

DUPLICATE ALSO



Forecasting Research

Met O 11 Technical Note No. 28

**Model error structure and
estimated analysis accuracy
with a network of wind profilers**

by

N. B. Ingleby and R. A. Bromley

April 1989

ORGS UKMO M

M
London Road
National Meteorological Library
FitzRoy Road, Exeter, Devon. EX1 3PB
t O 11)
G12 2SZ, England

METEOROLOGICAL OFFICE

154800
26 JUN 1989

LIBRARY

MET O 11 TECHNICAL NOTE NO 28

Model Error Structure and Estimated Analysis Accuracy
with a Network of Wind Profilers

by

N.B. Ingleby and R.A. Bromley

Meteorological Office, UK.

LONDON, METEOROLOGICAL OFFICE.

Met.O.11 Technical Note (New Series) No.28

Model error structure and estimated analysis
accuracy with a network of wind profilers.

01370789

551.509.313
551.509.5

FH2A

Met O 11,
Meteorological Office,
London Road,
Bracknell, Berkshire,
England, RG12 2SZ.

April 1989

Note: This paper has not been published. Permission to quote from it
must be obtained from the Assistant Director of the above Branch of
the Meteorological Office.

Part of this work was presented at the first European Workshop on
Wind Profilers, organised by COST-74, Paris, March 1989.

Model Error Structure and Estimated Analysis Accuracy
with a Network of Wind Profilers

N.B.Ingleby and R.A.Bromley

Meteorological Office, UK.

Abstract

Network studies, based on statistical analysis theory, provide a means for assessing (as yet) hypothetical observing systems from a knowledge of their error structure and the background error structure. The covariances of the observation minus model background values for the wind were compared for two different model resolutions and two different areas. The statistics show the influence of the data-density upstream of the study areas. These covariances have been approximated for use in a series of studies in which the estimated analysis errors resulting from networks of wind profilers are investigated. The results compare different accuracies and different spacings of the profiler network as well as aspects of the assumed background error.

1. Introduction

When a new type of observing device is about to be introduced into the global observing system, it is desirable for information to be available to indicate the likely effect of the new observations within the current systems for weather prediction. If expressed in a suitable form, such information may then be used by those setting up the new network to estimate either the observation density they require to meet a specified performance criterion, or the change in performance that might be expected from a network of the new observations with a specified separation between them.

Network studies provide a suitable method for generating estimates of the performance of a numerical weather prediction (nwp) system when new observations are introduced. Modern nwp systems use methods of data assimilation which work on the difference between the observed value of a model field, such as the wind, and the value forecast by the model from an earlier time, known as the background value. These methods require a knowledge of the spatial covariance of the errors of observation and the errors of the background. The observation errors can be determined from prototypes of the observing device that is to be deployed. The current background error structure can be estimated by comparing model data with current observations. It is then possible to estimate the error in the initial conditions for nwp (the analysis error) for a given network of observations.

Wind profilers are a developing form of instrument to determine the values of upper-air winds from a radar signal which is back-scattered as a result of the turbulence moving with the measured wind (Ikonen, 1988). Increasing numbers of these instruments are being deployed in the European region and efforts are being coordinated through the COST-74 program. A network of about 30 wind profilers is being set up in the USA. A simulation

of a possible network of wind profilers has been described by Kuo et al (1987)

In this paper, a network study has been performed to estimate the effect of a network of wind profilers on the errors of the numerical analysis. The study has been extended to consider the effects of varying observational accuracies, of different spacings of the network, and also of varying the assumed background error. Estimates of the covariance function for the background were obtained by studying the covariance of the differences between upper-air wind observations and the model background field at radiosonde stations chosen according to the requirement that they should all use the same wind-finding technique.

2 Theoretical basis

2.1 Statistical interpolation

Because the spacing of available observations is, in general, much larger than the spacing between model grid points some method of spreading observational information is needed in order to construct an analysis of the state of the atmosphere for a given validation time: this analysis provides the initial conditions for numerical weather prediction. Information from previous observations is included via a forecast which is used as a background, or first guess, for the analysis.

Early numerical analysis schemes used ad hoc weighting functions for spreading observational information. However it was shown that an optimal analysis (in a statistical sense) could be performed based on the spatial covariance of the background errors (see Rutherford (1972) based on earlier work by Gandin (1963)). This technique, known either as statistical analysis, or sometimes as optimal interpolation, is now very widely used operationally with considerable success. (A review of data assimilation may be found in Morel (1981)).

2.2 Characteristics of Network Studies

A network study uses estimates of the average analysis error, which can be calculated as part of a statistical analysis. The results depend heavily on the assumptions made in the analysis procedure, in the form of the observation error structure and the background error structure. Gilchrist (1986) has compared the network study technique with Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs). A network study neglects non-linear effects which are included in the more realistic OSEs.

The advantages of a network study are that no actual observations are required and that it is relatively quick and flexible to perform. The fact that an 'average' analysis error is produced is both an advantage and a disadvantage, depending on the application: the result should be appropriate as the mean to be expected over several cases, but it does not represent the extreme values that might occur in individual cases. The analysis error estimate may be over-optimistic, particularly in data-dense areas, partly because of the neglect of biases.

2.3 Observation quality

In a network study the addition of extra observations will always reduce (or at least not increase) the estimated error, whereas OSEs show that observations sometimes degrade the analysis, principally because of gross errors in the reports. Cats (1984) and Hollingsworth et al (1985) have shown that observations of dubious quality can have a substantial effect on the analysis in data-sparse regions, and on the subsequent forecast. As pointed out by Cats (1984), the analysis is sensitive to small changes in the quality control parameters or the observed value for observations near the accept/reject limit. Our experience with OWSE-NA, an extended OSE for the North Atlantic area (Bromley et al, 1988), was that a generally small, but beneficial, impact from upper-air ships was almost negated by the occasional larger, and detrimental, impacts due to erroneous observations.

In order to make the best use of wind profiler observations, it is necessary to know the accuracy of the observations and how it varies in the vertical, the scales of meteorological activity which the observation represents and the types of error which can occur. The observation error is likely to be correlated in the vertical, but the extent of this correlation is not yet clear. Extra information, such as a quality indicator derived from the consistency of the radar returns, is useful for quality control (Brewster and Schlatter, 1988). The combination of six-minute winds from the profiler into, for instance, hourly winds, should increase the reliability of the profiler reports and provide a useful means of checking their quality (Steiner and Richner, 1989).

3 Background error covariances

3.1 Relationship to the covariances of the (observed - background) winds.

In order to construct realistic covariances of the background error for the network study in Section 4, and also to look at the effects of model resolution and data density, the covariances of the differences (observed - background) between values of the wind field were computed for sets of radiosonde observations. In some respects this follows the work of Hollingsworth and Lönnberg (1986).

Autocovariances of longitudinal and transverse wind (components along and perpendicular to the line joining the station pair) are presented in Section 3.5. Cross-covariances were also calculated, but they are not shown. It is often assumed that the autocovariances, when expressed in these local coordinates are isotropic, so that they are functions of distance, but not of orientation. (Schlatter, 1975). This follows from the assumption, in Section 4, that stream function and velocity potential covariances are homogeneous and isotropic.

If B_i and O_i are the background and observed values at point i , and b_i and o_i are the background and observation errors at point i , then the observation minus background covariance (for distinct observations)

$$\begin{aligned}\langle B_i - O_i, B_j - O_j \rangle &= \langle b_i - o_i, b_j - o_j \rangle \\ &= \langle b_i, b_j \rangle + \delta_{ij} \epsilon_o^2\end{aligned}$$

is equal to the background error covariance. Here it has been assumed that observation and background errors are independent, so that $\langle b_i, o_j \rangle = 0$ for all i, j ; and that errors from different observations are independent, so that $\langle o_i, o_j \rangle = \delta_{ij} \epsilon_o^2$. At the origin the autocovariance is simply the variance, and, since the local coordinates are not defined for $i=j$, half the vector wind variance is plotted: the value at the origin also has a contribution from the observation error for $i=j$.

A more complete decomposition of observation-background differences is given by recognising the representativeness error - due to the difference between the space and time scales sampled by the observation and the model. Lorenc (1986) showed that 'errors of representativeness' are the errors due to the interpolation from model variables to observed variables.

3.2 Dependence on model resolution

As forecast models increase in resolution the initial conditions should also increase in resolution. Experiments with high resolution analysis have been performed by Lönnberg (1988). He found that there was less redundancy of observations and that this made their quality control more difficult. In a statistical analysis scheme more detailed analyses are produced by 'sharpening' the assumed background error covariance. However, the dependence of forecast error covariances on model resolution is not clear at present. It is possible that the main effect is at small separations, in which case modelling the covariance by a single scale parameter would be inadequate and a decomposition such as that by Hollingsworth and Lönnberg (1986) would be more appropriate. On the scale of the model grid there is a contribution from the interpolation operator.

Forecast error covariances can be modelled using a stochastic-dynamic approach. Balgovind et al (1983) modelled covariances using a forecast error equation; the equation is independent of any model grid, and therefore so also are the covariances. Phillips (1986), using model normal modes, found that the scale of forecast error is approximately proportional to grid resolution (his equation 3.6). However, as he pointed out, this result may be modified for a practical assimilation system by observation spacing, resolution of the covariance model used in the analysis, filtering (eg viscosity) in the forecast equations and smoothing in interpolation of the background to observation locations.

3.3 The nwp system.

In this paper the covariances of the differences between observation and background are compared for two models of different resolution, the coarse-mesh (CM) and fine-mesh (FM) models of the UK Meteorological Office. These models and the analysis system are described in Bell and Dickinson (1987). The coarse-mesh model has a resolution near the UK of about 150 km: the fine-mesh model is a limited-area version with a grid length half that of the coarse mesh. Since the fine-mesh model extends to 40°E, only stations west of 30°E were used, in order to reduce any effects due to the boundaries. Until late in 1988, the coarse-mesh and fine-mesh analyses used Gaussian correlation functions (see Section 4) with scales of $S=389$ km and $S=275$ km respectively. However, a new scheme was introduced in November 1988, using Markov correlation functions (see Section 4) with scales of 292km and 245 km respectively. Thus although the scale in the fine-mesh continues to be set to a value smaller than in the coarse-mesh, the two are now in closer agreement. Because the representativeness error is less for the fine mesh, the observation errors (defined to include representativeness) are reduced by 10% relative to the coarse mesh.

