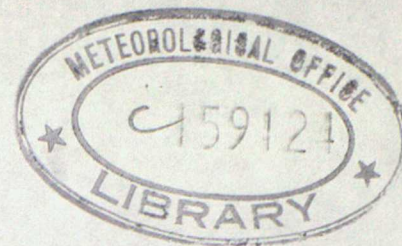


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THE USE OF AN OPERATIONAL DATA ASSIMILATION SYSTEM TO INFER
THE QUALITY OF WIND OBSERVATIONS FROM RADIOSONDES

by C D Hall

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Met O 8
Forecasting Products
Meteorological Office
London Road
Bracknell, Berkshire
RG12 2SZ

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THE USE OF AN OPERATIONAL DATA ASSIMILATION SYSTEM TO INFER THE QUALITY OF WIND OBSERVATIONS FROM RADIOSONDES

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1. INTRODUCTION

The numerical data assimilation systems in operational use today provide global analyses and short-term forecasts or background fields of wind, temperature, geopotential, humidity and surface pressure. They have proved to be of sufficiently high quality to achieve accurate numerical weather prediction, and it can be demonstrated that they have a valuable role in the monitoring of the quality of observations; they provide reliable reference values which may be used to compare observations separated in space and time and from which systematic departures may be noted. However, global models can at best only represent values on the coarse scale of their grid, while in data-sparse areas substantial systematic and random errors may also be found. Such factors limit the success of their application to data monitoring.

Hollingsworth et al (1986) have described some studies of data quality made at ECMWF. Similar studies have been carried out at the Meteorological Office using an archive (Observation Processing Database or OPD) containing all the observations used by the UK operational global data assimilation system, their differences from the model analyses and background fields at the observation position, and information on the flags raised by the objective quality-control scheme.

The basic assumption lying behind these monitoring methods is that the magnitude of the background errors (systematic and random) averaged over a period of a month or more varies only slowly in space. This is probably valid away from steep orography and the model's upper and lower boundaries. In contrast, observation errors may vary greatly between individual stations or between national groupings of stations operating different types of instrument. Differences from background which are larger than the local average can therefore, in most cases, be attributed to larger than normal observation errors. This note presents results of the monitoring of the quality of wind observations from radiosondes and several examples of stations producing suspect observations will be given here.

2. RADIOSONDE WIND-FINDING SYSTEMS

The global distribution of radiosonde systems reporting on a typical day is shown in figure 1 for the synoptic hours 12 and 18Z. The distribution of observations at 00 and 06Z is similar. Asterisks mark stations sending PILOT reports containing winds alone. It is clear that the best spatial and temporal resolution provided by the radiosonde network occurs over Europe, and it is the observations in this region which will be studied here. The four main types of wind-finding systems in use at operational radiosonde stations around the globe are described below.

2.1 Primary radar

Primary radars which measure elevation, azimuth and slant range provide in general the most accurate wind finding. An integration of the hydrostatic equation using temperature, humidity and pressure measured by the sonde provides an independent check on the height. Tests made at Beaufort Park, where a balloon was tracked by two independent radars (Edge et al 1986), have demonstrated that the reproducibility of wind measurements from the UK operational radar using 1-minute averaging was better than 1 m/s rms vector error at slant ranges less than 60 km, and about 1.5 m/s rms vector error at slant ranges of 90 km. Other countries using similar radar systems include Australia, Federal Republic of Germany, France and Sweden.

2.2 NAVAID

NAVAID (navigation aids) is the general term applied to systems for determining horizontal location at any point on the globe through the use of electromagnetic waves in the radio frequencies. Synchronised signals are transmitted from a number of well-spaced stations, and differences in the time of receipt at a sensor enable its position to be determined. Two systems are used for radiosonde wind finding; Omega (at some 100 upper-air stations worldwide) and Loran-C (at less than 10 upper-air stations). The 8 transmitter stations of the Omega system enable measurements of wind to be made at most places on the globe to an accuracy of 1-2 m/s for 2-minute averages, but around sunrise and sunset rapid changes in the height of the ionosphere reduce this accuracy to 1-4 m/s (Lange 1985). The characteristics of the Loran system allow wind measurements to an accuracy of better than 0.5 m/s to be made at a few places close to the transmitting stations, but more generally the accuracy is around 1-2 m/s. The observations are assigned to a pressure level determined from the pressure sensor on the sonde and the geopotential height is derived from a hydrostatic integration of the measured temperature, humidity and pressure. Because the sonde is needed to assign a level to the measured winds, wind-only PILOT reports are not normally produced from a NAVAID system. NAVAID is used operationally by Norway, Finland, Greenland, Denmark, Spain, Italy and Saudi Arabia, and most stations report 3 to 4-minute averages. It is also used for most ship-borne observations.

2.3 Radiotheodolite and secondary radar

Radiotheodolite is the most common wind-finding system and is in use in some form or other in USA, Canada, USSR, Japan, South Africa and several countries in Eastern Europe, South East Asia and Central and South America. Radio signals from the sonde are tracked by direction-finding antenna at the ground station enabling azimuth and elevation to be measured. The height is usually determined from the measurements of temperature, humidity and pressure in the same way as in NAVAID systems. At high balloon elevations and short slant ranges the accuracy obtained from radiotheodolites is comparable to the accuracy of NAVAID winds. However, at low balloon elevations, which are frequently encountered in the strong jet streams in middle latitudes, errors in the measurement of the elevation are much larger, especially if there is some misalignment of the receiving antenna. Differences between wind measurements from the USA and UK systems during the WMO International Radiosonde Intercomparisons (Nash and Schmidlin 1987) were found to be particularly large at low elevations (rms values of 4 to 5 m/s in each component) and were attributed to levelling errors in the US radiotheodolite equipment. In the USA and possibly in some other countries the operational practice is that winds are not reported where the elevation falls below some critical value (about 6 degrees). In some cases secondary radar or transponder systems are used to provide direct measurements of the slant range used in the wind finding, the sonde pressure still being used to assign the level. Such systems eliminate the

dependence of the derived wind on measurements of balloon elevation and usually lead to a reduction of the largest errors associated with radiotheodolite systems. Secondary radar or transponders are used operationally at many stations in the USSR and China and at some mountain stations in the USA.

