Forecasting Research

Forecasting Research Division
Technical Report No. 107

A Study Of Biases In Water Vapour Using Radiosonde Data

by

Dale M. Barker

August 1994

Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ
United Kingdom

Forecasting Research Technical Note No. 107

A Study Of Biases In Water Vapour Using Radiosonde Data.

Dale M. Barker

August 1994

Abstract

A large data-base of reliable observations of atmospheric water vapour is essential to accurately represent humidity in forecast and climate models. In this paper, a global forecast model verification study is carried out using radiosonde relative humidity and temperature observations over the UK and North America. Possible origins of model and measurement humidity biases are discussed as is the sensitivity of the large-scale cloud fraction to any tuning of the humidity measurements.

1 Introduction

Measurements of water vapour are required in the field of numerical weather prediction (NWP) for two main reasons. Firstly, humidity observations are assimilated into NWP models to provide the initial distribution of water vapour from which an operational forecast is integrated forward in time. Secondly, humidity observations are routinely used to verify the performance of both NWP and climate models.

Currently, the only source of regular upper-air humidity observations is the radiosonde network. As well as supplying temperature, wind and pressure information, the radiosonde measures relative humidity and converts it to a dew-point depression D which is sent over the Global Telecommunications System (GTS) to the various receiving centres. The variety of radiosonde types, different reporting practises e.g. addition of radiation corrections before transmission by some radiosonde stations but not by others, and software differences can lead to inconsistencies in both temperature and humidity measurements which could become biases in D received by weather centres. For example, the moist bias introduced by not reporting D below temperatures of $-40^{o}C$ (hence neglecting the coolest and presumably driest observations) was examined in Elliot et al [1]. As well as adversely affecting NWP forecasts, observational biases of this type make it difficult to isolate possible sources of humidity biases in the model itself.

In both assimilation and model verification work, allowance can be made for the known *accuracy*, good or bad, of humidity measurements. However, it is more difficult to allow for any systematic *bias*. Even a small 5% bias in relative humidity can have a large impact on other variables e.g. cloud (see Section 6) so it is important to isolate the source of such biases. This paper is concerned with this problem.

Radiosonde observations are spot values situated predominantly on land in the northern hemisphere. Spatial scales of variability of humidity in the atmosphere are typically smaller than e.g. temperature. Thus representivity errors in the moisture field are important.

In Section 2 a study is made of the effect of synoptic weather conditions on the humidity and temperature biases over the UK in October 1993. The UK area was chosen for its relatively high concentration of radiosonde observations from one type of radiosonde (currently the Väisala RS80). The 'spin-up' of the moisture field in the first few hours of a forecast after the observations have been assimilated is known to be particularly bad over the UK (see e.g. Lorenc [2]). It would therefore seem useful to study the development of humidity biases in the UK in the World Meteorological Organisation (WMO) block 03 area.

Observation/background error estimates are required in the data assimilation system. Currently, unlike corresponding temperature errors, the humidity errors depend only on pressure. Their dependence on weather type is investigated in Section 3.

Possible origins of the humidity bias in the model are studied in Section 4. Observational sources of bias are discussed in Section 5. The possibility of a measured humidity bias has led to studies of a possible recalibration of radiosonde humidity values at the United Kingdom Met. Office (UKMO). A discussion of this can be found in Bell [3]. In section 6 a simple recalibration formula is used to illustrate the effect of recalibration on the cloud amount predicted by the formula for large-scale cloud used at the UKMO (Smith [4]).

A short study of the correlation of humidity biases over the UK with wind direction and time of year is made in Section 7 followed by the conclusions of the study.

2 Cyclonic And Anticyclonic Conditions In October 1993

The month of October 1993 was chosen as it presented an opportunity to study the effects of synoptic weather type on mean temperature, humidity and associated biases. The first 15 days corresponded to generally cyclonic weather conditions, followed by a period of generally anticyclonic weather from days 16 to 31 over the UK.

The data is taken from the observation processing database (OPD) of the UKMO's unified model (UM, see Cullen [6]). The OPD contains all observations passed to the NWP suite together with relevant diagnostic information such as quality control (QC) flags and observation O minus model field B differences. In this paper, the value of B is taken from a previous 6-hour global forecast run interpolated to the radiosonde's ascent time and position. The data is stored on model levels (19 for the UM at global forecast resolution).

The data used has passed QC checks, which in the case of relative humidity r includes only a background check, i.e. only if $O - B$ exceeds a given error is the observation rejected from the assimilation process. This limit is currently in the region of 70% to 80% for r in the UM's assimilation scheme (allowing for a slight dependence on pressure). As r varies between 0% and 100% it may be concluded that the QC of humidity measurements in the UM is not as stringent as for other variables.

For each period during the month, the temperature and humidity O and $O - B$ data is time-meaned at each model level, giving mean vertical profiles of observed variables and their bias with respect to the model value.

The number of data values N of r and temperature T over the whole month at each model level is plotted in Figure 1. $N(r)$ starts to decrease significantly below $N(T)$ above model level 9 (at a pressure $P \simeq 400$mb) due to both equipment

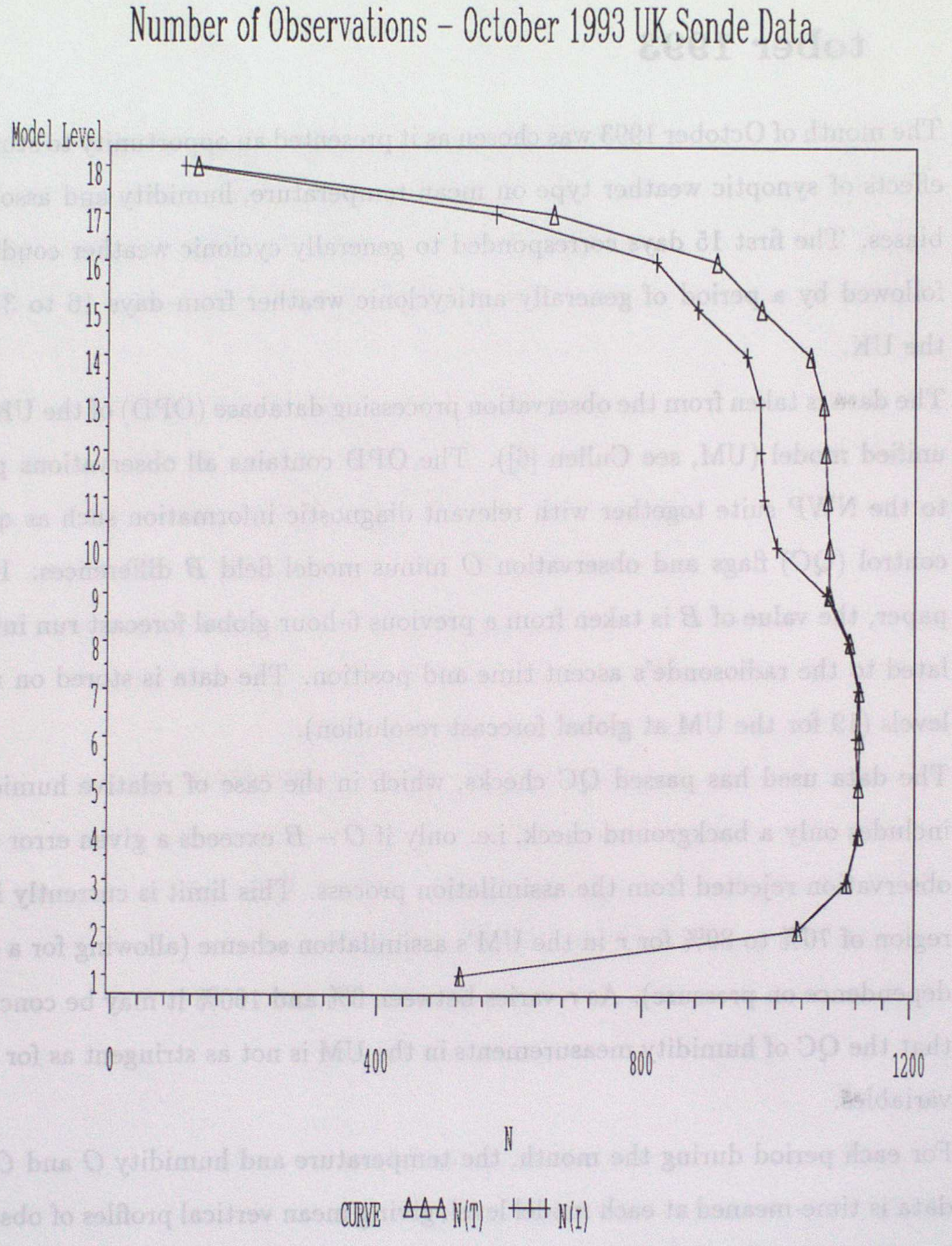

Figure 1: Number of temperature $N(T)$ and relative humidity data points, $N(T)$ and $N(r)$ respectively, at each model level used in the study of the October 1993 OPD data.

breakdown and failure to pass the QC background check. Similar failures drastically reduce both $N(r)$ and $N(T)$ in the stratosphere (P at level 14 $\simeq$ 150mb).

The mean temperature of radiosonde observations in both cyclonic and anticyclonic periods is plotted in Figure 2. Levels 1-4 are warmer on average during the cyclonic period, perhaps due to the insulation of the lowest levels by increased cloud amounts during the first half of the month. Of course, the annual cycle must also play a rôle. Above this region (corresponding roughly with the planetary boundary layer) the warmer conditions are found during the anticyclonic period. The temperature $O - B$ bias for each period is shown in Figure 3. A model cool (or measured warm) bias exists throughout the middle troposphere during the cyclonic period. During the second period the bias is not so clear-cut. In and above the upper troposphere a positive bias increases with model level during both periods.

Inter-comparisons of the various radiosondes used around the world are held every few years. One conclusion to be drawn from such studies is that temperature measurements do not suffer significantly from any large bias. It is therefore assumed in this paper that the positive temperature bias is due to a model cool bias of $\simeq 0.2^{o}$C in the lower to middle troposphere in cyclonic conditions. In both periods there exists a model cool bias in the upper troposphere which increases to $\simeq 1^{o}$C in the stratosphere.

The mean relative humidity is plotted against model level in Figure 4. During the cyclonic period the lowest levels are on average 10% moister than in the anticyclonic period. This difference increases to a maximum of $\simeq$ 40% in the middle troposphere and decreases again above this. The humidity $O - B$ bias is shown in Figure 5 for each period. There exists a -10% humidity $O - B$ bias near the surface which increases to nearly zero in both cases at level 4. This behaviour mirrors that of the temperature $O - B$ bias in Figure 3.

As r is a function of T, there exists the possibility that the moist bias is due to a

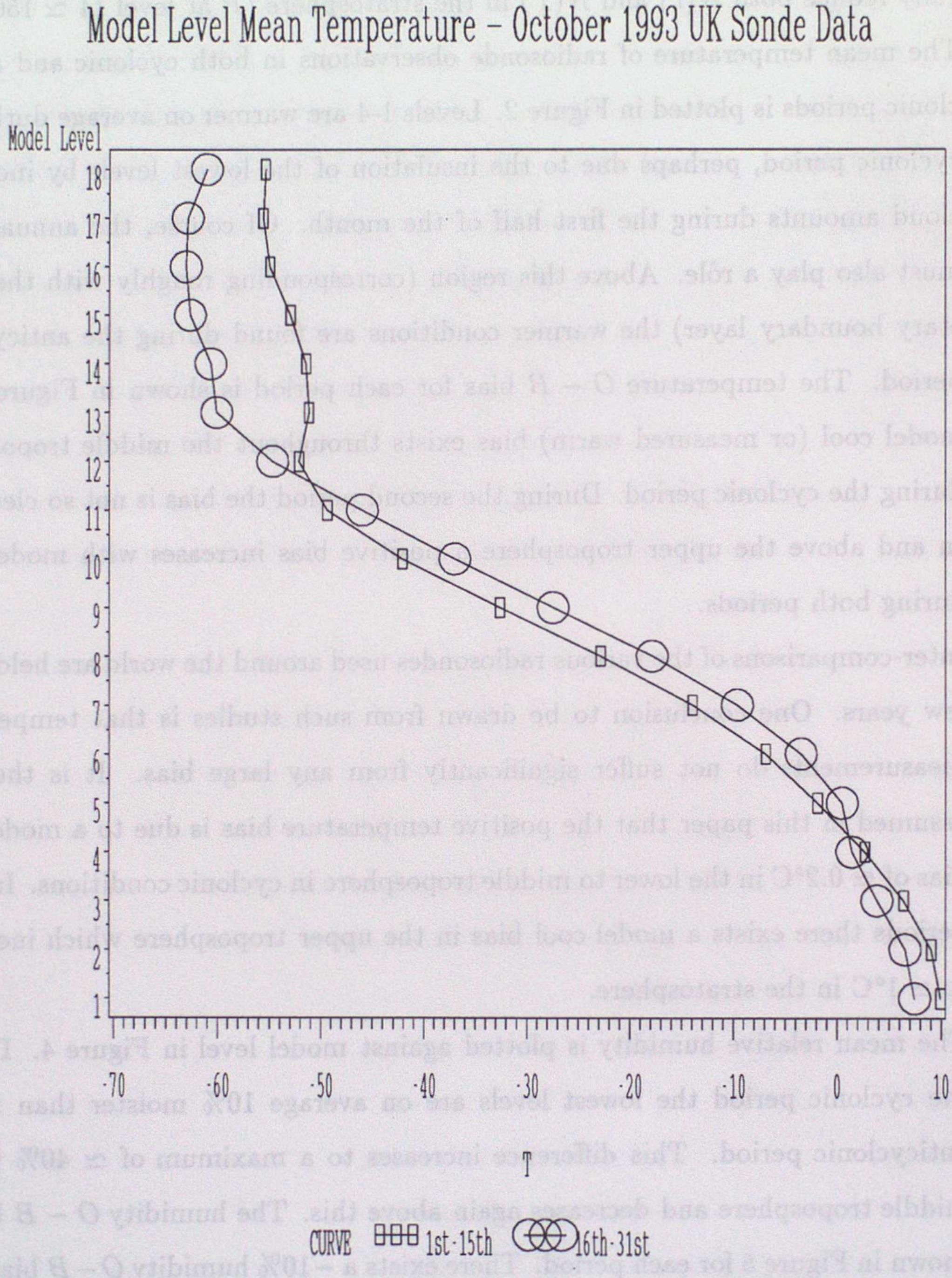

Figure 2: Model level mean temperature for UK radiosondes during cyclonic (1st to the 15th) and anticyclonic (16th to the 31st) periods in October 1993.