The coarse-mesh background is a six-hour forecast from the previous analysis. There are fine-mesh forecasts from 00Z and 12Z analyses each day. To prepare the 00Z (12Z) fine-mesh analysis the previous 12Z (00Z) coarse-mesh analysis is interpolated to the finer grid and four three-hour assimilations are performed. Lateral boundary conditions are prescribed from a coarse-mesh forecast. Only the observation-background differences for 00Z and 12Z are used in this study as the fine-mesh backgrounds at other times depend too heavily on the original coarse-mesh analysis.

3.4 Wind observations used

Covariances were computed from actual radio-sonde observations of the wind reported by upper-air stations in the British Isles (plus Gibraltar, which uses the same radar wind-finding technique) and in the Western Soviet Union. Both sets, each containing eleven stations, have a larger extent in the North-South direction than East-West. Results are presented in aggregates by station separation, in 100 km bins, centred on integral multiples of 100km. The station positions are shown in Figures 1 and 2 and their separations are given in Table 1 and 2. There are no pairs from the British Isles in the bins from 1200 to 1500km and there are no pairs from the Soviet Union in the bins at 100 and 1300km nor from 1500km upwards. Because of the prevailing Westerly wind, the forecast over the British Isles will be derived partly from previous analyses over the relatively data-sparse North Atlantic,

whereas the forecast for the Soviet Union has the benefit of the relatively dense observing network over Europe.

The period considered is December 1987 to February 1988. During this period, about 150 observations were available from most stations. However, there were only 55 observations from 03743, which with 03774 gives the only station pair in the 100km bin. Only observations within 90 minutes of the analysis time were used. In the preprocessing for the analysis the radiosonde ascents are averaged over model levels, so the results are presented in terms of σ (=pressure/surface pressure) the model variable.

3.5 Results: Observation/ Background Differences and their Covariance

Figures 3 to 5 show results for $\sigma=0.87$, 0.49 and 0.25 respectively. The scale of the covariances tends to increase with height as has been found in other studies. The covariances for the Soviet Union are about half of those for the British Isles - the most obvious effect of the increased observation density on the forecast. At $\sigma=0.49$ (Figure 4, approximately 500 mb) the Soviet Union covariances tend to zero faster than those for the British Isles, indicating a smaller length scale. There is also some evidence of this at $\sigma=0.25$, but not at $\sigma=0.87$.

At $\sigma=0.87$ (Figure 3) results from the two models are similar without any clear systematic differences. At $\sigma=0.49$ and 0.25 (Figures 4 and 5) the fine-mesh covariances are generally slightly lower than those for the coarse-mesh. This partly reflects a reduced error variance but there is perhaps a small change in scale also.

The root mean square (RMS) vector wind differences for both sets of stations for the period of the investigation are shown in Table 3. The differences are at their largest on the three levels $\sigma=0.39$, 0.31 and 0.25 (ie between about 400 and 250 mb). There is a large decrease between $\sigma=0.25$ and $\sigma=0.19$ presumably marking the transition to the stratosphere. In the stratosphere the results for the two models are very similar: in the upper troposphere the Fine Mesh is significantly nearer to the observations: and although the coarse-mesh fit is slightly closer in mid-troposphere, the situation reverses again in the lower troposphere.

Large observation-background differences in the upper troposphere were also found for the North American network by Hollingsworth and Lönnberg (1986). Their partitioning of the difference ascribes large errors to both the model and the observations (including representativeness). Kitchen (1988) compared radiosonde winds at different time and space separations and also found large differences in the upper troposphere, despite an almost constant measurement error. This supports the idea that strong wind shears at these levels give rise to large errors of representativeness. It is at these levels that the fine-mesh, with its extra resolution, improves most over the coarse-mesh.

4 Network study

4.1 Representation of background error covariances

Following Daley (1985), the wind covariances have been modelled by specifying covariances for the stream function and for the velocity potential (which determine the rotational and divergent parts of the wind), and then deriving the covariances of the wind components. The covariance is expressed as the variance multiplied by the correlation.

Two different functions were assumed for the correlation of both the stream function and velocity potential,

either Gaussian:- $\mu = \exp(-0.5 \cdot R^2/S^2)$,

or Markov:- $\mu = (1+R/S) \cdot \exp(-R/S)$,

where R is the distance between the two points and S is a scale parameter. A further parameter, ν , the ratio of the divergent wind error to the total wind error variance, was also used. The covariance between the streamfunction and the velocity potential was set to zero. Although the interpretation of S is slightly different in these two functions, they are equal to second order in (R/S) and hence have essentially the same behaviour at small separations (see Phillips, 1986). The 'Markov' function (Daley, 1985) is a special form of the second order autoregressive function.

Figure 6 shows the correlations for the longitudinal (LL) and transverse (TT) wind components derived from these two functions for $\nu=0.0, 0.1$ and 0.5 . The cross correlations between the longitudinal and transverse components are zero. As ν (and the divergence) increases, the LL correlation becomes sharper and develops a negative lobe and the TT correlation becomes broader and the negative lobe becomes less pronounced. $\nu=0.0$ corresponds to the background error being completely non-divergent, a traditional assumption in analysis. When $\nu=0.5$, the error is partitioned equally between the divergent and non-divergent wind: thus, the LL and TT correlations become equal, and the analysis is equivalent to a univariate analysis of wind components. A slightly divergent analysis, $\nu \approx 0.1$, was preferred by Daley (1985).

The wind covariances from the Markov function are sharper, with less of a negative lobe for the transverse covariances. The actual covariances, in Figures 3 to 5, become only slightly negative, if at all. Also the Gaussian covariances seem too large at small separation, although the number of station pairs at small separation is limited. These results suggest that the Markov function is slightly the more realistic of the two considered here. Thiébaux et al (1986) chose the Markov function - in preference to the Gaussian function - to model the correlations of differences between observed and forecast values of geopotential. In the current study, although neither function gives a close fit, they are both fairly realistic when the scale parameter S is set to about 300km.

4.2 Method

It is now possible to proceed to perform a network study using estimates of the required errors. The spatial covariance of the background error has been specified in section 4.1 on the basis of the results from the study of the radio-sonde stations. A rough estimate of the background error over Europe in current models can be obtained by halving the values in Table

3 to take account of the observation error and the conversion from vector wind error to wind component error. This gives values between about 1.6 m/s and 4.2 m/s depending on area, height and model. The observational error has been based on the estimates available in the literature. Although Strauch et al (1987) suggest profiler errors of between 1 and 2 m/s, the estimates used here are larger because the 'representativeness error' should be included in the observational error. Observational error has been set to range between zero and twice the background error.

The optimal interpolation method gives the estimated analysis error covariance matrix A_{aa} as

$$A_{aa} = B_{aa} - B_{ao}^T (B_{oo} + O)^{-1} B_{ao}$$

where B_{oo} , B_{ao} and B_{aa} are matrices of background error covariances between observation points (o) and analysis points (a) and O is the matrix of observation error covariances, assumed diagonal in this study. Usually only the diagonal elements of A_{aa} are considered: these are the mean square errors at analysis points. In these studies, the analysis error was determined at the centre of a regular 4 by 4 grid of profilers, with a variable resolution D km (Figure 7).

The correlation functions were used with S , the scale parameter, set to 300km. The results for the preferred value of v (0.1) are shown in Figure 8. In order to test the sensitivity to the divergence, two further studies were made for the specified Gaussian and Markov functions with v set to 0 and 0.5 (illustrated in Figure 6). Results are shown in Figure 9.

4.3 Results and discussion

The estimated analysis error has been calculated for a set of values of observation spacing and observation error. The observation and analysis errors were both expressed as a fraction of the background error. The results are shown in Figures 8 and 9 as a set of contoured fields, following the examples of Steinitz et al (1971) and Bergman and Bonner (1976). Although the distances are quoted in kilometres, it is the ratio of the observation spacing to the correlation scale which determines the results.

Using the Gaussian function has produced a large variation of the analysis error with observation spacing and observation accuracy, because of the relatively large correlations at small separation, which give unrealistically low errors. With the Markov function there is less sensitivity to these factors. The errors are larger everywhere using the Markov function because of its sharper fall-off with distance. The gradient of the contours gives useful information on possible trade-offs between accuracy and spacing of observations. The steeper gradients for the Markov function indicate relatively less sensitivity to the observation error. Although this implies a relatively greater sensitivity to the observation spacing, it is still much less than for the Gaussian at most separations.

As v increases, the analysis errors increase and, in general, the gradients of the contours increase. When $v=0.1$, the results are intermediate between those for $v=0$ and $v=0.5$, but for the Gaussian function the results are closer to those for $v=0.5$ over most of the range of the parameters considered.

The network study covers a range of observation spacings. The sensitivity to observation spacing depends on the background correlations that are used. The diagrams in Figures 8 and 9 could be used to specify the network required in order to achieve a given analysis accuracy, but the uncertainty due to the modelling of the background error structure will be reflected in the specification.

The network study approach could be extended to vertical profiles, but vertical aspects of the analysis are even less well known than horizontal aspects. It can also be adapted to examine a period of time if correlations can be modelled in time. It might also be applied to examine the accuracy of the gradients of the analysed fields by using the full analysis covariance matrix.

5. Summary

We have performed a network study for wind profilers, using estimates of the spatial correlations of the background error which were first compared with recent values of the differences between observed winds and model background values.

Results from the British Isles (influenced by the data-sparse North Atlantic) and the Western Soviet Union indicate a halving of the covariance with increased data density and a slight sharpening of the covariance at some levels. There is a slight reduction in the covariance in the upper troposphere when the model resolution changes from 150 to 75km. These results imply that the two models have a similar sensitivity to extra data.

The network study was carried out for a range of observation spacings and observational errors. The results, shown in Figures 8 and 9, may be used to identify the network parameters to be used in order for the analysis to meet a specified accuracy. For example, from Figure 8b, which shows the results for the preferred correlation function, an analysis error of 80% of the background error will be achieved if the observation error is the same as the background error when the spacing is 200km. In practice, the high frequency of the profiler reports may permit the use of an increased observation spacing, since in a truly four-dimensional analysis scheme there will be a trade-off between space- and time-resolution. (This two-dimensional study has not considered such effects). Figures 8 and 9 also demonstrate the sensitivity of the results to the modelling of the background error structure.

