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Note

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Abstract.

The problem of determining boundary layer depth from numerical model vertical profiles for use in the NAME long range transport, dispersion and deposition model is discussed, and an attempt made to account for the difficulties the model experienced at the time of the ATMES validation study. Model boundary layer depths diagnosed using six different methods are tested against actual radio-sonde ascents, at midday and midnight. Four of these, based on identifying the level at which a critical Richardson number is reached, gave poor results for the most part, particularly for the daytime boundary layer. Two further techniques, the new Sigma method and a ‘parcel’ method, were also tested, and recommendations made on the best approach for inclusion in the NAME model.

1 Introduction.

Following the nuclear accident at Chernobyl the ‘NAME’ long range transport (LRT) model was developed for use in emergency or accident analysis mode in the event of further incidents of this kind. A description of the model design and the way it would be used in the event of an emergency is contained in Maryon et al (1992), and the nuclear accident Emergency Instructions (MetO(PR) ITM 19).

At about the time the Fine Mesh version of NAME was completed the model was put forward for the international Atmospheric Transport Model Evaluation Study (ATMES). Organized jointly by the WMO, EC and IAEA during 1989-90, this used observations of the spread of radioactivity from the Chernobyl incident together with meteorological fields from the ECMWF and rainfall information from KNMI in a validation exercise, for which twenty or more models were eventually entered. Statistical and other tests of the model results were designed and carried out at the JRC Ispra, and summaries of the results published by Klug et al (Eds., 1992). It is not the purpose of this paper to discuss the statistical methods or results of the study other than to acknowledge that the NAME model put up a poor performance, for reasons which were not fully understood at the time. Indeed, no-one had had any experience of actually operating a Lagrangian multiple particle model over long range, and accordingly we still had much to learn. ATMES was an invaluable study in that the problems were highlighted at once: it is unfortunate that the results should reach publication long after new, improved versions of the model had been developed, and the causes of the difficulty established.

During the ATMES study it quickly became apparent that NAME was not simulating the plume at all well, and at first the answer was looked for in problems or errors which might have arisen in interpolating fields from the ECMWF data base, or in using an insufficient number of particles to carry out the 'Monte Carlo' type simulation. It was established that the interpolation involved no error and very minor degradation of the data, while a subsequent study (Maryon, 1993) suggested that the particle numbers used were about adequate, if perhaps not ideal. It had been noticed that the model's diagnosis of boundary layer (BL) depth had been giving rather low results, and required further testing and investigation, but it was not appreciated at the time that this could be a source of catastrophic error. Deadlines had to be met, however, and the model results were submitted to ATMES before very much progress in understanding the problem had been made.

2 The Model Boundary Layer.

NAME is based upon the products of the Met Office operational numerical weather prediction (NWP) models, formerly the Fine Mesh and now the Limited Area and Global versions of the Unified Model. As the methods of simulating diffusion would differ above and below the inversion capping the BL, it is necessary to compute the BL depth at the locations occupied by the individual particles. This can be done by developing a submodel or adopting some empirical technique, but it was considered important, from the outset, to use the NWP model profiles of wind and temperature to compute BL depth *so that it would be dynamically consistent with the NWP model output.* An empirical BL depth which exceeded that recognized by the NWP model would lead to errors in the particle spread.

It was known that diagnosis of BL depth from NWP model products would be difficult (Maryon 1989), but two options for estimating BL depth were incorporated into the early version of NAME (methods 2 and 4 below), although thorough testing could not be carried out prior to the ATMES exercise. It was established subsequently that these methods gave consistently very low estimates of BL depth for the ATMES study. This was not invariably the case, as what seem to be quite reasonable estimates of the boundary layer in the environs of the Persian Gulf were obtained using the same version of the model and methods (Buckland and Maryon, 1992). Verver (1993) established that the ECMWF profiles tended to give a marked underestimation of the BL depth, so it may be that the problem was compounded, for the ATMES study, by the nature of the data base (and perhaps by its poor time resolution—only 6-hourly fields were available). Many—or most—of the ATMES participants used empirical estimates for the BL depth. However, in what follows autumn BL's over parts of central and southern Europe were badly underestimated using NAME's standard routines, so it is evident that a serious problem exists.

This study is based upon the assumption that we should, in principle, try to find a satisfactory method of obtaining BL depth from NWP model profiles. The use of empirical methods or sub-models may be expedient but suffers from the strong disadvantages of inconsistency with the model dynamics, heavy additional storage of variables or computational effort (e.g. to obtain time of sunrise at different locations, and to integrate the BL depth up to the required time of day), and in addition there are problems of advection and inhomogeneity which it would require substantial computing efforts to overcome if they are not to be ignored.

3 Effects of Underestimating Boundary Layer Depth.

As stated, it was not realised that a poor representation of the BL depth could affect the NAME results so severely, and even now, after much investigation, the extent of the impact seems surprising. It may be that Monte Carlo formulations are particularly vulnerable to this problem, in that individual non-diffusing particles (clouds of particles diffuse, but individual particles carry a non-diffusive mass) become trapped in excessively shallow BL's. There are several ways in which consistently underestimated BL depths can affect the NAME model:

1. At each timestep particles below the BL top are randomly reassigned in the vertical, to give effect to BL turbulence (see Maryon et al 1992). In this way, each particle 'forgets' its position at the end of the preceding timestep and as time passes tends to experience the winds at all levels in the BL. Thus it is advected by (roughly) a mean BL wind. Above the BL top there is only a relatively slight vertical diffusion and particles are carried along in the tropospheric flow. One effect of consistently underestimated BL depth, then, is that transports will be in error.

2. Particles below the BL top undergo a random perturbation in the horizontal, to give effect, again, to sub grid scale motions. This is much reduced above the BL. Accordingly the diffusion of the cloud will be wrong if the BL depth is systematically in error.

3. Material lying above the excessively shallow BL's will not be entrained. This was very likely a major source of error in the ATMES experiment, as part of the source release was at 1500m on the first day—well above the inversion heights being diagnosed by NAME—and otherwise centred at 600m for the first 48 hr: this was the critical release period for the radionuclides affecting western Europe. Failure to entrain sufficient of this material most probably resulted in serious underestimates of near-surface concentrations.

4. Dry deposition is inversely proportional to BL depth:

$$\Delta m = -(v_d/z_i)m\Delta t,$$

where m is the mass or quantity of radioactivity carried by a particle, z_i is the inversion height and v_d the deposition velocity. Particles trapped in the shallow BL will experience excessive depletion, which upsets the surface concentration and deposition fields, and severe error develops as time passes. In addition, the model assumes a constant dry deposition velocity. This is another possible source of error which may well have aggravated the situation. The dry deposition velocity is likely to depend upon a number of factors which influence the aerodynamic and surface resistances, and the constant values used may well be excessive for many night-time conditions when the BL is not well mixed. By way of illustration, given the constant deposition velocity used for Iodine-131, 0.005m/sec, particles trapped in a fixed BL of 250m would deposit 97% of their material over 2 days (using 192 15-min timesteps), whereas with a fixed BL of 1200m only 51.5% would be lost—and there would be greater prospect of entraining 'fresh' material from aloft.

Effects 1. and 2. above may not be critical, although they are likely to assume greater importance as the period of the integration increases. It seems most likely that effects 3. and 4. combined to topple the NAME product in the ATMES exercise.