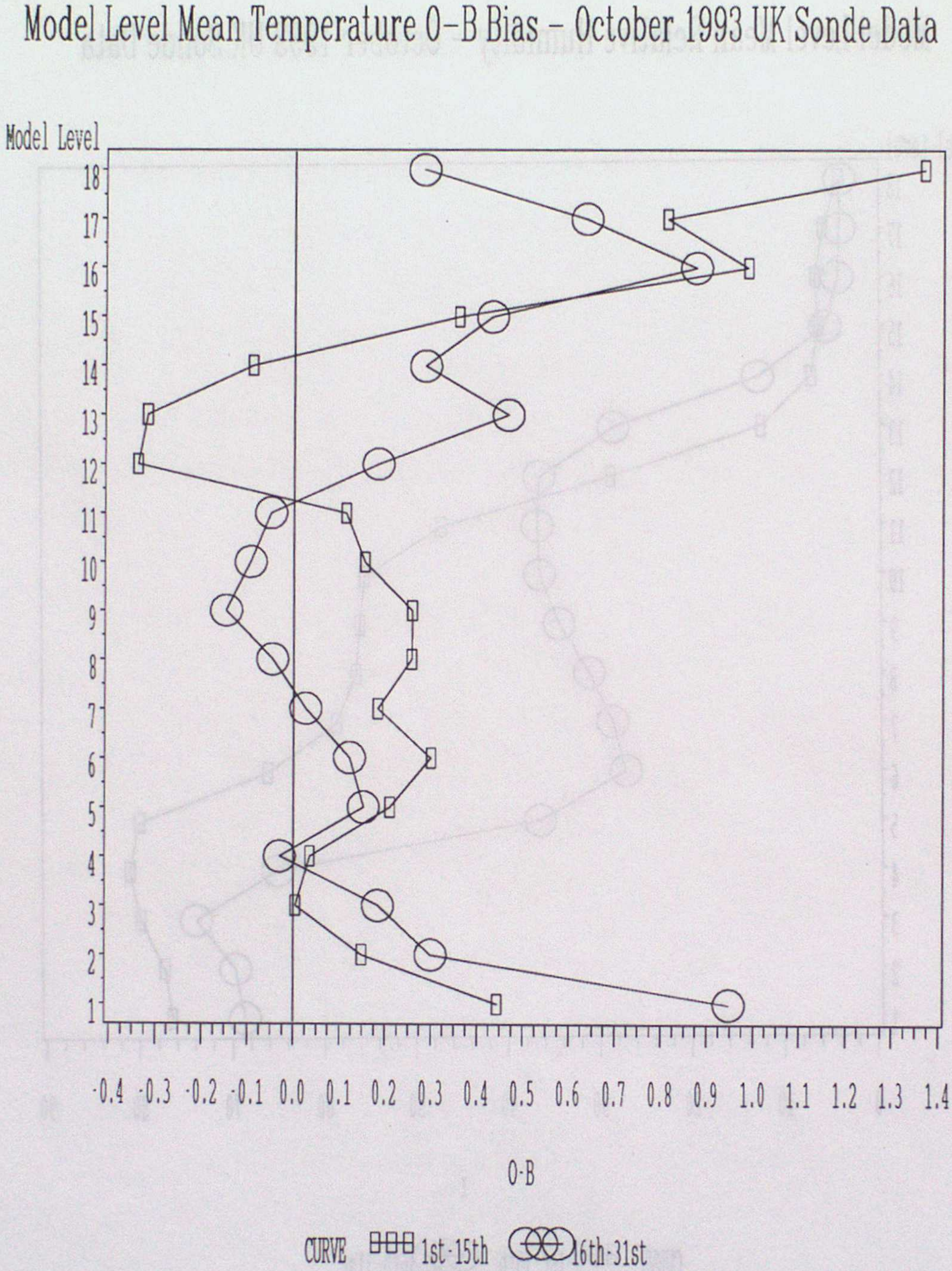

Figure 3: Temperature $O-B$ bias for UK radiosondes for each period in October 1993 plotted against model level.

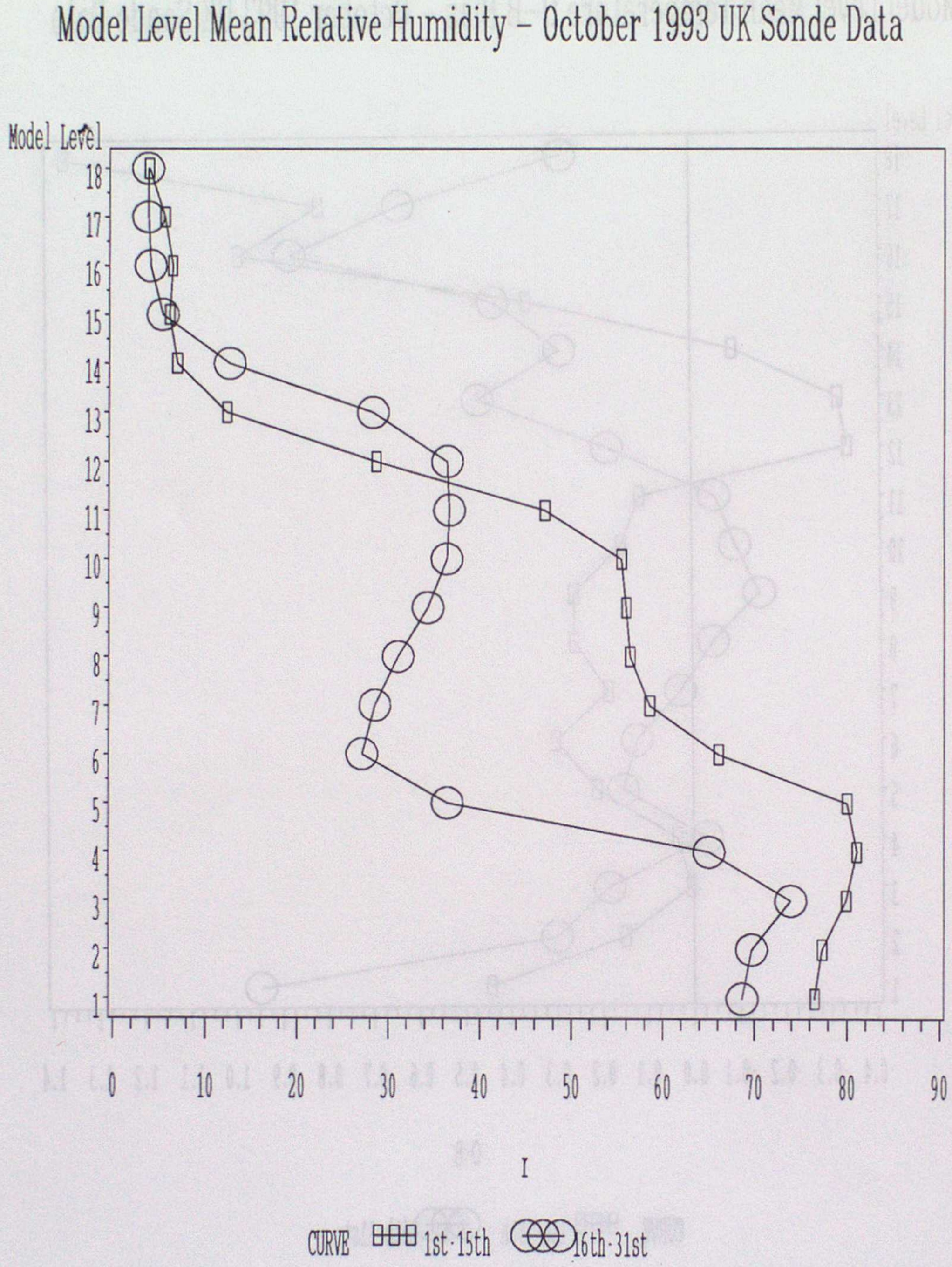

Figure 4: Model level mean relative humidity for UK radiosondes during each period in October 1993.

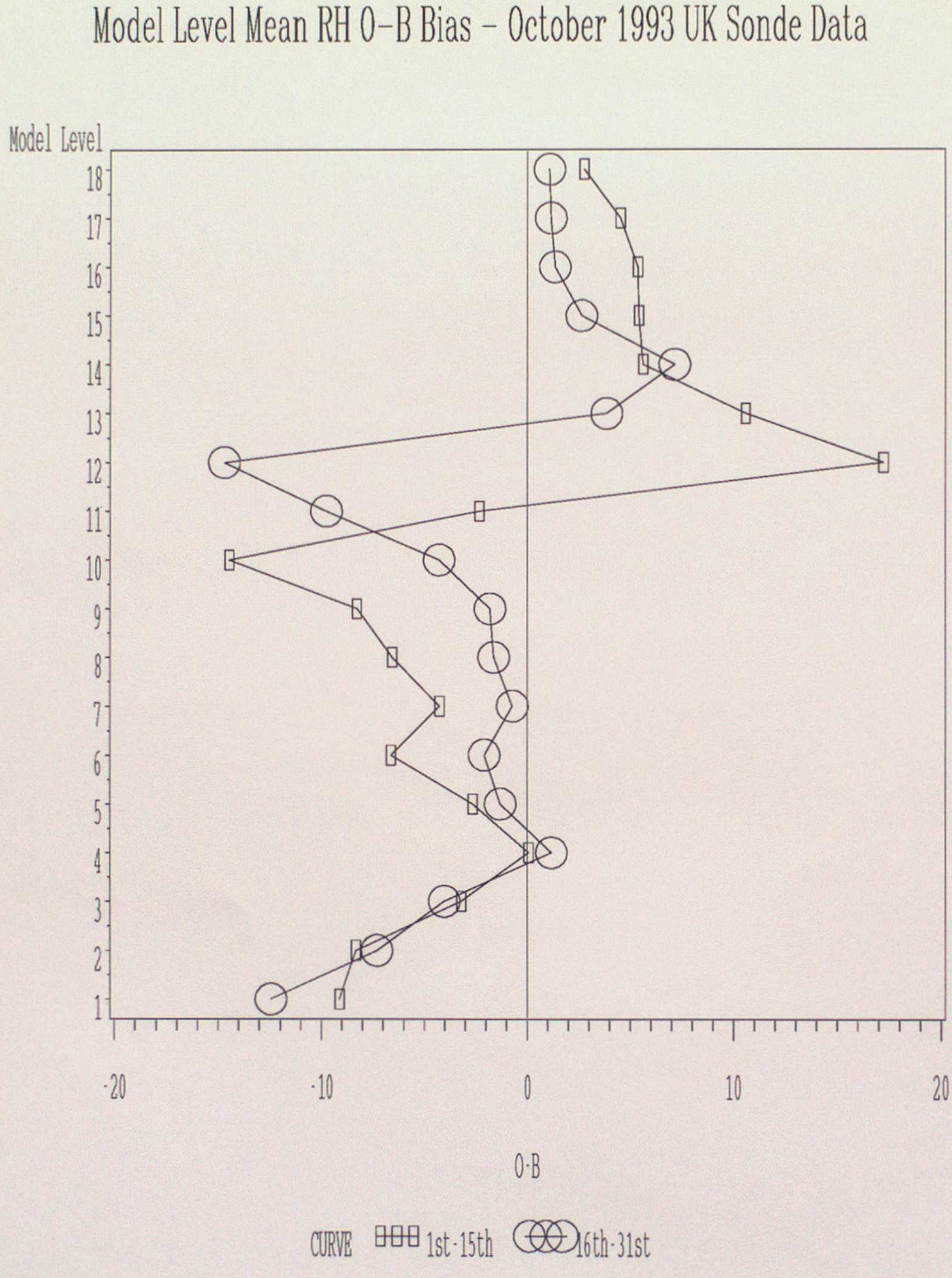

Figure 5: Humidity $O - B$ bias for UK radiosondes during cyclonic and anticyclonic periods in October 1993.

cool temperature bias at constant specific humidity q. This possibility is explored in subsection 4.1 below. Above level 4, the bias decreases with increasing model level to a maximum magnitude of $\simeq -15\%$ in the upper troposphere for both types of weather conditions. During the cyclonic conditions, a larger bias exists through the middle troposphere and reaches its maximum value at a lower model level than in the anticyclonic conditions (note: this behaviour is not mirrored in the temperature bias). It is noteworthy that the peak of the humidity bias in each curve in Figure 5 corresponds to the top of the region above which the mean relative humidity decreases rapidly. Above this level, the bias changes sign.

