IMPACT OF ATMOSPHERIC MOTION VECTORS (AMVS) ON THE ECMWF SYSTEM AND THE DEVELOPMENT OF A WATER VAPOUR AMV OBSERVATION OPERATOR

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ABSTRACT

A series of Observing System Experiments show that the current 4D-Var operational system benefits from the assimilation of both satellite data and conventional observations. In particular AMVs show a small positive impact in the Northern Hemisphere but are essential component of the observation system for the Tropics. Up till now there has been no attempt to model the vertical structure of the model wind in the observation operator for Water Vapour Clear Sky AMVs. AMVs are considered as single level wind such are aircraft observation. Work to investigate the use of deep layer model winds for an observation operator will be discussed.

1. INTRODUCTION

Atmospheric data assimilation is the process of determining a consistent four- dimensional atmospheric structure from information on the observational network, a dynamical model and other physical constraints. The time dimension can be accounted for in different ways. Four-dimensional variational assimilation (4D-Var) is the natural temporal generalisation of the three-dimensional variational analysis operational since January 1996 at ECMWF (Courtier et al., 1998, Rabier et al., 1998a, Andersson et al., 1998). It minimises a cost-function measuring the distance between a model trajectory and the available information (observations, background field coming from a previous short-range forecast) over an assimilation interval or window. Under the assumptions of linear dynamics and of a perfect model, it gives the same result at the end of the assimilation interval as the full Kalman filter and at a smaller cost (but does not provide explicitly the analysis and forecast error statistics).The potential of the 4D-Var algorithm was first shown in simple models in the mid- 80s (Lewis and Derber, 1985, Le Dimet and Talagrand, 1986, Courtier and Talagrand, 1987, Talagrand and Courtier, 1987) before being applied to primitive equation models at a relatively low resolution (e.g. Thépaut and Courtier, 1991, Rabier and Courtier, 1992, Navon et al., 1992, Zupanski, 1993). The incremental formulation of 4D-Var (Courtier et al, 1994), which comprises running a high-resolution model with the full physical parameterisation package to compare the atmospheric states with the observations to evaluate the cost-function and a low resolution model with simplified physics to minimise the cost-function, made its implementation feasible for operational models at high resolution. After extensive evaluation (Rabier et al., 1998b), it became operational on a 6-hour assimilation time-window at ECMWF on the 25th November 1997.

2. OBSERVING-SYSTEM EXPERIMENTS

2.1 Introduction

The operational observing network, which uses both conventional and satellite measurements, influences how accurately the initial atmospheric state can be prescribed and therefore to a large extent the resulting forecast accuracy. In order to evaluate the contribution made by the main ground-based and satellite-based observing systems to forecast quality a series of Observing System Experiments (OSE's) was performed. Similar experiments based on the 3D-VAR system operational in early 1997 are described in a previous study (Kelly et al., 1997). The 3D-Var system has been shown to benefit from the assimilation of both satellite data and conventional observations. The inclusion of each data type almost always improved the forecast which was not invariably the case in previous studies which were based on an analysis system using optimum interpolation (Kelly et al., 1993). The assimilation of the Tiros Operational Vertical Sounder (TOVS) radiance's directly in the 3D-Var analysis contributed largely to the improved benefit from satellite data.

A series of OSE experiments have been run using the operational 4D-Var system for 34 days in May and December 1997. For each experiment, the following observing systems have been removed from the full operational system:

(a) Satellite clear radiance data from the TOVS satellites (NOTOVS)
(b) Geostationary Atmospheric Motion Winds (AMVs) from cloud and water vapour (NOAMV)
(c) Radiosonde wind, temperature and humidity data (NORAOB)
(d) Aircraft winds and temperatures (NOAIREP)
(e) The combined removal of both a. and b. (NOSAT).

All these experiments have been compared to the full operational system (CONTROL). All verification statistics use the operational ECMWF analysis which had used all data, as it is considered to be the best for verification purposes. The influence of the data on forecast performance will be illustrated for the wind at 200 hPa where the impact is among the largest.

The results are grouped into two sections, first the experiments on the satellite measurements and second the experiments on the conventional upper-air measurements.

2.2 Experiments withdrawing satellite data

To evaluate the impact of satellite data in the 4D-Var framework we compared forecasts from the following four configurations:

(a) CONTROL which assimilates all data
(b) NOTOVS which excludes radiance data from the TOVS satellites
(c) NOAMV which excludes geostationary atmospheric motion wind data
(d) NOSAT which excludes both radiance data and geostationary atmospheric motion wind data

Comparing errors of the CONTROL forecasts (solid line) and the NOSAT forecasts (dashed line) in Figure 1 shows that the overall impact of satellite data varies in the short range from 1/3 of a day in the Northern Hemisphere, to 1 day in both the Tropics and the Southern Hemisphere. Both TOVS radiance's and AMVs Geostationary wind data have a positive impact in all areas. However, the combination of the two data sources produces the best forecasts. AMVs have most value in the Tropics. TOVS have a significant impact in the Tropics and large impact in the Southern Hemisphere. With the exception of AMVs in the Northern Hemisphere, all combinations of observational data show a positive influence on forecast performance throughout the forecast range up to 5 days.