4 The Causes of Underestimation.

It is well known that vertical profiles of wind and temperature from NWP model integrations are inaccurate, with the BL depth generally underestimated. The mean profiles respond to flux divergences, in accordance with the governing equations. Consider, for example, a finite difference computation of equations such as

$$\delta u/\delta t = f(v - V_g) + \delta\tau_x/\delta z$$

or

$$\delta B/\delta t = \delta H/\delta z$$

where $\mathbf{u} = (u, v)$ and V_g represent the wind and geostrophic wind, f the Coriolis parameter, τ_x a stress component, z height, B and H buoyancy and buoyancy flux respectively. The fluxes are parametrized using local gradients of u and B; a typical Richardson number dependent formulation is

$$\bar{\tau} = l_0^2(1 - R_i)^{1/2} S \delta \mathbf{u}/\delta z,$$

where R_i is the Richardson number, S the Smagorinsky deformation, and l_0 a mixing length. Now R_i, S, and $\delta\mathbf{u}/\delta z$ all depend upon estimates of gradients made from finite difference grids which may be quite coarsely resolved, and in particular will represent the steep gradients at the inversion very poorly. The effect of the underestimates of the steeper gradients may be quite complex, but at the BL top the flux divergence is generally underestimated as a result, and the mean profiles degraded. Figures 1 and 2 from Maryon (1989) demonstrate these effects; they are taken from integrations of a dry, one-dimensional BL model. Figure 1 shows the buoyancy flux divergence estimated at the grid point immediately below the inversion, plotted against resolutions ranging from 2.5 to 250m. It will be noted that at coarse resolution the flux divergence is an order of magnitude smaller than at the highest resolutions. Figure 2 shows corresponding buoyancy mean profiles for integrations at 10 and 150 m resolution, illustrating well the loss of detail at the inversion and underestimate of its height at coarse resolutions. The 'nose' of the inversion is associated with the conversion of turbulent kinetic energy to potential energy, and shows where cooler BL air is mixed into air of higher potential temperature above.

The fact that NWP models tend to produce inadequate vertical profiles does not, of itself, account for the difficulties experienced using NAME, as the model fields used in the NAME hindcasts are derived from the model *analyses*, which should give very high weighting to observational data, such as radio-sondes. Even the hindcasting archives contain short-period forecasts at intermediate times, however, while the analyses themselves may be influenced, during the assimilation process, by the background fields, which again are a forecast product. A series of radio-sonde profiles from the autumn of 1992 are used to examine the effectiveness of different methods of estimating midday BL depth, below, and it was thought worthwhile to compare these ascents with the corresponding model midday analyses to make an assessment of the similarity of the analysed temperature profiles to reality. This was done only in a subjective manner, and the sample (51 ascents) is a small one, but the results are considered worth reproducing here.

In the lower part of the BL about 47% of the model profiles were, in terms of stability, fairly close to the sonde, 21.5% were more unstable, 31.5% more stable (a couple of these latter were so unrealistically stable that the NAME model would have defaulted to its minimum allowable BL depth). In the upper BL no less than 74.5% of the model profiles were more stable than the observation, in almost all cases leading to an underestimate of BL depth. This must surely reflect the influence of the background field, and the discretization problem discussed above. In a few cases the 1.5m temperature, for some reason, was slightly lower than the lowest model temperature: this usually results in a supercritical R_i at the lowest half-level and a default to the model's minimum BL depth. In about 12% of cases the stability of the model was approximately similar to the observation, but both were just on the stable side of neutral, so that low BL's were deduced.

In order to investigate the handling of the inversion itself by the assimilation procedures, counts were made of (a) how many model BL's were mainly warm, cold or roughly similar to the sonde, and (b) whether the model grid-point next below the inversion as estimated from the sonde was warm, cold or roughly similar. The two sets are presented as a contingency table in Table 1. It will be noted that there is a roughly even likelihood of warm or cold estimates: 39% and 45% respectively, with 16% about correct. The sub-inversion points are very evenly spread with 37%, 30% and 33% warm, about right, and cold respectively. As one would expect, no cases of a warm or roughly correct BL temperature coincided with a cold sub-inversion point, but for 10% of the cases a cold or roughly correct BL temperature coincided with a warm sub-inversion point. This does tend to suggest that the inversion strength is not fully represented in the model profiles, although the signal is not a particularly strong one. This statistic by no means tells the whole story, however, as even a casual glance through the profiles shows that strong inversions are almost never properly reproduced by the model analysis. And indeed, the figures do make it clear that there is a great deal of inaccuracy in general. It might be added that the model wind profiles also compared very poorly with the soundings in a subset of the cases which were examined; this is not surprising as winds are not assimilated over land.

As a footnote to this subjective assessment, it was considered that method 3 for computing BL depth (described below; it is the best of the Richardson number based methods) yielded about 39% good estimates, 28% moderate or fair, 33% bad.

5 The Diagnosis of Boundary Layer Depth.

Given a strategy of diagnosing BL depth from NWP model profiles a number of alternative techniques suggest themselves. Figure 3 is a schematic NWP vertical temperature profile;

it is approximating a 'real' profile shown by the pecked line. In reality model profiles will, of course, be far less accurate than that in the diagram. Note that the wind and potential temperature, u, θ, will be held at the model levels 1,2, etc, and additionally at or near the surface. Conventional methods of fixing the height of the capping inversion use a critical value of the gradient Richardson Number

$$R_i = \frac{g}{\bar{T}} \frac{\delta\theta/\delta z}{(\delta \mathbf{u}/\delta z)^2}$$

at which turbulence tends to be suppressed (θ is the potential temperature, z the height coordinate, $\bar{T}$ the mean temperature of the layer, and g the acceleration due to gravity). The critical value $R_i(crit)$ is usually taken as +0.25 or somewhat higher, and for purposes of diagnosis from NWP model output a value of 1.3 was assumed. R_i can, of course, be estimated only at the model 'half-levels', as it requires the wind and temperature gradients. The critical value is sought by starting at the lowest half-level, computing R_i, testing against +1.3, and if it is smaller, moving up to the next half level. Eventually a half-level is reached at which R_i is super-critical.

At this point an assumption has to be made as to the precise level at which R_i becomes critical. Four alternatives are looked at here:

Method 1: Linear interpolation of R_i between the sub- and super-critical half-levels.

Method 2: Separate linear interpolations of $\delta\theta/\delta z$ and $(\delta \mathbf{u}/\delta z)^2$ between the sub- and super-critical half-levels and interpolating for $R_i(crit)$. This involves the solution of

$$\eta_{crit} = \eta_l + \frac{\left.\frac{\delta\theta}{\delta z}\right|_l - \left.\left(\frac{\delta \mathbf{u}}{\delta z}\right)^2\right|_l . K}{K.\left\{\frac{\left(\frac{\delta \mathbf{u}}{\delta z}\right)_l^2 - \left(\frac{\delta \mathbf{u}}{\delta z}\right)_u^2}{\eta_l - \eta_u}\right\} - \frac{\left.\frac{\delta\theta}{\delta z}\right|_l - \left.\frac{\delta\theta}{\delta z}\right|_u}{\eta_l - \eta_u}}$$

to find the level (η_{crit}) at which R_i reaches critical; here the subscripts l and u refer the the model half-levels flanking $R_i(crit)$, and $K = \frac{\bar{T}}{g} R_i(crit)$.

Method 3: A simple option is to assume that η_{crit} is at the half-level at which R_i becomes super-critical. This is above the critical level according to the NWP model, of course, but this may help compensate for model underestimates.

