Hydrology and Earth System Sciences, 4(4), *627–633* (2000) © EGS

Hydrology & Earth System Sciences

Short period forecasting of catchment-scale precipitation. Part I: the role of Numerical Weather Prediction

M.A. Pedder, M. Haile and A.J. Thorpe

Department of Meteorology, University of Reading, Reading RG6 6BB, UK
e-mail for corresponding author: m.a.pedder@reading.ac.uk

Abstract

A deterministic forecast of surface precipitation involves solving a time-dependent moisture balance equation satisfying conservation of total water substance. A realistic solution needs to take into account feedback between atmospheric dynamics and the diabatic sources of heat energy associated with phase changes, as well as complex microphysical processes controlling the conversion between cloud water (or ice) and precipitation. Such processes are taken into account either explicitly or via physical parameterisation schemes in many operational numerical weather prediction models; these can therefore generate precipitation forecasts which are fully consistent with the predicted evolution of the atmospheric state as measured by observations of temperature, wind, pressure and humidity.

This paper reviews briefly the atmospheric moisture balance equation and how it may be solved in practice. Solutions are obtained using the Meteorological Office Mesoscale version of its operational Unified Numerical Weather Prediction (NWP) model; they verify predicted precipitation rates against catchment-scale values based on observations collected during an Intensive Observation Period (IOP) of HYREX. Results highlight some limitations of an operational NWP forecast in providing adequate time and space resolution, and its sensitivity to initial conditions. The large-scale model forecast can, nevertheless, provide important information about the moist dynamical environment which could be incorporated usefully into a higher resolution, 'storm-resolving' prediction scheme.

Keywords: Precipitation forecasting; moisture budget; numerical weather prediction

Introduction

Flood forecasting requires accurate and timely predictions of the precipitation affecting a given catchment area. Appropriate lead times for such forecasts range from one hour to a day or more. The research reported here and in Part II (Bell and Moore, 2000) considers how these requirements might be satisfied using deterministic methods of rainfall prediction, based on both operational numerical weather prediction (NWP) and 'catchment-scale' model formulations. The ultimate objective of the research is to develop a system for predicting catchment-scale rainfall events using a high resolution forecast scheme which can incorporate information from an operational mesoscale forecast model as well as 'observations' such as measured surface weather variables and radar reflectivity data.

Given that other approaches are being studied within HYREX, it is worthwhile summarizing here the principles which lie behind NWP. The deterministic approach postulates that, at least over a certain time-period, the laws of physics, as applied to the atmosphere, can be solved (integrated forward in time) to find the forecast fields given initial data describing the current conditions. The time-period over which such forecasts are accurate depends on the spatial scale of the phenomenon of interest. In the case of local rainfall, it is believed that the atmosphere is predictable or 'deterministic' for up to a few hours ahead. However, one problem with this approach is the accurate specification of the initial state, which is generally under-determined by observations. NWP models attempt to overcome that problem by combining the information available from observations with data generated from a short-range forecast (initialised at some earlier time); this process is generally referred to as *data assimilation*. Data assimilation by NWP is effective in estimating the current state of the atmosphere so that the relationships between the various fields represented by the model are consistent with the physical laws assumed by the model. Nevertheless, uncertainty in the determination of an initial state is still one of the main sources of error in short-term weather forecasting.

A new development in deterministic weather prediction is the idea of starting a set of forecast integrations from slightly different initial conditions, reflecting the range of uncertainty in the estimated initial state. This *ensemble* approach allows a probability to be assigned to the likelihood of rainfall (for example). Although the ensemble approach is not considered here (and it has yet to be applied to mesoscale systems), it is generally accepted as the way forward for NWP, particularly in generating probability forecasts. To make the distinction between this and other purely statistically-based methods (such as described in other HYREX sub-projects) such an ensemble approach should be regarded as still conforming to a deterministic methodology.