2.3 Experiments withdrawing conventional upper air data

For the evaluation of the impact of conventional upper air measurements we have made assimilation for two more configurations excluding radiosondes or aircraft measurements and we compare forecast performance of the following experiments

(a) CONTROL which uses all data

(b) NORAOB which excludes both radiosonde winds, temperatures and humidity data
(c) NOAIREP which excludes both aircraft wind and temperature observations.

For the purposes of comparison, the NOSAT experiment will also be considered in this group in order to assess the relative importance of the AIREP and SAT wind observing systems.

The impact on the 200 hPa winds is shown in Figure 2. In the Northern Hemisphere the radiosondes have the largest effect, as their exclusion (NORAOB) reduces the forecast accuracy by 1/2 a day. The satellite data and AIREPs have a lesser effect and both have about equal weight, each degrading the forecast by 1/3 of a day at the start but the longer term effect of the AIREPs decreases with time.

In the Tropics and the Southern Hemisphere, satellite data has the largest impact of about 1 day. Removing radiosondes has more impact in the Tropics (about 1/2 a day) than in the Southern Hemisphere (1/3 a day). AIREPs have negligible effect in the Southern Hemisphere and a small impact in the Tropics of about 1/3 of a day. Both radiosonde and satellite data bring an almost constant improvement in forecast skill.

The results obtained in this first set of 4D-Var observing system experiments are encouraging. The current operational 4D-VAR system benefits from the assimilation of both satellite data and conventional observations. Its performance in each of the Northern Hemisphere, the Tropics and the Southern Hemisphere is broadly satisfactory. The results are very similar to those obtained for the 3D-Var system (Kelly et al., 1997). A difference might be that in the Tropics and Southern Hemisphere the 4D-Var forecasts keep the benefit of AMVs and radiosonde data further into the forecast range than 3D-Var. The two week periods of data assimilation that form the basis of the OSE's are most certainly too short to estimate any long term drift in the analysis quality arising from excluded observations. Therefore the impact of different observing systems is likely to represent an underestimation.

3. DEVELOPMENT OF AN OBSERVATION OPERATOR

3.1 4D-Var Analysis

We follow the general variational approach to the assimilation of data into an NWP system (Lorenc, 1986; Talagrand, 1988) by minimising the cost-function J(x) with respect to the atmospheric state x, where J(x) measures the degree of miss-fit to the observations and to the background information. If the errors involved have Gaussian distributions, then the optimal penalty function is a sum of quadratic terms:

$$
\begin{aligned}
J(x) &= J_o + J_b \\
J_o &= [y - H(x)]^T O^{-1} [y - H(x)] \qquad (1) \\
J_b &= (x - x_b)^T B^{-1} (x - x_b)
\end{aligned}
$$

where x_b is the background with estimated error covariance B, y represents the observations with estimated error covariance O, and H is the observation operator (or "forward" operator) which computes model equivalents of the observed quantities at the observation points. The matrix O should in addition to the observation error also include the representativeness error, i.e. the error in the forward operator. Eq.1 applies to a wide range of problems. It has the same form in one as well as three and four-dimensional applications. In the case of TOVS radiance’s, H specifically represents the radiative transfer model which calculates radiance’s from the state vector of the forecast model. In 4D-Var, H includes a model integration from the time of the background to the time of the observation (see Thépaut et al., 1993). 3D-Var is thus, in theory as well as in practice, equivalent to a 4D-Var without model integration.

The computation of the AMV cost function is organised like that for conventional data (Vasiljevic et al., 1992), there is no account for any vertical spread of the data or any horizontally correlated error. This may arise from AMVs if a group of winds have all the same height error. The forward operator H, is the product of all the operations necessary to go from the control variable x to model radiance's at observation points. The operator H is continuous in x. It may be linear or non-linear and it ought to be differentiable in general but it does not have to be differentiable for *all* v for example differentiable between model levels but not differentiable exactly *at* a model level. Once model winds at AMVs locations have been computed, the cost function and its gradient with respect to radiance's can be calculated. Then the adjoint operators are applied in the reverse order to yield the gradient of the cost-function with respect to the control variable. The J_o computation is followed by the computation of J_b and its gradient, and the whole procedure is repeated until the minimisation has reached convergence, or the maximum number of iterations has been reached.