The accuracy of radiosonde humidity measurements is seriously reduced above $P = 200$mb, so no comment is made on the origin of the high level bias. The secondary peak in humidity bias at model level 6 is interesting as it is at this level ($P \simeq 700$mb) that the maximum humidity $O-B$ bias was found in a similar study of data from the UM's mesoscale model (A. Maycock, personal communication). The negative tropospheric humidity $O-B$ bias could be due to a moist model bias or a dry bias in the radiosonde observations. The first possibility is discussed in Section 4 below. Possible humidity biases originating from the actual measurement or in reporting practises used to transmit the data are discussed in Section 5.

3 Observation/Background Error Estimates

Variances of observational $O-t$ and background $B-t$ errors where t is truth, denoted σ_o^2 and σ_b^2 respectively, are required by the UM to assign weights to the data in the assimilation system. Current values used in the UM for relative humidity are given in Table 3.1. Unlike e.g. temperature variances, the humidity variances are only dependent on pressure level.

Table 3.1: Table of humidity $(\sigma_o^2 + \sigma_b^2)^{1/2}$ values currently used in the UKMO assimilation scheme for pressure P corresponding to model level M.

P(mb)	1000	850	700	500	≤ 300
M	1	4	6	8	≥ 11
$(\sigma_o^2 + \sigma_b^2)^{1/2}$	15.6	15.6	17.8	21.6	23.9

The root mean square (rms) $O - B$ differences

$$\overline{(O-B)^2}^{1/2} = \left[\sigma_o^2 + \sigma_b^2 + \overline{(O-t)}^2 + \overline{(B-t)}^2\right]^{1/2} \qquad (3.1)$$

of the $O - B$ data are readily calculated from the OPD data used in Section 2. The rms values are plotted for each period in October 1993 in Figure 6, in which a clear dependence on synoptic conditions is seen.

Assuming unbiased model and observed humidities, from equation 3.1 $(\sigma_o^2+\sigma_b^2)^{1/2}$ in Table 3.1 would ideally follow the rms curves in Figure 6. This is roughly the case during the cyclonic period. However, we know from the work in Section 2 that a significant humidity $O - B$ bias does exists. The values in Table 3.1 overestimate the size of the combined observation/background error estimates needed to give the observed rms differences in cyclonic weather conditions.

4 Possible Sources Of A Model Moist Bias

In this section two possible origins of a model moist bias are investigated.

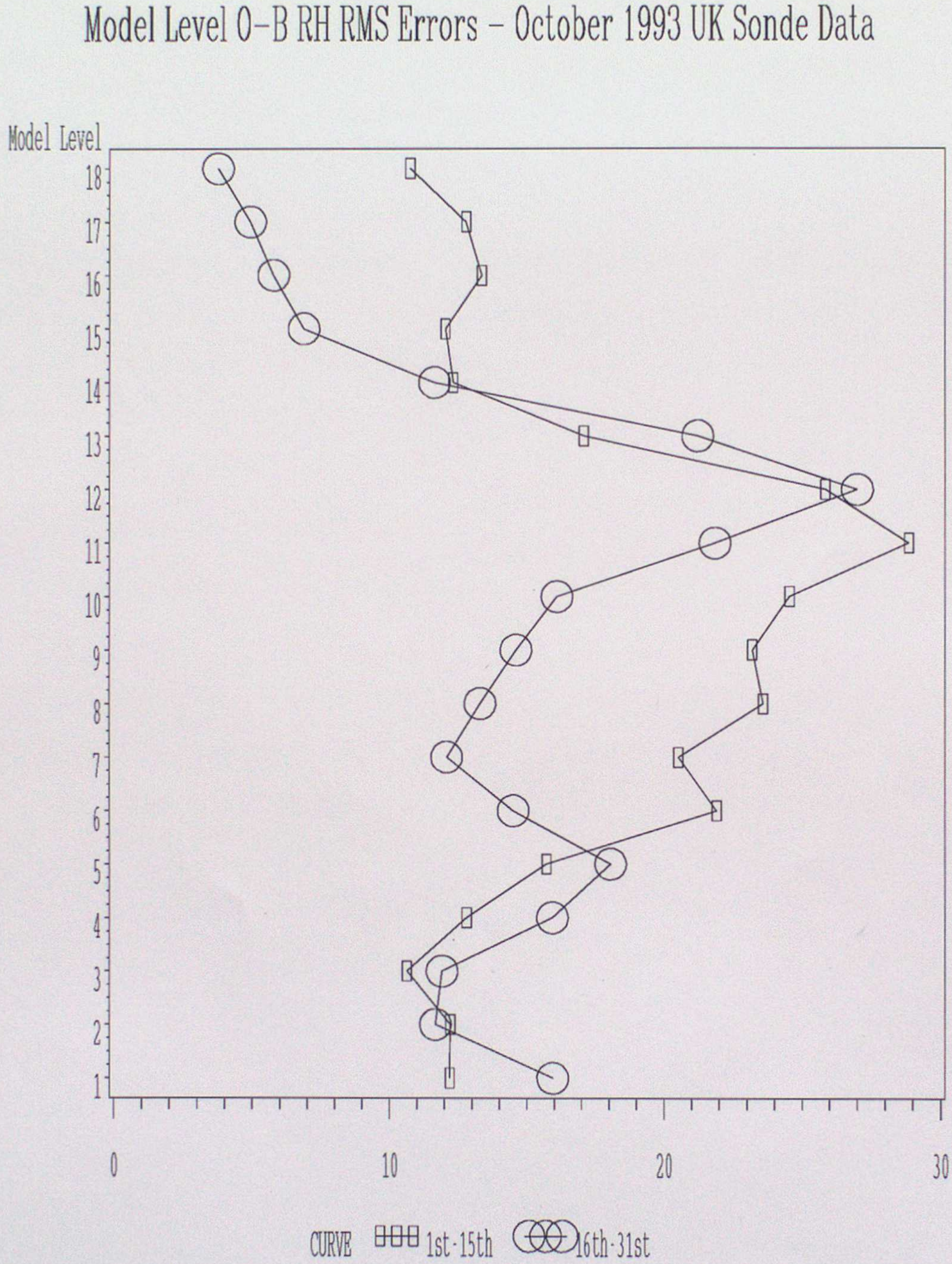

Figure 6: Model level rms humidity $O - B$ errors for UK radiosondes for each period in October 1993.

4.1 Model moist bias due to the model cool bias at constant q

Assuming a model cool temperature bias ΔT, the corresponding humidity bias Δr_1 at constant q is given by

$$\Delta r_1 = -2.3026 \left(\frac{\partial \log_{10} e_s}{\partial T} \right)_q \Delta T \tag{4.2}$$

using the relations $r = 100q/q_s$ and $q_s = 0.62198 e_s(T)/P$ where q_s is the saturated specific humidity. Values of the saturated vapour pressure e_s over ice and water are taken from the Goff-Gratch formula adopted by the World Meteorological Organisation (WMO) described in Landolt-Bornstein [7].

The humidity 'cooling correction' Δr_1 is calculated for each temperature $O - B$ datum in the October 1993 OPD data using equation 4.2. The resulting moisture bias is plotted as a dotted curve for each period along with the actual humidity $O - B$ bias in Figures 7 and 8. In both cases the coolng correction is considerably smaller than actual moist $O - B$ bias. Therefore the actual humidity bias cannot be explained by the model cool bias at constant q.

4.2 Model moist bias due to the model cool bias through lack of model precipitation

The thermal energy E of an air parcel is the sum of its sensible and latent heats:

$$E = c_p T + Lq \tag{4.3}$$

where c_p is the specific heat at constant pressure and L is the latent heat of vapourisation. After replacing q with r and differentiating equation 4.3 with respect to T at constant E we have

$$c_p + \frac{L}{100} \left(r \frac{dq_s}{dT} + q_s \frac{dr}{dT} \right) = 0. \tag{4.4}$$

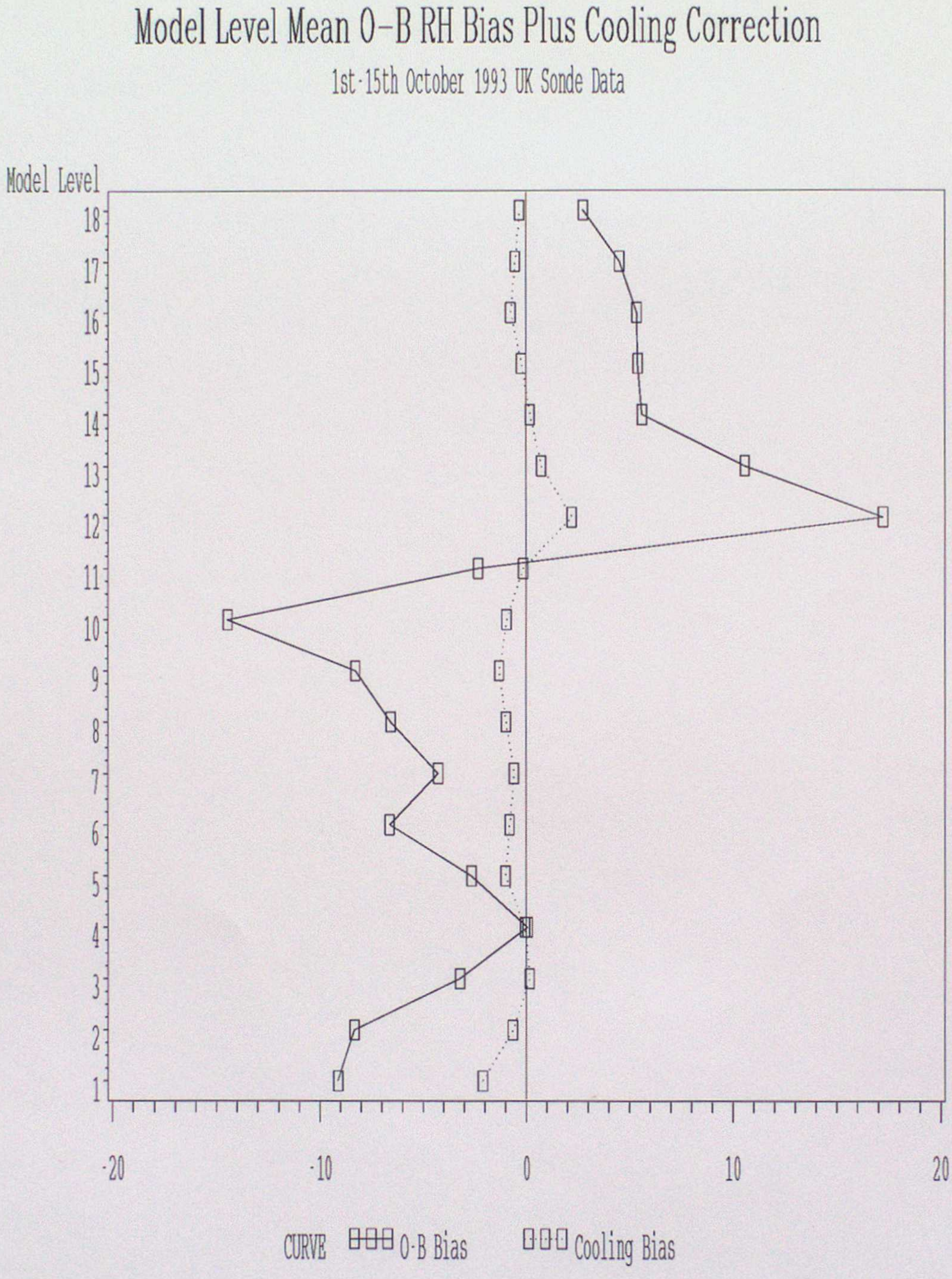

Figure 7: Actual humidity $O-B$ bias (solid line) and the humidity $O-B$ bias due to a temperature bias at constant specific humidity q (dotted line). 1st-15th October 1993 UK radiosonde data.