Accurate prediction of regional precipitation by deterministic methods is perhaps the most difficult problem in modern weather forecasting. While recent studies using regional NWP models have demonstrated skill in forecasting rainfall for hydrological purposes, at least on relatively large scales (Karstens *et al.*, 1996; Heise, 1996), performance so far falls far short of the requirements for successful flood forecasting on any significant lead time. Furthermore, operational NWP models do not provide the spatial resolution required to represent the substantial variations in precipitation which can occur within a single catchment, and which may be very important for determining catchment response. For short-term precipitation forecasting, a few schemes have been developed which attempt to combine information from a NWP model with near real time data to predict the movement and intensity of precipitation systems on scales below those explicitly resolved by the model. In Britain, the Meteorological Office NIMROD system, which has recently replaced its FRONTIERS system (Brown *et al.*, 1994; Golding, 1998), uses an objective prediction method which combines information from a short term forecast provided by an operational mesoscale NWP model with radar and satellite data to generate high-resolution forecasts of cloud and precipitation patterns on lead times of a few hours. Such a scheme is intended to apply over a relatively large area on a routine (operational) basis. It relies heavily on the principle of advecting individual precipitation features which have been identified from radar and satellite data, while the temporal evolution of individual 'storms' is taken into account more-or-less empirically. However, such a scheme is not intended primarily to provide predictions of catchment-scale precipitation in a form suitable for quantitative flood forecasting.

This paper outlines some general principles of precipitation forecasting by deterministic methods before describing, briefly, the role and performance of an operational, mesoscale NWP system. Here, the term *mesoscale* is used to refer to a range of space and time scales intermediate between the large scale global circulation and the small-scale of (for example) individual clouds. It implies a spatial resolution of a few tens of kilometres and a temporal resolution of the order of one thousand seconds. Part II describes the development and application of a "water-balance storm model", which is intended to provide a much higher time and space resolution than that available from the mesoscale model.

The atmospheric moisture budget

A crucial requirement for the successful forecasting of surface precipitation is an accurate representation of the time evolution of atmospheric sources and sinks of precipitable water. This is equivalent to solving a time-dependent moisture budget equation, which can be written:

$$P - E = -\frac{D(\bar{q} + \bar{\ell})}{Dt} \tag{1}$$

Here an over-bar symbol denotes mass-weighted vertical integration over a full atmospheric column of unit horizontal area; q is specific humidity (vapour concentration), ℓ the specific liquid (or solid) water concentration, P the surface precipitation rate and E the surface evaporation. The operator D/Dt is the so-called total or substantial time derivative. For a variable $\bar{\theta}$ that can be evaluated in a local frame of reference, a substantial derivative of the form $D\bar{\theta}/Dt$ can be written

$$\frac{D\bar{\theta}}{Dt} = \frac{\partial\bar{\theta}}{\partial t} + \overline{\mathbf{V}\cdot\nabla\theta} + \overline{\omega\frac{\partial\theta}{\partial p}} \tag{2}$$

The right-hand-side of this expression represents the sum of the local rate of change, horizontal advection by the horizontal wind $\mathbf{V} = (u,v)$ and vertical advection by the vertical component of velocity. For convenience, the so-called pressure co-ordinate system is used in which vertical gradients are represented by a variation with respect to pressure and vertical velocity is measured by $\omega = dp/dt$, which is the rate of change of pressure following a fluid element. In a hydrostatic atmosphere, $-\partial\omega/\partial p = \nabla\cdot\mathbf{V}$, which represents the horizontal divergence of the vector wind field. Assuming negligible vertical motion on the lower boundary, the time dependent moisture budget Eqn. 1 can be written in the form

$$P - E = -\frac{\partial\bar{q}}{\partial t} - \overline{\nabla\cdot(\mathbf{V}q)} - \frac{\partial\bar{\ell}}{\partial t} - \overline{\nabla\cdot(\mathbf{V}\ell)} \tag{3}$$

in which each substantial time derivative term has been expressed as the sum of a local (time) tendency and a horizontal flux divergence. Alternatively, the flux divergence term involving q can be written as the sum of two contributions:

$$\overline{\nabla\cdot(\mathbf{V}q)} = \underset{A}{\overline{\mathbf{V}\cdot\nabla q}} + \underset{B}{\overline{q\nabla\cdot\mathbf{V}}} \tag{4}$$

in which term (A) is a contribution from horizontal advection of water vapour and term (B) is a contribution from the horizontal wind divergence. The latter is closely related to the profile of vertical velocity within the column through the hydrostatic balance approximation (see above). On the scale of an individual precipitating cloud element, the contribution from horizontal wind divergence might be expected to be much larger than either the advective or local tendency term. However, the actual balance observed in practice will depend on the scale resolution characteristics of the analysis or forecast system that provides the estimated values of the 'aerological' variables V and q.

Although Eqn. 3 refers to a frame of reference that is fixed with respect to the Earth, a similar equation can be used to describe the atmospheric water balance in any 'system' frame of reference which is moving with some constant horizontal velocity $\mathbf{V}_s$. In that case, V is replaced by a system-relative velocity $\mathbf{V}' = (\mathbf{V} - \mathbf{V}_s)$ and a term of the form $\partial\theta/\partial t$ then interpreted as a rate of change following the system. Although not relevant for the analysis of data generated by an Eulerian model (as considered in this paper), such a formulation is useful in the development of a simple cloud resolving model, as described in Part II. In particular, if $\mathbf{V}_s$ is associated with the motion of a single cloud, then, in that frame of reference, it may be possible to ignore the contribution from the horizontal advection term A in Eqn. 2. The moisture budget equation can then be approximated by

$$P - E = -\frac{\partial \bar{q}}{\partial t} - \overline{\omega \frac{\partial q}{\partial p}} - \frac{\partial \bar{\ell}}{\partial t} - \overline{\omega \frac{\partial \ell}{\partial p}} \qquad (5)$$

This is the vertically integrated form of the continuity equation for atmospheric water substance viewed in a Lagrangian frame of reference, of the type assumed in the storm-resolving model considered in Part II. However, it is not clear whether it is in fact realistic to neglect horizontal advection terms, even for an appropriate choice of system velocity, and such an approximation is certainly not necessary for the diagnosis of atmospheric water balance derived from observations or NWP model data.

In principle, Eqns. 3 and 4 can be used to estimate P as a residual term, given measurements of the aerological variables V and q, subject to assumptions such as that E and terms involving ℓ can be neglected. Previous studies based on such a 'budget' approach to precipitation forecasting have highlighted the difficulty of obtaining realistic estimates of P in this way (Peixoto, 1973; Holopainen, 1996). A potentially more successful approach, which is used in many operational NWP models, is to treat P as a prognostic variable rather than a quantity which is diagnosed as a residual term in an approximated moisture balance equation. This involves taking into account the conversion of cloud water into precipitation, which is controlled by complex microphysical processes that cannot be represented explicitly by the model, but are instead parameterised as functions of the prognostic variables carried on the model grid.

However, a prediction of precipitation rate based on these parameterisations with input consisting of variables carried on the model grid generates only the so-called dynamic component of the total precipitation. Even mesoscale NWP and analysis systems cannot represent convective storms explicitly; these occur typically on scales below those which are resolved by the model grid and which excite dynamical modes that are effectively filtered-out by the model's integration scheme. Instead, the effect of such storms on the larger scale water balance is taken into account implicitly by a paramerisation of sub-grid scale convection, the input to which takes into account the gravitational stability of the model atmosphere as measured by the resolved profiles of temperature and humidity. For the type of model considered here, a useful by-product of this process is a partitioning of the total predicted precipitation (considered as an average over a grid cell) into dynamical (large scale) and convective (unresolved scale) components. The ratio of convective to total predicted precipitation can thus provide important information about the synoptic conditions associated with a particular precipitation event.