Method 4: is simply to assume η_{crit} is at the model level below the super-critical half-level.

Methods 2 and 4 were included in the NAME model from the beginning, and were chosen by specifying IBLD=0 and IBLD=1, respectively, in the input data stream. Method 2 was used during the ATMES study. Two further techniques were applied in the present study—

Method 5: The Sigma method: this method was developed by Middleton (1993). It is derived from work of Bultynck and Malet (1972) on the evaluation of atmospheric dilution factors: these authors observed that the vertical wind shear, which is squared in the denominator of R_i, could not be measured with sufficient accuracy (and this applies the more so to NWP model output). Accordingly they chose a parameter

$$S = \frac{\delta\theta/\delta z}{\mathbf{u}^2} \tag{1}$$

which for winds measured up to about 120m is closely linked to the Monin-Obhukov stability parameter, and is correlated with the dispersion parameters σ_y and σ_z. Empirical fits

$$\sigma_{y,z}(x, \dot{S}) = f(S)$$

were then obtained—specifically, equilateral hyperbolas such that

$$\sigma_{y,z}(x, |S|) = \sigma_{y,z}(x, 0)\left[\frac{j + 10^6 k|S|}{j + 10^6|S|}\right].$$

As stated, this is a function of the distance from source, x, which was taken as 1000m for application to a local rate of diffusion in the NAME model. At this distance the empirical values for the neutral case are

$$\begin{aligned} \sigma_y(1000, 0) &= 100m \\ \sigma_z(1000, 0) &= 73m \end{aligned}$$

The values of the constants j and k for different stability categories for the horizontal and vertical spread are contained in Middleton 1993. Here, the dispersion parameters are combined to give a dimensionless measure of the tendency of the atmosphere to undergo mixing:

$$\Sigma = \frac{\sqrt{\sigma_y(x)\sigma_z(x)}}{x}.$$

Division of top and bottom by t shows that Σ is related to turbulence intensity, as implied in Bultynck and Malet, who take the relationship of the Lagrangian to the Eulerian turbulence measures into account. The horizontal component of turbulence intensity decreases with height, although the vertical component can increase with height in the BL in convective conditions. All components are reduced sharply at the inversion, and this applies equally to Σ.

The method of determining the ABL depth is to assume a uniform $\delta\theta/\delta z$ between model levels, interpolate **u** linearly at 10 points between, and to step upwards (starting at the bottom) computing Σ until it falls below a value (Σ_0) of 0.06, which studies have suggested is a suitable value to define the ABL height. If Σ nowhere falls below Σ_0, then the minimum value (at its lowest level of occurrence) is taken as the required height. Following Bultynck and Malet, constant values of $\sigma_{y,z}$ are assumed where winds exceed $11.5ms^{-1}$, provided they are coupled with significant shear (at time of writing, shear exceeding $0.1667s^{-1}$).

This technique has the virtue that it more often provides reasonable estimates of ABL depth from model profiles than the established methods 2 and 4. However, it clearly has theoretical drawbacks. First, Bultynck and Malet's formulae were derived for the top (roughly) of the turbulent surface layer of the atmosphere, reflecting primarily mechanical mixing, and although the numerator and denominator of S (equation 1) may not change very rapidly with height in the convective ABL, the hyperbolic relations are not likely to remain unaffected. Secondly, the application of σ_y to the problem of determining ABL depth is rather unorthodox (and superfluous maybe) although it does reflect the presence of mixing motions.

Method 6: The dry, adiabatic layer: following the dry adiabatic lapse rate (DALR) from the surface or near-surface temperature and determining the level at which it intersects the environment curve as interpreted by the model profile should give a reasonable estimate of mixed layer depth during the daylight hours—see figure 3. This might be construed as a 'parcel' method, by analogy with the Normand construction. Some authors fix the dry adiabat at a temperature somewhat exceeding the surface value, and some (e.g. Verver 1993) use virtual potential temperature. The earlier comparison between modelled and real profiles suggests that this latter may not be worth the substantial additional processing involved: it would be justified, perhaps, using radio-sonde profiles, but not those of an NWP model. In the present study a small addition to the temperature at the lowest model level (not the surface values) was indicated.

These are the six methods which are used here to assess the accuracy of deducing BL depth from NWP model profiles.

6 Experimental Details and Results.

The objective of this experiment was to assess the accuracy of the six methods (detailed above) used in the NAME model for calculating the boundary layer depth. The data were used to find the best method and to see if this method was adequate.

Data were retrieved from radio-sonde ascents from continental Europe and Izmir in Asia Minor, for midday and midnight, over the period from 13/10/92 to 06/11/92, so that comparisons could be made between actual ascents and model results. It must be kept in mind that the model BL depths are diagnosed from the Unified Model profiles and not the observational data—these are just used as validation. Ascents were chosen in which the height of the boundary layer was reasonably obvious from the plots. Profiles of dew point and temperature were plotted from the soundings, and the height of the boundary layers measured.

To carry out the intercomparison the nearest model grid points to the radio-sonde stations were identified, the NAME model started and the boundary layer height calculated at the nearest grid points printed out. The surface pressure was taken from the radio-sonde profile and multiplied by the η value at the BL top, as determined by the NAME model, in order to find the height of the model boundary layer in millibars. This implies a simplified definition of η, but is adequate for the lowest few hundred mb. The NAME diagnosis of BL depth was then compared with the value obtained from the plot.

The results of the four Richardson number methods used in the NAME model are shown, for midday in Table 2 and for midnight in Table 3. The results for the 00Z ascents are somewhat obscured by the reversion of the various methods to default minimum BL's on many occasions—the main thrust of the exercise was to examine the convective BL, but on balance it was felt worthwhile taking a look at the 00Z performance of the model, despite the difficulties. These tables include the height of the boundary layer as determined from each of the ascents and by each of the four methods, and the degree of error. Ensemble statistics of RMS error, mean error and mean modulus of error are appended. In view of the disproportionate weight given to severe errors by the RMS, the mean modulus of error is perhaps the most useful error statistic. The mean error is very important, however, as highlighting systematic error.

Midday Boundary Layers: all of the Richardson number methods predicted boundary layers that were consistently too low, and were in fact severely in error. Method 3, which selects the half level above the critical level, proved to be the best, or least bad, of the Richardson number based methods. There was little to choose between the abysmal results of the other three techniques—one of which (method 2) had been used in the ATMES study. It was disappointing to find that none of the methods gave even a rough approximation to the correct boundary layer heights, and that systematic error—with its serious implications for the NAME integrations—was so large.

Midnight Boundary Layers: the default lower limit to the boundary layer height was diagnosed by the model for about half of the results, which explains why all four of the Richardson number based methods were so similar in their errors. Table 3 shows that there was little to choose between the Richardson number based methods, method 4 giving marginally the smallest mean modulus of error.

7 Critical Richardson Number

An obvious means of improving the Richardson number methods given the consistently large underestimates is to increase the value of $R_i(crit)$. This is conceptually a rather dangerous policy; nonetheless it was decided to utilise the results that we had obtained to find the value of the Richardson number that would give the best approximation to the boundary layer heights. A graph was plotted of Richardson number against the error in method 3, for each result. Method 3 was chosen because it uses the model half level at which the super-critical Richardson number is calculated by the NAME model as the boundary layer height, and also gave the better results of the Richardson number based methods on the whole. A line of best fit was used to read the Richardson number corresponding to zero error from the graph.