2.4 Optical theodolite

Optical theodolites may be used if there is only a requirement for low-level winds at airfields, or if the budget does not permit the installation of accurate wind-finding systems. A balloon is tracked optically by an observer using a theodolite to measure azimuth and elevation. The level of the balloon is either determined from the pressure sensor on the sonde, or more commonly where no sonde is used, from the assumption that the balloon ascends at a constant rate. The accuracy of the derived winds is in general not high and is very dependent on the standard of the observing practice. The height to which wind may be reported depends mainly on the cloud and observer skill and in most instances is below 500 hPa. Optical theodolites are used in Indonesia, some Pacific islands and in many countries in Africa.

3. OBSERVATION-MINUS-BACKGROUND DIFFERENCES

Observation-minus-background differences (O-B) are at the centre of many monitoring procedures. The background fields, derived from cycles of data assimilation, reflect the information contained in past observations as well as information relating to the structure of the atmosphere provided by the numerical model. Errors in the background fields, which are largest in data sparse areas, are a limiting factor in their use for observation monitoring, and indeed it is essential that all monitoring results are set in the context of estimates of model errors. Ashcroft and Hall (1989) presented global estimates of the errors in the background values of surface pressure used in the monitoring of marine surface data, and Hollingsworth and Lonneberg (1986) conclude that the background errors in data-rich areas are of similar magnitude to the observation error of radiosondes (measurement plus representativeness errors). An estimate of the errors of the background wind values used in this study is given in section 5.2. Background, rather than analysis values are used for the monitoring of observation quality because it is assumed that, being derived prior to the observation time, they are independent of the observation itself. This is probably not always strictly true; persistent systematic observation errors are not always filtered out by the data assimilation system and may influence the background field. A second basic assumption is made: namely that both the systematic and random background errors, averaged over periods of a month or more, vary only smoothly in space. This is probably true in the free atmosphere away from steep orography and the model's upper and lower boundaries. In contrast, errors arising from inaccurate measurements may vary greatly from station to station or between national groupings of stations. Differences from background which are larger than the local average can in most instances be attributed to larger than average errors at the observing station.

The difference between an observed value (O) and the value of the background interpolated to the observation position (B) may be expressed as

$$O-B = (O-T_o) - (B-T_o) - (T_o-T_o)$$

T_o is the true value of the observation. If the observation is a spot value, T_o is the true spot value, while if the observation represents some time or space average, T_o is the true value averaged over time or space. Likewise T_o is the true value on the scale that the model can resolve, which in the case of

the global model results presented here is approximately a 150km x 150km x 80hPa grid-box average. $O-T_o$ is referred to as the measurement error, $B-T_o$ as the background error, and T_b-T_o as the representativeness error. Squaring and taking an average over many observations:

$$\overline{(O-B)^2} = \overline{(O-T_o)^2} + \overline{(B-T_o)^2} + \overline{(T_b-T_o)^2} \\ - 2\overline{(O-T_o)(B-T_o)} - 2\overline{(O-T_o)(T_b-T_o)} + 2\overline{(B-T_o)(T_b-T_o)}$$

The assumption that the measurement and background errors are (almost) independent is equivalent to the first cross correlation term being zero or nearly zero. The final two terms are probably zero or small compared with the first three terms as there are no good reasons to expect the representativeness wind errors to be strongly correlated with the measurement or background errors. In this case

$$\overline{(O-B)^2} = E_m^2 + E_b^2 + E_r^2$$

where E_m , E_b and E_r are the rms measurement, background and representativeness errors respectively. In most published work the observation error E_o is defined by:

$$E_o^2 = E_m^2 + E_r^2$$

Radiosonde wind observations are received from TEMP and PILOT reports as values at standard levels. Values may also be given at special levels contained in the parts B and D of the report, but global exchange of these data between regions is not required by WMO and they are not received from some countries outside Europe (eg China and Mongolia). The standard and special level data together provide a vertical profile of wind at the station. The detail contained in the profile will be determined not only by the time averaging applied to the raw data referred to below, but also by the accuracy to which the observations have been encoded. WMO lays down that no measured data should fall more than 10 degrees in direction or 10 knots (5 m/s) in speed from a linear interpolation between the reported values. In addition the upper-air code only allows for the direction to be reported to the nearest 5 degrees and the speed to the nearest 1 knot (0.5 m/s). Both these factors limit the accuracy of the observations received over GTS.

Kitchen (1989) has calculated values of E_o using observations from the UK operational radiosonde network. He considers contributions to the wind observation error from several sources:

1. The random errors arising from the limitations of the wind-finding instrumentation.
2. Vertical assignment errors arising from a wrong estimate of the pressure level.
3. Truncation errors due to coding inaccuracy.
4. Errors due to assuming that all observed values are valid at the same time (the sonde takes up to 90 minutes to complete its ascent).
5. Errors due to assuming that all observed values refer to the same horizontal location (in strong winds the sonde may be displaced by up to 100 km at the top of its ascent).
6. Horizontal representativeness errors.