It was found in section 3 that model wind errors are largest in the upper troposphere. It is also at these levels that the higher resolution model shows its largest, but still modest, improvement over the low resolution model. Model backgrounds are generally of good quality, so that any improvements arising from the addition of profiler data are likely to be relatively small. The quality and quality control of all observations, including wind profilers, will continue to be an important consideration.

6. Acknowledgements

Thanks are due to J.Purser for the use of a modified version of his network study program and to A.Lorenc for useful discussions.

7 References

1. Balgovind, R., Dalcher, A., Ghil, M., Kalnay, E.: A Stochastic-Dynamic Model for the Spatial Structure of Forecast Error Statistics. - Monthly Weather Review, 111, 701-722 (1983).
2. Bell, R.S., Dickinson, A.: The Meteorological Office Operational Numerical Weather Prediction System. - HMSO. Met. Office Sci. Paper No. 41, Met O 979 (1987).
3. Bergman, K.H., Bonner, W.D.: Analysis Error as a Function of Observation Density for Satellite Temperature Soundings with Spatially Correlated Errors. - Monthly Weather Review, 104, 1308-1316 (1976).
4. Brewster, K.A., Schlatter, T.W.: Recent progress in automated quality control of wind profiler data. - Proceedings of Eighth Conference on Numerical Weather Prediction, American Meteorological Society, Baltimore, Md, 331-338 (1988).
5. Bromley, R.A., Reed, D.N., Ingleby, N.B., Ayles, M.A., Whitfield, P.A.: Numerical Weather Prediction Studies for the OWSE-NA. - Proceedings of Eighth Conference on Numerical Weather Prediction, American Meteorological Society, Baltimore, Md, 821-823 (1988).
6. Cats, G.J.: Current problems in medium range forecasting at ECMWF; Data assimilation scheme. - D M Burridge and E Källén (eds) 'Problems and prospects in long and medium range weather forecasting', Springer-Verlag, Berlin. 69-107 (1984).
7. Daley, R.: The analysis of synoptic scale divergence by a statistical interpolation procedure. - Monthly Weather Review, 113, 1066-1079 (1985).
8. Gandin, L.S.: Objective analysis of meteorological fields, Izdatel, Leningrad (1963).
9. Gilchrist, A.: Observing System Experiments and Observing System Simulation Experiments. - Proceedings of International Conference on the Results of the Global Weather Experiment and their Implications for the World Weather Watch Vol II, GARP publication series No. 26, WMO/TD No. 107, 471-498 (1986).
10. Hollingsworth, A., Lönnberg, P.: The statistical structure of short-range forecast errors as determined from radiosonde data. Part I: the wind field. - Tellus 38A, 111-136 (1986).
11. Hollingsworth, A., Lorenc, A.C., Tracton, M.S., Arpe, K., Cats, G., Uppala, S., Källberg, P.: The response of numerical weather prediction systems to FGGE level IIb data. Part I: Analyses. - Quarterly Journal of the Royal Meteorological Society, 111, 1-66 (1985).
12. Ikonen, I.: Wind Profilers - New tools to measure upper-air winds. Proceedings of WMO Technical Conference on Instruments and Methods of Observation, Leipzig, 157-169 (1988).

13. Kitchen, M.: Representativeness errors for radiosonde observations - ECMWF/WMO Workshop on Radiosonde Data Quality and Monitoring, 43 - 55 (1987).
14. Kuo, Y-H., Donall, E.G., Shapiro, M.A.: Feasibility of short-range numerical weather prediction using observations from a network of profilers. - Monthly Weather Review, 115, 2402 - 2427 (1987).
15. Lönnberg, P.: High Resolution Analysis Experimentation at ECMWF. - Proceedings of Eighth Conference on Numerical Weather Prediction, American Meteorological Society, Baltimore, Md, 165-171 (1988).
16. Lorenc, A.C.: Analysis methods for numerical weather prediction. - Quarterly Journal of the Royal Meteorological Society, 112, 1177-1194 (1986).
17. Morel, P.: An overview of meteorological data assimilation. - in Bengtsson, L., Ghil, M. and Källén, E. (editors): Dynamic Meteorology: Data Assimilation Methods, Springer-Verlag, New York (1981).
18. Phillips, N.A.: The spatial statistics of random geostrophic modes and first-guess errors. - Tellus, 38A, 314-332 (1986).
19. Rutherford, I.D.: Data Assimilation by Statistical Interpolation of Forecast Error Fields. - Journal of the Atmospheric Sciences, 29, 809-815 (1972).
20. Schlatter, T.W.: Some experiments with a multivariate objective analysis scheme. - Monthly Weather Review, 103, 246-257 (1975).
21. Steiner, A., Richner, H.: Deriving quality controlled wind profiles from profiler moment data. First European Wind Profiler Workshop, Paris, A27-A37 (1989).
22. Steinitz, G., Huss, A., Manes, A., Sinai, R., Alperson, Z.: Optimum Station Network in the Tropics. - Journal of Applied Meteorology, 10, 364-369 (1971).
23. Strauch, R.G., Weber, R.G., Frisch, A.S., Little, C.G., Merritt, D.A., Moran, K.P., Welsh, D.C.: The precision and relative accuracy of profiler wind measurements. Journal of Atmospheric and Oceanic Technology, 4, 563-571 (1987).
24. Thiébaux, H.J., Mitchell, H.L., D.W. Shantz.: Horizontal structure of hemispheric forecast error correlations for geopotential and temperature. - Monthly Weather Review 114, 1048 - 1066 (1986).

8. Tables

| Sta | 005 | 026 | 170 | 322 | 496 | 743 | 774 | 808 | 920 | 953 | 495 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Lat N | 60.13 | 58.22 | 56.43 | 53.55 | 52.68 | 51.20 | 51.08 | 50.22 | 54.48 | 51.93 | 36.15 |
| Lon W | 1.17 | 6.31 | 2.86 | 2.91 | -1.68 | 1.79 | 0.21 | 5.31 | 6.09 | 10.24 | 5.32 |
| 03005 | 0 | 362 | 423 | 739 | 847 | 994 | 1008 | 1132 | 694 | 1070 | 2683 |
| 03026 | | 0 | 287 | 561 | 795 | 832 | 885 | 892 | 416 | 743 | 2455 |
| 03170 | | | 0 | 320 | 509 | 586 | 620 | 709 | 297 | 693 | 2262 |
| 03322 | | | | 0 | 321 | 272 | 330 | 405 | 232 | 525 | 1944 |
| 03496 | | | | | 0 | 289 | 220 | 556 | 550 | 814 | 1918 |
| 03743 | | | | | | 0 | 111 | 271 | 465 | 589 | 1697 |
| 03774 | | | | | | | 0 | 372 | 547 | 700 | 1709 |
| 03808 | | | | | | | | 0 | 477 | 393 | 1565 |
| 03920 | | | | | | | | | 0 | 396 | 2039 |
| 03953 | | | | | | | | | | 0 | 1797 |

Table 1. Distances between stations in UK, Ireland and Gibraltar. Stations are shown in the left-hand column according to their WMO station identifiers. An abbreviated form of the identifier is used in the first row of the table and the station's latitude and longitude (in degrees west of 0) are shown in the next two rows. The remainder of the table shows the distances, in kilometres between the two stations appropriate to the row and to the column of the value shown.

| Sta | 038 | 258 | 406 | 422 | 629 | 702 | 850 | 008 | 631 | 658 | 815 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Lat N | 59.42 | 57.83 | 56.55 | 56.97 | 54.88 | 54.70 | 53.87 | 52.12 | 48.63 | 48.27 | 47.02 |
| Lon E | 24.80 | 28.35 | 21.01 | 24.07 | 23.88 | 20.62 | 27.53 | 23.68 | 22.27 | 25.97 | 28.87 |
| 26038 | 0 | 271 | 389 | 276 | 508 | 582 | 639 | 815 | 1211 | 1242 | 1405 |
| 26258 | | 0 | 464 | 274 | 428 | 590 | 443 | 701 | 1099 | 1075 | 1202 |
| 26406 | | | 0 | 192 | 258 | 207 | 510 | 522 | 885 | 980 | 1188 |
| 26422 | | | | 0 | 233 | 332 | 408 | 540 | 935 | 976 | 1153 |
| 26629 | | | | | 0 | 210 | 262 | 307 | 704 | 749 | 941 |
| 26702 | | | | | | 0 | 458 | 351 | 684 | 805 | 1030 |
| 26850 | | | | | | | 0 | 322 | 688 | 632 | 768 |
| 33008 | | | | | | | | 0 | 401 | 458 | 679 |
| 33631 | | | | | | | | | 0 | 275 | 524 |
| 33658 | | | | | | | | | | 0 | 258 |

Table 2. Distances between stations in Western USSR. Stations are shown in the left-hand column according to their WMO station identifiers. An abbreviated form of the identifier is used in the first row of the table and the station's latitude and longitude (in degrees east of 0) are shown in the next two rows. The remainder of the table shows the distances, in kilometres between the two stations appropriate to the row and to the column of the value shown.

| σ -level | BI: CM | BI: FM | SU: CM | SU: FM |
|-----------------|--------|--------|--------|--------|
| 0.065 | 3.98 | 4.05 | 3.21 | 3.21 |
| 0.125 | 4.06 | 4.09 | 3.18 | 3.12 |
| 0.190 | 5.31 | 5.16 | 3.87 | 3.59 |
| 0.250 | 8.06 | 7.65 | 5.45 | 4.97 |
| 0.310 | 8.48 | 7.65 | 5.93 | 5.27 |
| 0.390 | 7.74 | 7.26 | 5.31 | 4.88 |
| 0.490 | 6.17 | 5.99 | 4.21 | 4.09 |
| 0.590 | 5.39 | 5.47 | 3.66 | 3.73 |
| 0.690 | 4.47 | 4.63 | 3.35 | 3.56 |
| 0.790 | 4.32 | 4.34 | 3.44 | 3.63 |
| 0.870 | 4.50 | 4.37 | 3.68 | 3.82 |
| 0.935 | 5.00 | 4.66 | 5.09 | 4.89 |
| 0.975 | 4.99 | 4.68 | 5.07 | 4.84 |

Table 3. RMS vector wind observation - background (O-B) wind differences for December 1987 to February 1988 for the British Isles plus Gibraltar (BI), the Western Soviet Union (SU), in the coarse-mesh model (CM) and the fine-mesh model (FM). There are about 1600 observations in each set at most levels.