A best fitting Richardson number of 7.2 was obtained in this way. Comparisons were then made between this value and the original critical value (1.3). Unfortunately it was necessary to rerun the model, so the adjustment could only be tested on a relatively small number of cases still on the roll-over archive: Tables 4 and 5 show the results for midday and midnight respectively. The sample is very small, but it is evident that only limited improvement can be obtained in this way. Mean error can no doubt be reduced further by adjustments of this kind, but only at the expense of much increased modulus of error.

A second, equally arbitrary, procedure, is to increase the diagnosed BL depths by a fixed percentage. A program was written to calculate the percentage required to minimise the mean modulus error for each of the methods 1 to 4. Separate percentages were determined for day and night. Fortunately it was possible in this case to apply the adjustment retrospectively to all the earlier cases (the same applies to methods 5 and 6 described below). Table 6 shows the percentage increase calculated for midday and midnight, and the effect of the adjustment upon ensemble error. The results show a moderate improvement on the uncorrected heights. The values of the percentages for day and night are very different, and, it was felt, unlikely to be stable when applied over a large domain and in different seasons.

8 Methods 5 and 6.

At this stage it was not considered that a satisfactory technique had been found, and it was decided to include two further techniques in the trial: method 5, Middleton's Sigma method, and the parcel method (6). The results are shown in Tables 7 and 8 for midday and midnight ascents respectively. Method 5 again gave disappointing results with the BL heights, on the whole, still far too low. It did no better than method 3 for the midday ascents, or method 4 for the midnight ascents.

For completeness, the BL heights were increased by a suitable percentage for method 5 to see whether error could be further reduced. The same procedure was followed as for methods 1 to 4 discussed above, and the errors and corresponding percentages are included in table 6. It was clear from these results that increasing the height by an arbitrary percentage does not really improve the errors over the Richardson number method 3 when it is similarly treated.

For the parcel technique, method 6, it was decided to make an addition to the surface temperature from which the dry adiabat was 'drawn', and a program was written to find the offset that would minimise the errors. It was decided in doing this that the addition should be made to the model's first level ($\eta = 0.997$) instead of the surface level, as this latter occasionally exhibited apparent irregularities. It was found that the errors were reduced if the offset was in the range 1-1.5K, and were minimised (for the available data base) when an addition of 1.2K was made to the model's first level. The method is strictly for the daytime, although midnight results are included in Table 8 for interest.

The results for method 6 were encouraging: the midday R.M.S. and mean modulus errors were improved by about 9mb over the best of the other techniques, while the mean error is much reduced—indeed, this came down to 8.8mb from 34.0mb for the next best method, 3, so the systematic error is greatly improved.

9 A Practical Scheme.

For 24 hr coverage a practical option exists of taking the BL height as the maximum diagnosed from method 4 and method 6 with the 1.2 addition. Method 4 is a very simple technique for estimating the night-time BL depth, comparing reasonably with the other methods. There is little scientific justification for using method 6 at night, except possibly over the sea, so although Table 8 implies method 6 is as accurate as any at night it was felt safer to include method 4. Table 9 summarises the errors for the 6 methods discussed (excluding the percentage additions and increases in $R_i(crit)$, as concern was felt about the arbitrary nature and likely lack of stability of these refinements).

However, it was noticed that for a few of the midnight results, method 6 produced deeper boundary layer heights than method 4, and would accordingly be selected by the scheme. This is anomalous, and results from the addition of 1.2K to the model's first level potential temperature prior to constructing the DALR. It was decided at first that if the surface potential temperature is less than that at the model's first level (thus identifying the typical night-time or stable situation), then *no addition should be made* in obtaining a starting point for the DALR. This adjustment should filter out innumerable excessive estimates of night-time BL depth, where method 6 > method 4.

But to complicate matters, there were also some midday ascents with a surface potential temperature less than that at model layer 1 (for no known reason—reduced surface heating, advective effects or proximity to a coast might be the cause in reality, but the corresponding soundings showed no inversion close to the surface). It has to be concluded that there are occasional irregularities in the model surface layer. If the addition for the DALR is removed in these cases, an increase in error for the midday BL heights results. Figure 4 shows a typical daytime profile that has the surface potential temperature lower than that at level 1. It can be seen at once from this profile why constructing a DALR directly from θ_1 results in incorrect daytime BL heights. It is not known how commonly this (possibly) spurious 'surface inversion' occurs, but it appeared a number of times in the small sample, and on the existing evidence should be catered for. Thus it was decided that where the surface temperature is lower than that at model level 1, a small addition, 0.5K, should be used rather than none at all. This has the net effect of reducing the errors in the midnight BL heights without increasing the errors in the midday heights significantly—as it is to be expected that most daytime ascents will not exhibit the anomalously low surface temperature.

Izmir, more frequently than any other station, exhibited the low daytime surface temperature, and it was noted from Table 7 that the Izmir ascents gave consistently very poor results at midday, contributing largely to the ensemble errors for the midday boundary layer heights. In fact, if Izmir is excluded from our results, then using the final version of the practical scheme (taking the maximum of method 4 and method 6 with either 1.2K or 0.5K added, as explained above), reduces all of the errors to a relatively satisfactory magnitude (Table 9).

10 Conclusions and Recommendations.

The poor performance of the NAME model in the ATMES model intercomparison is believed to be due to systematic and severe underestimation of BL depth, which had the impacts discussed in section 3. The cause lies largely in the NWP model profiles which, due to coarse discretization, themselves underestimate BL depth, but were, in addition, found to be generally inaccurate when compared with corresponding soundings. Both potential temperature (especially in the BL) and winds were inaccurate, inversions were not well represented and the parametrization of the surface layer *seems* to have led to some irregularities. No other causes of the poor NAME performance have been discovered despite fairly intensive study at the time of and since the ATMES study—indeed, a comparison with Imperial College's 3-DRAW model using identical input data and fixed BL's found that the spread, concentrations and depositions of pollutant were consistent taking into account minor differences such as deposition velocity (Buckland and Maryon, 1992). The European Tracer Experiment (ETEX) scheduled for the spring of 1994 will provide another opportunity to test the model, this time against a perfectly known source profile and using its own meteorological data bases. This should establish whether the problem has now been completely solved, or whether the application of Monte

Carlo methods to the long range dispersion and deposition problem has other inherent drawbacks requiring investigation.

In this paper a comparison has been made between 6 different methods of estimating BL depth from NWP model profiles—only if no satisfactory method could be found would consideration have been given to empirical methods or a sub-model for estimating BL depth, for the reasons discussed in section 2. The four methods based on a critical Richardson number, and the Sigma method, were all found to give daytime results that were systematically underestimated and unsatisfactory to a greater or lesser extent, and it was not considered that they could be reliably improved by altering critical values or increasing the BL depth diagnosed by a fixed percentage. There was little to choose between any of the methods when they were applied to midnight profiles.

The best daytime results were obtained using the parcel method, and these were regarded as good enough to use in the NAME model. For the reasons given in section 9 the scheme finally adopted was to use the maximum of methods 4 (the level below the half-level at which $R_i > R_i(\text{crit})=1.3$) and method 6 (the parcel method) at each timestep to diagnose the Bl depth. Method 6 constructs a DALR from the lowest model (not surface or screen) temperature +1.2K, and calculates the point at which it intersects the environment curve of the model profile. Where the surface potential temperature is below that at model level 1, the offset is reduced to 0.5K for the reasons discussed above.

