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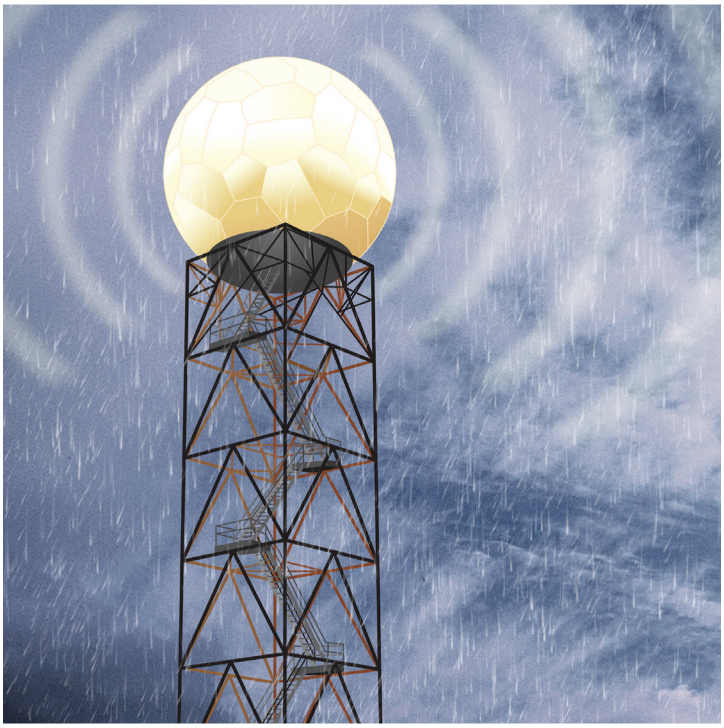

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Towards the assimilation of ground-based radar precipitation data in the ECMWF 4D-Var

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Several forecasting centres are now able to assimilate cloud and precipitation observations in their numerical weather prediction (NWP) systems. Taking advantage of its operational assimilation of satellite microwave brightness temperatures in cloudy and rainy regions, ECMWF has started to assess the impact of assimilating hourly rainfall rates from the precipitation radar network in the USA.

Preliminary 1D+4D-Var assimilation experiments showed that this data can have a beneficial effect on analyses and forecasts. In particular, results suggest that the improvement found over the USA up to day 3 reaches Europe after a few days. It was also demonstrated that the assimilation of radar data in the absence of all other moisture-related observations can adequately constrain the moisture field over the USA, which is encouraging.

Background

Given the strong impact of precipitation on human activities and despite potential errors in radar measurements (see Box A), it is not surprising that operational networks of ground-based precipitation radars have already been installed in the USA, Canada, Europe, Japan, Australia, and more recently China. For many years now, data from about 150 S-band radars in the NEXRAD network has been combined with rain gauge measurements to produce hourly precipitation analyses over the continental USA with a delay of just a few hours. Similarly, OPERA (Operational Programme for the Exchange of Weather Radar Information), in the framework of EUMETNET, has taken up the challenge of combining ground-based radar information coming from 29 European countries (more than 150 radars currently, mostly C-band) into quasi-real-time continental-scale precipitation composites. In particular, this requires the elimination of numerous heterogeneities that are still present among European countries in terms of radar calibration, data processing and data format.

Since the late 1990s, increasing efforts have been devoted to try to assimilate the rapidly growing number of cloud and precipitation observations, mainly from satellites, in NWP systems. This is expected to improve analyses and forecasts of the atmosphere and of the hydrological cycle. So far, several operational forecasting centres (including NCEP, Met Office, Météo-France, Japan Meteorological Agency and ECMWF) have started to feed cloud and mainly precipitation observations into their three- or four-dimensional variational data assimilation systems (3D- or 4D-Var).

However, developments for an efficient assimilation of such data have been constantly hindered by the nonlinear nature of moist processes (saturation threshold, precipitation formation) as well as by the still large and poorly documented model and observation errors. Methods to alleviate some of these problems have been proposed (e.g. development of well-behaved simplified linearized physics packages) and implemented operationally.

Experimental assimilation of radar data over the USA

Taking advantage of ECMWF's operational 1D+4D-Var assimilation of space-borne SSM/I microwave brightness temperatures in cloudy and rainy regions over oceans, the potential benefits of assimilating rain rates from ground-based radars have been recently investigated in an experimental framework. More details on the two-step 1D+4D-Var method can be found in *Lopez & Bauer* (2007) as well as in Box B.