Under the assumption that AMVs have uncorrelated errors J_o reduces to

$$J_o = \sum \frac{1}{2}\left(\frac{[y - H(x)]}{\sigma_o}\right)^2 \tag{2}$$

and for a AMV with components u and v the cost function for one observation

$$J_o = \left(\frac{u_o - u_p}{s_u}\right)^2 + \left(\frac{v_o - v_p}{s_v}\right)^2 \tag{3}$$

where

u_o AMV zonal wind component
v_o AMV meridional wind component
u_p interpolated zonal wind at observation point
v_p interpolated meridional wind at observation point
s_u standard deviation of the zonal AMV observation error
s_v standard deviation of the meridional AMV observation error

Currently the interpolated point is at the latitude, longitude and height given in the AMV but a weight form will be discuss below with a single case. The form will be :

$$u_p = \sum w_i u_{ip}$$
$$v_p = \sum w_i v_{ip} \tag{4}$$

w_i = weighting function of the radiative transfer and model levels
u_{ip} = interpolated zonal wind at model level i and location p
v_{ip} = interpolated zonal wind at model level i and location p

3.2 Preliminary results

A series of three Meteosat images were simulated using 15 hour forecast from the T639 version of the ECMWF model and sent to EUMETSAT. The current development version of the MSG/AMV software was used to produce AMVs. At first the model generated water vapour images were too smooth for the cross-correlation algorithm but using an Euclidean distance tracking method produced a coherent data set of AMVs. Figure 3(a) shows AMVs plotted in red and a weighted mean-model-layer-winds from the model in blue. Only AMVs are shown with quality control values greater than 0.65 (Holmlund, 1998) and the forecast mean winds are weighed with normalised values of the Meteosat contribution function for each profile (Kelly et al., 1996).

In this first study there is general agreement between model tracked winds and mean weighted winds but there differences in some regions that need further investigation. Perhaps three is strong vertical wind sheer or the weighting function has a double peaked.

For this first study there is also reasonable agreement between model tracked wind and mean weighted. It is well known that the ECMWF forecasts in the deep Tropics after six hours begin to diverge from observations and this offers an explanation for the some of the differences. In the next study three hour forecast winds will be used with both model simulated and satellite AMVs.

The model generated AMVs and the mean weighted layer-winds have been analysed to a regular grid using a Barnes method and are shown in Figure 4(a). Figure 4(b) shows the same model generated AMVs Barnes analysis but in blue winds are model winds that have been interpolated at the peak of the weighting function. This is somewhat similar to the way the clear sky water vapour AMVs are used at present. There is a clearly not as good agreement compared to using model weighted deep layer winds.

4. SUMMARY

The 4D-Var system makes good use of different types of observations as demonstrated in a series of observing system experiments. AMVs shown a small but positive impact in the Northern Hemisphere but in the Tropics they have a large impact and define the Tropical circulation.

It now appears possible to track model simulated imagery and this will enable the development of improved observation operators. Even in the very preliminary results, there are some regions where complex vertical atmospheric structures may suggest that the use of water vapour AMVs is not desirable.

The direct use of cloud free water vapour radiances may appear a better solution but there is a need to compare both methods. In cloudy regions AMVs will still be important data source.

An additional area that needs further study is the problem of correlated errors. Several experiments have been run at ECMWF with high resolution AMVs winds and the increase in density has lead to a deterioration in forecasts. These forecasts improved when the coverage was reduced. A possible reason is the correlated error in the AMVs. Correlated error can arise from height assignment errors and/or from height adjustments in the 'Auto Editor' used by NESDIS (Nieman,1997). Correlated AMV error needs to be modelled.