All of these studies, inevitably, used a much smaller data base than is desirable, and the stability of the techniques over wider domains and different seasons is an open question. It is believed, however, that the technique finally chosen should be reasonably robust, and the performance shown at the bottom of Table 9 (i.e. excluding Izmir) is about as good as it is reasonable to expect. Any further work should be aimed at a much expanded data base, however, in order to avoid the dangers of 'capitalization by chance'.

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FIGURE CAPTIONS:

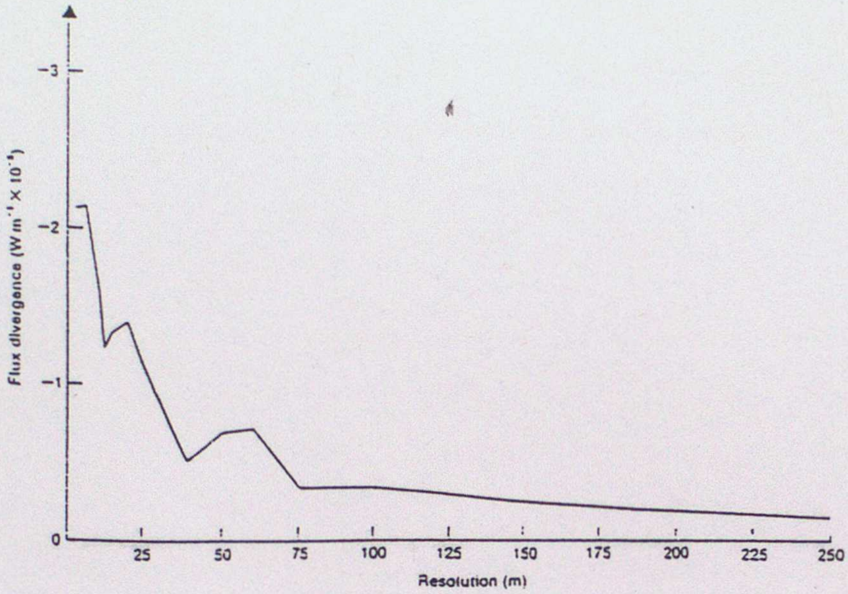
1. Buoyancy flux divergence estimated at the grid-point immediately below the inversion, plotted against resolution, from integrations of a one-dimensional, dry convective boundary layer model. (From Maryon 1989).

2. Fine ($10m$) and coarse ($150m$) resolution buoyancy profiles from runs of the one-dimensional model used for Figure 1. The curves are displaced for ease of comparison. The units are of buoyancy ($g(T-\bar{T})/\bar{T}$)—the actual magnitudes are immaterial here. (From Maryon 1989).

3. Schematic profile of potential temperature through the convective boundary layer, with a corresponding profile from a numerical weather prediction model, to illustrate the methods of diagnosing BL depth from model profiles.

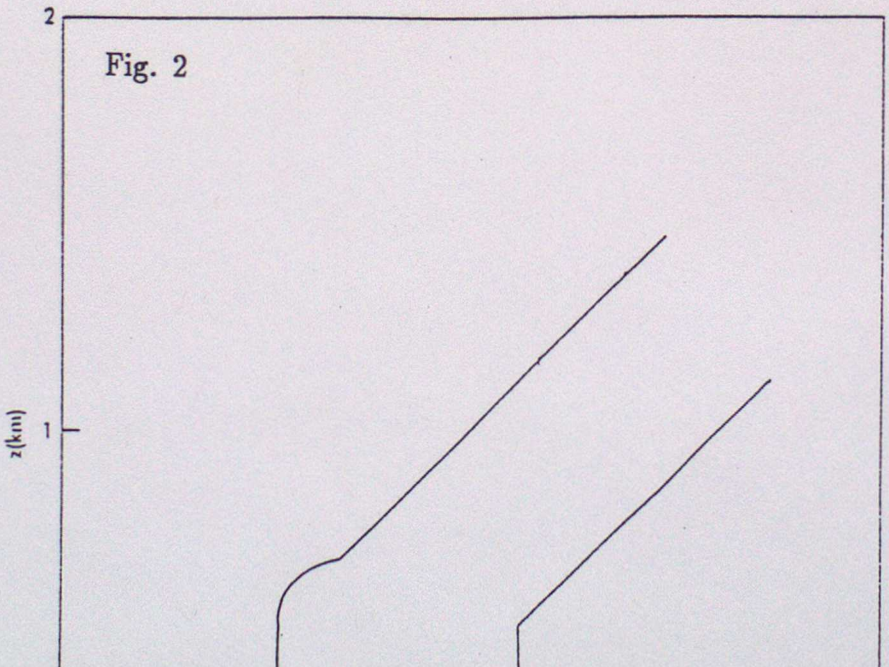
4. Typical 12Z profile with the potential temperature at the surface below that at model level 1 ($\eta = 0.997$). It is easy to see how this (probably) anomalous profile would upset the parcel method of estimating BL depth.

Fig. 1



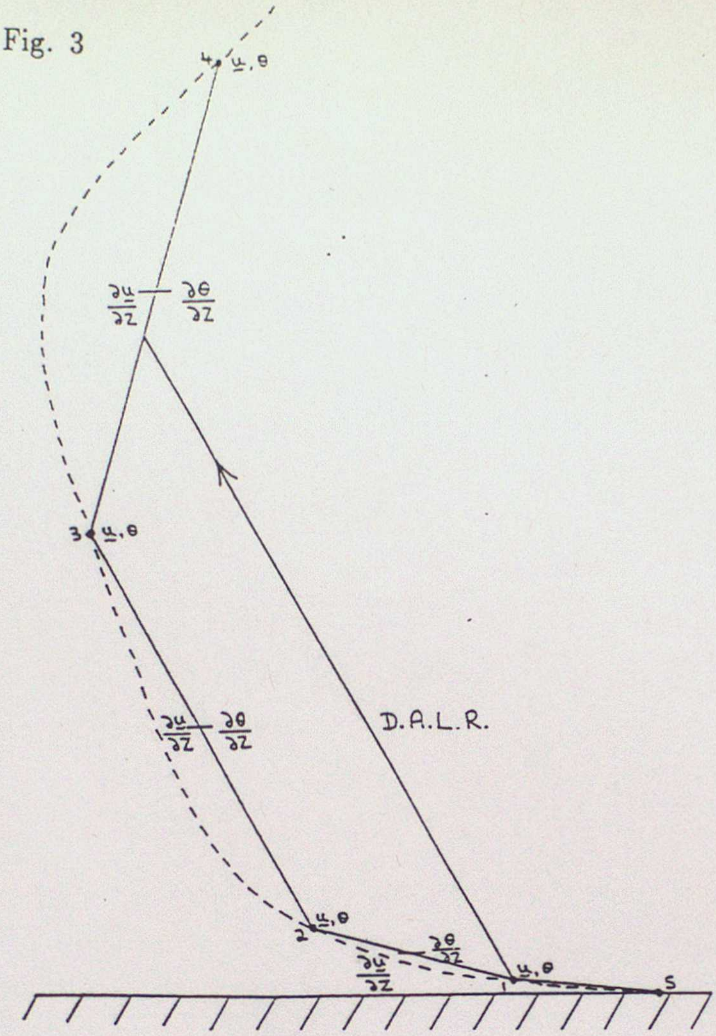
Flux divergence (W m^{-1} × 10^{-3})
−3
−2
−1
0
25
50
75
100
125
150
175
200
225
250
Resolution (m)