NCEP Stage IV hourly surface rain rate retrievals were selected because of their rather wide spatial coverage (mainland USA), their unified production and quality control processes, and their straightforward availability. This dataset combines rain rates retrieved from the NEXRAD ground-based radar network and rain gauge observations. Original 4-km resolution hourly rain rates were averaged onto ECMWF's model grid prior to assimilation. The rain observation relative error in 1D-Var was set to values between 20% over flat terrain and 50% over rugged orography. The assimilation of NCEP Stage IV rain rates was only performed at points that were rainy in both model background and observation. This led to an additional number of about 1,200 observations on average in each 4D-Var 12-hour window.

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Experiments were run globally using ECMWF's 4D-Var system (cycle 29r2) at T511 spectral resolution (about 40 km) and with 60 vertical levels. Two pairs of experiments were performed from 20 May to 20 June 2005, as detailed in Table 1.

"Denial" experiments (CTRL_noqUS and NEW_noqUS) were meant to assess the actual impact of radar observations when they are assimilated in the absence of all humidity-sensitive measurements from radio-soundings, SYNOP data, and satellite infrared and microwave instruments over the USA.

Weather radars and associated errors

A

Weather radars are designed to provide three-dimensional information on atmospheric scatterers at high spatial and temporal resolutions. Scattering particles are typically hydrometeors, but they can also be cloud particles, aerosols, insects or birds. The size of scatterers that can be detected with a given radar mainly depends on the wavelength of the emitted pulse. For instance, S-band (8–15 cm wavelength) and C-band radars (4–8 cm) can provide information on larger hydrometeors (raindrops, snow flakes, hailstones) at horizontal ranges up to 150–200 km. Such radars are usually referred to as precipitation radars and constitute the backbone of fixed operational national networks. Smaller and hence more mobile X-band radars (2.5–4 cm) are also increasingly being used to measure precipitation for hydro-meteorological and nowcasting applications, but they are penalized by stronger attenuation and a shorter maximum range (about 80 km).

Radars with Doppler capabilities can also provide information on the radial component of the wind (isolated radar) or even on the full three-dimensional wind field (several overlapping radars). Radars equipped with dual polarization can help identify the phase of hydrometeors (rain, snow, hail) as well as their characteristics (shape, size).

In spite of the appeal of their extended and high-resolution spatial coverage, various errors can degrade the accuracy of weather radar measurements. Major sources of errors include:

- Bad radar calibration.
- Tilting and widening of beam with range.
- Non-uniform filling of beam with scatterers.
- Beam crossing the melting layer (bright band with sharp gradients of reflectivity).
- Anomalous propagation (super-refractive/ducting conditions).
- Beam blocking by large obstacles (orography) and ground clutter (echoes returned from ground itself, buildings, wind turbines etc).
- Attenuation by scatterers (decreases with wavelength).
- Echoes due to non-meteorological airborne scatterers (birds, insects etc.)
- Invalid Rayleigh approximation when hydrometeor size is not small compared to radar wavelength.
- Uncertainties in reflectivity-precipitation relationship, particle type and size distribution.
- Orographic seeder-feeder precipitation enhancement.
- Attenuation by water or dirt on radome.
- Post-processing (e.g. averaging, compositing).

A detailed discussion of precipitation radar errors can be found in *Šálek et al.* (2004). Various procedures have been developed to identify and eliminate radar pixels that are likely to be contaminated by some of these errors.

Experiment Type	Experiment Name	Assimilated Observations
"Full"	CTRL	All operational observations
	NEW	All operational observation + NCEP rain rates
"Denial"	CTRL_noqUS	All operational observations – all moisture observations over mainland USA
	NEW_noqUS	All operational observations – all moisture observations over mainland USA + NCEP rain rates

Table 1 Description of the precipitation radar data assimilation exper- iments over the USA.

What is 1D+4D-Var assimilation?