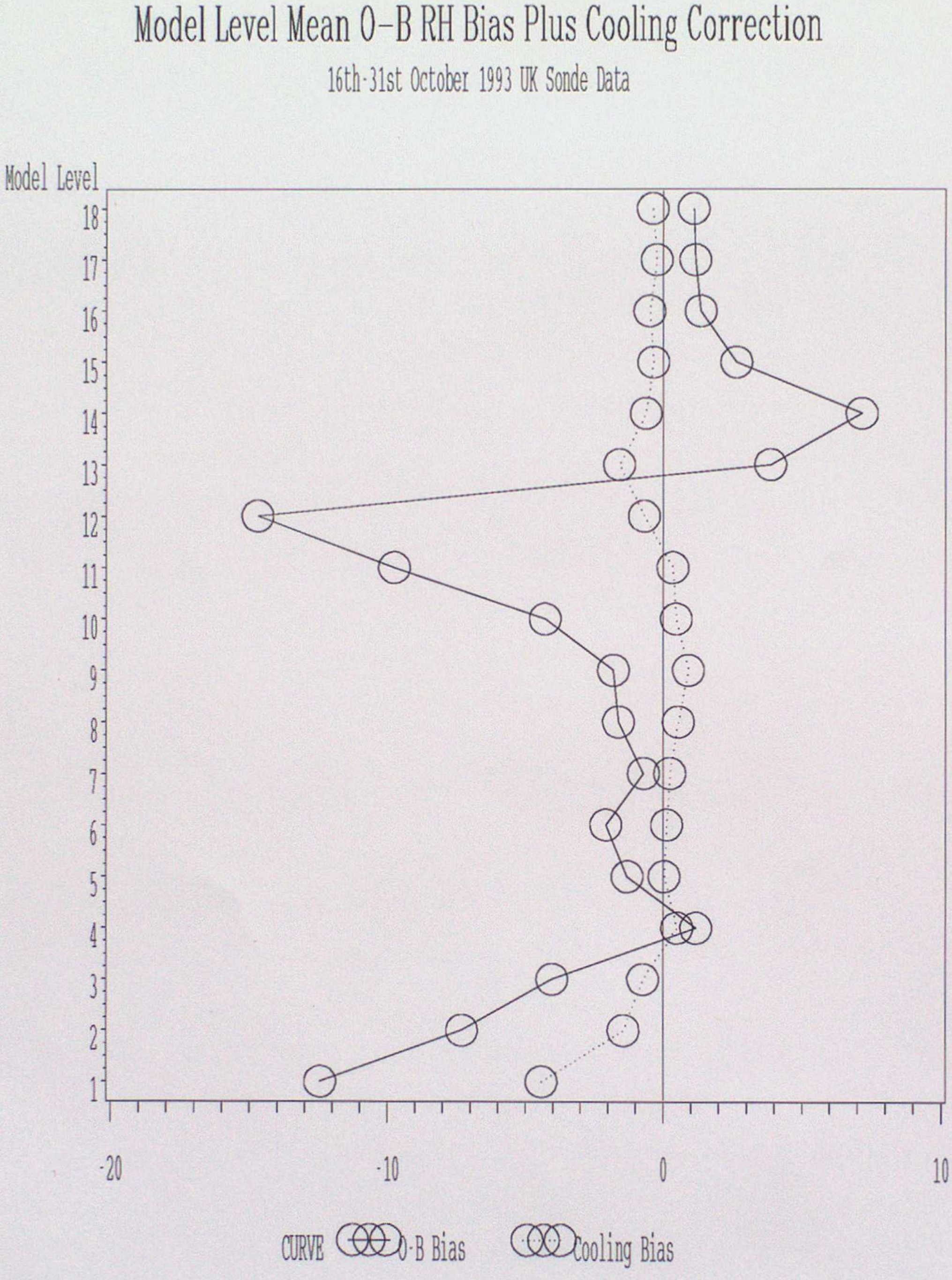

Figure 8: Same as Figure 7 but for the 16th-31st October 1993 UK radiosonde data.

Neglecting the second term in brackets on the left hand side (which we have shown in subsection 4.1 to be small), a temperature error ΔT will lead to a humidity error Δr_2 given by

$$\Delta r_2 \simeq -\frac{100}{q_s}\frac{c_p}{L}\Delta T \qquad (4.5)$$

Applying this equation to the October 1993 temperature $O-B$ errors leads to a moist bias as shown in Figures 9 and 10. During the cyclonic period, this source of moist bias possibly explains the majority of the actual humidity $O-B$ bias between model levels 4-8. Values of this moist bias are missing at certain levels in the upper troposphere. At these levels, the low temperature and hence q_s implies an unrealistically large due moist bias. In general, the moist bias shown could be an indication that the model is not removing enough moisture from the atmosphere through precipitation. Insufficient rain would be linked to a low value for the latent heat liberated by the model and hence would imply a cool bias. Further work would be required to investigate this scenario further.

5 Biases in Radiosonde Humidity Measurements

It cannot automatically be assumed that the humidity $O-B$ biases discussed above are due to a model moist bias alone. The possibility of a dry observational radiosonde humidity bias cannot be ruled out.

Initial evidence comes from observers commenting on the low maximum relative humidity reported by Väisala radiosondes (as low as 80%) when the radiosonde is known to have passed through cloud. Further evidence for a dry bias can be found in radiosonde intercomparisons which frequently indicate low values of r from Väisala radiosondes compared to others. Väisala radiosondes are not currently calibrated in the region 80% to 100% which may be lead to problems in the humidity range of most importance to meteorologists. Tests are underway at the UKMO to 'boost' the radiosonde humidity values between 80% and 100%

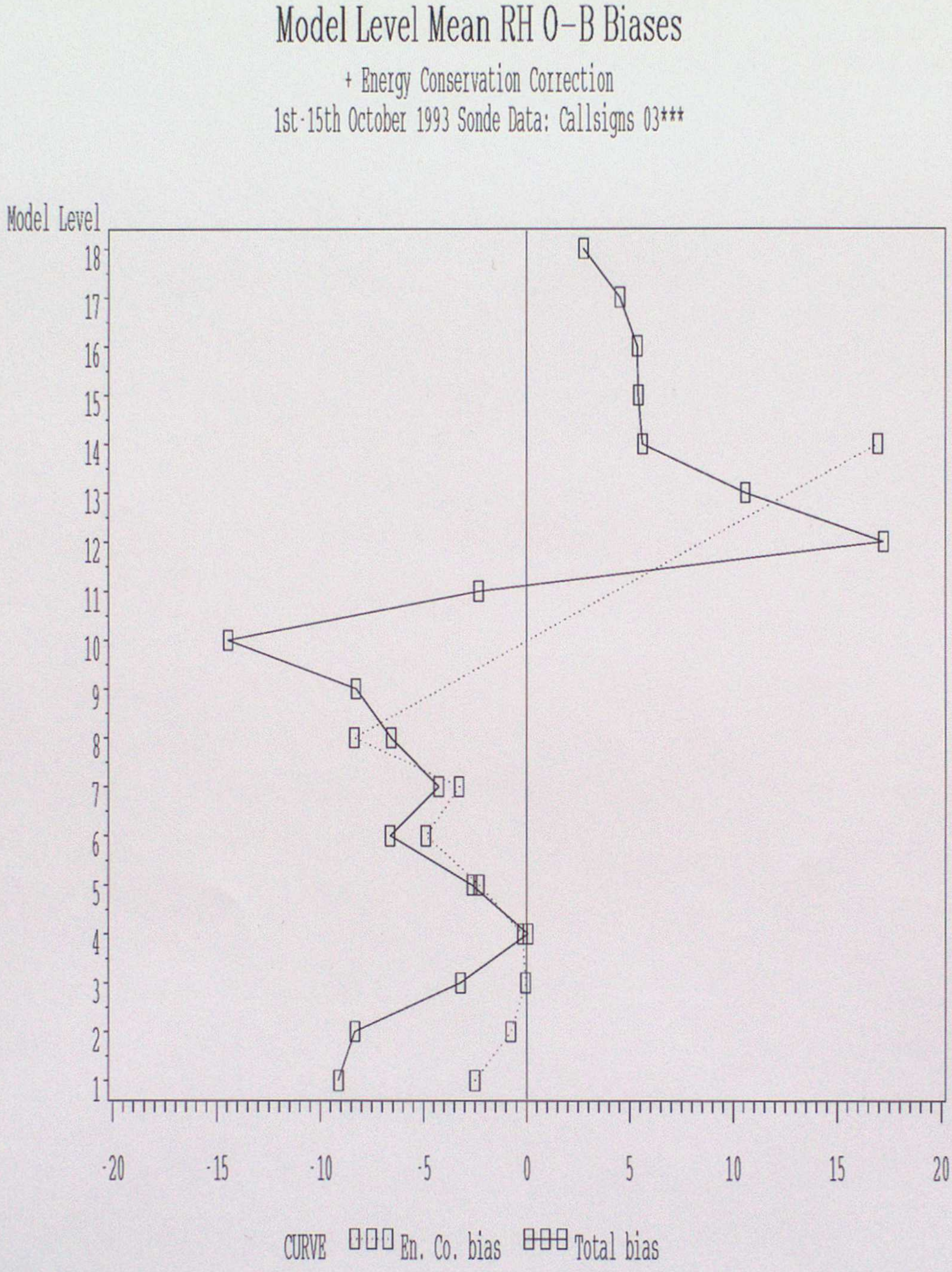

Figure 9: Actual humidity $O - B$ bias (solid line) and the humidity $O - B$ bias due to a temperature bias at constant E. 1st-15th October 1993.

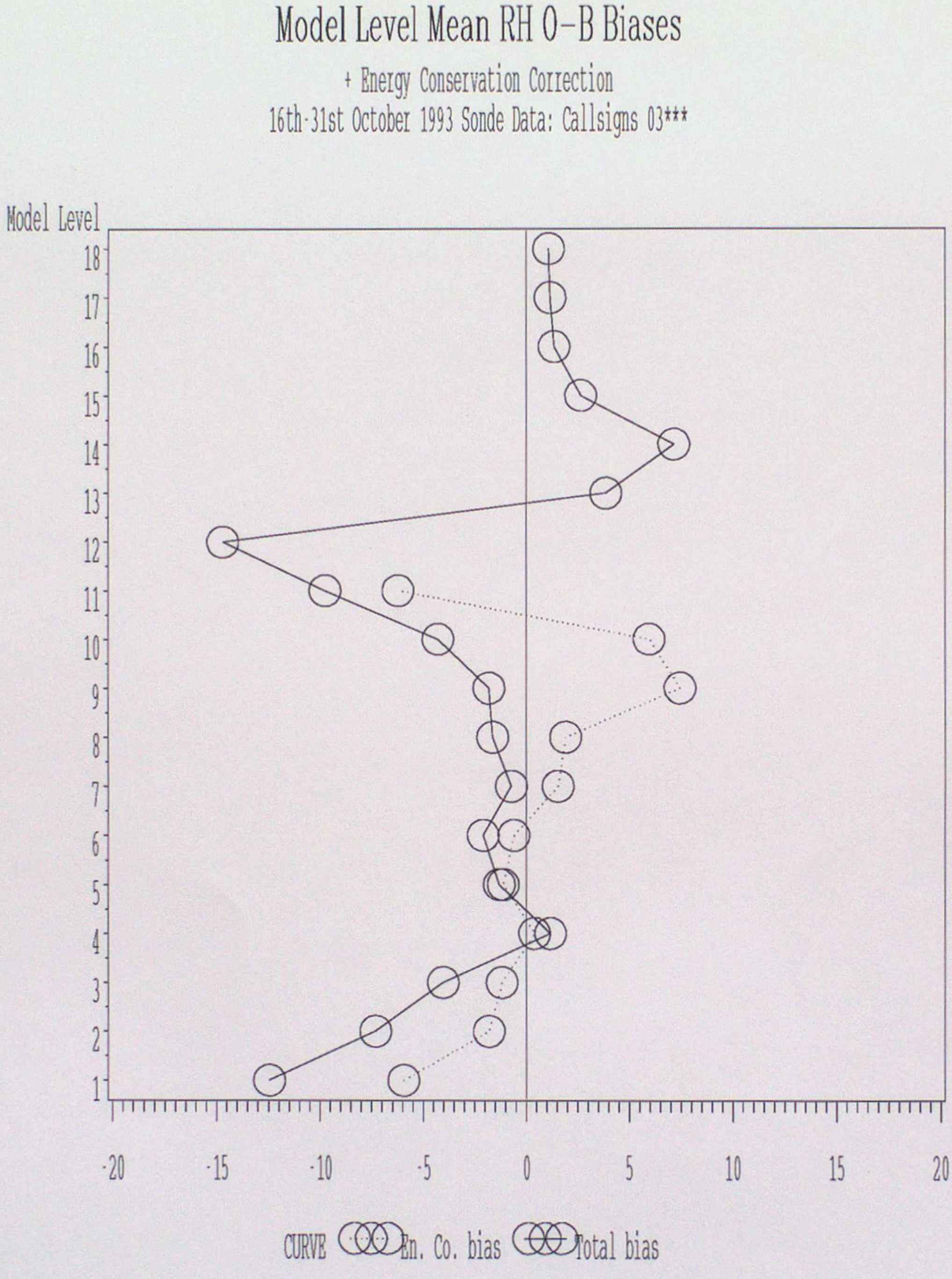

Figure 10: Same as Figure 9 but for the 16th-31st October 1993 UK radiosonde data.

to give the correct cloud amount. The calibration by Väisala radiosondes at the high r end would remove the need for such fixes.

Another problem known to occur during cloudy/rainy conditions is the 'wetting' of radiosonde humidity detectors. After passing through moist layers the radiosonde ascends to cooler levels which cause the detector to freeze. An erroneously large value of r is then reported. The wetting of radiosondes is shown in Figures 11 and 12 for UK and Canadian (mostly VIZ) radiosondes. The maximum value of r reached during the radiosonde's ascent is plotted against the value of r at the tropopause during October 1993 data. The tail of values with low r at the tropopause and maximum tropospheric values ranging from 25% to 100% represents the unwetted detectors. There also exists a tail with a whole range of values of r at the tropopause for which the radiosonde has passed through near saturated conditions. Such high values of r at the tropopause are almost certainly spurious and hence it is concluded that the humidity detectors on these ascents have suffered from wetting.

Wetting leads to a moist observational bias. Although this source of radiosonde humidity bias may be important in some circumstances, the $O - B$ bias found in the study of October 1993 OPD data above more likely indicates a dry, if any, observation bias.

Studies of $O - B$ statistics have been made of other areas of the globe, e.g. North America. The results indicate a much smaller humidity $O - B$ bias than that observed over the UK. Figure 13 is a plot of humidity bias for the October 1993 OPD US and Canadian area data. Only in the upper troposphere and stratosphere does the humidity bias exceed 3%. Above this level, the large moist bias is probably attributable to problems with VIZ radiosondes at high altitude and also the cut-off of reported humidities for $T \leq -40^oC$.