A well-formulated NWP model is capable of taking into account complex interactions between flow dynamics and those sources and sinks of latent heating which are associated with condensation and evaporation in the atmosphere. An important property of such model forecasts is that the predicted evolution of the atmospheric state represented by the model is forced to be consistent with those well-established laws of motion and continuity on which the model is based, including, for example, the moisture budget Eqn. 1. In this sense, NWP methods are superior to more empirical or approximate methods which do not result necessarily in consistent relationships between predicted field parameters. On the other hand, operational NWP models generally have to rely on rather crude parameterisations of cloud processes, and this may lead to large errors in the predicted 'precipitation efficiency' of the modelled cloud system. (These parameterisation schemes are the subject of intense research into the physics of clouds and are improving rapidly.) A more obvious limitation is the model's inability to represent small-scale precipitation events explicitly; this may be particularly important in the context of flood forecasting.

An operational mesoscale NWP model

The operational forecast model used in this study is the mesoscale version of the Meteorological Office Unified Model (Cullen, 1991; Golding, 1990). The Mesoscale Model (MM) is a gridpoint model with a horizontal resolution of approximately 16.8 km, extending over a domain measuring roughly 1500 by 1500 km (Fig. 1). The model has a vertical co-ordinate system which is 'terrain-following' at low levels; its vertical resolution varies from a few tens of metres near the lower boundary to just over one kilometre at a height of 8 km. Initial conditions on the model domain boundaries are taken from a large-scale analysis generated by the limited area (Atlantic sector) version of the Unified Model. However, the MM also has its own data

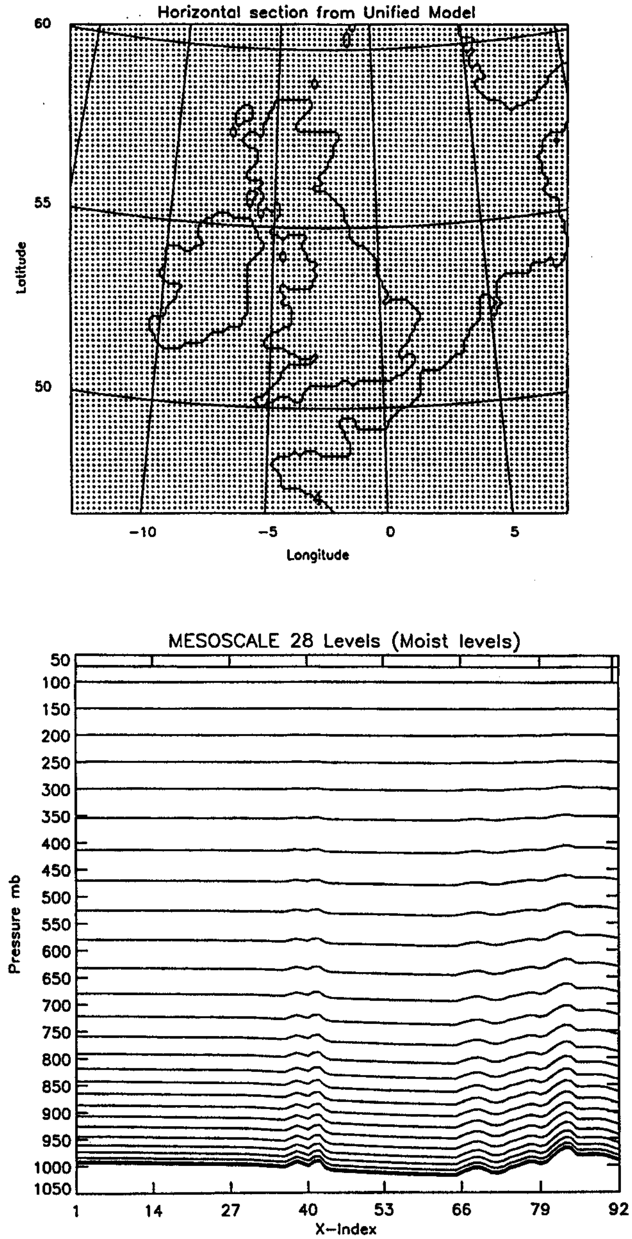

Fig. 1. *The mesoscale model gridpoint domain. Upper panel shows the horizontal domain with gridpoint resolution 16.8 km. Lower panel shows the distribution of model levels in (vertical) pressure coordinate space for a typical East-West section across the model domain.*