He found that for winds 2 and 3 were generally small compared with the other four factors. His estimates of E_o on the scale of the global model grid (150 km) ranged from 2-3 m/s in the lower troposphere to 3-5 m/s at jet-stream levels except for cases of large (3 hour) time displacement (seldom occurring in the cases considered in this paper). Vertical representativeness errors, not considered by Kitchen, are an important factor too. In general the reported values contain some time smoothing which will vary from system to system. For

the UK operational radiosonde network the reported winds are 64-second averages, German civil stations use 1-minute averages, French stations use 1-minute averages at heights below 6 km and 2-minute averages above this level, and countries with Omega NAVAID systems use 3 to 4-minute averages. Even with some vertical smoothing most wind-finding systems can resolve a great deal of fine structure in the vertical as figure 2 (from Edge et al) shows. The wind-speed profiles in the figure were derived from two radars 52 km apart tracking the same target. The fine structure observed by the two instruments is almost identical demonstrating that it is a real characteristic of the atmosphere. The very strong wind shear around the jet is not unusual. Of particular interest also is the wave structure of small vertical scale in the stratosphere, arising from, for example, quasi-inertial waves (Kitchen and Tolworthy, 1987) which have a horizontal wave length of a few hundreds of kilometres. Although real, these features of the atmosphere are best eliminated before comparing observed and model values. Within the NWP system at Bracknell, vertical averaging is performed so that the full radiosonde profile (using the reports in parts A and B) is transformed to values on the model levels before being used in the data assimilation or for monitoring purposes. Vertical representativeness errors can therefore be ignored in the comparisons between observations and model values presented here.

4. OBSERVATION PROCESSING AND QUALITY CONTROL

Before use by a numerical data assimilation system, observations pass through processing and quality-control stages in order to be transformed from their raw state to a form suitable for use by numerical models. The monitoring results presented here relate to the observations in their processed form. Although some information on quality is inevitably lost during processing, there are advantages in being able to compare like with like; model values are interpolated bilinearly in the horizontal to the observation position, and the observed profile is transformed to layer-mean values of the u and v components at each model level. The model fields used are from the UK operational global model valid at the main synoptic hour (00, 06, 12 or 18Z) nearest to the observation time. Interpolation in time has not been performed between model fields, but in the case of operational radiosondes where most ascents start at, or one hour prior to, one of the main synoptic hours and take perhaps 60-90 minutes before balloon burst, the difference between the actual observation time and the validity time of the model field is seldom large.

On receipt at Bracknell, the full radiosonde report first undergoes objective checks on its quality. Checks are performed on the message format, excess over climatological extremes, internal consistency, closeness to model background values, and spatial consistency. Quality control is performed in two stages: checks made without reference to model values (stage I), and checks made using model values (stage II). In the case of radiosonde wind observations stage I checks are made for impossible wind directions (greater than 360 degrees), wind speeds and vertical shear in excess of climatological extremes, and inconsistency between data reported on standard levels and those reported on special levels. Before passing onto stage II the observed radiosonde profiles are converted to values on the sigma levels of the model. Layer-mean values are calculated for the half sigma levels using only those data passing the stage I checks. Since the model's vertical resolution is in general considerably less than the resolution of the observations, this step represents a smoothing of the data and a reduction of the detail in the vertical structure.

In stage II the check against background requires that the inequality

$$(O-B)^2 < N_1 (E_o^2 + E_b^2)$$

is satisfied; O and B are the observed and background values on a sigma level, E_o and E_b are estimates of the observation and background errors and N_1 is an adjustable factor which in the case of radiosondes equals 12. The final check in the quality-control procedures ensures that there is consistency between neighbouring observations. It requires that an inequality of the type

$$(O-A)^2 < N_2 (E_o^2 + E_a^2)$$

is satisfied.; A is the analysed value at the observation position calculated using all the observations which have passed the background check with the exception of the one which is the subject of the check, E_a is an estimate of the analysis error, and N_2 is another adjustable factor which in the case of radiosondes again equals 12.

A final quality-control flag, specifying that the observation is unsuitable for use by the data assimilation system, is set on those observations failing the check against their neighbours defined above. A final flag may also be set if the station is on a blacklist of stations known to provide unreliable observations or if the observation has been rejected by the manual checking procedures in the Central Forecasting Office at Bracknell. The last two conditions are rare occurrences for radiosonde winds. Quality-control checks are performed separately at each sigma level; if a final flag is set at more than 4 levels of a radiosonde ascent the observation is considered unreliable and a final flag is set on values of the variable at all remaining levels.

5. MONITORING RESULTS FOR RADIOSONDE WIND OBSERVATIONS

5.1 Quality-control flags

The flags raised by the objective quality-control checks are a simple means of identifying stations providing regularly erroneous observations. Figures 3 and 4 show the percent of wind observations with a final flag averaged over the layers 400-150 hPa and 150-40 hPa during the whole of 1988 for an area covering much of Europe. The percent flagged is mostly very small which reflects not only the general reliability of the observations, but also the limitations of the rather simple quality-control methods. The distance between stations is usually at least 250 km which is rather too large for the second equation in section 4 to provide a reliable indication of mutual inconsistency. However, several stations over south east Europe and one or two over western parts of the USSR stand out with between 2 to 10 percent of observations flagged. Some of these stations will be investigated in more detail in the rest of the section.

5.2 Mean and rms differences from background

Figure 5 shows vertical profiles of the mean and rms O-B differences in 1988 at Crawley (51N, OW) and is typical of values found at the great majority of mid-latitude stations. Mean differences are small except in the boundary layer where O-B values of speed and direction are negative. This is a characteristic of almost all stations over land and is probably due to both

systematic errors of the model and representativeness errors. The rms vector wind differences lie between 3 and 6 m/s (6-12 knots); the maximum values around 300 hPa are associated with large random model errors within the jet stream and with the strong horizontal wind shears often observed at this level which are beyond the resolution of the model. Consequently the height of this maximum varies with latitude and season in the same way as the level of the jet stream. In the tropics rms O-B differences at these levels are generally smaller than values in mid latitudes. In order to introduce some consistency to the comparisons of statistics from stations at different latitudes, the mean and rms differences presented here have been averaged over two layers of the atmosphere: 400 to 150 hPa, which includes the jet-stream maximum under most circumstances, and 150 to 40 hPa, which in most cases lies in the stratosphere.