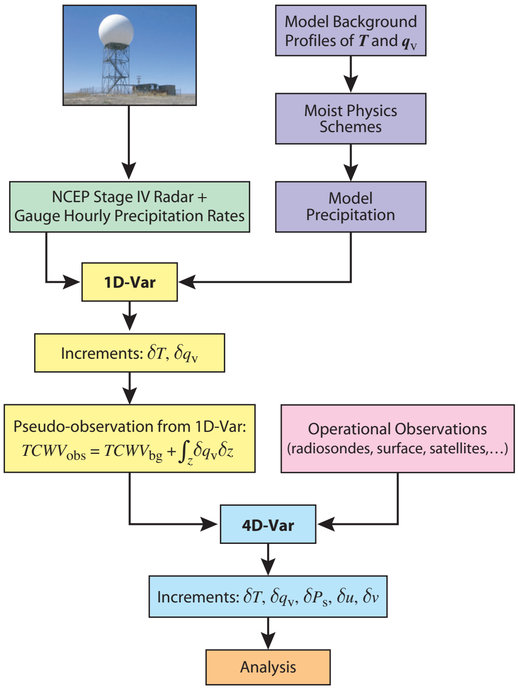
B

The 1D+4D-Var method was originally developed by *Marécal & Mahfouf* (2003) and subsequently implemented in operations at ECMWF in June 2005 (*Bauer et al.,* 2006a,b) to assimilate SSM/I data in cloudy and rainy regions.

In this two-step approach summarized in the diagram, observations are first passed to a 1D-Var procedure that computes vertical profiles of temperature and moisture increments at each model grid point. ECMWF's physics yields temperature increments that are usually significantly smaller than moisture increments, so that they can be neglected. Moisture increments are then vertically integrated to create a pseudo-observation of total column water vapour (TCWV), which is eventually assimilated into the full 4D-Var system.

Both 1D-Var and 4D-Var rely on the minimization of a cost function that measures the distance of the unknown model state to a set of observations (single in 1D-Var) on one hand, and to a background model state (usually a short-range forecast) on the other hand, each of them being weighted with their respective error statistics (confidence).

In the case of ground-based radar precipitation observations, the choice was made to assimilate the decimal logarithm of ground-based radar rain rates rather than rain rates themselves. This ensures that distributions of errors are closer to Gaussian, which is a requirement for the variational analysis to be optimal.



Flow chart of the 1D+4D-Var assimilation method applied to NCEP Stage IV rain rate data.

Results from "full" experiments

1D-Var, which retrieves temperature and humidity information from the rain rates, was found to be well-behaved, with no need for *a priori* bias-correction. Also there was proper convergence of the iterative minimization for most points, and improved match between model and observed precipitation after 1D-Var.

As far as the final impact of the retrieved humidity information on 4D-Var analyses and forecasts is concerned, Figure 1 displays the mean NEW–CTRL differences in 4D-Var analyses of total column water vapour (TCWV) over the month of the experiments. One can see that assimilating the radar data does impact on TCWV, with well-structured patterns of drying or moistening reaching ±1.5 kg m^{-2}.

On the other hand, forecasts scores for ranges up to 10 days exhibit only insignificant changes at the scale of the northern or southern hemisphere. However, over smaller sub-domains such as North America, the North Atlantic and Europe, significant improvements can be identified when radar data is assimilated. Figure 2 displays an example of changes in anomaly correlation of 1000 hPa geopotential over North America and Europe. There is a clear improvement over North America during the first 3 days of the forecast, and over Europe around days 7 and 8. This suggests that the positive signal seen over the USA propagates downstream across the North Atlantic and over Europe. The quality of precipitation forecasts is also slightly improved but only for forecast ranges up to 24 hours.

The relatively modest overall impact of radar data on 4D-Var performance is believed to be mainly caused by the competition between the radar data and other operational observations. In particular, radiosoundings and surface station data are usually considered to be reliable and therefore are given a large weight in 4D-Var analyses.

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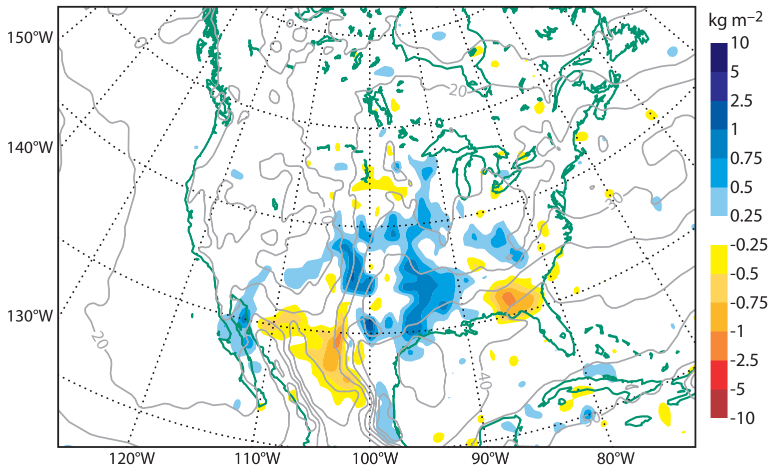