Fig. 2



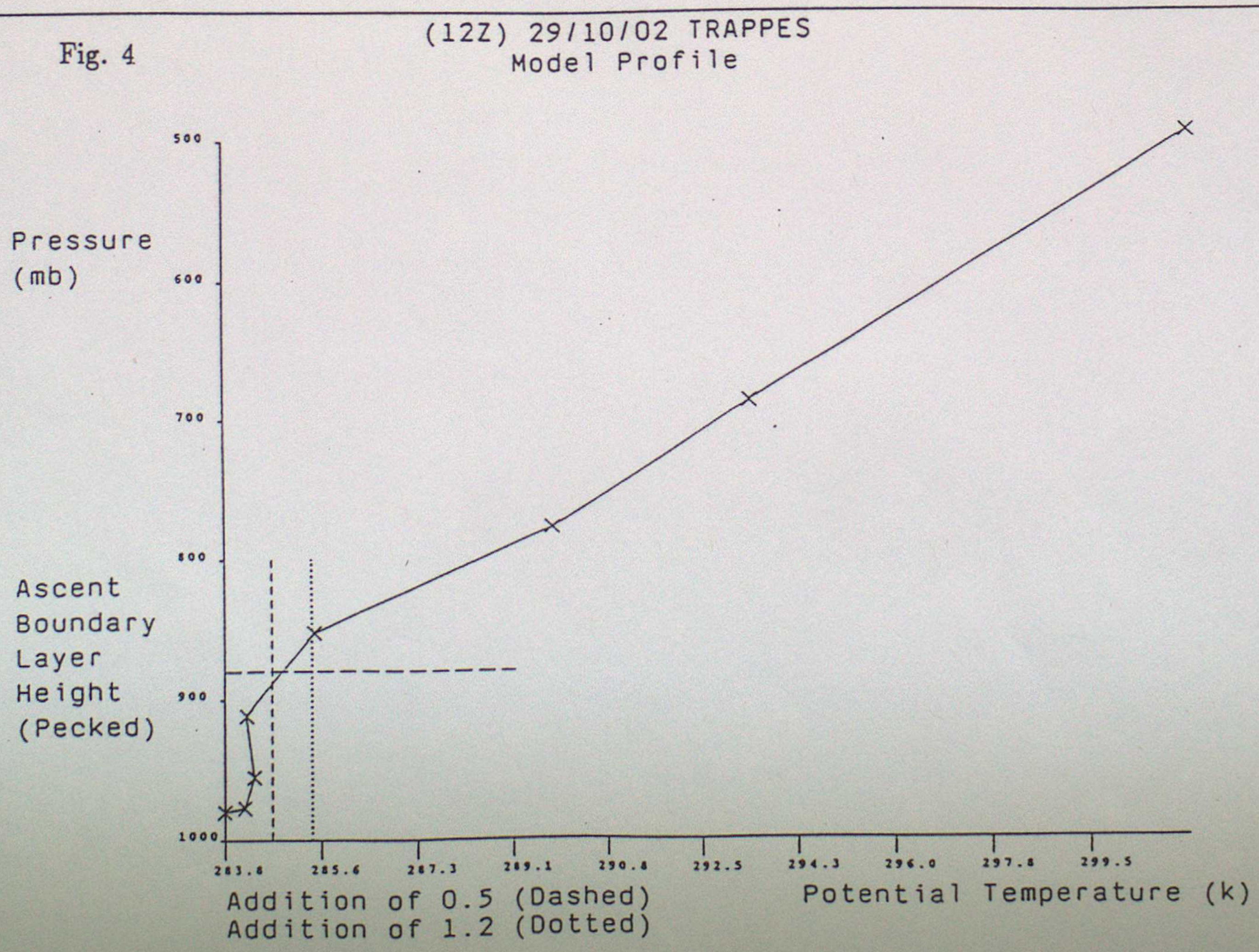
2
1
0
z(km)
Buoyancy

Fig. 3



4
u, θ
∂u/∂z — ∂θ/∂z
3
u, θ
∂u/∂z — ∂θ/∂z
D.A.L.R.
2
u, θ
∂θ/∂z
∂u/∂z
1
u, θ
s

Fig. 4



(12Z) 29/10/02 TRAPPES
Model Profile
Pressure
(mb)
500
600
700
800
900
1000
Ascent
Boundary
Layer
Height
(Pecked)
283.8
285.6
287.3
289.1
290.8
292.5
294.3
296.0
297.8
299.5
Addition of 0.5 (Dashed)
Addition of 1.2 (Dotted)
Potential Temperature (k)

Table 1: Contingency table. Rows: Percentage of model BL's warm, roughly similar and cool compared with soundings; Columns: Percentage of model grid points *next below inversion* (as estimated from sounding) warm, roughly similar and cool compared with sounding.

27	12	0	39
4	12	0	16
6	6	33	45
37	30	33	

Table 2: Midday BL depths estimated using the Richardson number based methods, in mb.

MIDDAY RESULTS										
Date	*Station*	*Ascent*	*Method 1*		*Method 2*		*Method 3*		*Method 4*	
			Ht.	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*
13/10/92	Athens	890	941	51	945	55	923	33	949	59
	Berlin	930	946	16	975	45	928	-2	953	23
	Izmir	850	867	17	878	28	848	-2	883	33
	Munchen	880	916	36	912	32	873	-7	897	17
	Praha	850	945	95	941	91	896	46	921	71
14/10/92	Munchen	880	916	36	912	32	873	-7	897	17
	Trappes	920	954	34	950	30	904	-16	930	10
15/10/92	Budapest	875	925	50	942	67	900	25	925	50
	Gibraltar	950	1010	60	996	46	975	25	995	45
16/10/92	Izmir	805	996	191	981	176	961	156	980	175
	Trappes	835	889	54	911	76	887	52	911	76
17/10/92	Berlin	845	905	60	937	92	905	60	930	85
	Bordeaux	890	899	9	897	7	835	-55	870	-20
	Gibraltar	870	921	51	944	74	914	44	939	69
	Izmir	880	996	116	996	116	970	90	990	110
18/10/92	Athens	975	919	-56	954	-21	919	-56	944	-31
	Budapest	920	942	22	951	31	942	22	960	40
	Trappes	910	927	17	934	24	895	-15	921	11
19/10/92	Budapest	895	935	40	948	53	910	15	935	40
	Lisboa	930	997	41	973	43	956	26	975	45
	Munchen	915	918	3	924	9	918	3	936	21
20/10/92	Athens	930	961	31	972	42	928	-2	953	23
	Izmir	880	986	106	979	99	975	95	995	115
	Lisboa	940	990	50	985	45	960	20	980	40
	Trappes	875	924	49	913	38	924	49	916	41