Vertically-averaged mean O-B differences of the vector wind at stations over Europe for 1988 are shown in figures 6 and 7 for the two layers 400-150 hPa and 150-40 hPa. At many stations the mean differences are as small as 1 m/s or less but nevertheless there is a consistent large-scale pattern, particularly in the lower of the two layers where there are northerly values over Scandinavia turning to northwesterly values over the UK and central Europe. It is difficult to imagine that observation errors could be so consistent over such a wide range of conditions and wind-finding equipment, and such a pattern can only reasonably be explained by large-scale background errors. In the tropics systematic model errors are on average considerably larger at around 1-4 m/s in the troposphere (Hall 1988) and larger still in the top 2 or 3 model levels. Mean O-B differences over the eastern Mediterranean and the Black Sea are generally greater than further north and west and there is much more variability from station to station. It will be shown in the remainder of this section that many of the largest values can be explained by large observation errors.

Figures 8 and 9 show values of rms O-B differences of the vector wind in units of tenths m/s for the same area, period and levels as figures 6 and 7. Clearly there is a good deal of consistency from station to station particularly where accurate wind-finding systems are known to be in use, eg NAVAID (Italy, Spain, Norway and Finland), or radar (UK, France, Sweden and Germany); and it seems that the assumption of low spatial variability of the background errors is justified. Over continental regions of northern Europe, the high observation density and the lack of complicating effects of mountains no doubt lead to smaller than average background errors, and account for the lowest values of rms O-B which occur there. Values are rather larger on the Atlantic coast where the influence of the data sparse areas upstream is clearly evident. Most estimates of the reproducibility of reliable wind-finding systems (in this case E_b) are no larger than 1-2 m/s, and the values of 4-6 m/s found in figures 8 and 9 therefore represent good estimates of the background plus representativeness errors (E_b and E_r). Using Kitchen's estimates of E_r it seems that in most places E_b is indeed of the same order of magnitude as suggested by Hollingsworth and Lonneberg. However, the values of rms O-B do not follow a uniform pattern everywhere; a few stations stand out as having values considerably larger than those of their neighbours and also many stations within certain countries (eg Turkey, Greece and Romania) have values much larger than at other stations in similar latitudes. The only realistic explanation for such large values is the existence of large observation errors.

All the statistics presented so far have been calculated using all available observations irrespective of the deviation of O-B from the population mean. Individual "wild" observations, occurring for instance as a result of miscoding, may distort unrealistically the sample characteristics, and for comparison maps of rms O-B differences using only those observations passing the quality-control checks are shown in figures 10 and 11. The values are smaller, but in most cases not by much. However, in the 150-40 hPa layer the

0.5 percent of flagged observations at 01152 (67N, 14E) contribute about 60 percent to the variance of O-B and there is a similar contribution to the variance from the 1.1 percent of flagged observations at 02527 (57N, 12E). In the 400-150 hPa layer 0.3 percent of the observations at 16245 (41N, 12E) contribute about 75 percent to the variance. The use of only those observations passing the quality-control checks enables an estimate to be made of O-B values for reliable observing systems, however, the criterion is too restrictive for general monitoring as those observations of greatest interest will often be excluded. In section 5.4 a less restrictive screening method has been used.

Excluding cases where there is large contribution to the variance from a small percent of flagged observations, it is possible to identify a number of stations with values of rms O-B which are significantly larger than at surrounding stations. In general there is consistency between the two layers presented; those stations with large differences in one layer also have large differences on the other layer. 12 stations have been identified which have a value of rms O-B which is more than 50 percent larger than the lowest values in the surrounding region. They are underlined in figures 8 to 11 and listed in table 1 below. The information on the wind-finding equipment has been taken from the 1984 WMO Catalogue, except in the case of stations in the USSR for which information has been obtained on the equipment in use in 1989.

Station	Position	Wind finding	% flagged		% obs MOD(O-B).GT.50m/s	
			400-150	150-40	400-150	150-40
15120	46.8N 23.6E	RT+SR Meteorit	2	*	0.0	0.1
15420	44.5N 26.1E	RT+SR Meteorit	2	*	0.1	0.2
15480	44.2N 28.6E	RT+SR Meteorit	2	4	0.1	0.1
16622	40.5N 23.0E	RT	10	*	0.0	0.0
17030	41.3N 36.3E	?	0	0	0.0	0.0
17352	37.0N 35.3E	?	1	1	0.0	0.2
22522	65.0N 34.8E	RT Malahit	5	8	0.2	0.1
22550	64.6N 40.5E	RT+SR AVK-MRZ	1	0	0.0	0.0
22802	61.7N 30.7E	RT Malahit	4	4	0.0	0.0
27037	59.3N 39.9E	RT+SR AVK-MRZ	2	2	0.0	0.2
27595	55.8N 49.2E	RT Malahit	3	4	0.0	0.0
34009	51.7N 36.2E	RT+SR AVK-MRZ	3	2	0.0	0.0

Table 1. 12 stations with largest values of rms O-B vector winds relative to their neighbours. January to December 1988. RT = radiotheodolite, SR = secondary radar; Meteorit, Malahit and AVK-MRZ are three main systems in use in USSR and some Eastern block countries.

The distribution of the O-B values for these stations at one particular model level (level 11, pressure around 250 hPa) is shown in the histograms in figure 12. In most cases the distribution is nearly Gaussian with only small non-Gaussian tails of larger values (outliers). It seems that the vast majority of the O-B values at these stations, that is those which are not outliers, have Gaussian distributions with standard deviations significantly larger than those of their neighbours.

The methods described above and in section 5.1 are valuable for identifying unreliable stations, but they do not provide much information on the nature of the problems. A more detailed study of O-B differences can reveal much more useful information, especially if it is based on a knowledge of the likely sources of error in the wind-finding system. Three such examples are presented in sections 5.3, 5.4 and 5.5.

5.3 Wind direction errors

One of the simplest sources of wind error comes from a misalignment of the direction of true north, and it shows up as a bias in wind direction relative to background and nearby stations which is constant with height. Two of the stations in the above list, 22550 and 27037, stand out as having clear direction errors as table 2 demonstrates.