assimilation scheme, which incorporates a wide variety of observational data from surface, upper-air and satellite systems. The version used here can generate forecasts initialised at 00, 06, 12 or 18 UTC, each of which represents a 'data cut-off' time prior to which the model runs (for 3 hours) in data assimilation mode. Forecast variables are output at 15 minutes intervals, including surface precipitation accumulated over the previous 15 minutes. (For verification purposes, the latter are here converted to 15-minute average values of precipitation rate.)

In relation to the prediction of moisture budget parameters, an important component of the MM analysis is the Moisture Observation Pre-processing System (MOPS; Wright, 1993). This uses satellite and radar imagery in combination with surface observations and a short term forecast to generate a three-dimensional analysis of cloud height and cover. The cloud data are then converted to profiles of relative humidity using the MM cloud scheme relationships, which are subsequently assimilated into the Model via its own data assimilation scheme. The MM analysis/forecast system thus incorporates information from a variety of data sources, but only to the extent to which these can impact on scales resolved by the model grid.

Model performance and limitations

The main objectives in using the MM model for this study are i) to provide a 'benchmark' of predictability for catchment-scale precipitation events and ii) to investigate the relative contributions from different components of the mesoscale moisture budget Eqn. 2 and their sensitivity to varying lead time and initial data.

In relation to i), verification was based on interpolating from the model grid to one with the same spatial resolution centred on the Brue Catchment area (132 km^2 centred on 51.12°N, 2.45°W). The evaluation of moisture budget parameters was based on standard differencing methods applied on the same grid. Simple averaging methods were used to estimate budget parameters over areas larger than that defined by a single grid cell, to simulate the effect of degrading model resolution.

In relation to ii), use has been made of data collected during designated HYREX Intensive Observation Periods (IOPs). These were periods of up to 24 hours duration, identified in advance, when significant rainfall was expected to affect the Brue catchment area. During IOPs, additional meteorological data were collected to complement the automatic rainguage network in the Brue catchment (Moore *et al.*, 2000). These included 3-hourly radiosonde ascents from operational stations and at a site within the Brue catchment (though data from the latter were used for verification purposes only and were not assimilated into the mesoscale model).

Results obtained from the HYREX IOP 3 event, on 6th/7th December 1994 illustrate MM model performance. During this period, a band of moderate frontal (non-convective) precipitation moved from West to East across the British Isles, producing over 20 mm of rainfall in 24 hours over Cornwall. Figure 2 compares MM predictions of surface precipitation rates with catchment-scale averages estimated from the dense gauge network (15-minute averages; see Wood *et al.*, 2000). Results for two MM runs are shown: run (a) is based on an initialisation (data cut-off) time of 18.00 on 6th December, which is before a period of intensive (3-hourly) upper air observations made in connection with the experiment; run (b) is based on an