9 Figure Legends

Figure 1. Stations from Britain, Ireland and Gibraltar used in the study of wind error covariances. The position of each station is indicated by a small triangle with the station identifier printed alongside. Lines of latitude and longitude at intervals of 10 degrees are also shown.

Figure 2. Stations from the western Soviet Union used in the study of wind error covariances. The position of each station is indicated by a small triangle with the station identifier printed alongside. Lines of latitude and longitude at intervals of 10 degrees are also shown.

Figure 3. Computed covariances of the observation-background difference for winds on the model level at $\sigma=0.87$ as a function of station separation. Results are for the period December 1987 to February 1988. They have been binned at intervals of 100km centred on integral multiples of 100km. The solid line shows results from the coarse-mesh model; the dashed line shows results from the fine-mesh model. a) Longitudinal covariances, British Isles set; b) Transverse covariances, British Isles set; c) Longitudinal covariances, Soviet Union set; d) Transverse covariances, Soviet Union set.

Figure 4. As Figure 3, except for $\sigma=0.49$.

Figure 5. As Figure 3, except for $\sigma=0.25$.

Figure 6. The correlation functions, with a scale parameter, S , of 300km, as a function of station separation. The solid curve is for $v=0$; the dashed lines are for $v=0.1$ and $v=0.5$. a) Longitudinal correlations, Gaussian function; b) Transverse correlations, Gaussian function; c) Longitudinal correlations, Markov function; d) Transverse correlations, Markov function.

Figure 7. Diagram of the grid of observation points with the analysis point at its centre.

Figure 8. Contours of the analysis error, normalized by the background error, as determined by the network study for a range of distances between the observations and for a range of normalized observation errors. Correlation functions have scale of 300km with $v=0.1$. a) Gaussian; b) Markov.

Figure 9. Contours of the analysis error, as in Figure 8, but drawn to show the effect of varying v . Solid line is for $v=0$; dashed line is for $v=0.5$. a) Gaussian; b) Markov.

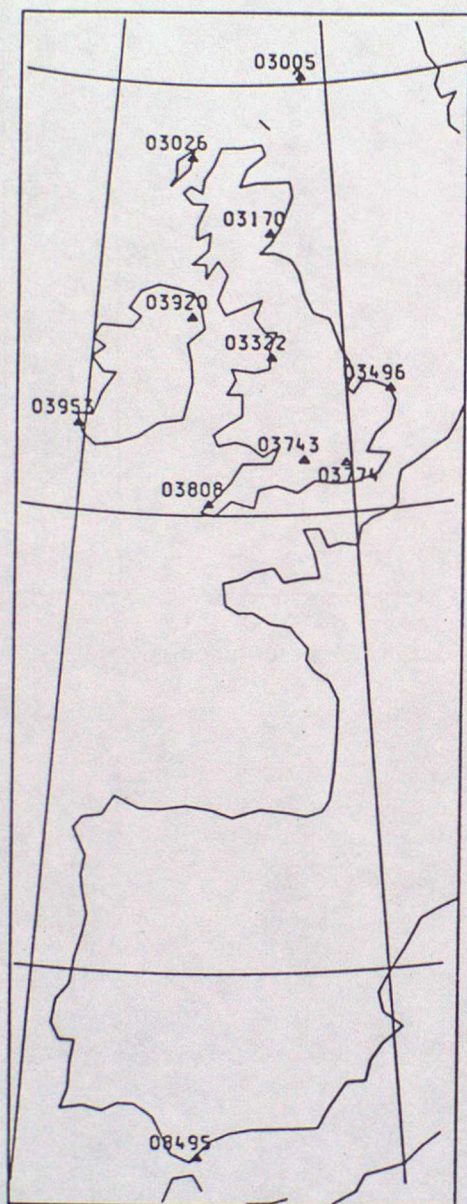


Figure 1

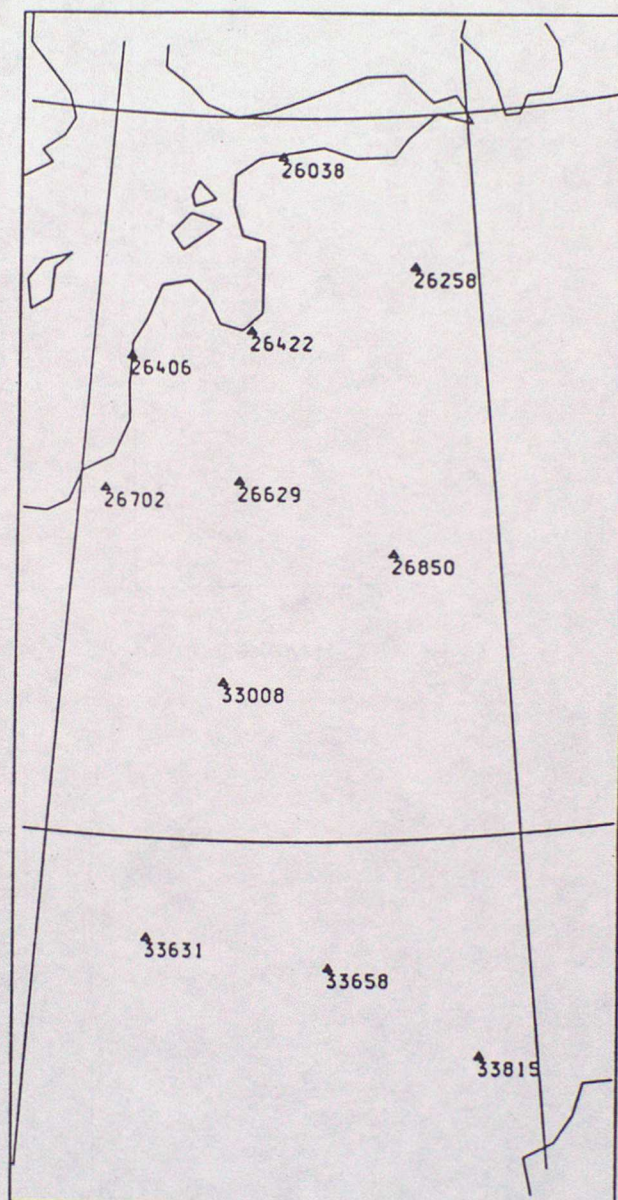
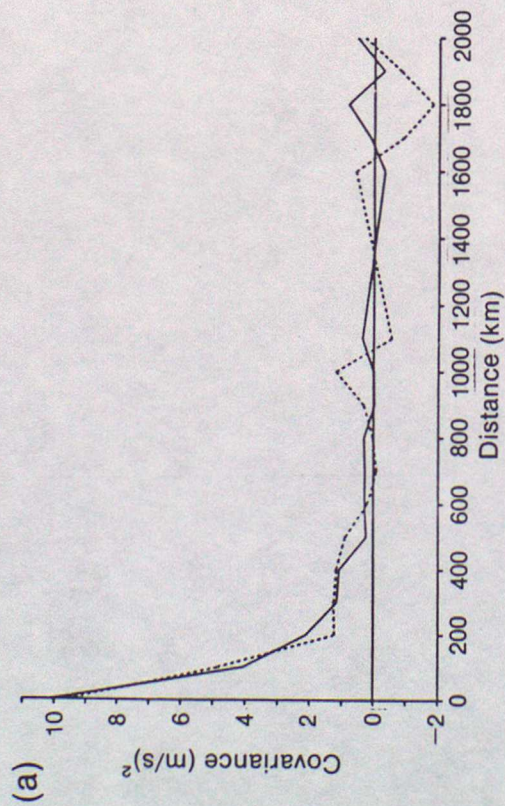


Figure 2

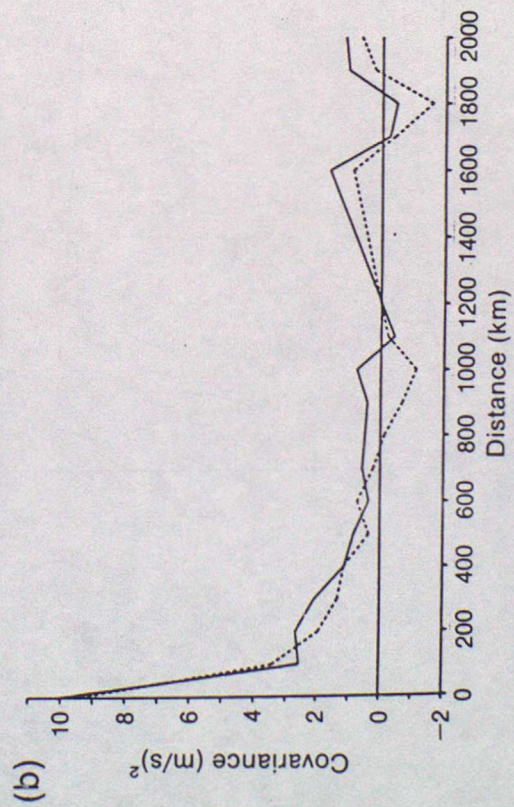
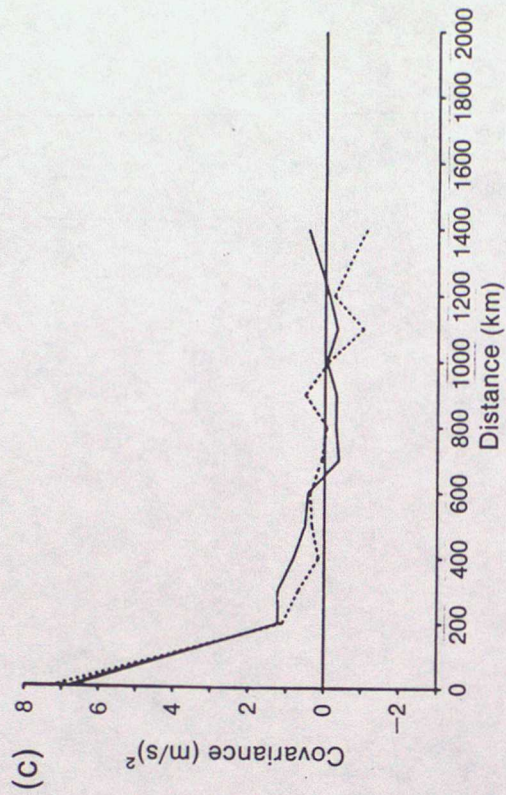
$$\sigma = 0.87$$