	22550	22271	22550-22271	27037	26298	27037-26298
sigma 0.998	5.6	-3.5	9.1	-17.5	-27.6	10.1
0.975	-3.2	-7.3	4.1	-24.5	-14.5	-10.0
0.935	-1.4	-6.9	5.5	-26.9	-11.1	-15.8
0.870	3.9	-3.2	7.1	-20.0	-4.1	-15.9
0.790	6.2	-1.4	7.6	-16.8	-0.8	-16.0
0.690	8.4	-0.5	9.9	-16.0	-0.4	-15.6
0.590	8.7	0.6	9.3	-16.9	-1.6	-15.3
0.490	9.6	0.9	8.7	-16.8	-2.4	-14.4
0.390	10.3	1.3	9.0	-16.1	-2.7	-13.4
0.310	11.1	1.9	9.2	-16.1	-1.9	-14.2
0.250	12.5	1.6	10.9	-15.5	-1.6	-13.9
0.190	13.1	2.0	11.1	-15.4	-2.4	-13.0
0.125	12.8	2.6	10.2	-16.7	-3.4	-13.3
0.066	10.1	2.0	8.1	-14.7	-2.8	-11.9
0.025	3.4	-5.0	8.4	-17.5	-7.0	-10.5

Table 2. Mean values of O-B wind direction at each model level for stations 22550 and 27037 and their neighbours 22271 and 26298.

The varying direction biases in the boundary layer can be attributed to the same model and representativeness errors seen at Crawley, but where a comparison is made with a neighbouring station the relative bias is nearly constant with height. The reported wind appears to be 14 degrees backed with respect to the true flow at 27037 and 9 degrees veered at 22550. There are 3 other stations with direction errors in excess of 10 degrees in the area shown in the figures, 11952 (49N 20E, 11 degrees backed), 34880 (46N 48E, 12 degrees backed), 37260 (42N 41E, 13 degrees backed), and over the rest of the globe another 10 stations. They all show mean and rms values of O-B which are significantly larger than at neighbouring stations.

5.4 Wind error dependence on balloon elevation

For those radiotheodolite systems which have no means of measurement of the slant range, winds are calculated from measured values of balloon azimuth (a), elevation (e) and a value of the height (h) derived from the pressure/temperature profile measured by the sonde. The balloon range is given by

$$r = h \cot e$$

and the velocity component along the line of sight to the balloon by

$$v_s = dr/dt$$

$$= \cot e \, dh/dt + h \operatorname{cosec}^2 e \, de/dt$$

At low elevations (small e) $\text{cosec}^2 e$ is approximately e^{-2} and the second term dominates:

$$v_a = h e^{-2} de/dt$$

The accurate measurement of e and de/dt at low balloon elevation requires precise alignment of the antenna in the horizontal and vertical which is unlikely always to be the case. It is quite possible that errors in e and de/dt are a substantial proportion of the observed value, in which case errors in v_a may be very large. In recognition of this fact some stations operating with radiotheodolites cease reporting winds once the observed elevation falls below a critical value, however, even this practice will not eliminate observations with large error where the instrument is badly misaligned. The component of wind perpendicular to the line of sight to the balloon is given by

$$v_p = h \cot e da/dt$$

At low elevations (small e) $\cot e$ is approximately e^{-1} and

$$v_p = h e^{-1} da/dt$$

Again errors in the measurements of wind will increase at low balloon elevations but only as e^{-1} rather than e^{-2} .

The above estimates allow a prediction to be made of the characteristics of radiotheodolite systems which have problems with the direction-finding antenna; the errors in the observed along-sight component (v_a or a-component) are expected to increase much more rapidly as the elevation becomes small than errors in the perpendicular-to-sight component (v_p or p-component). This can be investigated using model fields where background values of v_a and v_p are evaluated at the balloon position. The balloon downwind range can be estimated from the observed wind profile given in the radiosonde report, and the height can be calculated assuming a value for the ascent rate (taken to be 5 m/s here). Of course it is not known how model errors in the a and p-components of wind differ; for small e they are both likely to be larger than average as low balloon elevations result from strong winds at jet-stream level where it is known that model and representativeness errors are large. In addition the magnitude of model errors at low balloon elevation may depend on location; low elevation implies the existence of a strong (usually westerly) jet, which in turn implies the rapid propagation of errors. In such cases, model errors on the western coasts of continents, just downwind from data-sparse oceans, are likely to be larger than at sites further inland. These model characteristics are impossible to quantify without working from observational results, and as before model plus representativeness errors will be estimated by reference to wind-finding systems of known high quality.

Figures 14 to 21 show values of the mean and rms O-B differences for the a and p-components of wind as a function of $\cot e$ for several wind-finding systems. All observations have been included with the exception of those making an exceptionally large contribution to the variance of O-B. These outliers have been identified using standard statistical techniques on each sample of observations having values of $\cot e$ within a specified range. In practice far fewer observations are eliminated than have flags raised by the quality control checks. Averages are presented over stations within the national networks of UK, France, Germany, Sweden and Australia (figures 14 to 17) where primary radar is used operationally, and of Finland, Spain, Italy and Saudi Arabia (figures 18 to 21) where Omega NAVAIID is used. To give an indication of values in data-sparse regions, the isolated stations OWS Lima (57N 19W) and Mount Pleasant Airport (52S 58W) with Omega systems are included in figures 18 to 21. All reports (TEMP and PILOT) received in 1988 have been used and vertical

averages have been performed over two bands; the first between sigma levels 9 and 12 (band I: approximately 400 hPa to 150 hPa) which includes the jet-stream maxima in most latitudes and seasons, and the second between sigma levels 13 and 14 (band II: approximately 150 hPa to 40 hPa) which lies in the stratosphere in the non-equatorial regions considered here.