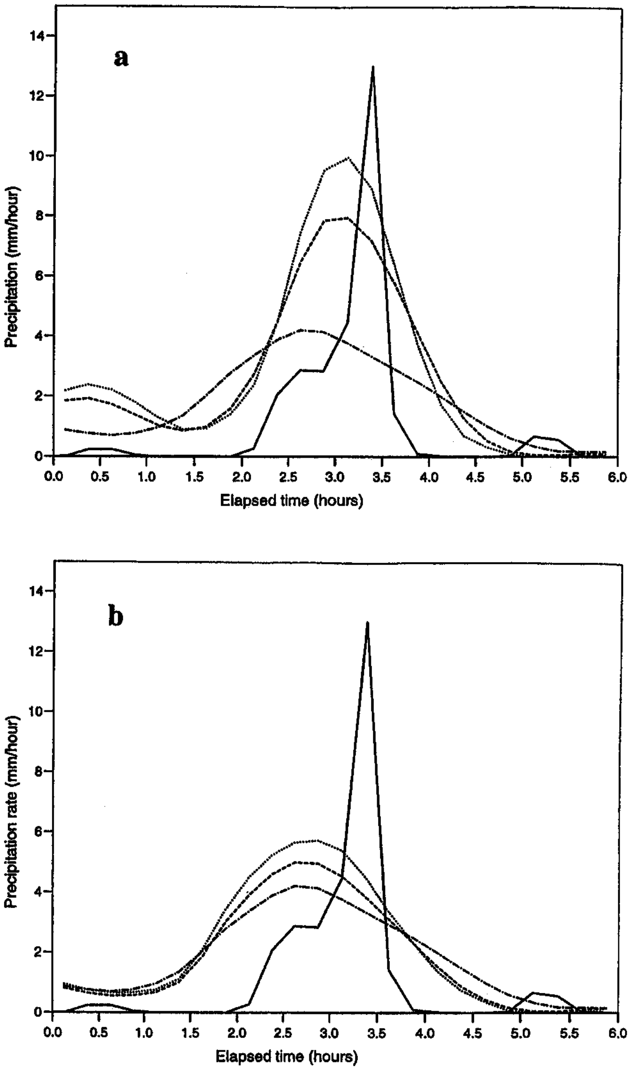

Fig. 2. *Comparisons between MM predicted and observed precipitation rates over the period 22.00 6 December 1994 to 04.00 7 December 1994 (HYREX IOP3): a) data assimilation cut-off time 18.00; b) data assimilation cut-off time 00.00. Continuous line is observed rate averaged over the Brue Catchment area (15 minute averages). Other lines join predicted values at model resolution (16.8 km; dotted), averaged over a 64 km by 64 km area (dashed) and averaged over a 128 km by 128 km area (dot-dash).*

initialisation time of 00.00 on 7th December, which should be influenced by upper-air soundings from British radiosonde stations made at 21.00 and 00.00. At the model resolution, run (a) provides the better prediction of peak rate but substantially over-predicts the total rainfall during the 6-hour period of interest (17.2 mm as against an observed 7.2 mm). Run (b) provides an improved estimate of total rainfall (12.5 mm) but under-estimates peak rainfall rate by a factor of more than two. Although the model prediction of peak precipitation rate is not particularly impressive, the estimated peak catchment value derived from the FRONTIERS network radar was 4.5 mm hr^{-1}, which also represents an under-estimation of the observed peak rate by more than a factor of two, even though it is based on real-time data. For this particular case, the MM forecast initialised at 18.00 UT provides an estimate of peak precipitation rate which is actually closer to the gauged value than one based on the real-time radar data, though the latter did provide a much better estimate of accumulated precipitation (5.2 mm) than either of the MM forecasts.

To a first approximation, the MM predictions of catchment rainfall rate can be considered as 'smoothed' versions of the observed variation, with some offset in the timing of peak rate. Although the horizontal scale of a single gridpoint cell (~17 km) is actually somewhat larger than that characterising the Brue catchment area (~12 km), this difference is not sufficient to explain the observed difference in the time variation in P. Figure 2 also shows the effect of decreasing spatial resolution, by averaging the model values of P over different numbers of grid cells centred on the Brue catchment area. Reducing resolution by a factor of four has relatively little impact on either the total rainfall amount or duration. This behaviour is consistent with the model tending to over-estimate the width of the main rainband rather than under-estimating its translation velocity. In other words, the model provides a rather poorer spatial resolution of the observed event than that which might be implied by its own gridpoint resolution scale.