British Isles



Longitudinal
covariance

USSR



Transverse
covariance

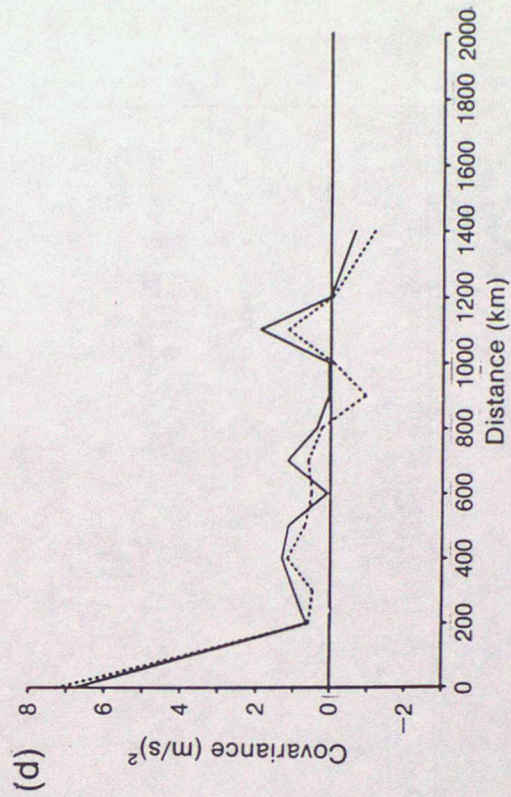
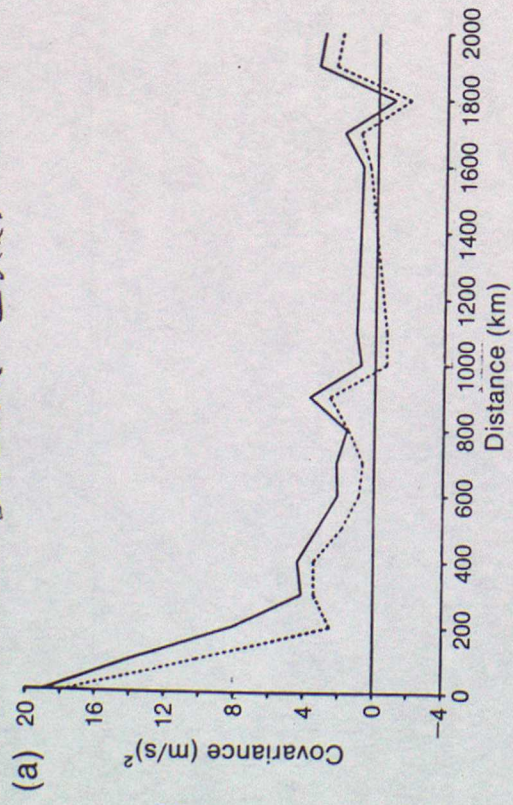


Figure 3

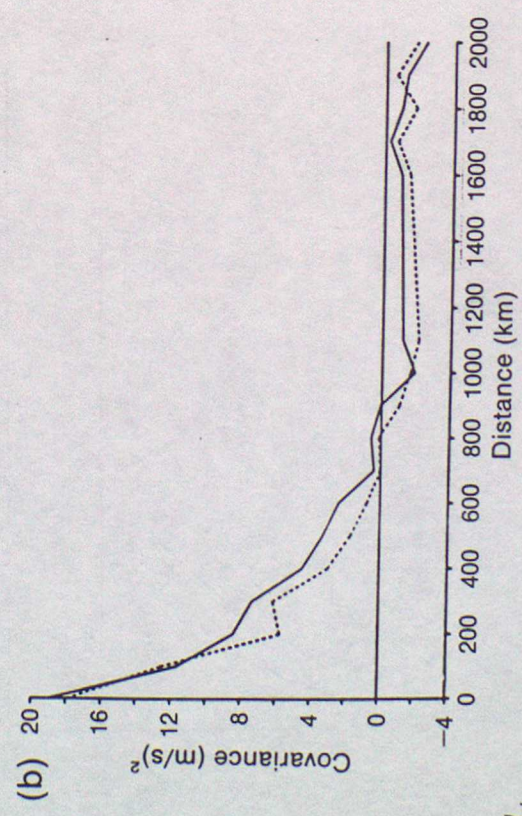
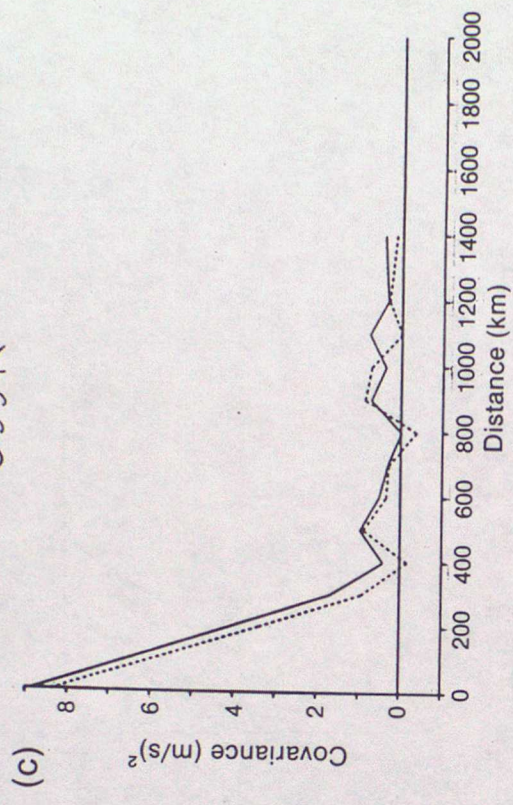
$\sigma = 0.49$