As anticipated the O-B differences do indeed increase with cote but not by much in the case of the p-component. There is in general good agreement in the values from system to system and many of the differences which exist can be explained by the factors mentioned above. The larger values for Australia and Mount Pleasant no doubt reflect the larger model errors in the data-sparse southern hemisphere. Values also seem to be larger around latitudes 30 to 40N in band I than at latitudes further north. Mean O-B differences are mostly between -2 and +2 m/s except for the a-component in band I where biases of +2 to +4 m/s at low elevations (strong winds) are consistent with the known under estimation of jet strengths in the model. It is interesting to note that values at OWS Lima are not substantially larger than elsewhere in the northern hemisphere, showing that numerical data assimilation systems successfully make use of all types of observations and spread information from the data-rich to the data-sparse areas. The lower values in the p-component in Finland and in nearby Sweden cannot easily be explained. There also seem to be some abnormally large values in the a-component in band II at low elevations over Sweden, which are a foretaste of what is to follow in this section, and point to possible observational errors. Comparing the Swedish with the Finish values in band II it seems that considerably more Swedish stations are flagged (see table 3). Also, there are fewer occasions when the balloon reaches this high level, particularly when its elevation is low, which is a indication of possible problems.

	N Rep	N BdII	Flag	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
Finland	4154	3734	3	414	966	985	683	405	181	70	22	5	1
Sweden	5432	1781	46	212	553	503	270	134	61	23	3	0	1

Table 3. Number of reports, number of ascents reaching band II, number of observations flagged in band II, and number of observations in band II with cote in the ranges 0-1, 1-2, ..., 9-10 for all stations in (a) Finland and (b) Sweden in the year 1988.

Values from the 9 northern hemisphere national networks or individual stations have been averaged together to provide a standard (S_1) against which other stations may be compared. A similar average has been calculated for the southern hemisphere (S_2) from the 2 systems presented here. No attempt has been made to include any dependence on latitude. In all the examples which follow these reference plots (S_1 or S_2) have been represented by thick lines for comparison against the individual station values represented by thin lines. The stations shown in figures 22 to 28 are 15120, 15420, 15480, 16622, 17352, 22802 and 34009. They are 7 of the 12 stations on the list in section 5.2 having notably larger rms O-B values than their neighbours or other stations at a similar latitude. Two other examples are given in figures 29 and 30 of stations with abnormally large rms O-B differences which fall outside the region shown in the figure. They are 54497 (40N 124E) and 68816 (34S 19E).

It is immediately clear that the dependence on balloon elevation of the rms O-B differences of the a and p-components of wind differs considerably from the standard. The values for the p-component are generally larger than the standard but show little dependence on the elevation, while the a-component values increase rapidly at small elevations. At some stations observations cease where the elevation falls below some critical level, no doubt as a result of the local observing practice. Where observations continue at very low elevations massive rms O-B differences can be found (eg 16622, 54497 and 68816).

The only reasonable explanation of the characteristics shown in these examples is error in the measured winds; indeed the dependence on cote closely agrees with the prediction in the first part of this section. Radiotheodolites are known to be prone to large errors at low balloon elevations as small errors in the alignment of the direction-finding antenna can lead to large errors in the derived wind. The errors found here seem to be systematic to some extent in that a-component biases generally mirror the rms dependence on elevation and account for a substantial part of the variance. In all except one instance they increase positively with cote, or equivalently, there are positive speed biases at high levels. In most cases too the a and p-component characteristics in band II are similar to those in band I reflecting the common source of error in the ground station equipment. 15480 has large a-component biases of different sign in the two bands which cannot easily be explained. The characteristics of the O-B values of wind at 22802 are also a little different; biases in the a and p-components are small as is the rms at high balloon elevation, but as the balloon elevation lowers random errors in the measured wind seem to increase rapidly.

Wind measurement errors at the remaining three stations from Table 2, 17030, 22522 and 27595 are not easy to categorize, though there does seem to be a small (5 degree) direction bias at 27595. The errors in the a and p-components (not shown) are larger than average both at high and low balloon elevations. Perhaps the nature of the errors is genuinely random, or perhaps there are other characteristics of radiosonde wind-finding systems which remain to be identified using model background values.

It is interesting to note that the only three stations in European USSR operating radiotheodolites without secondary radar, the old Malahit A-22 system, are included in the 12 stations considered here (22522, 22802, 27595) which probably accounts for the larger errors of mostly a random nature. Station 34009 is currently operating the most modern Soviet system, the AVK-MRZ, but this is a recent modernisation and the previous system in use in 1984 (and still in 1988?) was also a A-22. The information on the systems in use outside the USSR is less accurate.

5.5 Errors in the assignment of height

The level assigned to a radiosonde wind observation may be reported as a pressure or a height in metres and is derived in a number of different ways depending on the instrumentation. A height in metres can be simply derived from the slant range and balloon elevation provided by a range-finding radar, and the pressure element on a sonde gives a direct measurement of the pressure level. Where a virtual temperature profile is available from the sonde, pressure can be converted to height, and vice versa, by using the hydrostatic equation. Various combinations of these parameters are measured by the radiosonde systems in operational use.

1. For systems with range-finding radar and a sonde providing pressure and temperature, two independent estimates of the height may be obtained and cross checked. These systems probably provide the most accurate values of height.
2. Where there is range-finding radar but a sonde is not used, as in a PILOT ascent, wind can be only directly assigned a height in metres and in the part B the special levels are reported in this way. The standard pressure levels in the part A of the report are in fact assigned fixed heights which are determined by each Regional Association of WMO. This will introduce considerable inaccuracy on occasions.
3. For systems with a sonde providing pressure and temperature but with no range finding, for example NAVAID and radiotheodolites without secondary radar, the pressure level assigned to the wind observations is simply the value measured by the sonde.
4. For systems with range finding and a sonde having a temperature but no pressure element, for example the Meteorit and AVK-MRZ sondes used at most stations in the USSR, the pressure level may be derived using the hydrostatic equation.
5. Simple optical systems, having no sonde or accurate means of measuring the range, rely on the assumption of a constant known balloon ascent rate to estimate the height.