Table 2 continued

MIDDAY RESULTS										
Date	*Station*	*Ascent*	*Method 1*		*Method 2*		*Method 3*		*Method 4*	
			Ht.	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*
21/10/92	Athens	975	974	-1	971	-4	923	-52	949	-26
	Gibraltar	930	946	16	964	34	923	-7	949	19
22/10/92	Gibraltar	915	965	50	973	58	928	13	953	38
23/10/92	Gibraltar	940	997	57	994	54	980	40	999	59
	Lisboa	870	995	125	978	108	970	100	990	120
24/10/92	Gibraltar	975	1013	38	1013	38	1013	38	1013	38
	Lisboa	925	1010	85	1001	76	975	50	995	70
25/10/92	Berlin	810	981	171	968	158	956	146	975	165
	Lisboa	930	1000	70	988	58	970	40	990	60
26/10/92	Trappes	825	898	73	895	70	831	6	866	41
27/10/92	Budapest	870	898	28	941	71	896	26	921	51
	Praha	875	914	39	920	45	882	7	907	32
28/10/92	Izmir	865	1012	147	995	130	975	110	995	130
29/10/92	Bordeaux	930	982	52	986	56	961	31	980	50
	Izmir	940	1005	65	983	43	970	30	990	50
	Munchen	810	872	62	876	66	860	50	883	73
	Trappes	880	887	7	921	41	887	7	911	31
30/10/92	Lisboa	900	953	53	947	47	905	5	930	30
31/10/92	Bologna	935	998	63	998	63	998	63	998	63
	Lisboa	930	980	50	969	39	970	40	990	60
01/11/92	Lisboa	925	993	68	974	49	975	50	995	70
02/11/92	Lisboa	880	1008	128	1008	128	1008	128	1008	128
03/11/92	Athens	905	994	89	991	86	980	75	999	94
	Lisboa	945	1013	68	1003	58	975	30	995	50
04/11/92	Athens	965	1015	50	1006	41	980	15	999	34
	Bologna	880	985	105	995	115	975	95	995	115
R.M.S. ERROR			72.6		70.9		56.7		69.5	
MEAN MODULUS ERROR			60.3		60.9		42.7		58.1	
MEAN ERROR			58.1		60.0		34.0		55.1	

Table 3: Midnight BL depths estimated using Richardson number based methods, in mb.

MIDNIGHT RESULTS										
Date	*Station*	*Ascent*	*Method 1*		*Method 2*		*Method 3*		*Method 4*	
			Ht.	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*
26/10/92	Athens	1010	1008	-2	1008	-2	1008	-2	1008	-2
	Bologna	980	972	-8	959	-21	961	-19	980	0
	Budapest	955	949	-6	940	-15	949	-6	960	5
	Izmir	980	962	-18	960	-20	923	-57	949	-31
27/10/92	Bologna	975	993	18	993	18	993	18	993	18
	Lisboa	955	995	40	977	22	966	11	985	30
28/10/92	Bologna	1005	998	-7	998	-7	998	-7	998	-7
	Bordeaux	980	950	-30	938	-42	905	-75	930	-50
	Budapest	970	889	-81	868	-102	830	-140	866	-104
	Izmir	980	1009	29	994	14	970	-10	990	10
29/10/92	Athens	1010	1008	-2	1008	-2	1008	-2	1008	-2
	Bologna	975	977	2	959	-16	961	-14	980	5
	Bordeaux	975	959	-16	955	-20	956	-19	975	0
	Budapest	950	968	18	945	-5	937	-13	956	6
30/10/92	Athens	970	1014	44	995	25	975	5	995	25
	Bologna	980	998	18	998	18	998	18	998	18
	Budapest	960	978	18	978	18	978	18	978	18
	Munchen	950	946	-4	929	-21	913	-37	931	-19
31/10/92	Bologna	940	997	57	974	34	966	26	985	45
03/11/92	Gibraltar	980	1013	33	1013	33	1013	33	1013	33
04/11/92	Bologna	985	1008	23	1008	23	1008	23	1008	23
	Lisboa	975	1002	27	990	15	966	-9	985	10
05/11/92	Bologna	1000	1013	13	1013	13	1013	13	1013	13
	Lisboa	975	1003	28	985	10	966	-9	985	10
06/11/92	Athens	1010	1019	9	984	-26	980	-30	999	-11
	Lisboa	990	1008	18	1008	18	1008	18	1008	18
R.M.S. ERROR			34.1		32.9		39.1		33.1	
MEAN MODULUS ERROR			24.6		24.3		26.3		22.5	
MEAN ERROR			11.2		1.3		-7.5		5.1	

Table 4: Comparison of two critical Richardson numbers for midday results.

MIDDAY RESULTS										
Date	*Station*	*Ascent*	*Method 1*		*Method 2*		*Method 3*		*Method 4*	
			Ht.	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*
R_i(crit) = 1.3										
30/10/92	Lisboa	900	953	53	947	47	905	5	930	30
31/10/92	Bologna	935	998	63	998	63	998	63	998	63
	Lisboa	930	980	50	969	39	970	40	990	60
01/11/92	Lisboa	925	993	68	974	49	975	50	995	70
02/11/92	Lisboa	880	1008	128	1008	128	1008	128	1008	128
03/11/92	Athens	905	994	89	991	86	980	75	999	94
	Lisboa	945	1013	68	1003	58	975	30	995	50
04/11/92	Athens	965	1015	50	1006	41	980	15	999	34
	Bologna	880	985	105	995	115	975	95	995	115
R.M.S. ERROR			79.1		76.1		66.8		78.5	
MEAN MODULUS ERROR			74.9		69.6		55.7		71.6	
MEAN ERROR			74.9		69.6		55.7		71.6	
R_i(crit) = 7.2										
30/10/92	Lisboa	900	945	45	935	35	905	5	930	30
31/10/92	Bologna	935	900	-35	900	-35	843	-92	879	-56
	Lisboa	930	966	36	951	29	919	-11	944	14
01/11/92	Lisboa	925	973	48	969	44	923	-2	949	24
02/11/92	Lisboa	880	973	93	939	59	923	43	949	69
03/11/92	Athens	905	971	66	957	52	928	23	953	48
	Lisboa	945	1012	67	995	50	975	30	995	50
04/11/92	Athens	965	1012	47	1001	36	980	15	999	34
	Bologna	880	981	101	989	109	975	95	995	115
R.M.S. ERROR			75.3		66.6		62.7		72.4	
MEAN MODULUS ERROR			67.9		57.4		45.1		59.4	
MEAN ERROR			60.9		50.4		24.1		48.2	

Table 5: Comparison of two critical Richardson numbers for midnight results.

MIDNIGHT RESULTS										
Date	*Station*	*Ascent*	*Method 1*		*Method 2*		*Method 3*		*Method 4*	
			Ht.	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*	*Ht.*	*Diff.*
R_i(crit) = 1.3										
31/10/92	Bologna	940	997	57	974	34	966	26	985	45
03/11/92	Gibraltar	980	1013	33	1013	33	1013	33	1013	33
04/11/92	Bologna	985	1008	23	1008	23	1008	23	1008	23
	Lisboa	975	1002	27	990	15	966	-9	985	10
05/11/92	Bologna	1000	1013	13	1013	13	1013	13	1013	13
	Lisboa	975	1003	28	985	10	966	-9	985	10
06/11/92	Athens	1010	1019	9	984	-26	980	-30	999	-11
	Lisboa	990	1008	18	1008	18	1008	18	1008	18
R.M.S. ERROR			29.4		23.1		21.9		23.6	
MEAN MODULUS ERROR			25.9		21.5		20.1		20.4	
MEAN ERROR			25.9		15.0		8.1		17.6	
R_i(crit) = 7.2										
31/10/92	Bologna	940	902	-38	888	-52	843	-97	879	-61
03/11/92	Gibraltar	980	1000	20	981	1	980	0	999	19
04/11/92	Bologna	985	1008	23	1008	23	1008	23	1008	23
	Lisboa	975	994	19	978	3	966	-9	985	10
05/11/92	Bologna	1000	978	-22	961	-39	928	-72	953	-47
	Lisboa	975	964	-11	945	-30	914	-61	939	-36
06/11/92	Athens	1010	1015	5	977	-33	980	-30	999	-11
	Lisboa	990	956	-34	954	-36	923	-67	949	-41
R.M.S. ERROR			23.8		31.7		55.1		35.4	
MEAN MODULUS ERROR			21.5		27.1		44.9		31.0	
MEAN ERROR			-4.8		-20.4		-39.1		-18.0	

Table 6: Percentage additions to BL depth for methods 1 to 5.