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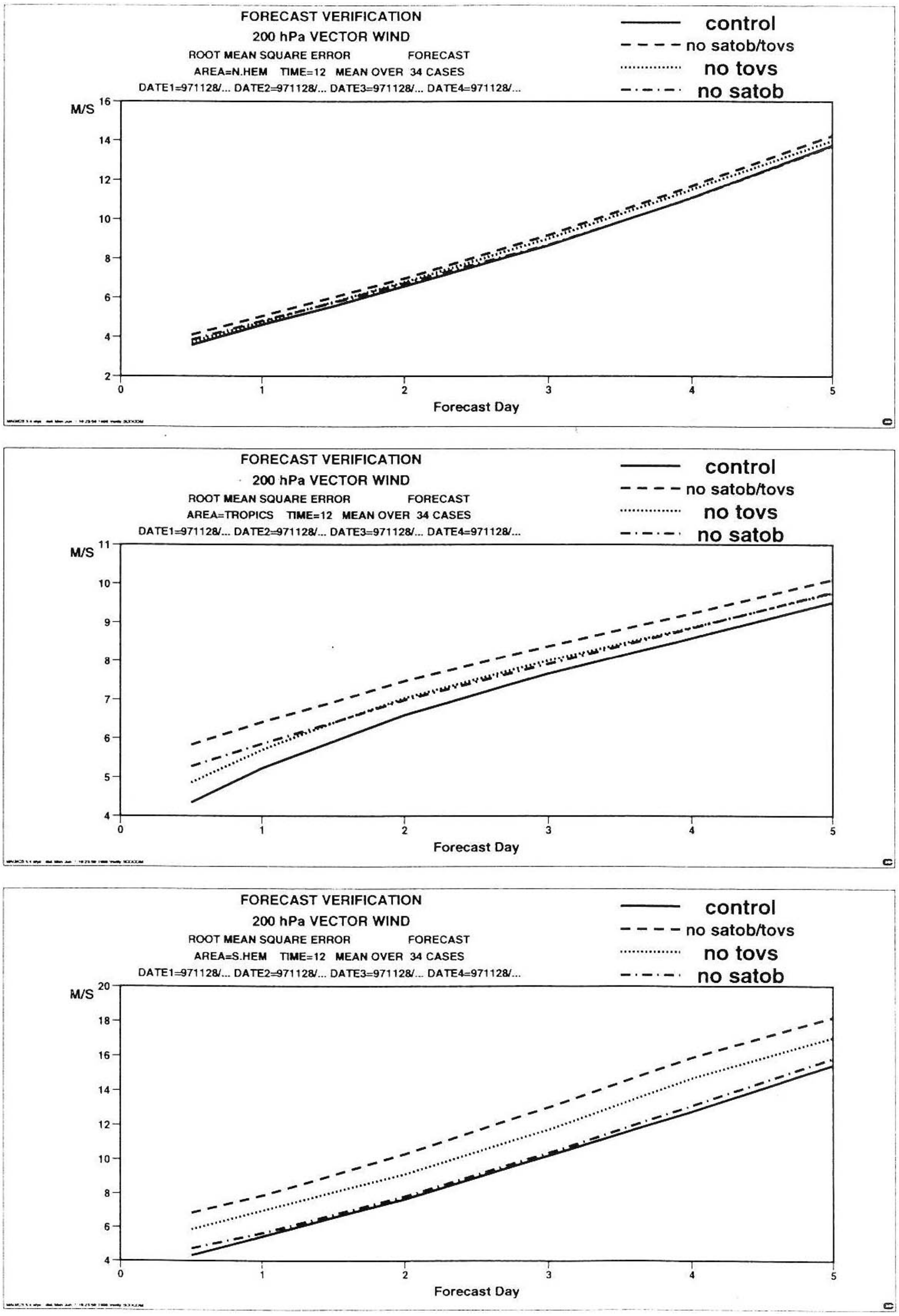

Figure 1: 200hPa vector wind root-mean-square forecast error for the Northern Hemisphere (top panel), the Tropics (middle panel) and the Southern Hemisphere (bottom panel) for the satellite OSEs.