In addition to possible biases in the observation, the practice of converting r to dew-point depression D before sending it across the GTS to the UKMO (where

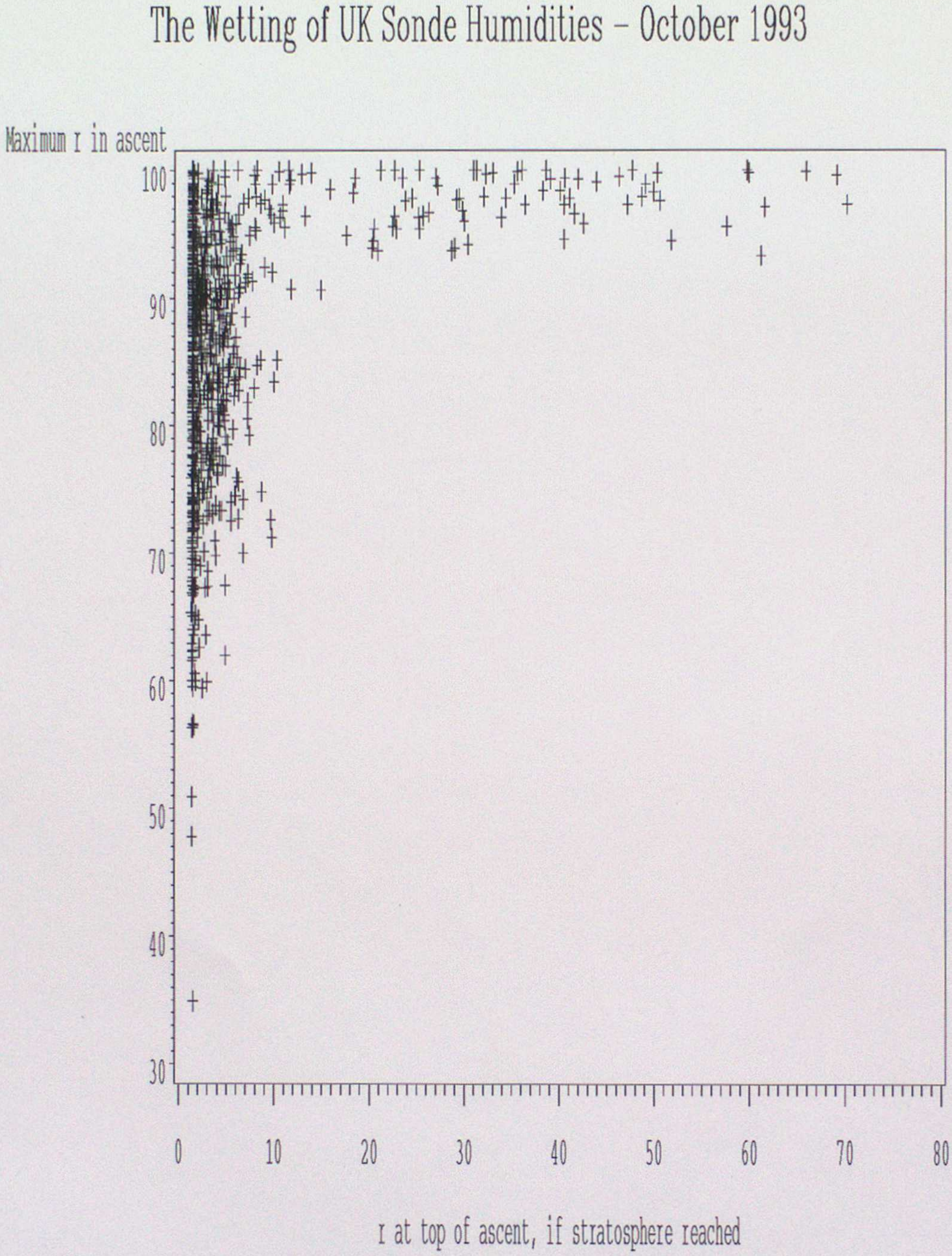

Figure 11: Illustration of the 'wetting' of UK radiosondes during October 1993. The maximum relative humidity measured by the radiosonde during the ascent is plotted against the humidity measured at the tropopause. The tail of values with high tropopause humidities tend to correspond to ascents which have passed through near saturated conditions.

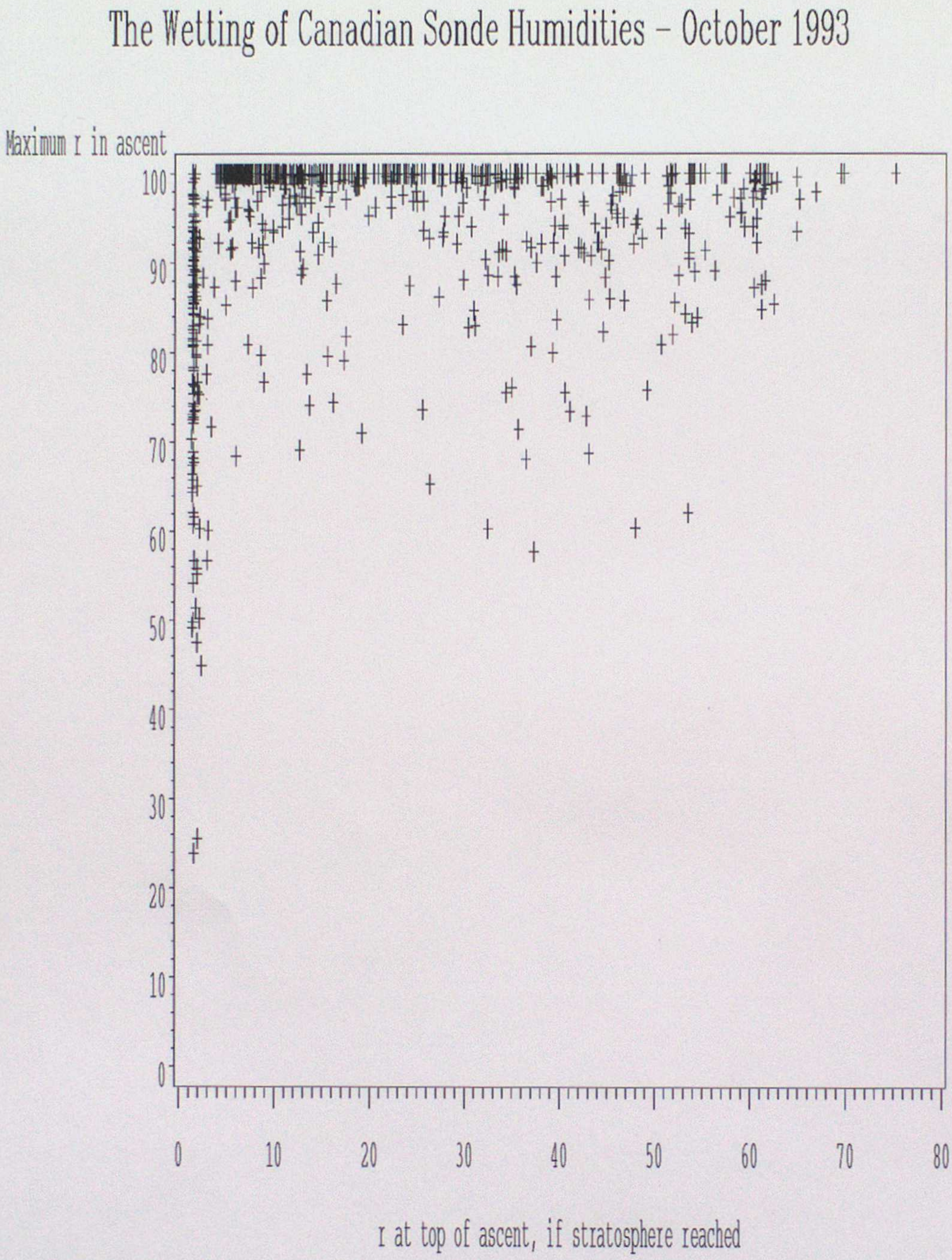

Figure 12: Same as Figure 11 but for Canadian (mostly VIZ) radiosondes, showing that the problem of wetting is not in Väisala radiosondes alone.

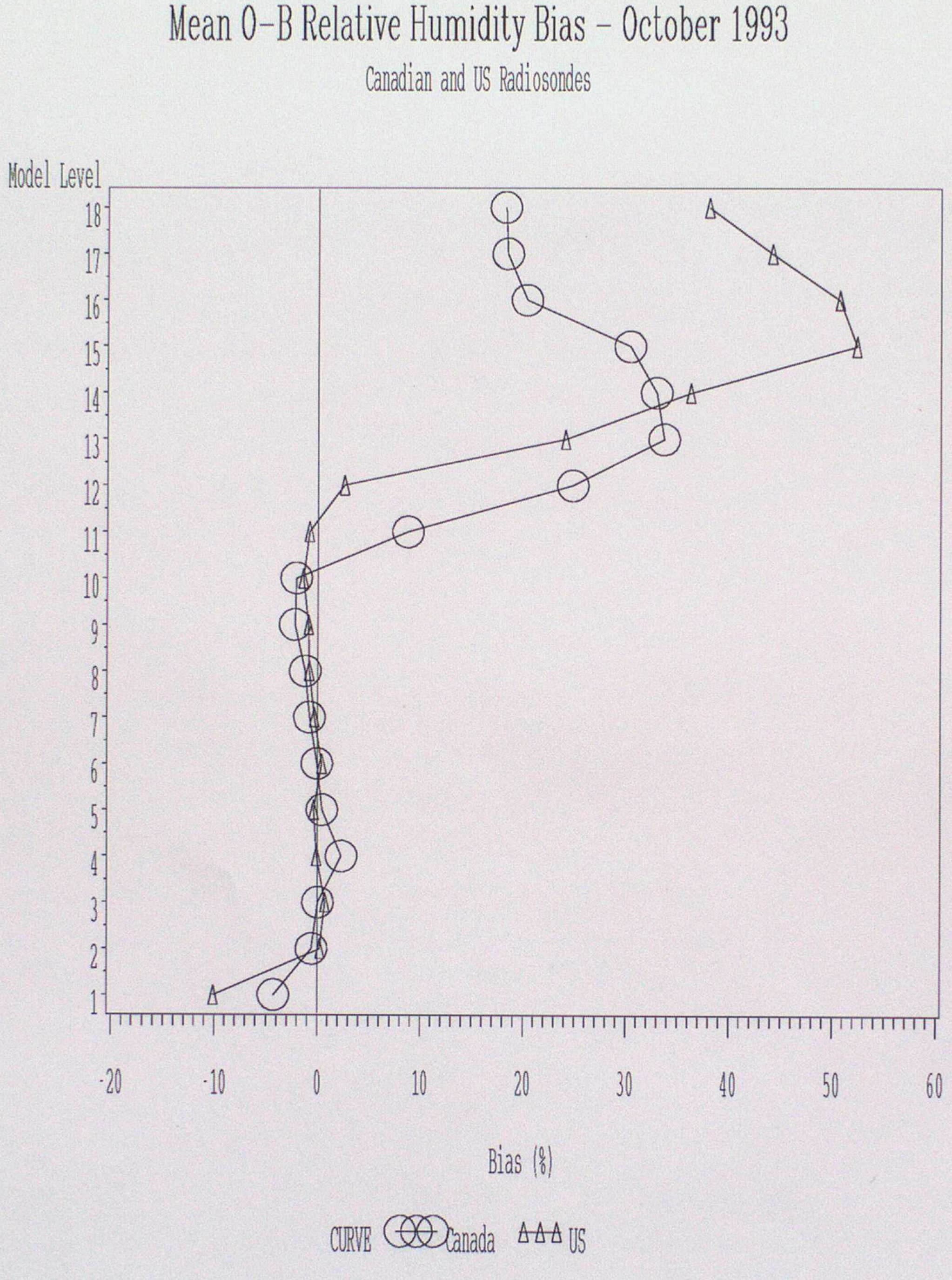

Figure 13: Humidity $O - B$ bias over the USA and Canada in October 1993.

it is then converted back to r) introduces several potential problems. Gaffen [8] compared results from 26 different expressions used around the world for conversion of r to D. Differences of a few degrees in D were found using some formulae which could lead to regional dry or moist humidity biases. A two-digit number (0-99) only is allowed for D in the report sent over the GTS. The range 0-99 would be more sensibly used for r, but perhaps a more relevant point is the inconsistency with which D is reported. Digits 00 to 50 correspond to $D = 0.0$ to 5.0^{o}C with accuracy 0.1^{o}C, digits 56 to 99 correspond to $D = 6.0$ to 49^oC (the maximum) with accuracy of 1°C. Digits 51 to 55 are not used for some as yet unknown reason which excludes $5.1 \geq D \geq 5.9$ as a possible value of D. Although not leading to a bias, the gaps and rounding errors introduced by such reporting practices produce unnecessary errors.

It is a WMO ruling that D is not reported if $T \leq -40^oC$. Although understandable in terms of the previous inaccuracy of humidity measurements, it should be noted that this procedure could introduce a moist bias as the coolest and frequently driest observations are discarded.

Although the purpose of this paper is to study the origin of model humidity biases, it was felt necessary to include a discussion of biases and inconsistencies in humidity measurements used in assimilation and verification work as they perhaps explain a significant fraction of the biases observed. As radiosonde types and reporting practises improve around the world at different rates it is a major task to keep up with all the changes. The example of radiation corrections being added to radiosonde temperatures at some radiosonde sites whilst it must be added at the UKMO to others is one example of an inconsistency which requires continual monitoring.