Figure 3 shows the time variation of some of the vertically integrated moisture budget parameters represented in Eqns. 1 and 2, as derived from the MM model data at gridpoint resolution. The variation in $-D\overline{q}/Dt$ matches almost exactly that of the model's predicted surface precipitation rate while this is significantly greater than zero; this implies that contributions from evaporation and changes in liquid water concentration in a frame of reference following the main rainband are negligible. Hence, the model associates most of the precipitation with the 'aerological' source term $-D\overline{q}/Dt$. In the local frame of reference, the largest contribution is associated with vapour flux convergence $-\nabla\cdot\overline{(q\mathrm{V})}$, a large part of which is attributable to the contribution from the horizontal wind convergence term $-\overline{q\nabla\cdot\mathrm{V}}$ (see Eqn. 4). This result is consistent with the idea that the model interprets the precipitation event as mainly 'large-scale' (little or no contribution from moist convection on the sub-grid scale), so that the rate at which precipitation is generated within the grid cell is determined mainly by the profiles of vertical velocity and humidity variables carried on the model grid.

A significant feature of the budget time series is the relative insensitivity to initial conditions of the horizontal advection term $-\overline{\mathrm{V}\cdot\nabla q}$. This result implies the predicted humidity and total horizontal wind fields are not influenced greatly by the impact of additional data during the assimilation period. Furthermore, it turns out that this horizontal term is almost equal and opposite in sign to the (negative) tendency term $-\overline{\partial q/\partial t}$ (not shown). Such a balance is consistent with the idea that the local changes in

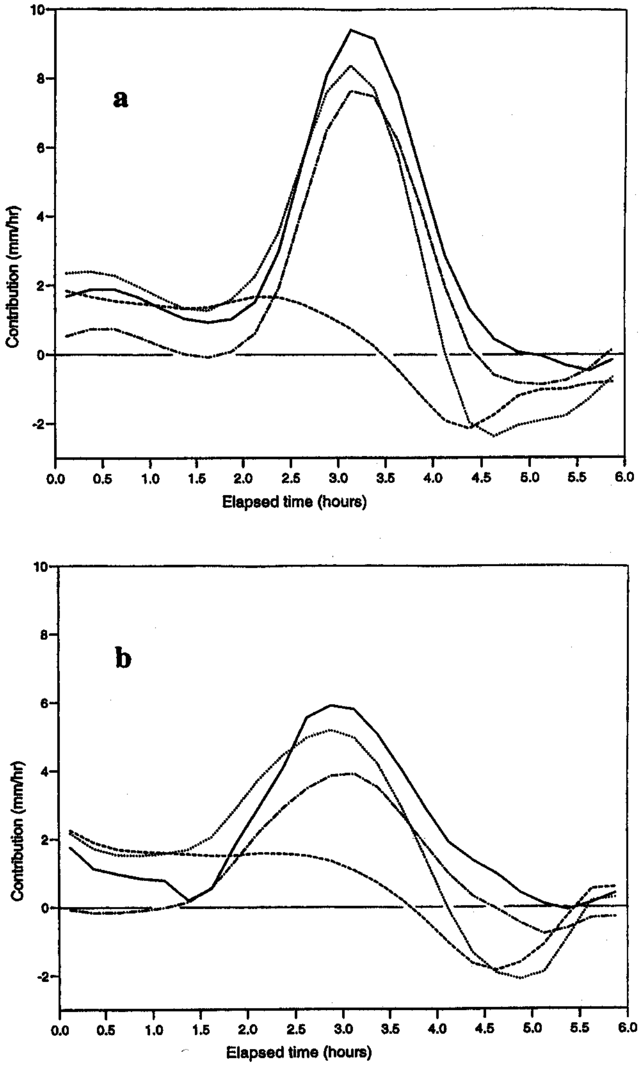

Fig. 3. *Column integral time series of MM moisture budget parameters* $-Dq/Dt$ *continuous curve),* $-\mathbf{V}\cdot\nabla q$ *(dashed curve),* $-q\nabla\cdot\mathbf{V}$ *(dot-dash curve) and* $-\nabla\cdot(q\mathbf{V})$ *(dotted curve). Panels a) and b) refer to different MM runs, as in Fig. 2.*