A instrumental error may lead to the wrong vertical assignment of the observations. A possible way of detecting systematic biases in the height assignment is through an examination of the characteristics of the O-B temperature differences from the sonde and two examples are given in figure 31. At station 34300 (49N 36E) O-B increases steadily from near zero at the surface to a large positive value around 300 hPa before falling suddenly to zero again at higher levels. Neighbouring stations show no such characteristic. It is difficult to imagine how a defect in the temperature element could result in this sudden change with height unless it has a quite exceptionally long response time. More probable is a bias in the assignment of height which is largest at high levels. In the near-isothermal stratosphere errors in height will not lead to a temperature bias, but just below the tropopause the +3K bias implies a systematic error in the height of perhaps as much as +500m. The other example in figure 31, station 26422 (57N 24E), also shows a sudden change in O-B temperature values around the tropopause, but the whole profile appears shifted to the right compared with the first example. Again a height assignment bias seems the only likely explanation of the change, but in addition there must be a temperature bias relative to background and neighbouring stations which increases to around +2K in the stratosphere. Stations in this region usually apply a radiation correction and it seems that the practice at this station is different from normal. Perhaps the station recognised that its 100 hPa heights were inconsistent with its neighbours and has mistakenly altered its temperature correction to compensate. According to up-to-date information, a Meteorit-MARS system is in use at both these stations which are part of the USSR network. There is no pressure sensor on the sonde and the observation level is obtained from the slant range provided by the secondary radar, the balloon elevation provided by the radiotheodolite, and the temperature profile provided by the sonde. Some possible causes of the identified O-B biases are a levelling error at the ground station leading to a bias in the measured balloon elevation, a bias in the range finding, or an erroneous temperature correction. Further investigations into the dependence of the O-B temperature bias at 300 hPa on slant range have not been carried out.

6. CONCLUSIONS

Background values from high-resolution numerical models provide a powerful means of monitoring the quality of observations. Three components contribute to the differences between observations and background: measurement errors, background errors and representativeness errors. For reliable operational wind-finding systems measurement errors are generally no larger than 1-2 m/s; Kitchen has estimated representativeness errors at jet stream levels to be in the range 3-4 m/s which leaves a residual attributable to the background error of a further 3-4 m/s over the data-rich regions of Europe. The magnitude of the background errors is the limiting factor in their use for monitoring and even over Europe some significant systematic model biases have been noted. The results presented here seem to provide justification of the assumption that background errors averaged over long periods of time vary only slowly in space. This is critical for identifying stations with larger than average measurement errors. In general rms O-B values of vector wind have uniformly low values highlighting the reliability of the observations, but a few stations stand out with values significantly larger than others in the immediate neighbourhood. 12 such stations over Europe with the largest discrepancies have been picked out and studied in more detail. In most cases O-B has a near-Gaussian distribution with a standard deviation that is larger than average. Few of the observations are flagged by the model's quality-control checks which merely reflects the limited information that can be extracted from just a single report. Long-period averages of O-B reveal some of the characteristics of the errors; 7 of the 12 have problems at low balloon elevations typical of those known to occur with the radiotheodolite systems in use; and 2 of the 12 have direction biases, constant with height, which can presumably be attributed to a misalignment of the direction of true north. The remaining 3 stations have errors of a more random nature.

The methods outlined here provide a basis for the regular monitoring of radiosonde wind observations worldwide. To convince those responsible for producing the observations of the power of monitoring methods based on the use of products from numerical models, it is important that information of the nature of the alleged errors is given. A number of techniques have been outlined here and no doubt more could be developed. The information presented here is also of great value for improving the use of observations by the numerical assimilation systems; estimates of the observation error at each station can be used to give more reliable weights to the observations, and some of the more obvious errors can be corrected. An essential requirement of all these applications of monitoring results is a continual updating of the monitoring information.

7. REFERENCES

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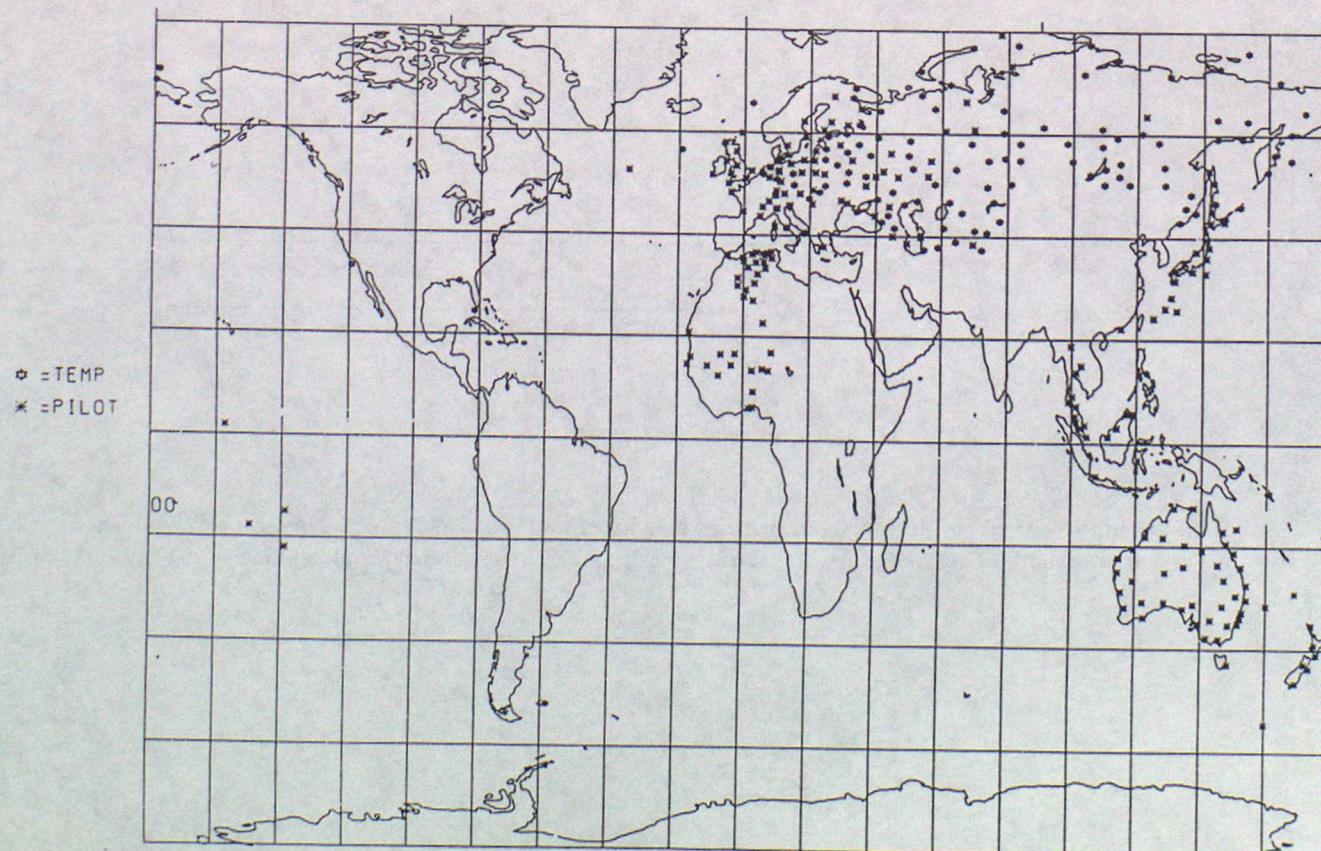
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Fig. 1