6 Recalibration Of Radiosonde Relative Humidity

In Section 5 the possibility of a dry radiosonde humidity bias for Väisala RS80 radiosondes was discussed. Suggestions have been made that a recalibration of RS80 humidities in the $r = 80\%$ to 100% range should be tested. A number of recalibration methods have been put forward including renormalisation of the maximum relative humidity during the radiosonde ascent to 100% in cloudy regions or the addition of a piece-wise linear increment to the observed relative humidity. In this section, the concern is not so much with the actual form any recalibration should take (as it is ultimately only a temporary fix until the calibration and accuracy of the radiosonde is improved) but with the impact of a slight modification to observed humidity on cloud in the model.

In the UKMO cloud scheme (Smith et al [5]) the cloud fraction C is explicitly only a function of the grid-box average relative humidity r_g. The radiosonde humidity r is a point observation. If it can be assumed that a boost in r will lead to an equivalent change in r_g then the effect of the recalibration on C can be estimated.

A simple recalibrated relative humidity r_n can be expressed in the form of a quadratic increment added to the radiosonde value r:

$$r_n = r + a(r - r_c)(100 - r). \tag{6.6}$$

The increment is applied in the $r_c < r < 100\%$ region where r_c is the critical relative humidity for cloud formation ($r_c = 92.5\%$ for the bottom 3 model levels and 85% for levels 4 to 11).

As a first step the coefficient a can be set by fixing $dr_n/dr = 0$ at $r = 100\%$, which gives $a = 1/(100 - r_c)$. This is the maximum value of a which ensures that r_n is nowhere greater than 100%. Curves of r_n against r with this value of a are plotted in Figure 14 for levels 1-3 and 4-11. A disadvantage of this form of r_n is that it does not recalibrate evenly over the range of r: the bias is arbitrarily chosen to be a maximum at the midpoint of the range. In addition, equation 6.6 does not allow significant recalibration near $r = 100\%$.

Values of r and r_n can be inserted into the cloud fraction C given in Smith et al [5] equations P292.18, P292.20 and P292.21 to illustrate the change in C as a result of recalibration. The dotted and full curves in Figure 15 are $C(r)$ and $C(r_n)$ respectively. Separate curves for each region with different r_c are included. The cloud fraction is obviously quite sensitive to relative humidity. For example, recalibrating a radiosonde humidity of 95% for $r_c = 85\%$ using equation 6.6 leads to an increase in C from 0.25 to 0.65.

More sophisticated recalibrations can be imagined using equation 6.6 by tuning a to compensate for a known radiosonde humidity bias. The simple recalibration discussed here corresponds to a radiosonde humidity bias of 1.25% and 2.5% in levels with $r_c = 92.5\%$ and 85% respectively. The actual radiosonde dry bias is probably larger than this. Another possible method would be to tune a so that the cloud produced using the cloud fraction formula with observed radiosonde relative humidity is equal to that stored in cloud reports. However, in this section it is merely intended to illustrate the sensitivity of cloud fraction on relative humidity. How the UM will adjust to this boost in relative humidities is a complex nonlinear problem which cannot be predicted *a priori*. A detailed study of humidity recalibration is presently underway at the UKMO.

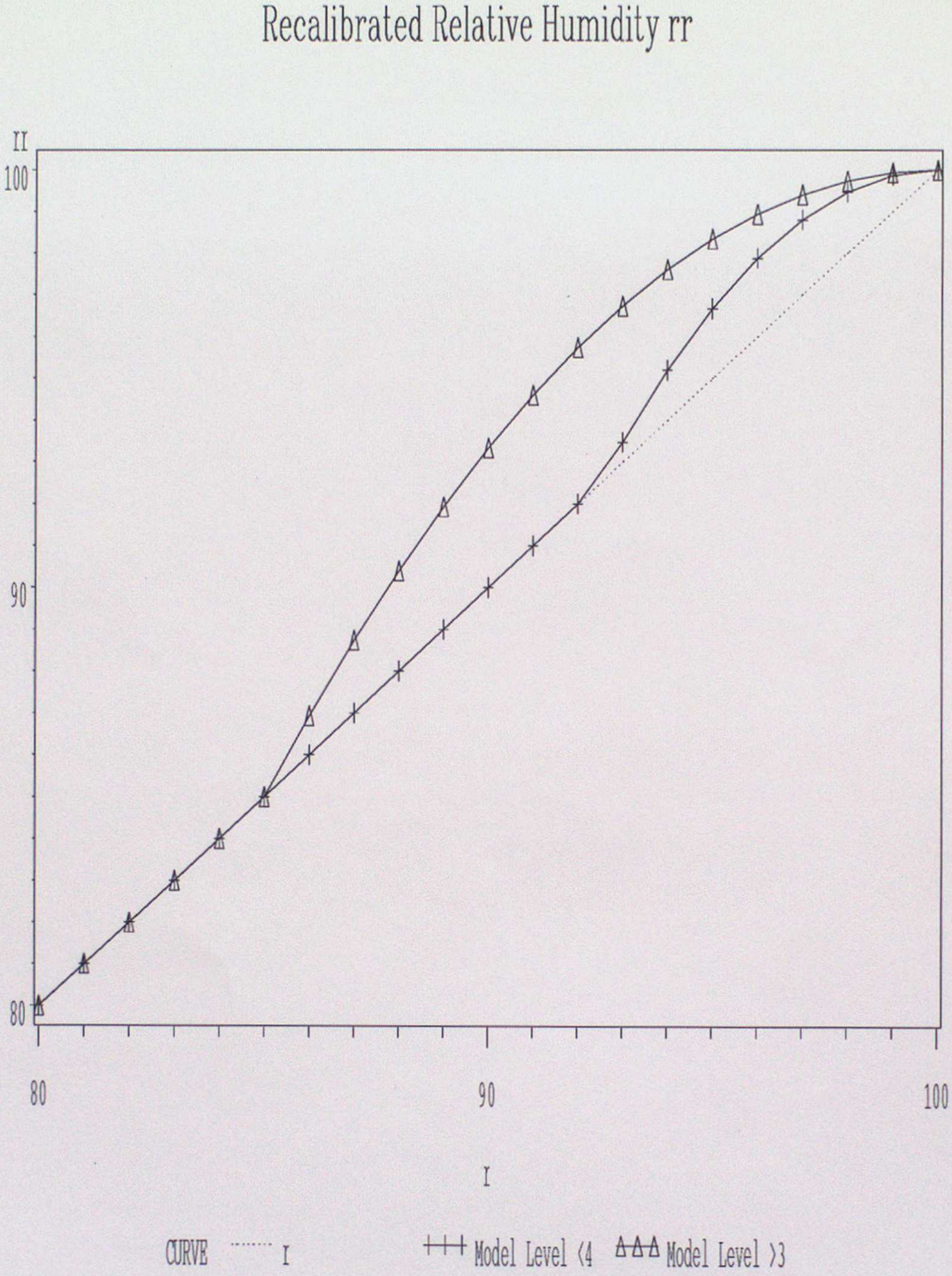

Figure 14: The effect of boosting relative humidity r when $r \geq r_c$. In this simple case, the size of parabolic increment is set to be the maximum allowed without having r values greater than 100%. There are two curves because of the different values of r_c for model levels 1 to 3 and above.

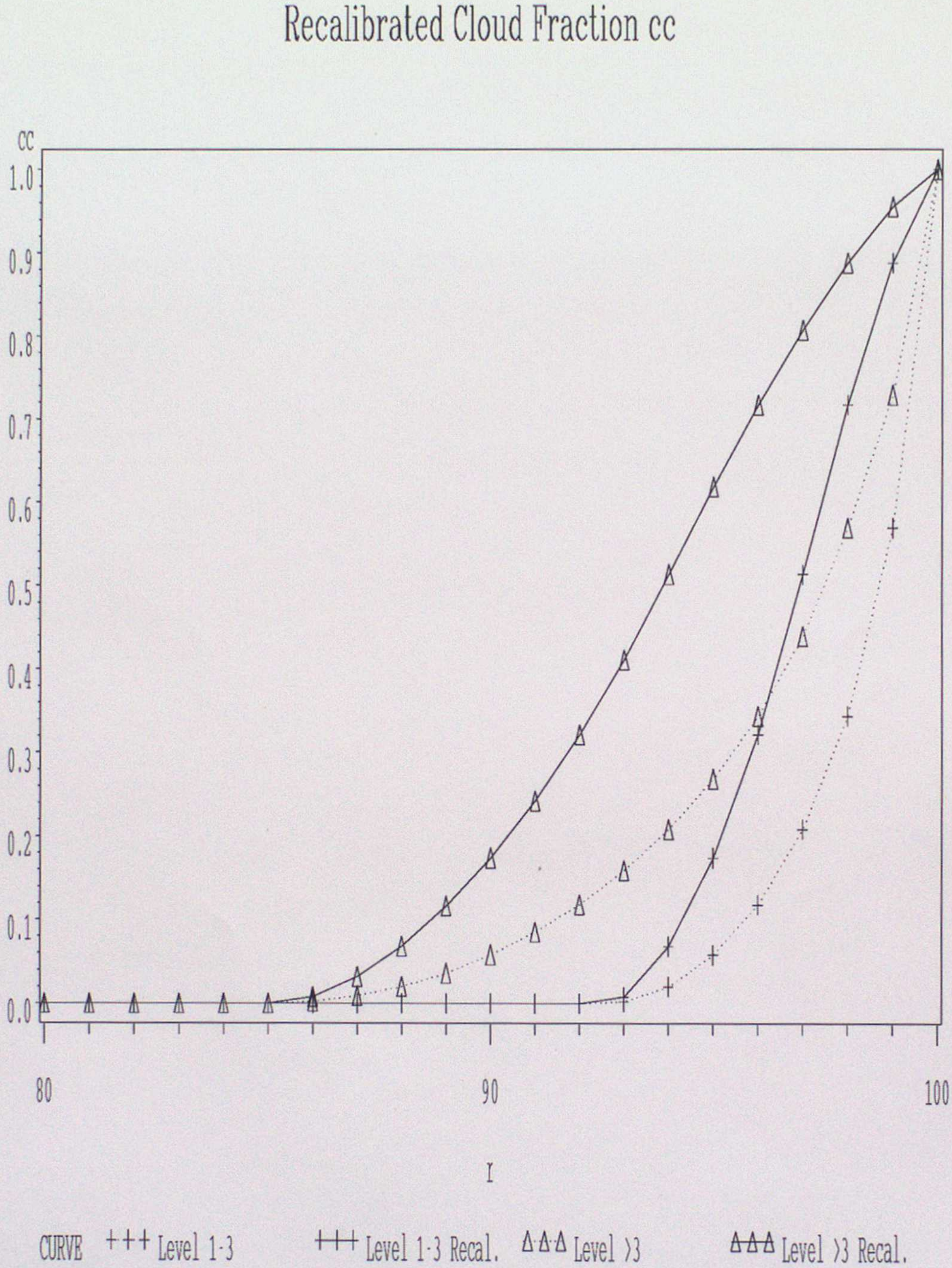

Figure 15: Theoretical cloud fractions $C(r)$ (dotted lines) and $C(r_n)$ (solid lines) corresponding to original and boosted relative humidities respectively. The two curves are for the different values of r_c for model levels 1 to 3 (crosses) and above (triangles).

7 Correlation Of Moist Bias With Wind Direction and Time Of Year

7.1 The effect of wind direction on the UK humidity bias

Again using the October 1993 OPD, the possibility that the relative humidity $O-B$ bias for UK radiosondes might depend on wind direction was considered. No significant correlation was found between the sign and magnitude of the humidity $O-B$ bias and wind speed.

The humidity $O-B$ biases, binned with wind direction, are plotted in Figure 16. No large correlation exist between humidity bias and wind direction in the cyclonic period but during the latter part of the month the maximum humidity bias clearly occurs for winds from a west-south-westerly direction.

Figure 17 shows the mean radiosonde relative humidity with wind direction. The mean relative humidity appears to be a maximum for west-south-westerly winds so there exists a correlation between wet conditions and the negative humidity $O-B$ bias in the anticyclonic second half of October 1993. No significant correlation is found between humidity bias and mean temperature with wind direction in either period.