	Method 1	*Method 2*	*Method 3*	*Method 4*	*Method 5*
MIDDAY RESULTS					
Percentage	45%	63%	7%	43%	23%
R.M.S. Error	67.9	59.9	55.2	63.1	56.8
Mean Modulus Error	51.1	46.6	41.4	48.2	44.3
Mean Error	38.4	33.6	28.8	34.8	28.7
MIDNIGHT RESULTS					
Percentage	-47%	-44%	-43%	-28%	-67%
R.M.S. Error	29.7	26.5	26.4	28.6	31.5
Mean Modulus Error	21.7	19.5	19.2	21.3	24.5
Mean Error	17.4	11.5	6.0	10.3	18.2

Table 7: Midday BL depths estimated using methods 5 and 6, in mb.

MIDDAY RESULTS						
Date	*Station*	*Ascent*	*Method 5*		*Method 6*	
			Height	*Diff.*	*Height*	*Diff.*
13/10/92	Athens	890	942	52	886	-4
	Berlin	930	947	17	916	-14
	Izmir	850	958	108	917	67
	Munchen	880	892	12	898	18
	Praha	850	915	65	899	49
14/10/92	Munchen	880	892	12	880	0
	Trappes	920	924	4	908	-12
15/10/92	Budapest	875	919	44	897	22
	Gibraltar	950	989	39	960	9
16/10/92	Izmir	805	953	148	915	110
	Trappes	835	906	71	782	-53
17/10/92	Berlin	845	924	79	889	44
	Bordeaux	890	862	-28	883	-57
	Gibraltar	870	933	63	863	-7
	Izmir	880	985	105	939	59
18/10/92	Athens	975	938	-37	914	-61
	Budapest	895	955	35	947	27
	Trappes	910	915	5	858	-52
19/10/92	Budapest	895	929	34	860	-35
	Lisboa	930	970	40	920	-10
	Munchen	915	931	16	858	-57
20/10/92	Athens	930	947	17	927	-2
	Izmir	880	971	91	936	56
	Lisboa	940	975	35	926	-14
	Trappes	875	849	-26	830	-45
21/10/92	Athens	975	942	-33	918	-57
	Gibraltar	930	942	12	888	-42
22/10/92	Gibraltar	915	947	32	916	1
23/10/92	Gibraltar	940	994	54	944	4
	Lisboa	870	926	56	886	16
24/10/92	Gibraltar	975	994	19	980	5
	Lisboa	925	989	64	995	40
25/10/92	Berlin	810	970	160	933	123
	Lisboa	930	985	55	946	16

Table 7 continued

MIDDAY RESULTS						
Date	*Station*	*Ascent*	*Method 5*		*Method 6*	
			Height	*Diff.*	*Height*	*Diff.*
26/10/92	Trappes	825	858	33	836	11
27/10/92	Budapest	870	915	45	881	11
	Praha	875	901	26	872	-3
28/10/92	Izmir	865	980	115	926	61
29/10/92	Bordeaux	930	975	45	914	-16
	Izmir	940	975	35	960	20
	Munchen	810	819	9	858	48
	Trappes	880	876	-4	854	-26
30/10/92	Lisboa	900	900	0	884	-16
31/10/92	Bologna	935	998	63	994	59
	Lisboa	930	918	-12	892	-38
01/11/92	Lisboa	925	942	17	911	-14
02/11/92	Lisboa	880	989	109	942	62
03/11/92	Athens	905	994	89	949	44
	Lisboa	945	989	44	968	23
04/10/92	Athens	965	994	29	980	16
	Bologna	880	989	109	945	65
R.M.S. ERROR			60.8		43.1	
MEAN MODULUS ERROR			48.1		33.7	
MEAN ERROR			42.6		8.8	

Table 8: Midnight BL depths estimated using methods 5 and 6, in mb.

MIDNIGHT RESULTS						
Date	*Station*	*Ascent*	*Method 5*		*Method 6*	
			Height	*Diff.*	*Height*	*Diff.*
26/10/92	Athens	1010	1008	-2	1008	-2
	Bologna	980	940	-40	999	19
	Budapest	955	955	0	956	1
	Izmir	980	1008	28	895	-85
27/10/92	Bologna	975	993	18	1004	29
	Lisboa	995	980	25	955	-40
28/10/92	Bologna	1005	998	-7	1005	0
	Bordeaux	980	782	-198	930	-50
	Budapest	970	983	13	988	18
	Izmir	980	1003	23	992	12
29/10/92	Athens	1010	1008	-2	1014	5
	Bologna	975	993	18	987	12
	Bordeaux	975	924	-51	888	-86
	Budapest	950	968	18	970	20
30/10/92	Athens	970	1008	38	1014	44
	Bologna	980	998	18	1001	21
	Budapest	960	978	18	982	22
	Munchen	950	944	-6	945	-5
31/10/92	Bologna	940	998	58	989	49
03/11/92	Gibraltar	980	1013	33	997	17
04/11/92	Bologna	985	1008	23	1013	28
	Lisboa	975	980	5	964	-11
05/11/92	Bologna	1000	1013	13	1015	15
	Lisboa	975	998	23	1003	28
06/11/92	Athens	1010	1013	3	1005	-5
	Lisboa	990	1008	18	1007	17
R.M.S. ERROR			49.1		33.3	
MEAN MODULUS ERROR			29.0		24.7	
MEAN ERROR			5.4		2.8	

Table 9: Summary of the errors for all methods.

Method	*Root Mean Square Error in mb.*	*Mean Modulus Error in mb.*	*Mean Error in mb.*
MIDDAY RESULTS			
1. Linear Interpolation	72.6	60.3	58.1
2. Non–Linear Interpolation	70.9	60.9	60.0
3. Half Level > R_i(crit)	56.7	42.7	34.0
4. Level < Method 3	69.5	58.1	55.1
5. Sigma	60.8	48.1	42.6
6. Dry Adiabat	43.1	33.7	8.8
Maximum of Methods 4 and 6	41.5	31.6	6.0
Final method: Maximum of Methods 4 and 6 with second offset 0.5 for ($\theta_2 > \theta_1$)	45.2	33.7	9.7
Final method without Izmir results	38.0	28.9	1.9
Number of cases		51	
MIDNIGHT RESULTS			
1. Linear Interpolation	34.1	24.6	11.2
2. Non–Linear Interpolation	32.9	24.3	1.3
3. Half Level > R_i(crit)	39.1	26.3	-7.5
4. Level < Method 3	33.1	22.5	5.1
5. Sigma	49.1	29.0	5.4
6. Dry Adiabat	33.3	24.7	2.8
Maximum of Methods 4 and 6	36.9	24.8	-7.4
Final method: Maximum of Methods 4 and 6 with second offset 0.5 for ($\theta_2 > \theta_1$)	33.7	22.8	-5.0
Final method without Izmir results	33.5	22.2	-3.8
Number of cases		26	