Figure 1 Mean impact of NCEP Stage IV rain rate observations on 4D-Var TCWV analyses in full experiments (NEW–CTRL). Results shown using the colour scale with positive (negative) values indicating a moistening (drying) with respect to CTRL. Isolines show the mean analysed TCWV from CTRL. Units are in kg m^{-2}.

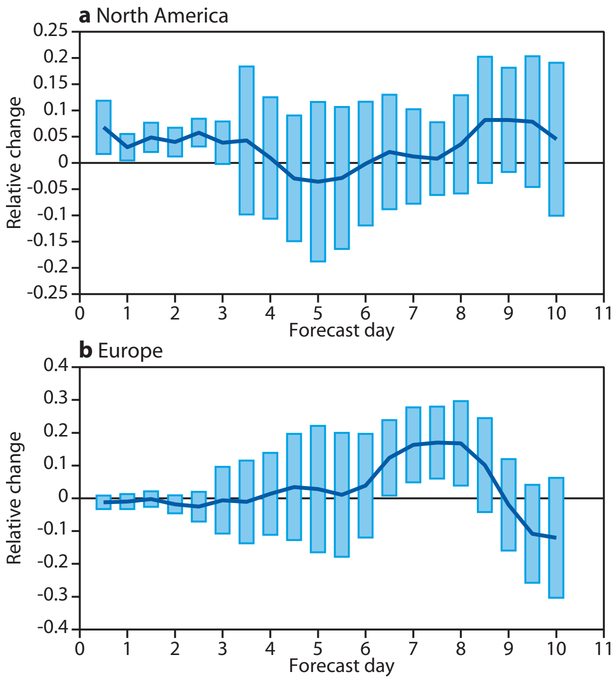

Figure 2 NEW–CTRL relative changes (unitless) in anomaly correlation of forecast 1000 hPa geopotential brought by the assimilation of NCEP Stage IV rain rates as a function of forecast range (up to 10 days) over (a) North America and (b) Europe. Positive (negative) values indicate an improvement (degradation) and blue bars show the 90% confidence level. Own verifying analyses have been used over the period 20 May to 9 June 2005.

Results from denial experiments

The purpose of the denial experiments was to investigate the potential impact of NCEP Stage IV rain rates when they are assimilated as the only source of humidity information over the USA. Figure 3 compares the mean impact on 4D-Var TCWV analyses of rejecting all operational humidity-sensitive observations from the control experiment over mainland USA [panel 3a] with the mean impact of assimilating the radar data alone [panel 3b]. Figure 3a shows that the lack of moisture observations leads to a substantial drying in the analyses, especially over the eastern part of the country where TCWV is usually high in springtime. On the contrary, Figure 3b clearly indicates that just adding the NCEP Stage IV rain rate data can help the analyses to recover from most of the drying seen in Figure 3a. This is encouraging and confirms that the rather small impact of radar observations found in the full experiments is due to the competition with other moisture-related observations.

Furthermore, the assimilation of radar rain-rate observations in the absence of any other moisture-sensitive data over the USA significantly improves forecast scores versus own verifying analyses over this area. This is illustrated in Figure 4 that displays the relative change in 850 hPa temperature anomaly correlation, computed over 21 days over North America. The positive effect of NCEP Stage IV data on North American scores (relative improvement up to 5%) lasts for up to four days. A similar improvement is found in relative humidity and dynamical fields (not shown). Over other regions of the globe, the impact remains more neutral.