British Isles



Longitudinal
Covariance

USSR



Transverse
Covariance

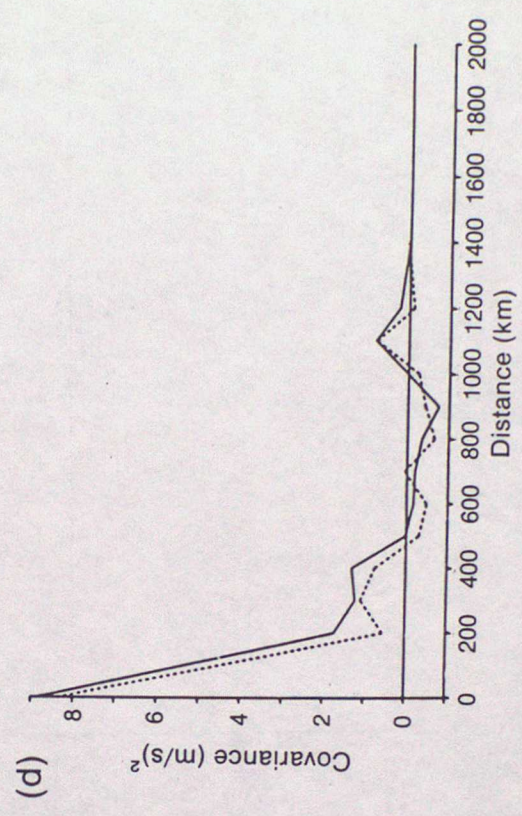


Figure 4

$$\sigma = 0.25$$

British Isles

USSR

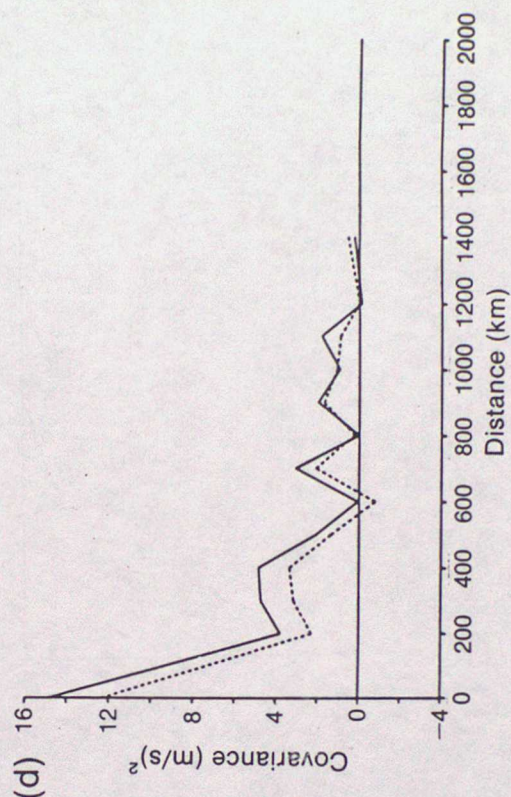
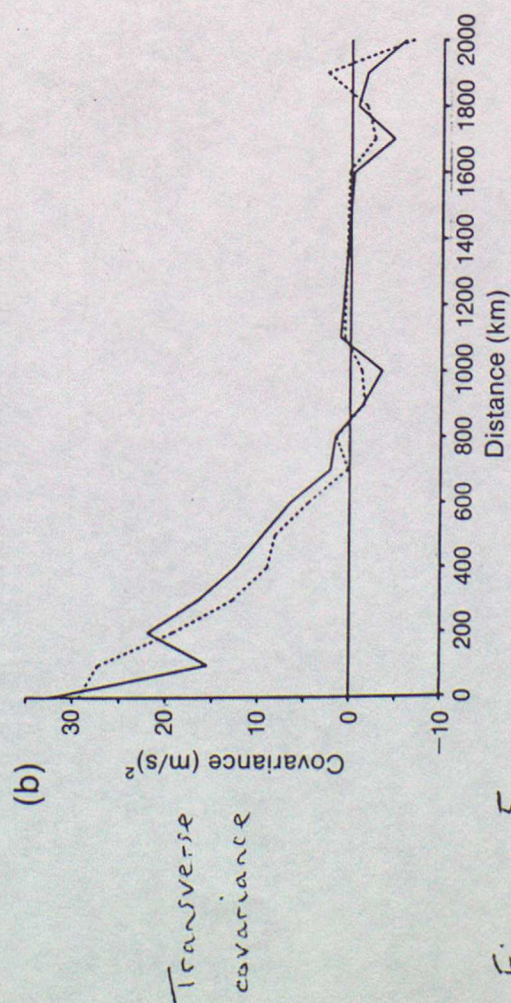
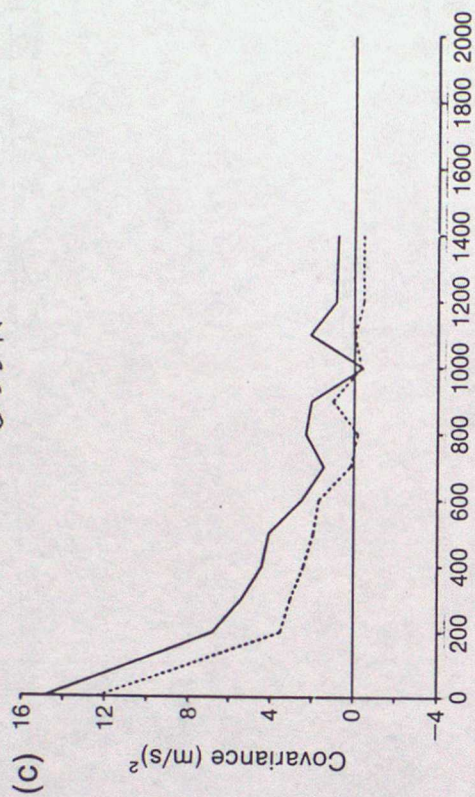
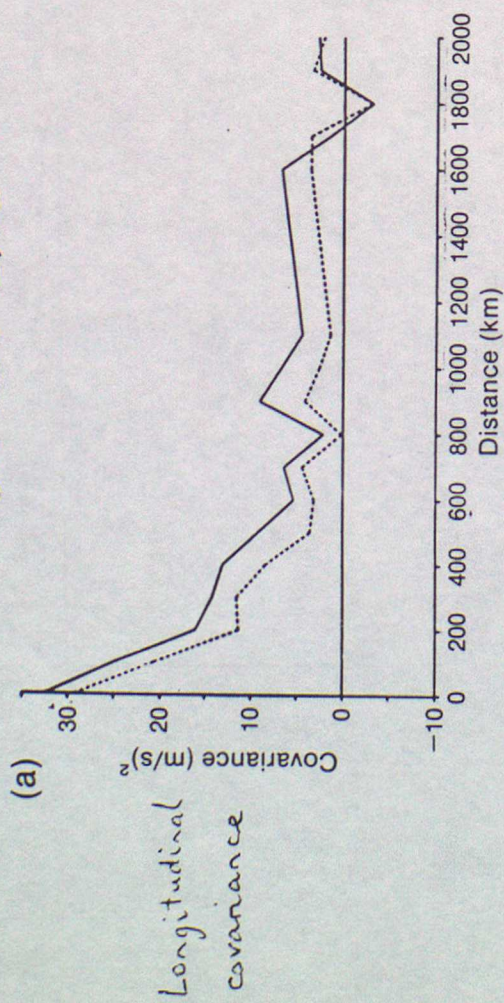
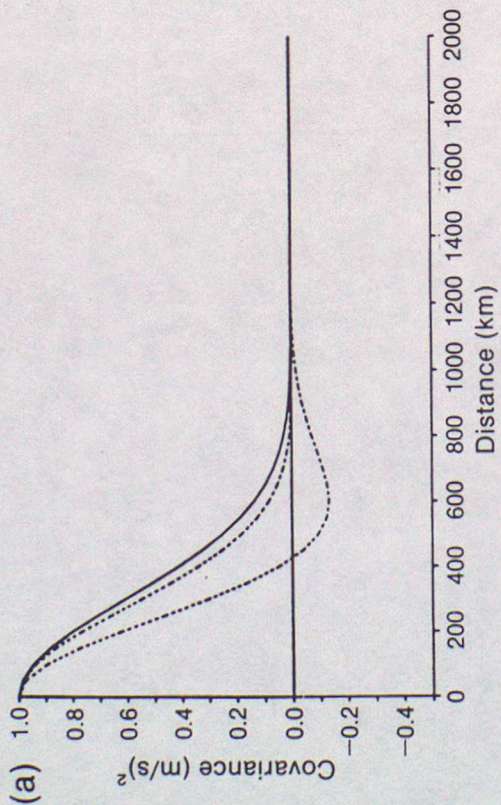


Figure 5

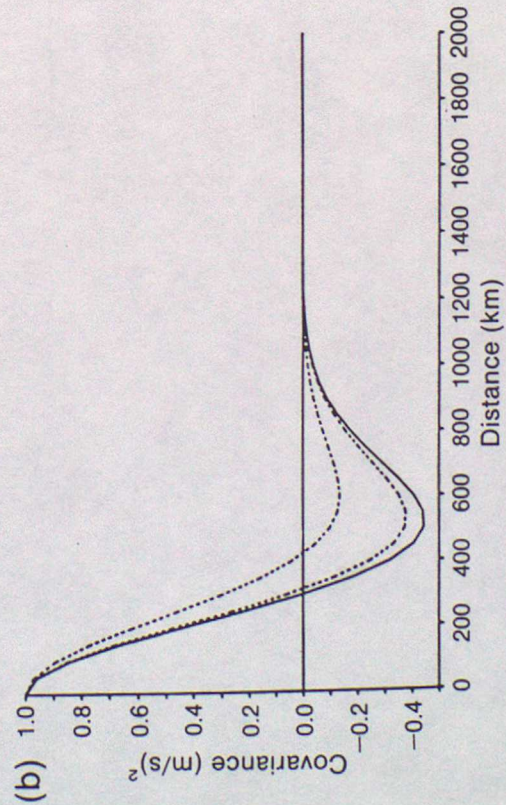
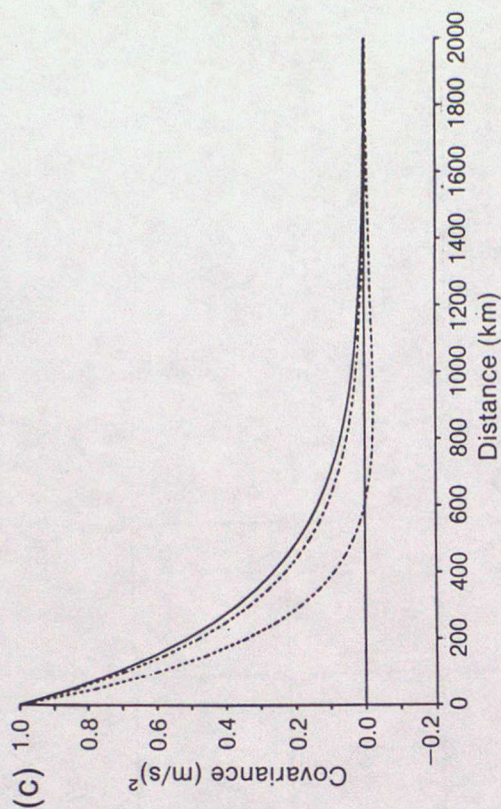
$\gamma = 0$ (solid line), 0.1 & 0.5