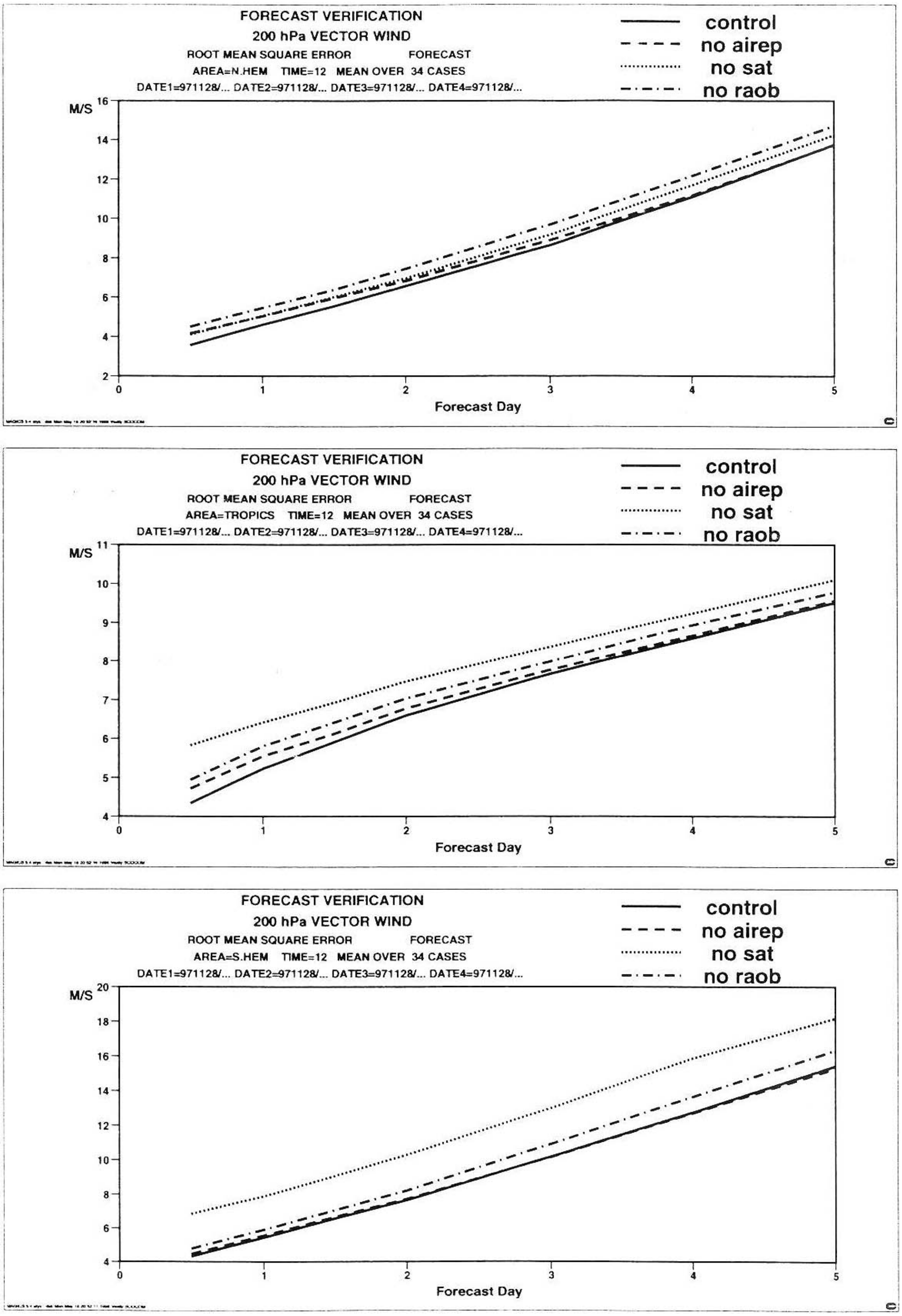

Figure 2: 200hPa vector wind root-mean-square forecast error for the Northern Hemisphere (top panel), the Tropics (middle panel) and the Southern Hemisphere (bottom panel) for the conventional upper air OSEs.

