability and the accuracy of the VAD winds of the Swedish radars have been investigated. The availability of the VAD winds is about 80% at 925 hPa, and it drops to about 15% at 400 hPa. The vector difference between the VAD winds and the radiosonde winds has an average magnitude of about 3 m/s. Comparisson with HIRLAM winds at 850 and 700 hPa gave simular results. Operational assimilation of VAD winds at NCEP started in 1997 and ended in 1999 because problems with the data became evident. Recently, a quality control for VAD winds has been developed at NCEP which removes winds with very small magnitude, clear outliers, and migrating birds "winds" (Collins, 2001).

1.6 Conclusion

Accurate measurements of on-ground rainfall using radar are troubled by measurement errors in the reflectivity values, by clutter, and by uncertainties introduced by the translation of reflectivity values to on-ground rainfall rates. Normal propagation and anomalous propagation clutter, gradients in the vertical reflectivity profile, and nondetection of precipitation at far ranges are generally believed to be the major sources of errors in the estimation of the on-ground rainfall from radar data.

Radial winds can be aliased due to the limited maximum range and velocity measured by a Doppler radar. There are several algorithms available to de-alias measured radial winds. The aliasing problems can, however, be overcome by using different measurement techniques, like dual PRF or staggered PRT. Radial wind data can be processed to obtain wind profiles at the radar site using a VAD-like or VVP algorithm. Representativeness of the winds obtained from Doppler radars, for both the radial winds and the wind profiles, is the major problem when using this data.

2 The process of data assimilation

Our knowledge on the state of the atmosphere at any time is given by observations of various quantities related to the atmosphere, such as pressure, temperature, wind, humidity, cloudines, satellite radiance and radar intensity. These observations are in general irregularly distributed in space and time. The process of combining the observations with a Numerical Weather Prediction (NWP) model to conclude about the total spatial distribution of atmospheric variables (for example pressure, temperature, wind, humidity and cloudines) and to produce the best possible initial state for the model is generally referred to as the process of data assimilation. The number of observations is in general small compared to the number of variables in the initial state of the forecast model. To resolve this, we need to introduce *a priori* information, for example a short-range forecast and statistical knowledge about the errors of this forecast, in addition to statistical knowledge about the observation errors. We may also utilise additional *a priori* information regarding, for example, balances between different forecast model variables.

The statistical knowledge of the short range forecast error correlations and knowledge about balances between different forecast model variables may be utilised to describe how the information added to the model by an observation should be spread spatially and influence different model variables. These correlations and balances are known reasonable well and can be modeled. The spatial patterns of forecast error correlations are usually referred to as *structure functions.* The assimilation is said to be univariate in case the cross-correlations between different variables are zero, i.e. each variable is analyzed independently of the other variables. Multivariate assimilation is more general, and in most cases more physically justified. Also the forecast model itself may be utilised to distribute the observational information spatially. A challange when merging the observational data with model information are that some of the observed quantities are non-linearly related to the model state variables and that measurements may be associated with complicated error structures. Besides that the error structures are complicated, most assimilation schemes are not designed to easily handle these correlations, although it would be theoretically possible. These difficulties have generally been circumvented in data assimilation by applying data selection and pre-processing algorithms that is assumed to remove the observational error correlations. The importance of removing the spatial error correlations have not yet been very well established. Furthermore, the observed information should ideally be projected on scales that can be represented by the model.

Early data assimilation techniques were simple spatial interpolation, for example based on polynomial fitting (Panofsky, 1949) or distance weighting (Bergthorsson and Döös, 1955), were used to adjust a 12 h forecast locally to observed values in the vicinity of each model grid point. A first step towards more advanced methods was taken with the *statistical* interpolation or *optimum* interpolation (Eliassen, 1954; Gandin, 1963). Essentially this technique applies linear minimum variance estimation of analysis errors locally in each grid point. Simplified error covariance models, assuming for example horizontal homogeneity and isotropy, were applied for this assimilation technique. Three-dimensional multi-variate statistical interpolation schemes (Gustafsson, 1981; Lorenc, 1981) dominated operational numerical weather prediction during the period 1975-1995. With an increasing amount of observations that are non-linearly coupled to the forecast model variables the linear spatial interpolation techniques were considered unsatisfactory for an optimal use of the data. Furthermore, it was considered necessary to make better use of the model simulation abilities within the data assimilation process. These requirements forced development of more advanced 3-dimensional and 4-dimensional variational data assimilation techniques (Le Dimet and Talagrand, 1986; Lewis and Derber, 1985), which are based on the minimization of a cost function.