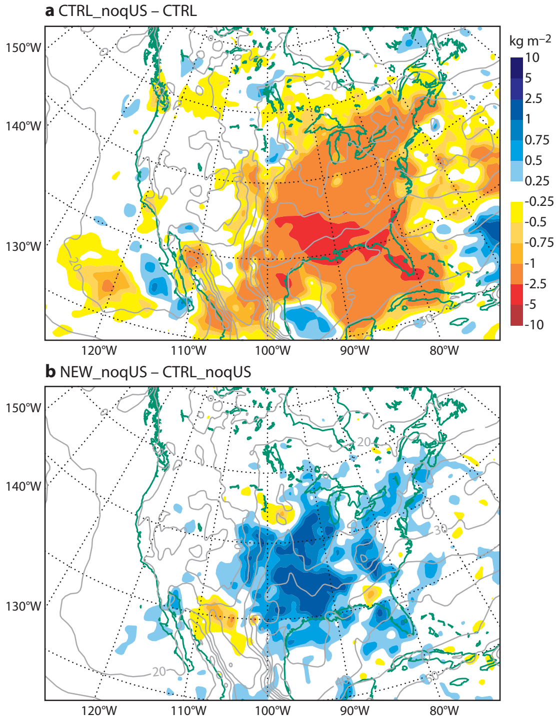

Figure 3 Mean impact on 4D-Var TCWV analyses of (a) discarding all moisture-sensitive observations over the USA in 4D-Var (CTRL_noqUS–CTRL) and (b) adding NCEP Stage IV rain rate observations on their own (NEW_noqUS–CTRL_noqUS). Results shown using the colour scale with positive (negative) values indicating a moistening (drying) with respect to the relevant control. Isolines show the mean analysed TCWV from the control experiments (CTRL for (a) and CTRL_noqUS for (b)). Units are in kg m^{-2}.

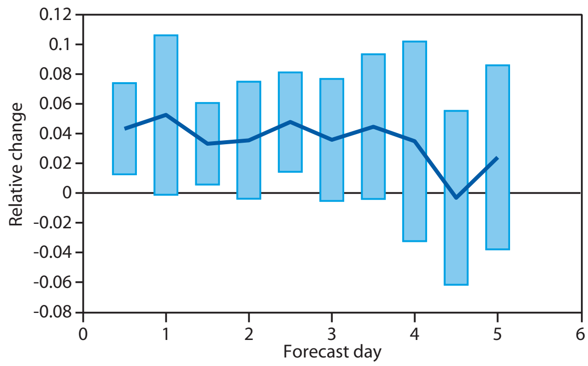

Figure 4 Relative changes (unitless) in 850 hPa temperature anomaly correlation over North America brought by the assimilation of NCEP Stage IV rain rates as a function of forecast range (up to 5 days), from "denial" experiments. Same layout and period as in Figure 2.

Remaining issues for cloud and precipitation assimilation

The assimilation of cloud or precipitation observations with the variational method requires efficient linearized simplified moist physical parametrizations (convection and large-scale condensation). These parametrizations, which are used in the tangent-linear and adjoint computations of the 4D-Var minimization, must be specially designed to ensure the best compromise between realism, nearness to their full nonlinear counterparts, computational efficiency and linearity. In particular, all switches associated with moist processes (e.g. saturation) must be eliminated or at least smoothed out to avoid the spurious growth of perturbations during tangent-linear and adjoint integrations.

Some questions can also be raised concerning the optimality of the indirect 1D+4D-Var approach. It is not satisfactory that this method uses the same background fields twice (first in 1D-Var, then in 4D-Var), which must result in an underestimation of the impact of precipitation observations in 4D-Var analyses. Also, the discarding of temperature increments after 1D-Var in our approach might not be suitable for all meteorological situations. In addition, feeding TCWV pseudo-observations into 4D-Var implies a loss of information about the vertical structure of the moisture field. All these reasons explain why efforts are currently dedicated to the implementation of a direct 4D-Var assimilation of rainy observations at ECMWF.

When precipitation rates or reflectivities are to be assimilated, another problem appears whenever the model background is non-rainy. In this case, the model moist physics becomes insensitive to initial conditions (mainly temperature and moisture) and the minimization of the cost function cannot be performed. Employing a first-guess which is artificially modified from the background so as to produce precipitation might alleviate this problem. This will be tested soon.

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Remaining issues specific to radar assimilation

It was found that the NCEP Stage IV hourly rain rate estimates are still occasionally contaminated by anomalous propagation (see Box C) and by ground clutter, despite NCEP's quality control. For the studied period in spring 2005, such events occurred quite often over land around the Gulf of California. Figure 5 displays an example of spurious rain echoes over this region on 1 June 2005 at 2100 UTC. Most of the echoes seen on this map are due to the radar beam impinging on surrounding orography around Yuma and Phoenix, and are not associated with genuine precipitation. Feeding such data into the assimilation system might be disastrous. A stricter screening of radar data in mountainous regions should therefore be implemented in future experimentation.