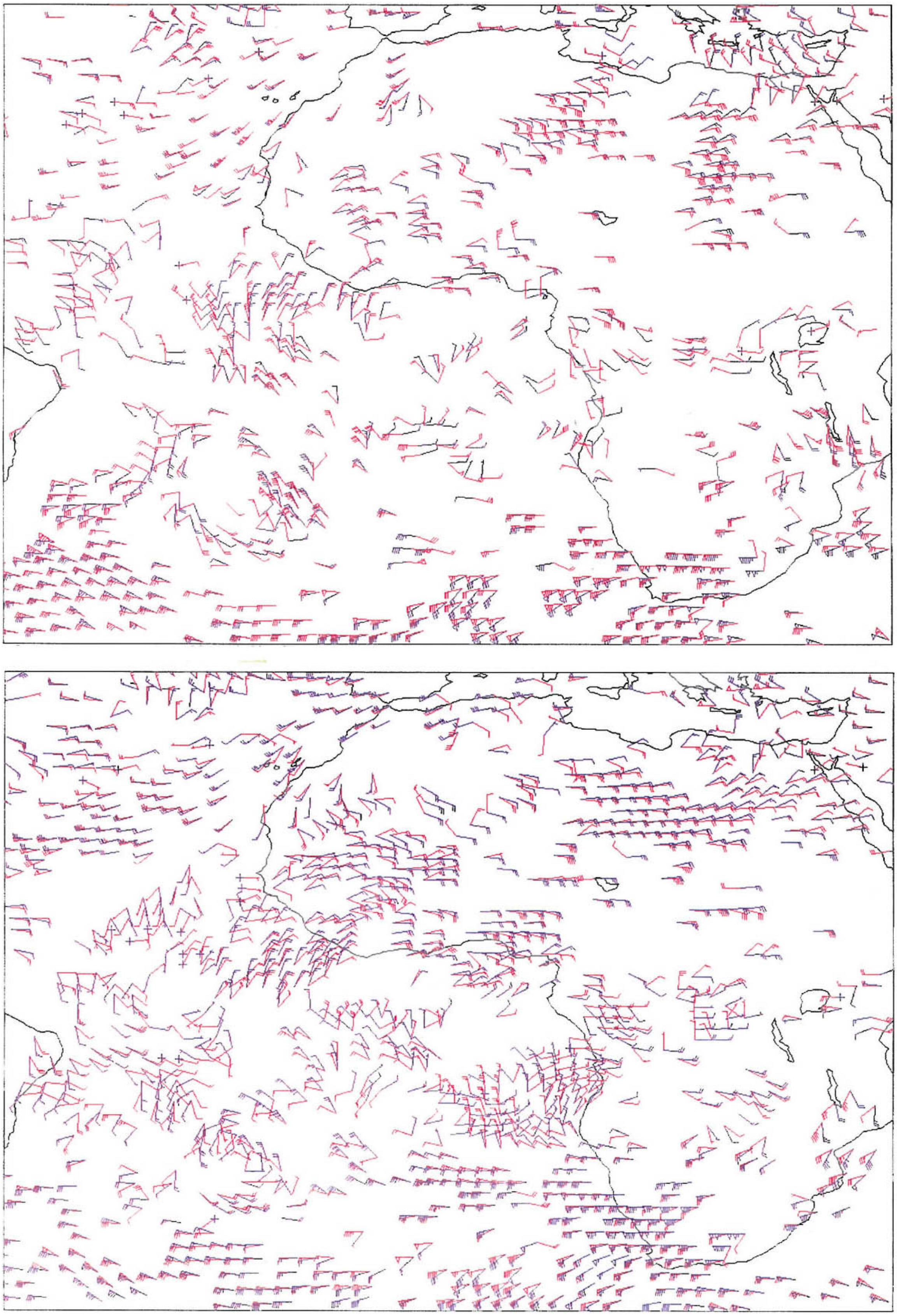

Figure 3(a): AMVs produced from simulated model Water Vapour imagery in red, model weighted using radiative transfer in blue.