Almost all data assimilation is carried out within an *intermittent* data assimilation cycle. This mean, if for example a 6 h data assimilation cycle is used, that a 6 h model forecast is merged with observations during the assimilation procedure to produce an initial state for a new model integration. The 6 h forecast launched from the new model integration is 6 h later merged with a new set of observations to produce an initial state, and so fourth.

Parallel to the development of increasingly more advanced assimilation schemes, as described above, a method generally refered to as "nudging" has been developed and frequently used (Macpherson et al., 1996). With this method observations may be "nudged" into the prognostic equations of the model at each time-step of the integration by adding an extra term to the equations, forcing the model towards the observations. The "nudging" technique is conceptially rather simple and the influence of the observations on the model is dependent on tunable "nudging-coefficients", but the method, however,takes advantage of the forecast model during the assimilation procedure.

A charm of data assimilation is the great number of less established approaches that have been developed for specific purposes, in addition to the methods just described.

3 Assimilation of radar precipitation data in NWP models

The COST-717 Action has a working group (No 3) on "Using Radar Information for Assimilation into Atmospheric Models". As an initial part of its plan, the group is reviewing previous attempts to assimilate radar data. The main techniques used to assimilate precipitation data - physical initialization, latent heat nudging and variational assimilation are described. Most previous studies have worked with surface rain rate estimates, but attempts to assimilate reflectivity directly are also covered.

3.1 Introduction

The idea of introducing precipitation data into NWP models came from the tropics. In lower latitudes there is a lack of "classical" data (synop and rawinsode stations) (Krishnamurti et al., 1984). Perhaps even more important is the fact that in tropics there is no such successful theory as quasi-geostrophic theory in mid latitudes which usually carve out a reasonable moisture field through diagnosed vertical motions (Krishnamurti et al., 1991). Both facts result in large errors in analysed moisture field and consequently (since convection is major forcing term) also in divergent wind field and rather slow equilibration (few days) of evaporation and precipitation on global scale (Heckley, 1985). Therefore a procedure that includes moisture data (mostly satellite derived data on global scale) improves forecasts substantially (Krishnamurti et al., 1993; Treadon, 1996).

However also in mid latitudes there is a need of improving precipitation forecasts since mesoscale details are usually not represented well enough in analysed fields. This is important specially in first few hours of forecast when precipitation forecasts suffer from spin-up effect (balancing the hydrological cycle). Therefore, even short, a positive impact of precipitation assimilation on precipitation forecasts would be very welcome for short range forecasting and nowcasting. It was, however, shown that in some cases improvements can last 30 hours into forecast (Chang and Holt, 1994). Several sensitivity studies have shown that positional errors of precipitation data led to significantly reduced forecast improvement compared to rate errors (Jones and Macpherson, 1997). Therefore also radar derived rain rates which have low quantitative accuracy, may still be used in a precipitation assimilation scheme.

Recently attempts were made to assimilate radar data in meso-γ scale models, i.e., non-hydrostatic models with horizontal resolution ranging between 6 km to 500 m.