Anomalous propagation events were also recently identified in OPERA data over the North Sea from a comparison to satellite precipitation retrievals, rain gauges and ECMWF short-range forecasts (*Lopez,* 2008b). Figure 6 provides an illustration of spurious radar surface rainfall estimates associated with an anticyclonic spell between 2 and 11 May 2008 over the North Sea. A procedure that diagnoses anomalous propagation and in particular ducting occurrence from model fields has been developed (see Box C). This information can help to reject dubious radar observations prior to the assimilation, as shown in Figure 6.

Also, on a few occasions, bull's-eye structures were found in the NCEP Stage IV hourly data when only rain gauge data was used to produce the rain retrieval. In the future, these undesirable patterns will be eliminated before the assimilation.

Over regions of steep orography, the accuracy and representativeness of ground-based radar precipitation retrievals are likely to be less than over flat terrain. Accuracy might also be an issue in snowy situations. Ideally, the question of the specification of radar observation errors should be addressed more precisely.

In addition, whether to assimilate rain retrievals or reflectivities directly is still unclear. Both methods imply underlying errors in the retrieval procedure or in the reflectivity simulator, respectively. Furthermore, neither of these approaches avoids the issue of non-rainy model background.

One should also consider whether accumulating radar data over periods of several hours could make its assimilation easier by smoothing out the effects of potential nonlinearities in the model physical parametrizations.

Eventually, a crucial prerequisite for the operational implementation of the assimilation of ground-based precipitation radar observations in the ECMWF system will be their real-time availability and exchange. This is already almost the case over the USA (NCEP Stage IV) and over Europe (OPERA).

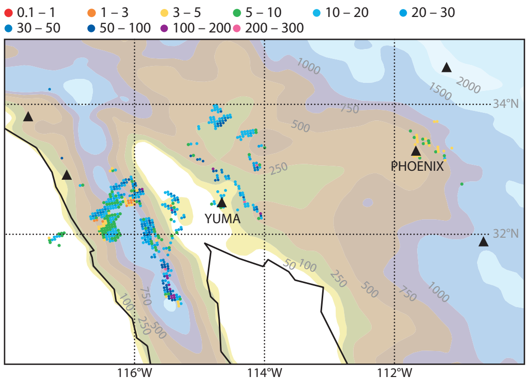

Figure 5 Example of NCEP Stage IV spurious hourly rainfall estimates over South California caused by radar beam impinging on orography (1 June 2005). Orography is colour shaded, radar rain pixels are shown as colour-coded dots and black triangles indicate radar site locations (NEXRAD network).

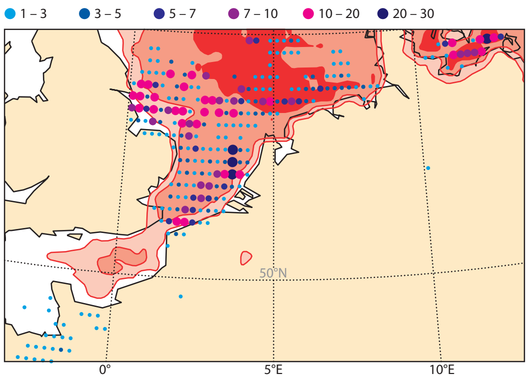

Figure 6 Spurious OPERA surface rainfall rates (dots; in mm day^{-1}) associated with anomalous propagation over the North Sea. Precipitation amounts are averaged between 2 and 11 May 2008. Frequency of ducting occurrences computed from ECMWF model analyses are shaded in red (from above 50% in pink to above 90% in red).

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Anomalous propagation and ducting

B

The propagation of electromagnetic waves through the atmosphere is governed by Snell's law. In other words, it mainly depends on the spatial variations of atmospheric refractivity, N, which can be estimated using:

$$N = 0.776\ P/T + 3730\ e/T^2$$

where P is the pressure in Pascals, T the temperature in Kelvin and e is the water vapour partial pressure in Pascals. Anomalous propagation of electromagnetic waves occurs in the atmosphere for tilt angles of emission, α, lower than a few degrees and when N sharply decreases with height. It is generally assumed that when the vertical gradient of N (i.e. $\partial N/\partial z$) becomes lower than $-0.157\ \mathrm{m}^{-1}$, the wave can become trapped inside a layer (ducting) and even be deflected towards the surface. More generally, four different propagation regimes are distinguished depending on the value of $\partial N/\partial z$, as illustrated in the figure.