Gaussian



Longitudinal

Markov



Transverse

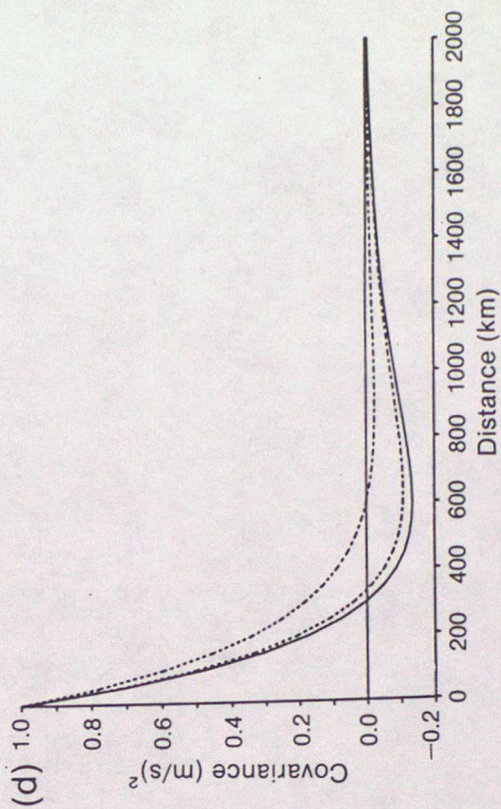


Figure 6

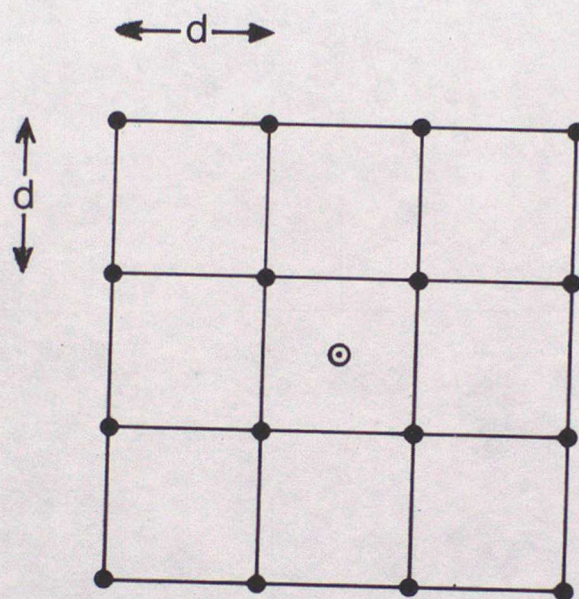
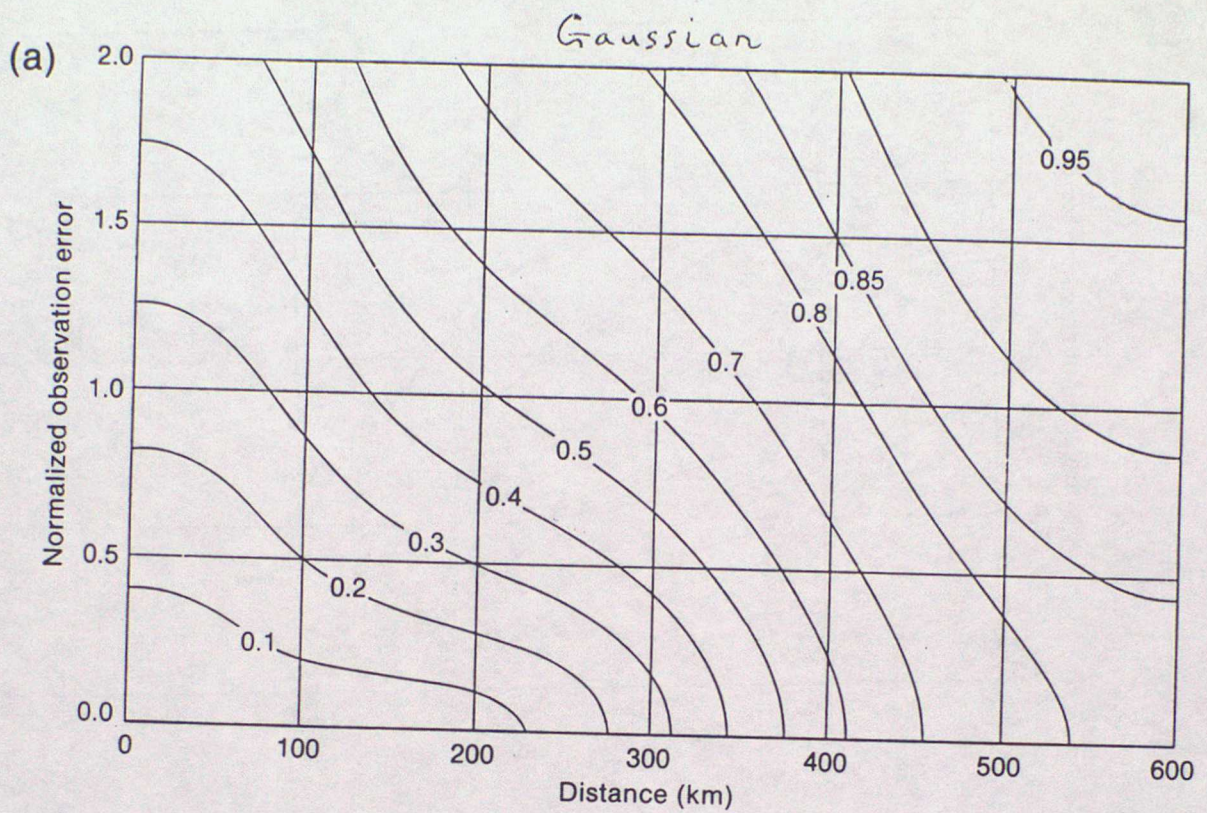


Figure 7

$\gamma = 0.1$



$\gamma = 0.1$

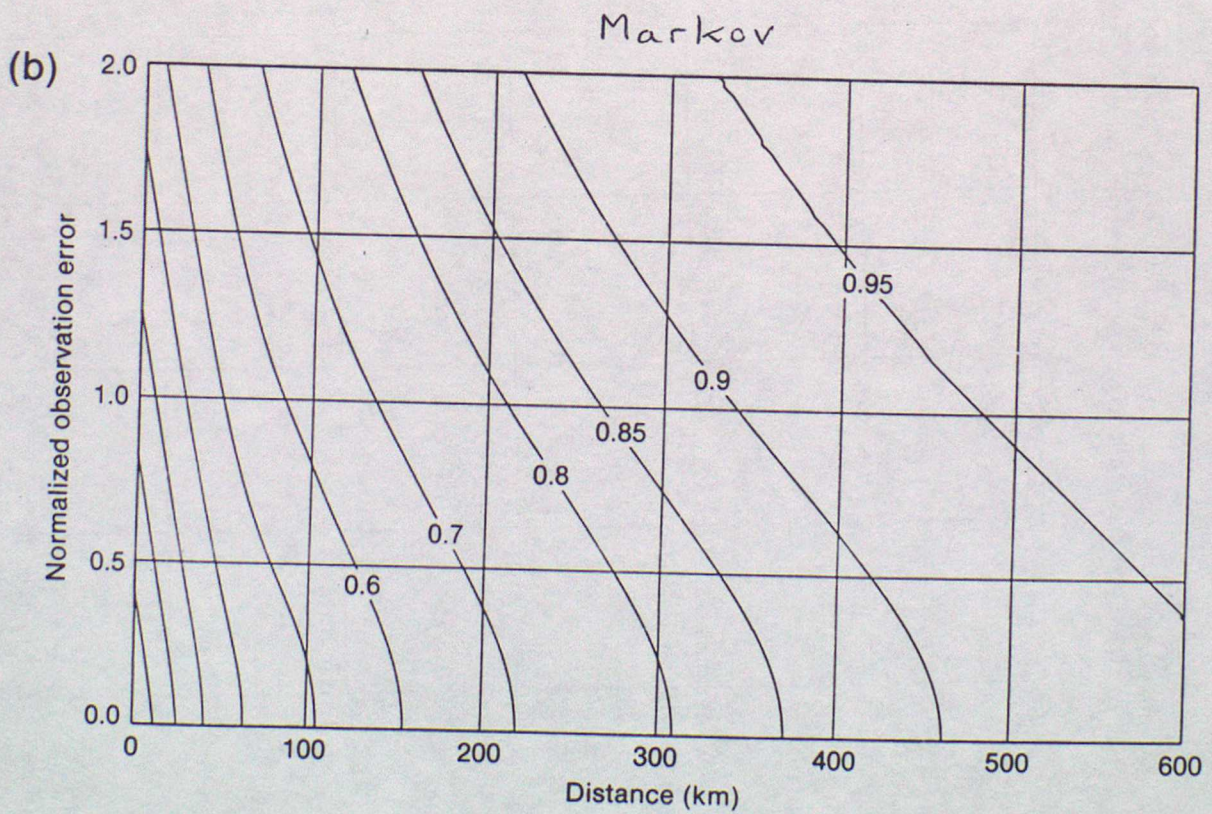


Figure 8

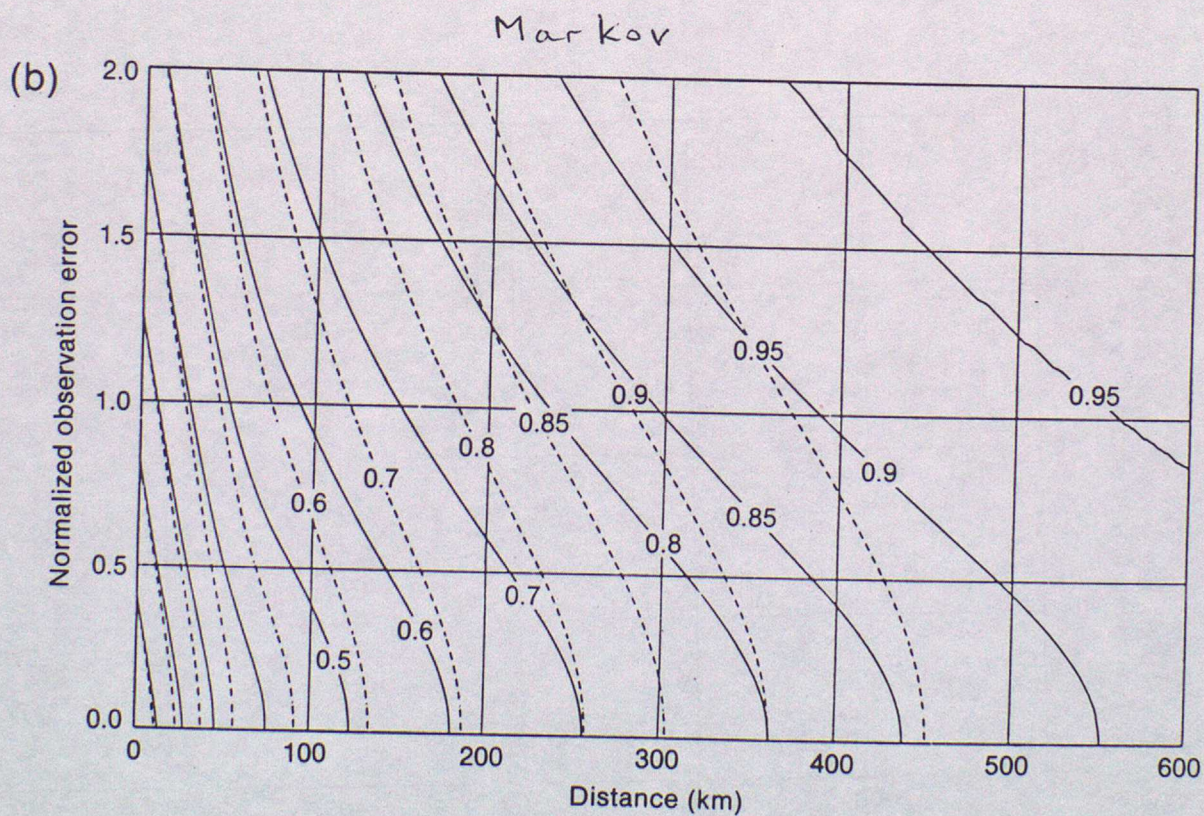
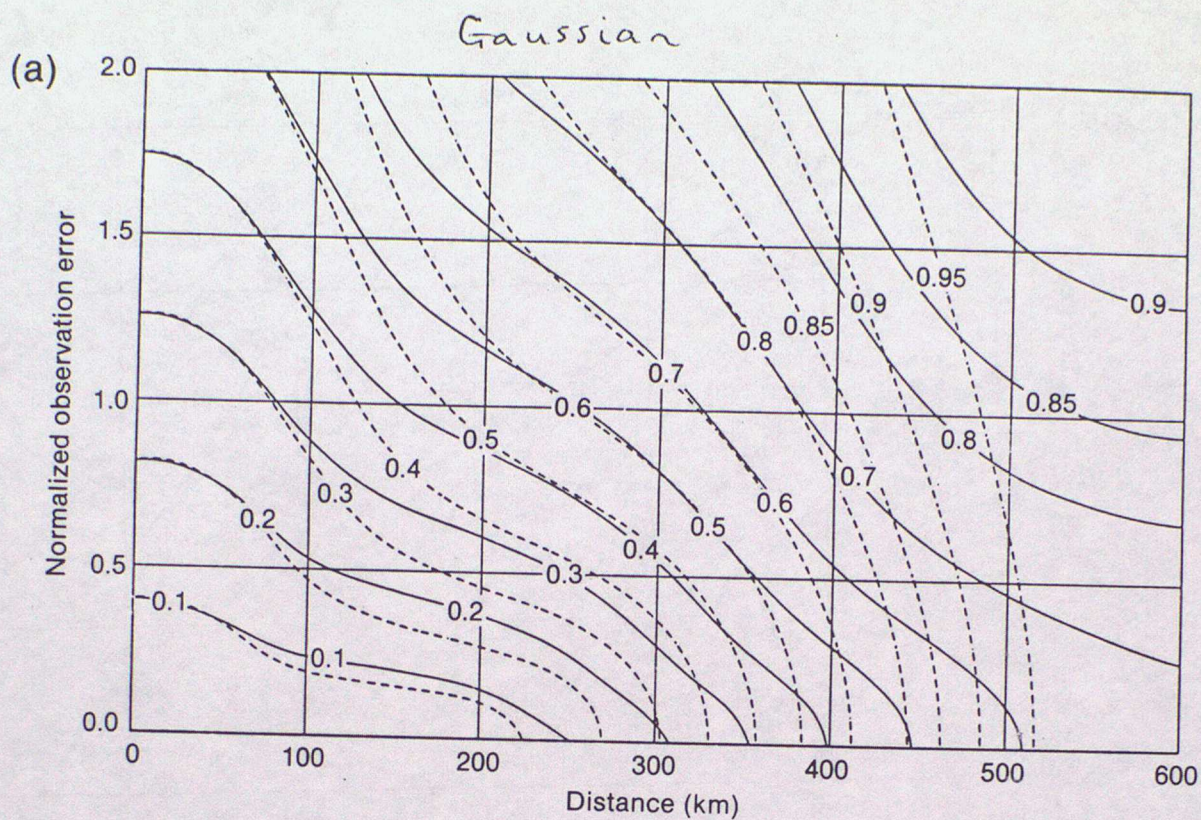