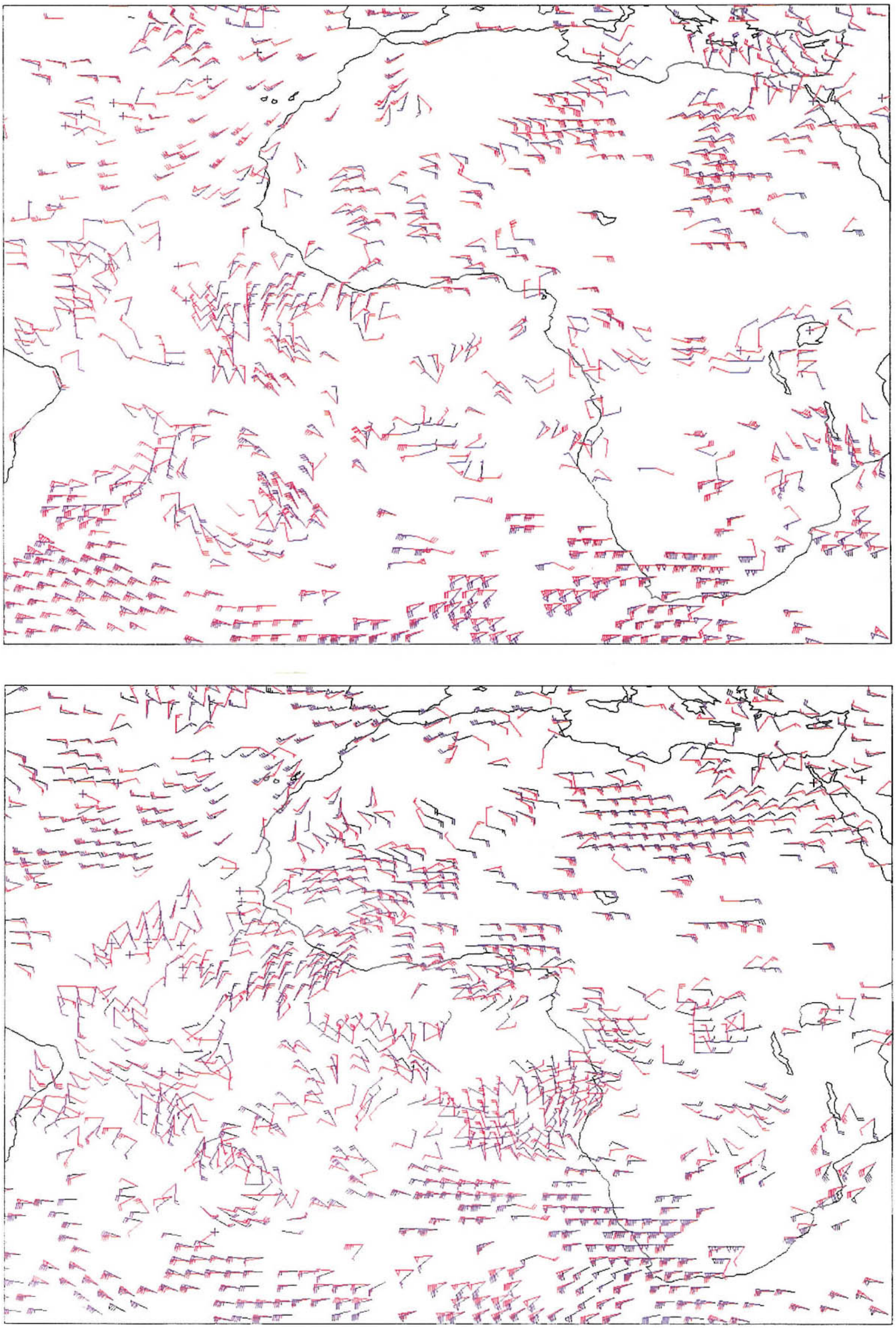

Figure 3(b): AMVs produced from Meteosat Water Vapour imagery in red, model weighted using radiative transfer in blue.

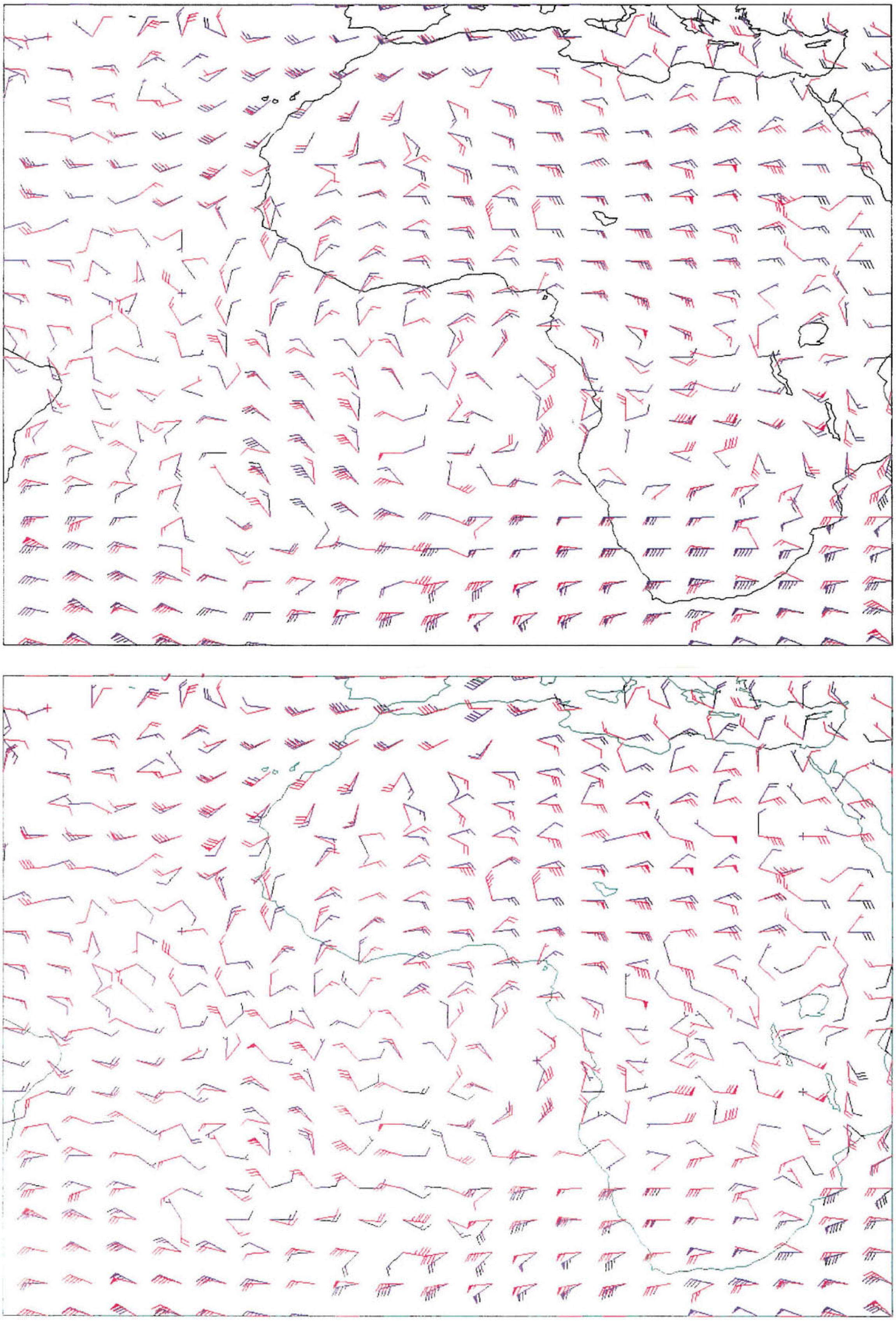

Figure 4(a): Barnes analysis AMVs produced from simulated model Water Vapour imagery in red, model winds vertically weighted using radiative transfer weighting function in blue.