7.2 Annual variability of UK humidity bias

The study of the OPD data was extended to the months of December 1992, March 1993 and June 1993 in an attempt to check the variation of the biases through the different seasons. The mean level relative humidity for each month is shown in Figure 18. The general vertical profile remains throughout the year with a region between model levels 6 and 11 in the middle to upper troposphere with approximately constant relative humidity during each month. This may be due the radiosonde humidities reported in this region covering the entire range

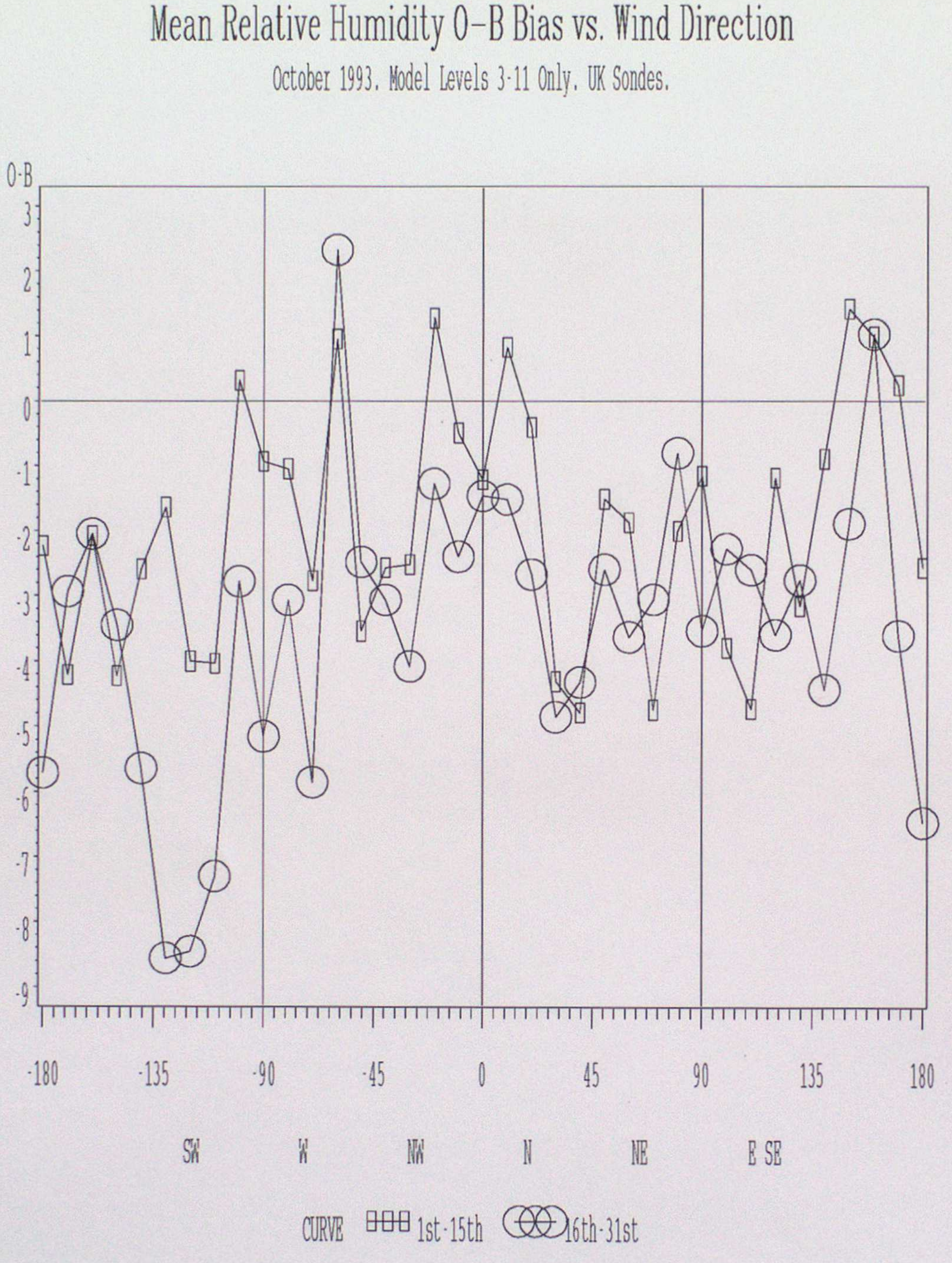

Figure 16: Humidity $O-B$ bias for both cyclonic and anticyclonic periods, plotted against wind direction.

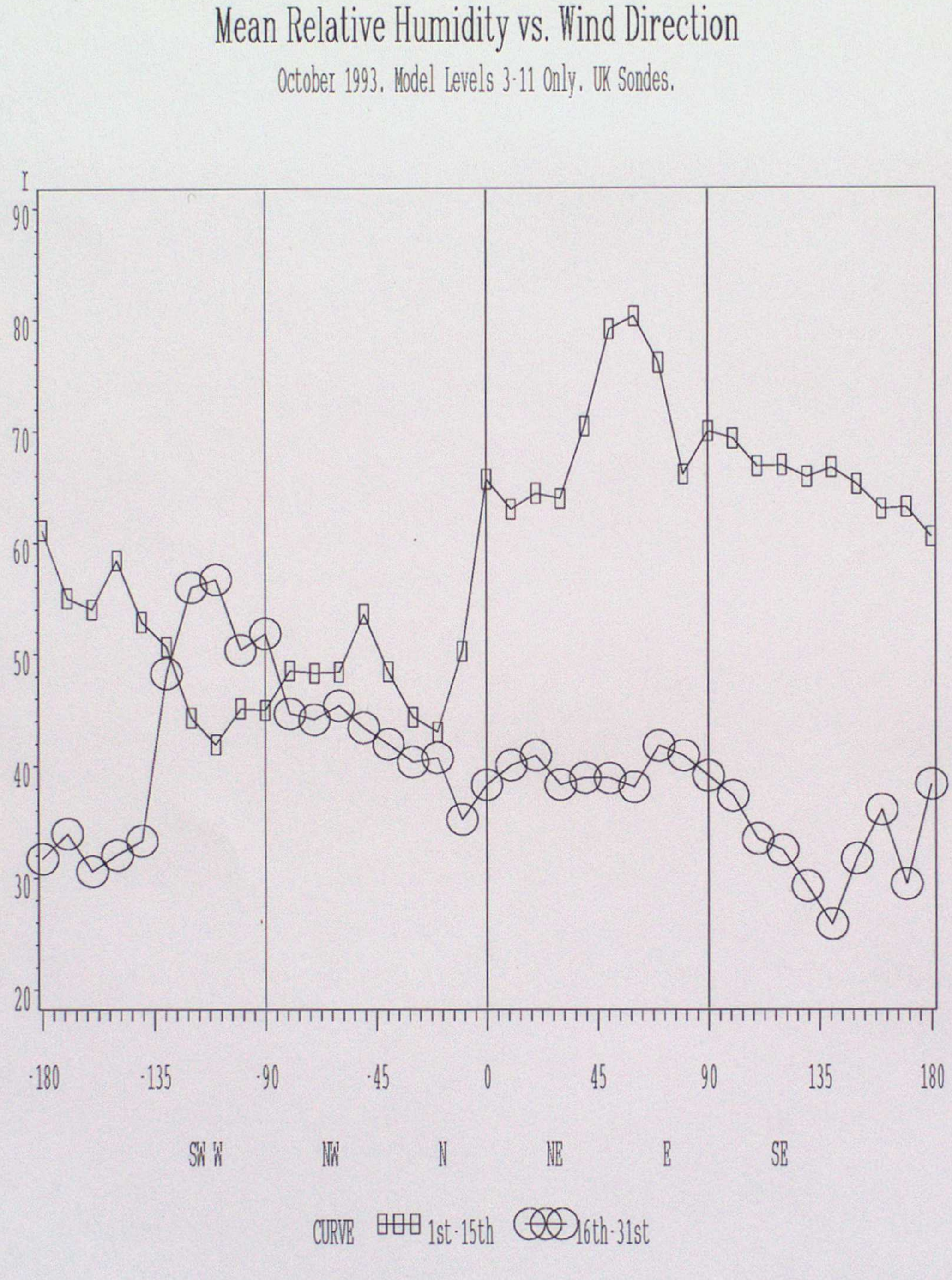

Figure 17: Mean relative humidity for each period, binned into wind directions.

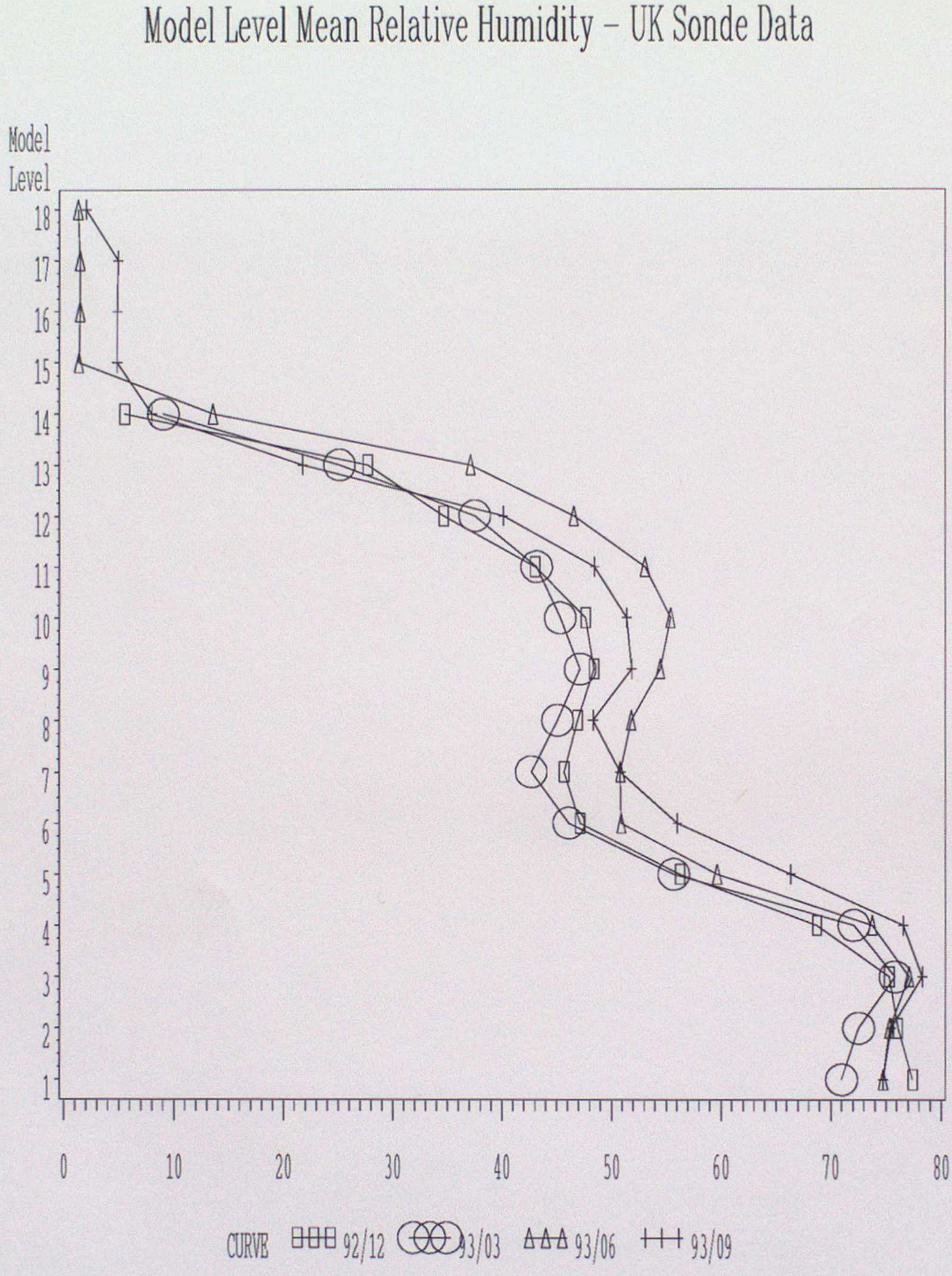

Figure 18: Mean radiosonde relative humidity measurements for the months of December 1992 (squares), March 1993 (circles), June 1993 (triangles) and September 1993 (crosses).

of possible values (0% to 100%) with similar frequency. In this case, the mean humidity would be expected to be near the mid-point of the range, i.e. 50%.

Figure 19 shows a typical frequency distribution of radiosonde humidities reported in sample model levels (3, 8 and 13) in the lower, middle and upper troposphere. The distribution in the lower and upper troposphere is heavily skewed to the higher and upper ends of the humidity range respectively whilst in the middle troposphere the whole range is represented.

The humidity $O - B$ bias does not change dramatically in the period considered (Figure 20).

There exists a bias of $\simeq -5\%$ in the middle troposphere in all months. This rises to $\simeq -15\%$ in the relatively dry upper troposphere (see figure 18) of March 1993. However, in the only slightly wetter upper troposphere encountered by UK radiosondes in December 1992, the humidity bias was not so large.

7.3 UK radiosonde versus ECMWF model results

Global monthly mean radiosonde temperature, humidity, wind and geopotential height statistics are created each month (since December 1993) at ECMWF for each radiosonde station. By combining all the UK station data, similar vertical bias profiles can be produced using the ECMWF model against radiosonde as in section 2 with the UKMO UM. Figure 21 shows the temperature and humidity standard deviations and biases for December 1993. The solid line is the $O - B$ curve, the dashed line in each plot is the $O - A$ (radiosonde observation minus analysis) curve.