Three main approaches of assimilation of precipitation data are described in this paper: physical initialisation, latent heat nudging and variational assimilation both for NWP mesoscale models and meso-γ research models

3.2 Physical initialisation

3.2.1 NWP mesoscale models

Physical initialisation (PI) was among the first methods that enabled assimilation of precipitation data into NWP models. It was derived for moisture analysis in the tropics (Krishnamurti et al., 1984; Donner, 1988) for the reasons covered in introduction. Use of PI in tropics improved precipitation forecasts and reduced spin-up substantially (Krishnamurti et al., 1993)

The initialisation procedure consists of two steps (Krishnamurti et al., 1991): i.) diagnostic calculation of surface fluxes and humidity analysis consistent with observed precipitation rates. ii.) Relaxation of diagnosed fluxes into the model in pre-integration phase. The humidity analysis is done by inverting the PBL and cumulus parameterization schemes. First fluxes of sensible and latent heat that correspond to measured precipitation rates are calculated. Reverse similarity theory is used to obtain temperature and humidity above constant flux layer. Finally a reverse cumulus parameterization scheme yields vertical profile of humidity.

A combined initialization method has been proposed for the Japan spectral model using precipitation observations from a radar-raingauge network over Japan (Aonashi, 1993; Matsumura et al., 1997). Within this initialization a physical initialization method calibrates the thermodynamic and dynamic variables of the objective analysis data in such a way, that model precipitation from calibrated data is equal to precipitation observations. Afterwards, a non-linear normal mode initialization (NMI) with the precipitation process is conducted. The combination of physical initialization and NMI makes diabatic heating in the NMI consistent with that produced in the model forecast. Forecast experiments show that the initialization method reduces both spin-up error and position error of precipitation forecasts.

3.2.2 Meso–γ scale models

At the cloud-resolving (meso-γ) scale, the first initialisation procedure using radar data was developed by Lin et al. (1993). They initialised their numerical simulation with three-dimensional dynamical, thermodynamical and microphysical fields derived from multiple Doppler radar observations. The horizontal resolution of the simulation was 2 km, and only warm microphysical processes were parameterised in the numerical model. The procedure initialised the winds with the Doppler wind data, and filled the data voids region in order to provide a smooth transition from the observational domain to the base state. The pressure and potential temperature perturbations were obtained from a thermodynamic retrieval method following Hane and Ray (1985). The water vapour content was imposed to its saturated value where the radar had detected precipitation and above the lifting condensation level. The rainwater content was derived from the reflectivities by using a $Z-M$ relationship whereas the cloud water was assumed to be zero. After having established the feasibility of the initialisation method with simulated storm data, it had been tested with multiple Doppler radar observations from a tornadic storm. The very short range prediction (less than 15 minute) showed good agreement with the observations, although the modelled storm seemed to evolve faster than the observed storm.

The same approach of moisture and microphysical adjustments has been developed in Xue et al. (1998), Bielli and Roux (1999), Haase et al. (1999), Ducrocq et al. (1999 and 2000) and to some extent in Zhang (1999). All of these experiments used a cold microphysical scheme, except Haase et al. (1999).

In their study, Xue et al. (1998) utilized reflectivity data to deduce the initial cloud water content and to moisten the initial state. A distinctive feature of this work is that the adjustments to the water vapour and cloud water fields were applied during an intermittent data assimilation period: in their experiments, the reflectivity and the radial velocity were assimilated at a 15 minute intervals during the last hour of the assimilation period. They found that the assimilation of radar reflectivity had a large positive impact on the simulation of a squall line case.

As for them, Bielli and Roux (1999) used the production rate of precipitation to modulate the adjustment of the water vapour content in the observed precipitation areas: the relative humidity was assumed to be 100%, except where the production rate of precipitation was negative. In some of their experiments, the cloud water content was imposed to some empirical values inside the precipitation areas and also where the production rate of precipitation was positive. The Doppler-derived three dimensional wind fields were also used to initialise the model. The results obtained from simulations of a tropical mesoscale convective system data set have shown that it was important to describe, even crudely, the saturated and unsaturated areas in connection with the updraft and the Rear-To-Front flow described by the Doppler winds. Initialising cloud water contents did not bring significant improvements. In their initialisation method, Haase et al. (1999) modified the vertical wind on the base of the radar reflectivities in addition to the specific humidity and the temperature profiles.