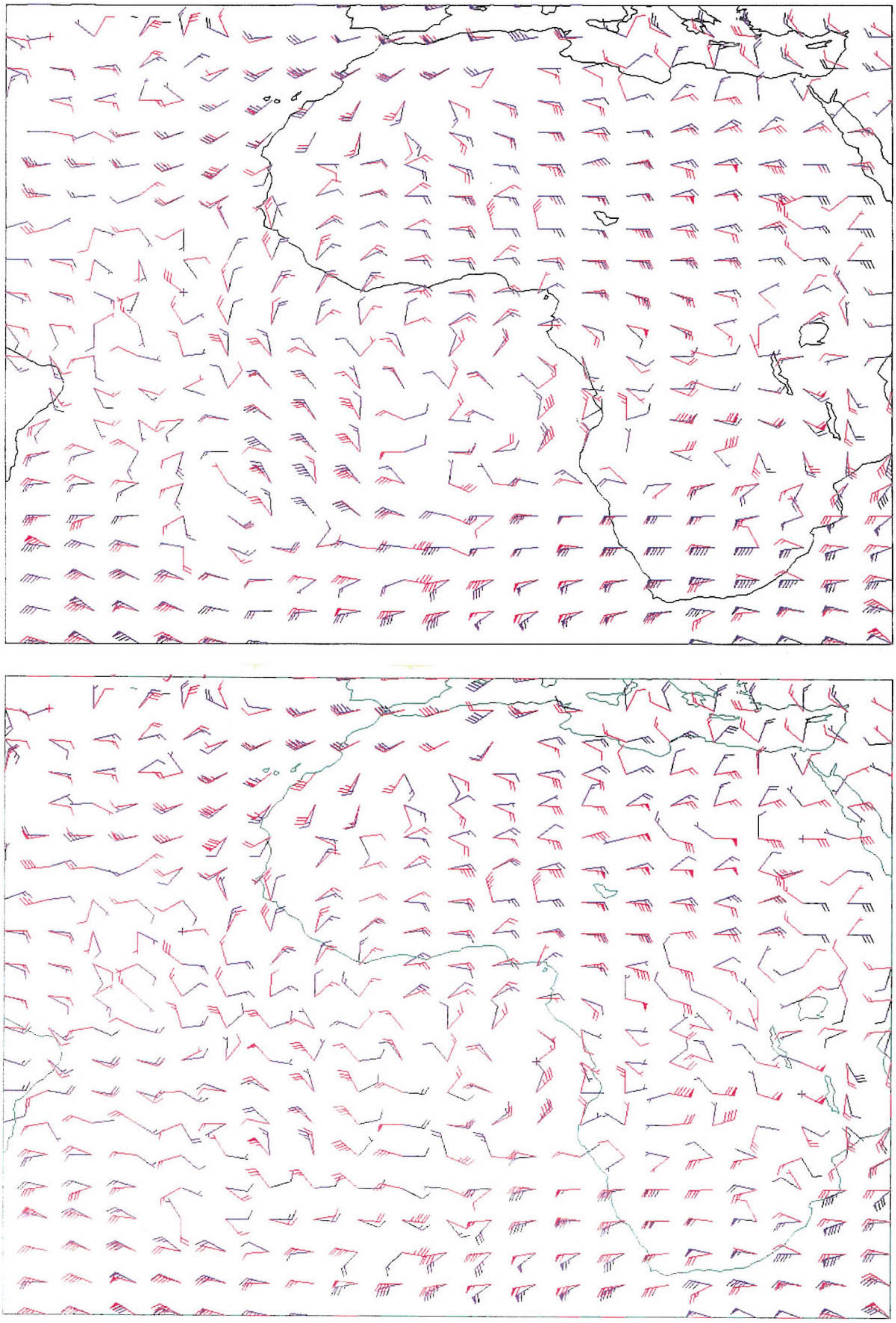

Figure 4(b): Barnes analysis AMVs produced from simulated model Water Vapour imagery in red, model winds at the peak of the radiative transfer weighting function in blue.