As for the UKMO results, there exists a relatively small temperature bias in the troposphere rising to a larger $1 - 2^oC$ bias in the stratosphere. The figure shows a similar negative $O - B$ humidity bias above the surface and in the middle tropospheric levels. The ECMWF bias peaks at a slightly larger -22% than the UKMO bias (peaks at -15%). It is reported that this bias is smaller over the

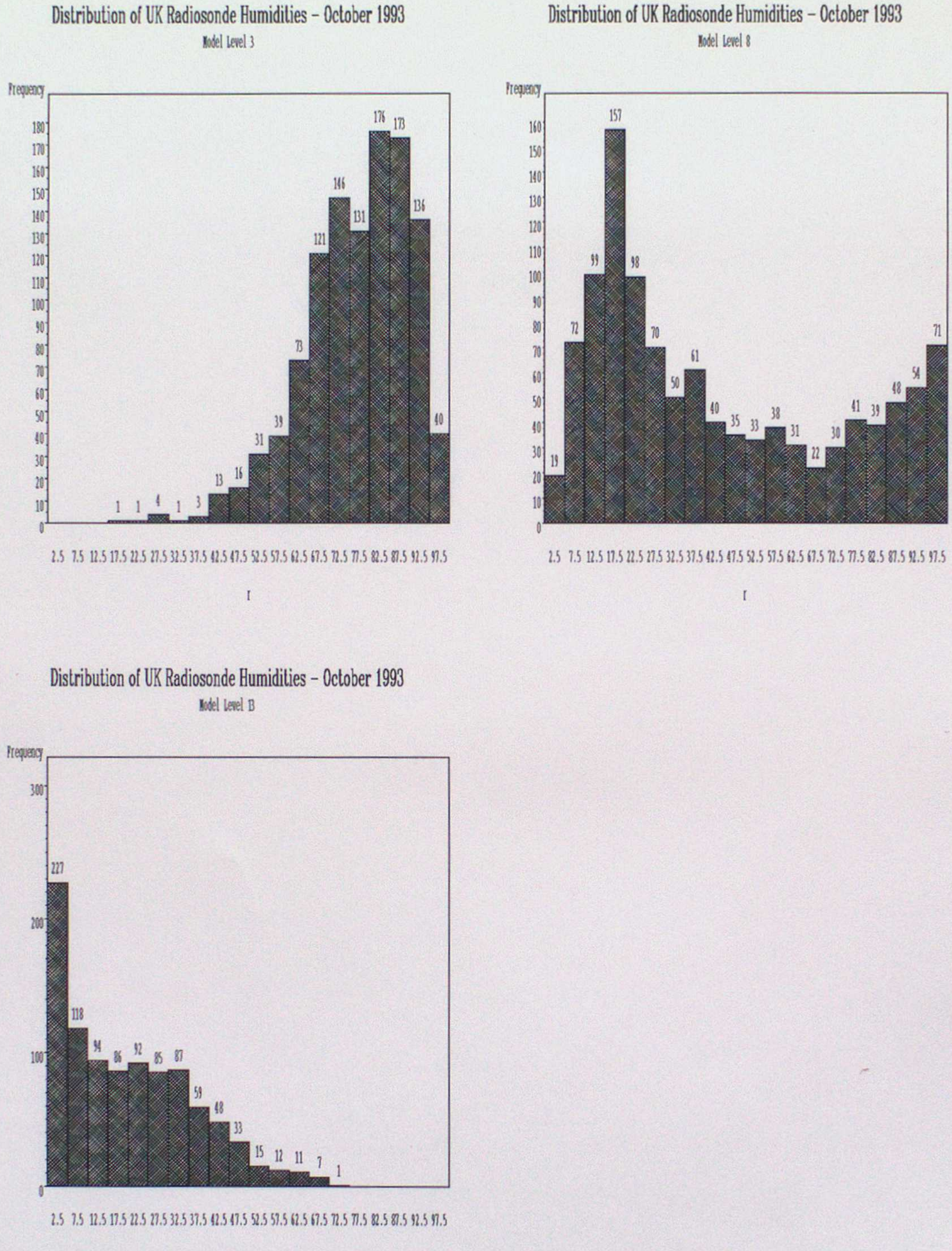

Figure 19: Frequency distribution of radiosonde humidity measurements for layers in the lower, middle and upper troposphere. October 1993 UK OPD data.

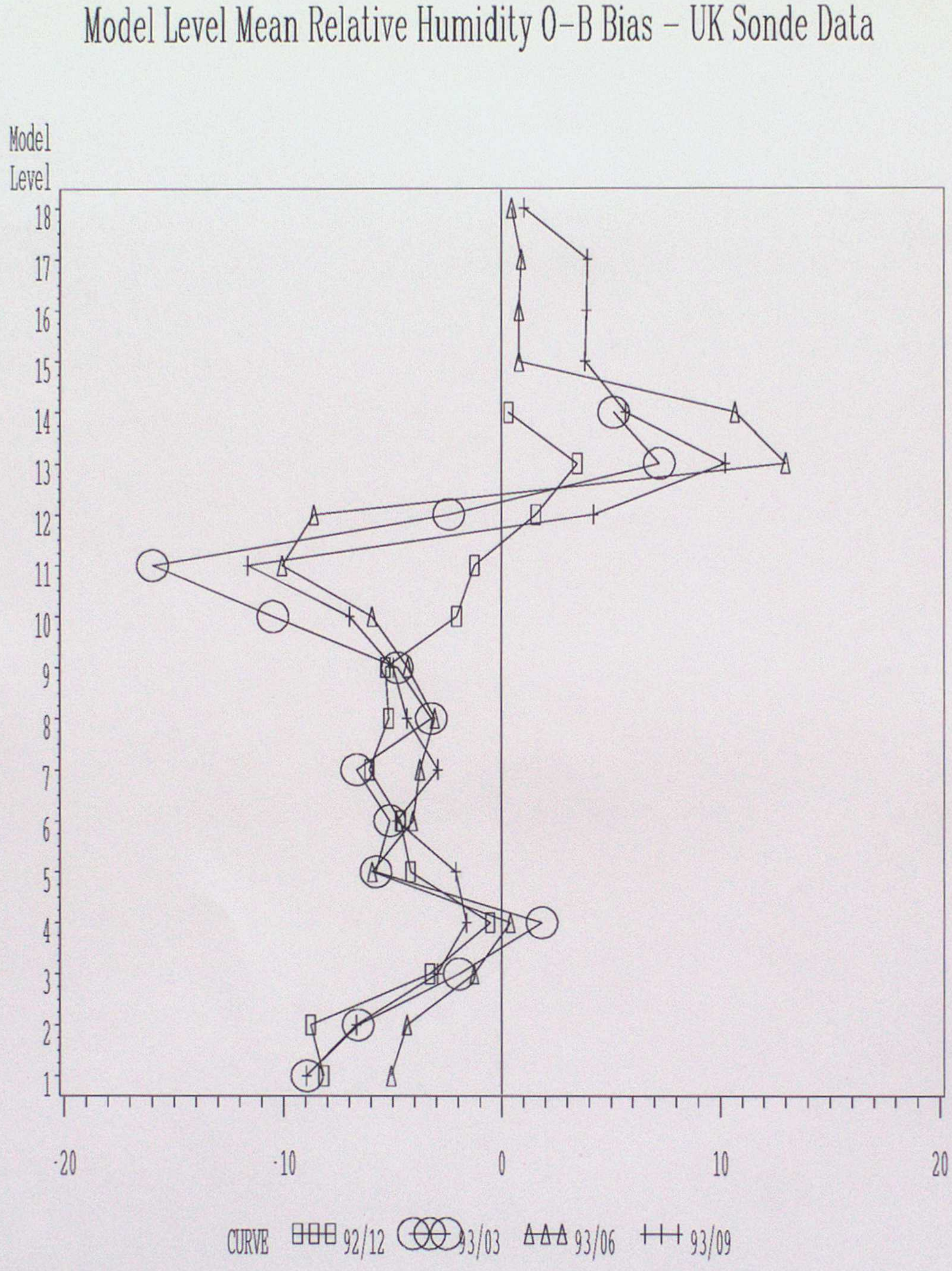

Figure 20: Relative humidity $O - B$ bias for the months of December 1992 (squares), March 1993 (circles), June 1993 (triangles) and September 1993 (crosses).

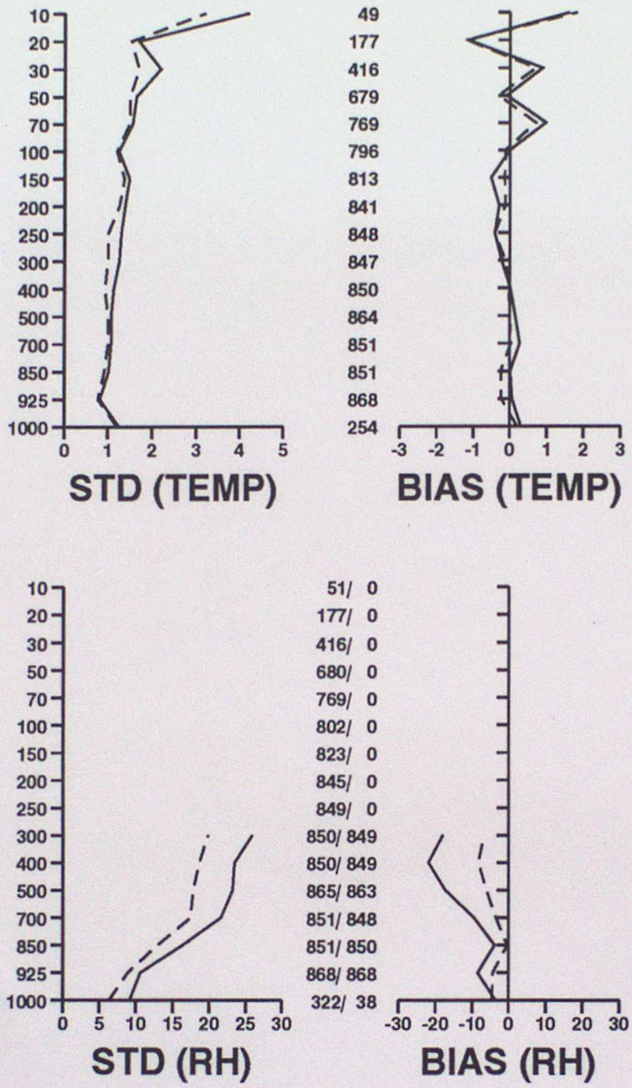

Figure 21: Plot of ECMWF temperature and relative humidity $O-B$ and $O-A$ biases for December 1993. The second vertical coordinate is the number of data points at each level.

continent. In studies of other areas humidity biases have been reported which are known to be related to a poor description of stratocumulus clouds. Of course, the general similarity in humidity bias between the two models does not remove the possibility that a sustantial part could be due to a bias in the actual UK radiosonde humidities measurements. The reduced bias over the continent reported actually adds weight to this possibility.

8 Conclusions

A comparison of radiosonde humidities against values predicted by an NWP forecast has been attempted for different weather conditions over the UK. Study of two extremes of weather conditions lead to the conclusion that humidity biases possibly originate from different sources, depending on the synoptic conditions.
The effect of different synoptic conditions on humidity error estimates has been shown to be significant. Whether it is worthwhile including a dependence of the humidity errors used in the assimilation on weather type is uncertain. Tuning of the error values used is probably less important at this stage than attacking the problem of the origin of the humidity bias.
It seems impossible to attribute the source of the tropospheric humidity biases reported above to either observation or model with any certainty, although a possible link between a moist model humidity bias and a cold model temperature bias due to too little moisture precipitating out of the model atmosphere in the troposphere is suggested by these results.
The possibility of an Väisala RS80 dry bias has been discussed and work to rectify the problem has been suggested. Comparison of results between ECMWF and the UKMO has revelaed a similar humidity bias over the UK in the two models. A recalibration of radiosonde humidities is perhaps not the most satisfactory solution to the problem but until improvements are made in the calibration/accuracy

of radiosondes it must suffice as a temporary fix. The sensitivity of the cloud fraction formula to relative humidity has been highlighted. With such uncertainties in the raw humidity data entering the cloud scheme it is not surprising that inaccuracies occur in operational forecasts of the moisture field. Research into the direct assimilation of cloud into the UKMO model is currently being carried out at the UKMO.

To progress to a better understanding of the origin of humidity biases requires much more work, both by the workers in the observations field (e.g. new instruments, standardisation of reporting practises) and the modellers. The lack of understanding of the origin of the biases in humidity is a major problem for meteorologists and climatologists. It is maybe surprising that the true distribution of atmospheric humidity, which is of central importance to an understanding of the state of the earth's atmosphere appears to be so poorly understood.

Thanks go to Andrew Lorenc, Bruce Ingleby, Nigel Richards and many others in FR division for useful comments concerning this work. Also thanks to Ray McGrath at ECMWF for supplying the ECMWF results in section 7.3 and for figure 21.

Bibliography

[1] Elliot, W.P. & Gaffen, D.J., 1992 "Effects of changes in radiosonde instruments and practices on climatological tropospheric humidity data". WMO Instruments and Methods of Observing Report No. 49. p455.

[2] Lorenc, A.C., 1994 "Assimilation of satellite data in models for energy and water cycle research". Adv.Space.Res., 14, p145.

[3] Bell, R.S., 1994 "Moisture spin-up - a possible solution". Forecasting Research Division Technical Report No. 90., UKMO.

[4] Smith, R.N.B., 1990 "A scheme for predicting cloud layers and their water content in a general circulation model". Quart.J.Roy.Met.Soc., 117, p59.

[5] Smith, R.N.B., Gregory, D. & Wilson, C., 1990 "Calculation of saturated specific humidity and large-scale cloud". Unified Model Documentation Paper No. 29, Forecasting Research Division, UKMO.

[6] Cullen, M.J.P., 1990 "Introduction to the unified/forecast climate model". Unified Model Documentation Paper No. 1, Forecasting Research Division, UKMO.

[7] Landolt-Bornstein, 1987 In: Numerical data and functional relationships in science and technology. Group V/Vol. 4B Meteorology. Physical and chemical properties of air, p35.

[8] Gaffen, D.J., 1992 "Preliminary results of the CIMO survey on historical changes in radiosonde instruments and practices". WMO Tech. Conf. On Instruments And Methods of Observations. Report No. 49, p426.