Zhang (1999) used a cloud analysis system to synthesize several data sources (radar, satellite observations) and to construct a three dimensional cloud analysis. This system, called ADAS (Brewster, 1996; Zhang et al., 1998), is based on the LAPS cloud analysis with several modifications. The three- dimensional radar reflectivities are used to impose clouds and to determine the hydrometeor type and mixing ratio. Indeed, if the reflectivity exceeds a threshold, clouds are inserted in the radar echo region. The type of hydrometeors is determined from the wet bulb potential temperature and hail is diagnosed when the three-dimensional radar reflectivity is above a given threshold. Then, the mixing ratio of the hydrometeors are derived from hydrometeor type-dependent $Z - M$ relationships. The outputs of the cloud analysis system were then provided to a moisture and diabatic initialisation scheme. It imposed simply the cloud water and ice mixing ratio to the analysed values. The rainwater, snow and hail mixing ratios were usually initialised to smaller values than the analysed values, as inserting the total amount of precipitate could prohibit, by their drag, the development of updrafts. Then, the thermal field was adjusted to account for the latent heating associated with the inserted cloud water. The relative humidity field was also modified and cloudy regions were moistened. The impact of the initialisation on the meso-γ scale numerical prediction has been validated on simulated storm data.

The initialisation method of Ducrocq et al. (2000) is also based on cloud and precipitation analyses, but adapted to the French networks. The reflectivities, available only on single PPI, were used to determine the rainy areas and to impose cloud where the reflectivities are greater than a given threshold. The vapour mixing ratio was imposed to its saturated value in cloudy regions, and a $Z - M$ relationship was used with an empirical vertical distribution to initialise the rainwater mixing ratio. In some experiments, cloud water have been imposed to a constant value. The initialisation have been applied for simulation of a real case of convective system. It has been found a large impact on the results : using radar and satellite observations allow to trigger the convection which is not the case when simulations start from a classical large scale analysis. These results have been confirmed on another convective case also over flat areas (Ducrocq et al., 1999) Inserting cloud water was found to have no significant impact.

So, to sum-up the use of radar reflectivity in cloud resolving models, reflectivity is always used in an indirect way to modify the moisture fields. In some of the works, the reflectivity data is also used for initialisation via $Z - M$ relationships, the contents of the non-precipitating and/or precipitating species.

3.3 Latent heat nudging

Latent heat nudging (LHN) is a method of forcing NWP model with observed precipitation rate. In this case the model is forced with heat released by observed precipitation. One is not limited with profiles imposed by parameterization scheme as in case of PI. However since only two-dimensional observations are available some kind of heating profile should be prescribed. There are two possibilities: idealised profiles or scaled model profiles. Manobianco et al. (1994) and Jones and Macpherson (1997) have chosen the second possibility.

The second choice has some advantages: it ensures consistency with model's parameterization scheme and it allows evolution of the profile with time. It is assumed that the model's separation of explicit (stratiform) and implicit (convective) precipitation is correct. If one does not trust the model separation, it is possible to treat the convective part separatly (through closure assumptions in the parameterization scheme). This algorithm does not work in case when the model point is dry and precipitation are observed.

In that case algorithm must include search for nearby points.

LHN was found to be useful in mid latitudes. In studies of winter cyclogenesis the impact of assimilation was noted far beyond assimilation period (impact on surface pressure 30 hours into forecast) (Chang and Holt, 1994). Some authors report dramatic impact on quality of precipitation forecasts (Wang and Warner, 1988), others have found smaller yet noticeable positive impact in general (Jones and Macpherson, 1997), with occasional larger benefits (Macpherson, 2000).

3.4 4D variational assimilation

Four dimensional variational assimilation (4DVAR) is a completely different approach to assimilation problem as the former two techniques. It makes use of linearised versions of NWP models and their adjoints. The task of 4DVAR is to find a perturbation of initial conditions of the model which lead to "best fit" of trajectory in model's phase space according to specified measure (usually square distance between observations and corresponding model variables). This idea was applied to meteorological applications in 80s using simplified adiabatic models (Lewis and Derber, 1985; Talagrand and Courtier, 1987; Courtier and Talagrand, 1987). Recently also adjoints of linearized physical parameterizations were developed and 4DVAR was successfully applied to operational global models (ECMWF, NMC, Arpege/IFS ...).