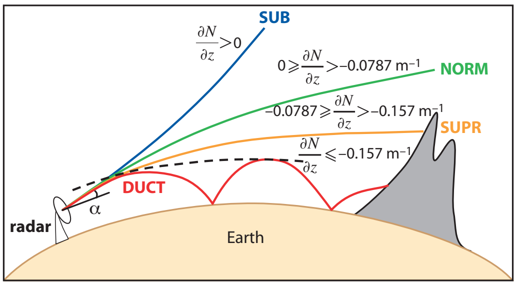
Meteorological situations favourable to the occurrence of anomalous propagation are characterized by an upward increase of temperature (inversion) and/or strong upward decrease of moisture, which includes:

- Temperature inversion due to nocturnal radiative cooling inside the planetary boundary layer (PBL) over land.
- Temperature inversion over a moist PBL, due to anticyclonic subsidence in the trade wind region.
- Dry air advection over sea or wet land.
- Low-level moist and cool air advection from the sea.
- Outflow of low-level moist and cold air from thunderstorms.

In the case of precipitation radars, anomalous propagation can lead to the return of spurious ground echoes and hence erroneous rainfall rate estimates.

Keeping in mind the obvious limitations associated with spatial resolution, ducting occurrence can be diagnosed from model temperature, moisture and pressure fields using the above definition of refractivity. This approach has recently led to the production of a five-year global climatology with 40-km resolution of super-refraction and ducting from ECMWF's operational analyses (*Lopez,* 2008a). This climatology might be relevant to the radar and Global Positioning System (GPS) communities but also to the broader field of telecommunications. An atlas of this climatology is now accessible to ECMWF Member States at the following address:

www.ecmwf.int/products/forecasts/d/inspect/catalog/research/physics/ducting/.



Radar beam propagation regimes according to the vertical gradient of atmospheric refractivity, $\partial N/\partial z$: SUB=sub-refractive, NORM=normal, SUPR=super-refractive, DUCT=ducting.

Summary and prospects

The assimilation of NCEP Stage IV hourly rain rates over mainland USA have been tested at ECMWF in month-long global experiments, using the 1D+4D-Var technique already applied in operations to SSM/I brightness temperatures inside cloudy and rainy regions. When the radar data is assimilated in the presence of all other observations, the largest impact is found in the 4D-Var moisture analyses and for forecast ranges up to two days. Standard forecast scores (temperature, wind, geopotential) become slightly better over North America during the first three days but also over Europe on the medium-range. Precipitation forecast errors are noticeably reduced, but only within the first 24 hours. On the other hand, denial experiments without operational moisture-sensitive observations over mainland USA exhibited a large improvement in the moisture field and significantly better forecast scores over North America in the first five days when radar rain rates are assimilated. This suggests that the full benefit of the new data in 4D-Var might not be obtained in this well-observed region because of the competition with other more conventional measurements.

Ground-based radar precipitation observations have the advantage of being complementary to satellite microwave brightness temperatures that are currently assimilated over oceans only, because of strong heterogeneities in land surface emissivity. At the same time, radar data usually benefits from an excellent

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temporal coverage, which is not the case for microwave instruments onboard polar orbiting satellites. Furthermore, although tests performed so far at ECMWF only dealt with surface precipitation observations, one could envisage the assimilation of three-dimensional information on hydrometeors obtained from multiple radar beam elevations. The assimilation of precipitation radar data might be beneficial not only to the results of operational 4D-Var assimilation but also to those of future reanalyses as well as to soil moisture and temperature analysis.

However, several issues remain to be addressed before the operational assimilation of radar data at ECMWF becomes reality. These include:

- Selection of the best assimilation method (indirect 1D+4D-Var versus direct 4D-Var).
- Choice of the observed quantity to be assimilated (precipitation or reflectivity).
- Quantification of error statistics for radar precipitation retrievals (including the probable degradation over mountains and in snowy situations).
- Efficient rejection of dubious measurements (e.g. due to anomalous propagation or ground clutter).
- Relevance of averaging the data in time to ensure a smoother assimilation.

Eventually, the main prerequisite to the operational implementation of radar observation assimilation on a continental scale remains whether good quality data can become available in quasi real-time, at least initially over the USA and Europe.

Further Reading

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