Figure 9
 $\nu = 0$ (solid lines) & $\nu = 0.5$ (dashed lines)

CURRENT MET O 11 TECHNICAL NOTES (JANUARY 1989)

The Met O 11 Technical Notes which contain information of current use and *which have not been published elsewhere*, are listed below. The complete set of Technical Notes is available from the National Meteorological Library on loan, if required.

- 186. The representation of boundary layer turbulence in the mesoscale model.
Part 1. The scheme without changes of state.
R.N.B. Smith
April 1984
- 187. The representation of boundary layer turbulence in the mesoscale model.
Part 2. The scheme with changes of state.
R.N.B. Smith
April 1984
- 195. Assessment of HERMES data: a case study comparison with the
operational analysis for 2nd March 1984.
W. Adams
August 1984
- 196. Solutions in flow over topography using a geometric Lagrangian flow.
S. Chynoweth
November 1984
- 197. An investigation into the likely causes of spurious rain in anticyclones
in the fine mesh model.
W. Hand
October 1984
- 199. The impact of data from the HERMES system on the fine mesh data
assimilation scheme - a case study.
R.S. Bell and O.M. Hammon
February 1985
- 203. Using an interactive radiation scheme in the fine mesh model.
A.D. Darlington
March 1985
- 204. Snow forecasts from NWP models during the winter of 1984/85.
O.M. Hammon
March 1985
- 205. Results of a trial of a parametrization of gravity wave drag in the
operational forecast model.
J.E. Kitchen, M.J. Carter and A.P. Day
April 1985

- 206. Parametrization of viscosity in three dimensional vortex methods and
 finite difference models.
 S.P. Ballard
 April 1985

- 207. A mesoscale simulation of the cold front of 12.11.84.
 B.W. Golding
 October 1985

- 208. Subgrid-scale cloudiness in the UKMO mesoscale model.
 N. Machin
 May 1985

- 209. An examination of the structure of fronts in the Met. Office and ECMWF
 models.
 W. Hand
 August 1985

- 211. Solutions of a Lagrangian conservation law model of atmospheric motions
 M.J.P. Cullen, J. Norbury and R.J. Purser
 August 1985

- 212. The analysis of high resolution satellite data in the Met Office.
 A.C. Lorenc, W. Adams and J. Eyre
 August 1985

- 215. A shortcoming of the operational convection scheme at higher resolution
 M.W. Holt
 September 1985

- 219. Three dimensional vortex methods and their application to the direct
 simulation of turbulence.
 S.P. Ballard
 October 1985

- 222. An implicit version of the operational model boundary layer routine.
 J.E. Kitchen
 1986

- 224. Four-dimensional analysis by repeated insertion of observations into
 a NWP model.
 A.C. Lorenc and R. Dumelow
 December 1985, revised July 1987

- 226. A study of the structure of mid-latitude depressions in a numerical
 model using trajectory techniques, II. Case studies.
 B.W. Golding
 1986

- 228. Investigation of balance in the operational global model with normal
 mode initialization.
 B. Macpherson
 April 1986

- 229. A parametrization of deep convection for use in a non-hydrostatic
 mesoscale model.
 R.T.H. Barnes and B.W. Golding
 March 1986

- 230. Boundary layer structures and surface variables in operational
 forecasts.
 R.S. Bell
 April 1986

- 231. Meteorological Office mesoscale model: an overview, version 1.
 B.W. Golding
 December 1986

- 235. Snow forecasts from the fine mesh model and mesoscale model during
 the winter 1985/86.
 O.M. Hammon
 June 1986

- 236. Vertically-propagating quasi-inertia waves: simulated and observed.
 M.M. Booth and G.J. Shutts
 November 1986

- 239. Mesoscale case study - Project Haar.
 W.R.P. Taylor
 February 1987

- 240. A trial of modified diffusion in the coarse mesh model.
 R.S. Bell and R.A. Downton
 September 1986

- 243. The global impact of the recent developments of the physical
 parameterisation schemes.
 R.S. Bell
 November 1986

- 247. Some experiments with two-dimensional semi-geostrophic and primitive
 equation models, with sigma as the vertical coordinate.
 C.A. Parrett
 February 1987

- 248. Moist frontogenesis in the geometric model.
 M.W. Holt
 March 1987

- 249. Mesoscale model trial of a revised convection scheme and cloud
 modifications.
 O.M. Hammon
 May 1987

- 250. Results from the fine mesh trial of a modified physics package.
 O.M. Hammon
 July 1987

251. Verification of mesoscale model forecasts during the winter, November 1986 - February 1987.
O.M. Hammon
March 1987
252. Mountain wave generation by models of flow over synoptic-scale orography.
M.J.P. Cullen and C.A. Parrett
March 1987
253. Development of the analysis correction scheme, I. The observational weights.
B. Macpherson
September 1987
256. Experiments with divergence damping and reduced diffusion in the mesoscale model.
S.P. Ballard
May 1987
258. Trials of the interactive radiation scheme in the global model.
M.D. Gange
May 1987
261. Modifications to the automatic quality control of ship data and an assessment using case studies.
B.R. Barwell and C.A. Parrett
1987
263. Results from a fine mesh model trial using a modified evaporation scheme.
O.M. Hammon and C.A. Wilson
August 1987

NEW SERIES (Commenced October 1987)

1. An assessment of the results of trials of a new analysis scheme for the operational global model.
R.S. Bell
October 1987
2. A case study showing the impact of analysis differences on medium range forecasts.
R.A. Downton and R.S. Bell
January 1988
3. Development of the analysis correction scheme. II. Inclusion of an observation density analysis.
B. Macpherson
September 1988

4. An assessment of a trial to test small changes to the Convection scheme in the mesoscale model.
O.M. Hammon
January 1988
5. Trial of proposed changes to the Mesoscale model for November 1987.
O.M. Hammon
December 1987
6. Assessment of HERMES soundings processed using the new cloud-clearing scheme.
R. Swinbank
March 1988
7. An assessment of the impact of a correction to the Mesoscale model turbulence/vertical diffusion scheme implemented in March 1988.
S.P. Ballard and O.M. Hammon
April 1988
8. Comparison of algorithms for the solution of cyclic, block, tridiagonal systems.
M.H. Mawson
May 1988
9. A comparison of alternating direction implicit methods for solving the 3-D semi-geostrophic equations.
M.H. Mawson
May 1988
10. The automatic quality control of surface observations from ships: the final trial, latest statistics, operational implementation and future work.
C.A. Parrett
May 1988
11. "Panel-beater": a proposed fast algorithm for semi-geostrophic finite-element codes.
R.J. Purser
June 1988
12. The 5-day forecast trial of the AC scheme.
R.A. Downton, R.A. Bromley and M.A. Ayles
September 1988
13. A theoretical study of the information content of the ERS-1 scatterometer data.
R.J. Purser
August 1988
14. A further global trial of the analysis correction scheme - Christmas 1987.
R.S. Bell
August 1988

15. The sensitivity of a medium range forecast with the analysis correction scheme to data selection in the horizontal.
B. Macpherson and R.A. Downton
Not yet issued.
16. The sensitivity of fine-mesh rainfall forecasts to changes in the initial moisture fields.
R.S. Bell and O.M. Hammon
August 1988
17. Conservative finite difference schemes for a unified forecast/climate model.
M.J.P. Cullen and T. Davies
July 1988
18. Interpreting results from numerical models.
T. Davies
August 1988
19. A comparison of the OWSE assimilation scheme with the operational global assimilation scheme.
D.N. Reed and M.A. Ayles
October 1988
20. Improvements to low cloud forecasts from the mesoscale and fine mesh models.
O.M. Hammon
October 1988
21. The effect of route choice on aircraft wind observations over the North Atlantic.
D. Lang and N.B. Ingleby
October 1988
22. Maximum likelihood de-aliasing of simulated scatterometer wind fields using adaptive descent algorithms.
R.J. Purser
January 1989
23. A proposal for assimilating detailed aircraft wind data in a local area.
R.J. Purser
January 1989
24. Basic formulation and boundary conditions of the mesoscale model.
S.P. Ballard
Not yet issued.
25. Development of a new physics package for the global forecast model.
C.A. Wilson and J. Slingo
January 1989

26. **The Trial of the Fine-Mesh Version of the Analysis Correction Scheme.**
O.M. Hammon, R.A. Bromley and B. Macpherson
May 1989.
27. **The new Meteorological Office Data Assimilation Scheme.**
A.C. Lorenc, R.S. Bell and B. Macpherson
April 1989.
28. **Model Error Structure and Estimated Analysis Accuracy with a Network
of Wind Profilers.**
N.B. Ingleby and R.A. Bromley
May 1989.