More recently performed studies demonstrated usefulness of 4DVAR for precipitation data (Zupanski and Mesinger, 1995; Zou and Kuo, 1996). In case of precipitation observation highly non-linear precipitation parameterization schemes (both implicit and explicit) should be linearized for development of adjoint version. The main problem is discontinuous ("on-off") nature of those schemes. (Zou, 1997) gives a review of approaches dealing with this problem. Mainly there are two approaches: i.) to ignore this problem, that is to keep the time of switching the schemes same in tangent-linear and adjoint integration as in reference non-linear integration; ii.) to include perturbations of switching times in assimilation procedure. Zou (1997) reported that minimization procedure converges well without dealing with switch time. However theoretical studies (Bao and Kuo, 1995; Xu, 1996) have shown that ignoring the variation of the switch point due to perturbations in initial conditions could cause significant errors in gradient calculations. There is also a practical problem of trajectory in model's phase space - in practice saving the whole trajectory is not feasible due to limits in memory and disk space. Saving trajectory in larger increments (say half an hour) may change the robust behaviour of minimization procedure.

Recently adjoint of a cloud resolving model was applied for assimilation of three dimensional radar data (Sun and Crook, 1997, 1998). They developed a 4D-variational data analysis system that can be used to assimilate data from one or more Doppler radars. The horizontal resolution of the cloud scale model was 500 meters, and only the warm microphysical processes were parameterized. The thermodynamical and microphysical fields, as well as the three-dimensional wind were determined by minimizing a cost function defined by the difference between the observed radial velocities and the reflectivities (or rainwater mixing ratio) and their model counterparts. The derivation of the adjoint of physical processes with on/off switches follows that of Zou et al. (1993) and the microphysical scheme has had to be modified for the evaporation of rain and the rainwater fall velocity. It has been found that assimilating the rainwater mixing ratio obtained from the reflectivity data results in a better performance of the retrieval procedure than directly assimilating the reflectivity. In Sun and Crook (1998), differential reflectivity data are used to produce a better estimate of the rainwater mixing ratio, and hence to improve the microphysical retrieval. Wilson et al. (1998) briefly described results of a flash flood case simulation using the variational retrievial technique of Sun and Crook (1997, 1998) to initialise the cloud-scale model. They found that the numerical forecasts significantly improve over persistence and extrapolation in the 60-min time frame. Afterward, Wu et al. (2000) have extended the application of Sun and Crook (1997) to convective storms where the ice phase plays an important role. As a complete ice microphysics parameterization will have a complex adjoint model with poor convergence properties for the assimilation due to many non-linearities, a simplified cold microphysical scheme has been developed : no snow category and only one category for the non-precipitating species (cloud water and cloud ice). The differential reflectivity was used to discriminate between the rain and hail and allowed to employ phase-dependant $Z - M$ relationships. The results of this work were mitigate : although the analysis system was able to retrieve all the main features of the storm, the simulations were unable to reproduce the evolution of the observed storm; the simple microphysical parameterization was unable to follow the actual cloud physics.

3.5 Summary

The main three approaches to assimilation of precipitation data have been described in this paper - physical initialization, latent heat nudging and variational assimilation. There is no prefered technique for assimilation of radar derived data. The most natural one seems to be 4DVAR but there are theoretical (treatment of "on-off" nature of precipitation parameterization schemes) and practical (large integration time and required disk space) problems to be solved.

4 Assimilation of radar wind data

4.1 Introduction

Assimilation of Doppler radar wind data into atmospheric models has recently received an increased interest. This is because of the wide use of limited area high resolution numerical models for weather prediction. The models require observations with high spatial and temporal resolution for determining the initial conditions, for which purpose radar data are particularly appealing.

Radar wind data, fully or partially pre-processed (see previously) have been assimilated into a number of atmospheric models, with considerably different spatial resolutions. A lot of different assimilation techniques have been used and the efforts made are presented in this paper. Most of the work to be described here has so far been applied in research mode, but radar winds are also assimilated operationally.