the total precipitable water content of the atmospheric column are associated mainly with the advection of an airmass transition zone within which the horizontal gradient of humidity changes only slowly in response to the release of precipitation. To a reasonable approximation, for this particular event the forecast precipitation can be diagnosed directly from the horizontal wind convergence term, in the sense that

$$\langle P\rangle \cong \langle -\overline{q\nabla\cdot\mathbf{V}}\rangle \equiv \left\langle \overline{q\frac{\partial\omega}{\partial p}}\right\rangle$$

where the braces imply time-averaging over the period of significant precipitation. Such a result could be important in the context of attempting to forecast smaller-scale features using a storm-resolving model. It suggests that it is mainly a realistic 'disaggregation' of the wind field convergence (or, equivalently, vertical velocity) that is required to represent successfully, the distribution of precipitation on scales smaller than those resolved by the mesoscale model (though small scale variations in both the specific and relative humidity should probably also be taken into account for additional accuracy).

Any model which solves the moisture balance equation at high resolution also needs to represent the vertical distribution of the individual aerological source terms adequately. Figure 4 shows the MM-generated profiles of $-Dq/Dt$, $-q\nabla\cdot\mathbf{V}$ and $-\mathbf{V}\cdot\nabla q$, averaged over a period of four hours centred on the time of maximum predicted precipitation rate. These again emphasise the dominant influence of the predicted wind field convergence in determining the source of precipitation by moisture transport. It is notable that a

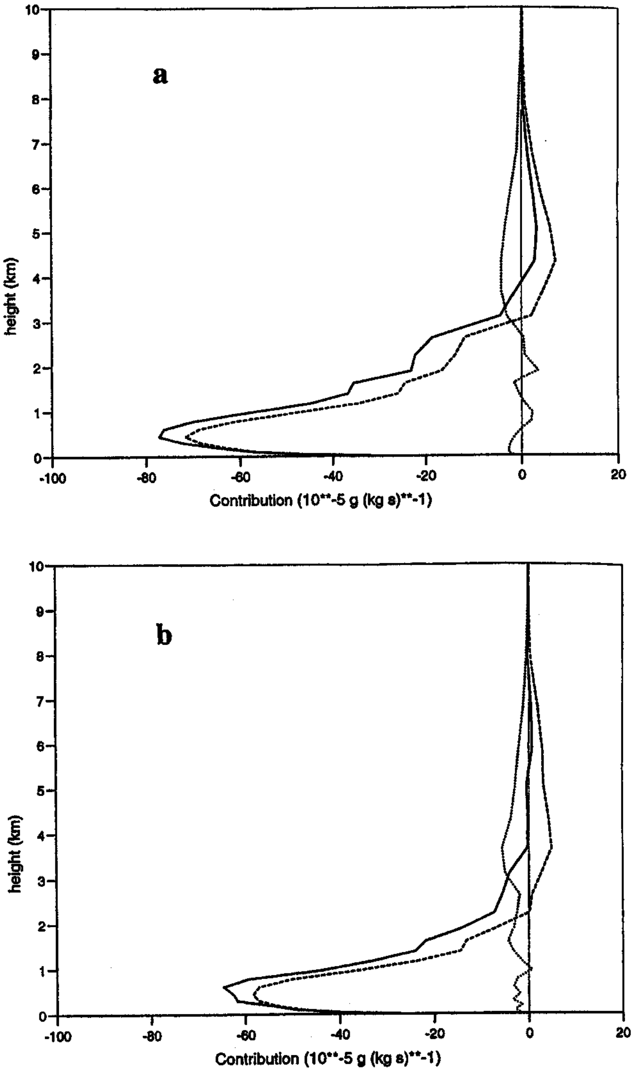

Fig. 4. *Vertical profiles of model predicted moisture budget parameters* $-Dq/Dt$ *(continuous curve),* $-q\nabla\cdot\mathbf{V}$ *(dashed curve) and* $-\mathbf{V}\cdot\nabla q$ *(dot-dash curve), averaged over a 4-hour period centred on the time of maximum predicted precipitation rate. Panels a) and b) refer to different MM runs, as in Fig. 1.*