4.2 Optimal Interpolation

Radar wind information is assimilated operationally in the form of VAD-wind profiles within the multivariate Optimal Interpolation (OI) scheme used in the Rapid Update Cycle (RUC) atmospheric prediction system (Parrish, 2000) at the National Centers for Environmental Prediction (NCEP). The RUC atmospheric prediction system is the operational version at NCEP of the Mesoscale Analysis and Prediction System (MAPS) developed at NOAA's Forecast Systems Laboratory (FSL). The RUC system is applied on a limited area with an intermittent data assimilation cycle.

The OI scheme of the RUC system (Benjamin et al., 1991) uses a hybrid vertical coordinate system, that combines a terrain following coordinate system near the ground with a potential temperature coordinate system above. The analysis variables are the horizontal wind components, the Montgomery stream function and the condensation pressure. Due to the choice of vertical coordinate system and analysis variables some pre-processing of observations is needed. The VAD-wind profiles are treated as standard PILOT balloon observations. The observation errors are assumed to be uncorrelated. Multivariate structure functions are used for the background error correlations.

4.3 Variational assimilation

VAD-wind profiles can be assimilated using both Optimal Interpolation and variational methods. Variational methods, however, are also ideally suited for assimilation of Doppler radar radial winds. The observation operator projects the model wind along the radar beam direction, and only a partial pre-processing of the data is needed.

4.3.1 4D-Var

An early attempt of using 4D-Var for assimilation of radar radial winds into an atmospheric model was carried out by Wolfsberg (1987). Unfortunately the assimilation encountered severe convergence problems. Some years later further attempts for assimilation of radar wind data by using 4D-Var were reported by Kapitza (1991). Simulated radar radial wind observations were assimilated into a dry non-hydrostatic mesoscale model. The 4D-Var formulation used in Kapitza's assimilation contained no background *a priori* information.

Kapitza performed a series of identical twin experiment with the 4D-Var system. A reference model integration was started from an atmosphere at rest, but including a sub-area with a temperature excess of 1 K. The temperature excess caused a hot bubble of air rising through the initially neutrally stratified model atmosphere, as the integration preceded. During the first 200 seconds all dependent variables were sampled at each time step and for all grid points. These data then served as observations in the experimental runs. In one experiment only the east-west wind component of the reference run were assimilated. This case represented a situation when radar radial winds were the only source of data. The assimilation only approximately managed to recover the thermal structure of the hot rising bubble. Significant improvements were achieved if temperature data from the reference run was assimilated, in addition.

At the National Center for Atmospheric Research (NCAR) a 4-dimensional variational Doppler radar analysis system (VDRAS) has been developed (Sun and Crook, 1997) to assimilate radial winds and reflectivities from single or multiple Doppler radars. A cloud scale non-hydrostatic numerical model is used to represent the evolution of the motion in the atmosphere. Before assimilation the data are interpolated from the original polar geometry to a cartesian grid. The observation error correlations are neglected and a relatively simple model is used to model the background error covariances. The assimilation system uses univariate horizontal structure functions for the background error correlations. The VDRAS system has been applied to both simulated and real data. The application of the system to different stages of a convective storm demonstrated that the detailed structure of wind, thermodynamics and microphysics could be obtained with reasonable accuracy (Sun and Crook, 1998).

Recently Lin et al. (2000) performed a number of identical twin experiments, using an improved version of the VDRAS-system described above. The improvements included a surface flux model and a height dependent eddy viscosity model in addition to the smoothness penalty term. Radial wind data were generated by the model itself. They observed that the velocity field obtained with the applied smoothness constraint was insensitive to spatially correlated errors.

All 4D-Var schemes that so far have been used to assimilate radial wind data suffer from the lack of a multivariate formulation of the structure functions. These ensure that the radial wind observations modify also the thermodynamic fields. Instead, in the 4D-Var schemes just described the model equations and the time dimension are used to obtain the 3-dimensional wind, as well as thermodynamic fields.

4.3.2 3D-Var

Three-dimensional variational data assimilation (3D-Var) were used operationally in the NCEP ETA forecasting system to assimilate radar wind information in the form of VAD-wind profiles (Parrish, 2000). In this scheme, like in the OI scheme of the RUC system, the VAD-wind profiles are treated as standard PILOT balloon observations. VAD-wind profiles, as well as wind profilers and radial winds are assimilated into the 3D-Var version of the MAPS system at FSL (Devenyi, 2000).

Radial winds in the form of radial wind superobservations have been assimilated into the NCEP ETA forecasting system (Parrish and Purser, 1998)as well as into the 3D-Var scheme of the HIgh Resolution Limited Area Model (HIRLAM) forecasting system (Lindskog et al., 2000). In both of these systems the radial wind raw observations are spatially averaged, to be representative of the characteristic scale of the model. The calculation of the model counterpart of the radial wind superobservation involves a relatively simple projection of the horizontal wind along the radar beam line.

The 3D-Var systems described above, as well as the OI scheme of the RUC system at NCEP, include multivariate structure functions, which ensure that the observed radar wind observations affect also the thermodynamic fields. The observation errors of the radar winds are assumed uncorrelated.

4.4 The successive correction method

At NOAA's Forecast Systems Laboratory (FSL) the Local Analysis and Prediction System (LAPS) has been developed (Mc Ginley, 1989). The analysis is performed on a resolution of approximately 10 km horizontally and 50 hPa vertically. The observation residuals are spread vertically using simple vertical structure functions. The analysis are then performed level by level and it is based on the successive correction method (Bergthorsson and Döös, 1955). The analysis system uses information from various data sources and radar wind data play a key role and are subject to some special treatment (Albers, 1995). Observational errors are assumed uncorrelated and the background error structure functions are modeled.

The LAPS analysis system has been used on places other than FSL to assimilate radar wind data. At Servizio Meteorologico Regionale in Bolonga, Italy, the LAPS system has been applied and the use of radial wind Doppler radar data was reported to refine the wind analysis (Alberoni et al., 2000).

4.5 Nudging

The impact of a hypothetical network of wind profiling radars on determining the model initial state and on the proceeding forecasts has been investigated by the Swiss Meteorological Institute (SMI) (Bettems, 1999). Observing system simulation experiments (OSSE) were performed with a mesoscale non-hydrostatic primitive equation model and a data assimilation scheme based on nudging. A series of case studies were performed and it was indicated that the impact of a hypothetical wind profiler network was most noticeable for short range (i.e. less than 12 h) wind forecasts.

Radar wind data in the form of VAD wind profiles are nudged into an operational mesoscale assimilation and forecasting system at U.K. Met. Office (Macpherson et al., 1996).

4.6 Methods utilizing thermodynamic retrievals

Liou (1990) developed an assimilation procedure, which is a blend of a direct insertion method (Charney et al., 1969), the Gal-Chen (1978) thermodynamic retrieval technique and a wind adjustment method. Simulated radial wind data were nudged into a dry version of the non-hydrostatic, fully elastic model of the Colorado State University Regional Atmospheric Modeling System (RAMS). The fields were then adjusted variationally to fulfill the equation of continuity and some other constraints and finally thermodynamic fields were retrieved from the wind field.

The method was demonstrated through identical twin experiments. First, a control run was conducted to generate a time series of the east-west component of the wind, which served as simulated observational data. The control run was started from a perturbed initial state for the potential temperature. During the model integration the perturbation developed to a thermal bubble which rose toward the upper boundary. A number of additional runs were performed from different initial states, without the initial perturbations in the potential temperature field. Observation information from the control run were then nudged into the integrations with different frequencies. It was shown that the potential temperature perturbation could not be completely recovered from wind data only. In addition some detailed potential temperature data were needed. The success of the assimilation was also related to the frequency of the insertions of observations. Assimilation of real data from Doppler radars were among the suggestions for future work.

Lin et al. (1993) applied a somewhat different approach to initialize the forecast model of the RAMS system, with moist processes included. The model was initialized through a procedure which is based on a combination of a technique for filling observed radar winds into areas of missing data and a thermodynamic retrieval technique. Encouraging results were obtained in case studies, both with simulated and real data, although further investigations, especially on fast developing storms, were recommended.

A method reminding of the one applied by Lin et al. (1993) was applied by Bielli and Roux (1999) to utilize airborne radar radial winds for initialization of the MESO-NH cloud-scale non-hydrostatic model. The technique relied on filling of observed radar winds into areas of missing data and a thermodynamic retrieval technique, although an improved technique were under development. A meso-scale convective system was simulated and it was found that, even with this relatively simple initialization technique, radial wind data were necessary for the simulation of a deep convective circulation.

4.7 Some remarks on radar wind assimilation

A variety of different methods for assimilation of radar wind data into atmospheric models have been presented. One of the main differences between the various approaches is the way in which the thermodynamic fields are adjusted to be in accordance with the analyzed wind field. The method used in the OI and 3D-Var schemes presented here is to use multivariate structure functions. The structure functions applied in OI and 3D-Var only permit linear relations between the different model variables and, moreover, the time history of hydrostatic models have been utilized to derive the statistics needed for these constraints. In the methods based on nudging and 4D-Var the governing equations of the model and the time dimension are used to assure that the thermodynamic are consistent with the wind field. Non-linear relations as well as non-hydrostatic processes may be implicitly included in 4D-Var and nudging approaches. Still another method, used by Liou (1990) and Lin et al. (1993) is to make use of various pre-processing methods to derive the thermodynamic fields.

A difficult problem which probably will receive more attention in the future is the issue of observation errors for radar wind data and their correlations. To assimilate data with spatially correlated observation errors the assimilation scheme should, in addition to structure functions for the background errors, include structure functions for observational errors. The first challenge is to accurately describe the observational error correlations. The second problem is that most assimilation schemes are not designed to easily handle these correlations, although it would be theoretically possible. These difficulties have generally been circumvented in data assimilation by applying data selection and pre-processing algorithms that is assumed to remove the observational error correlations. The importance of removing the spatial error correlations have not yet been very well established. However, recently Lin et al. (2000) presented some results in this area, but further research is required. A connected issue is the quality control of the radar wind data, which has been treated previously.

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5 Appendix: Glossary

DA	3DVAR
DA	4DVAR
RAD	CEVAD – concurrend EVAD
RAD	Doppler winds cartesian
RAD	Doppler winds radial
RAD	EVAD – extended VAD
DA	LHN – latent heat nudging
DA	NMI – normal mode initialisation
RAD	Nyquist velocity
DA	OI – optimum interpolation
DA	OSSE – observing system simulation experiments
MOD	PE – primitive equations
DA	PI – physical initialization
RAD	PPI – plan position indicator
RAD	VAD – velocity-azimuth display
RAD	VVP – volume velocity processing
RAD	X-, C-, S-band
RAD	Z-M relationship
RAD	Z-R relationship
DA/MOD	adiabatic model
DA	adjoint model
RAD	aliasing of velocity
DA	analysis errors
DA	analysis field
DA	analysis increment
RAD	anomalous propagation
RAD	antenna pattern
DA	assimilation
RAD	attenuation
RAD	azimuth
DA	background error covariances
DA	background field
DA	background residuals
RAD	beam filling
MOD	closure assumptions in parametristion schemes
SAT	cloud analysis system
RAD	clutter map
RAD	dual polarization radar
RAD	elevation angle
DA	forward model
RAD	ground clutter

MOD	hydrostatic model
DA	initialisation
DA	intermittency in data assimilation
DA	model phase space
DA	moisture and initialisation scheme
DA	multivariate analysis
MOD	non-hydrostatic model
DA	nudging
DA	observation operator
MOD	parametrization of physical processes
RAD	pre-processing of radar data
RAD	pulse repetition frequency (PRF)
RAD	radar beam
RAD	radome
RAD	range bin
RAD	raw data
RAD	retrieval method
RAD	sidelobes
MOD	spin-up effect
DA	structure function
RAD	super-observations
DA	tangent linear model
DA	univariate analysis
DA	variational assimilation