Radiosonde reports 12Z 1 August 1988 (± 3 hrs)



Radiosonde reports 18Z 1 August 1988 (± 3 hrs)



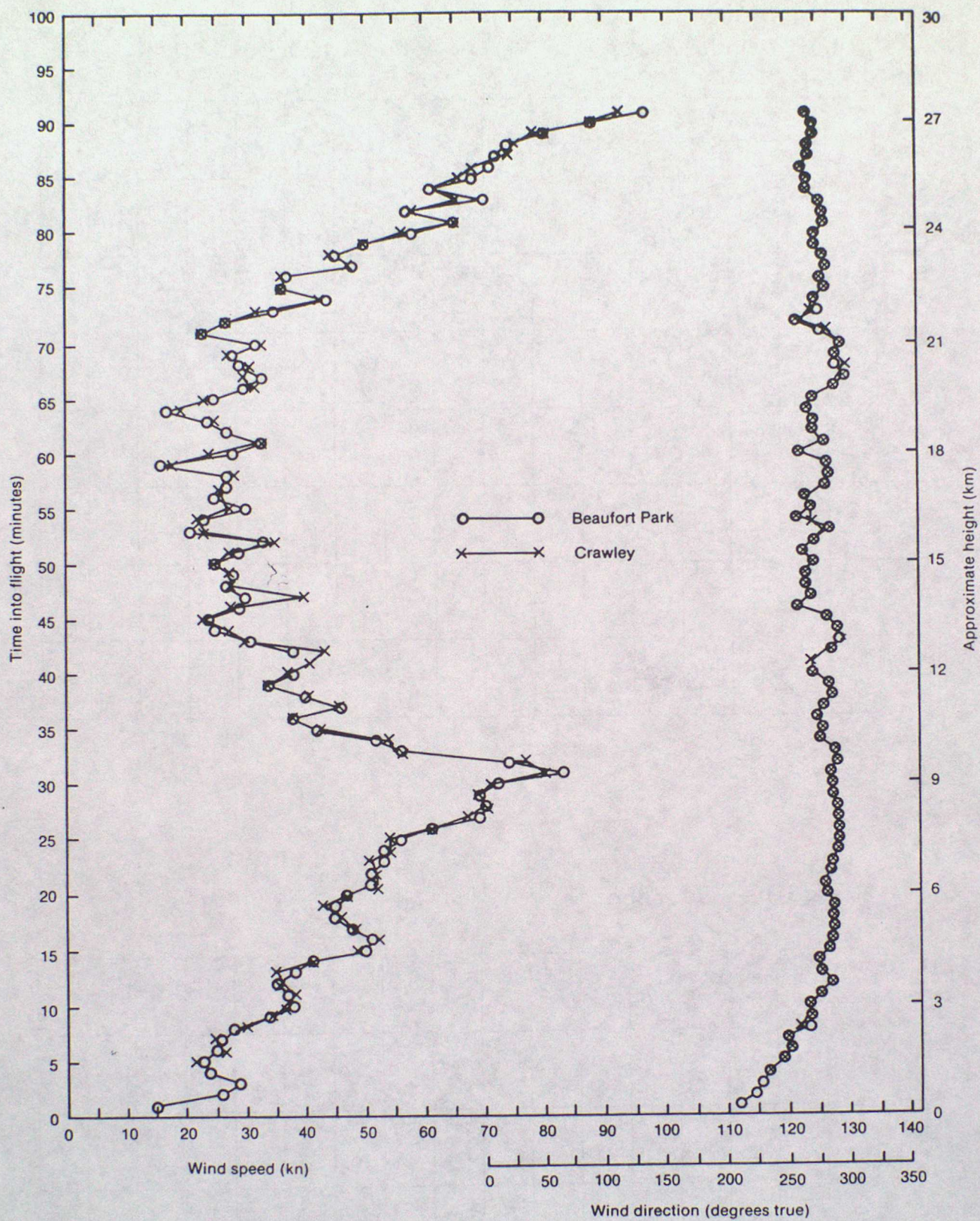


Fig. 2 Example of high vertical resolution wind profiles measured at 1500 GMT on 20 November 1984. The same radar target was tracked by Cossor radars at Beaufort Park and Crawley (horizontal separation 52 km).

Fig. 3

DATA DERIVED FROM CM OPD 1 JAN 1988- 30 DEC 1988 & PLOTTED BY BAND(SIGMA DTP):
OBSERVATION AND FLAG COUNTS FOR MODEL DATA TYPE TMP.DAT UNUSUED:NONE
PLOT IS: TOP:IDENTIFIER,LEFT:% FINAL FLG,RIGHT:N. OBS USED FOR STATISTICS
VARIABLE:VT WD PRESSURE BAND: 400- 150MB ANALYSIS HOUR: ALL

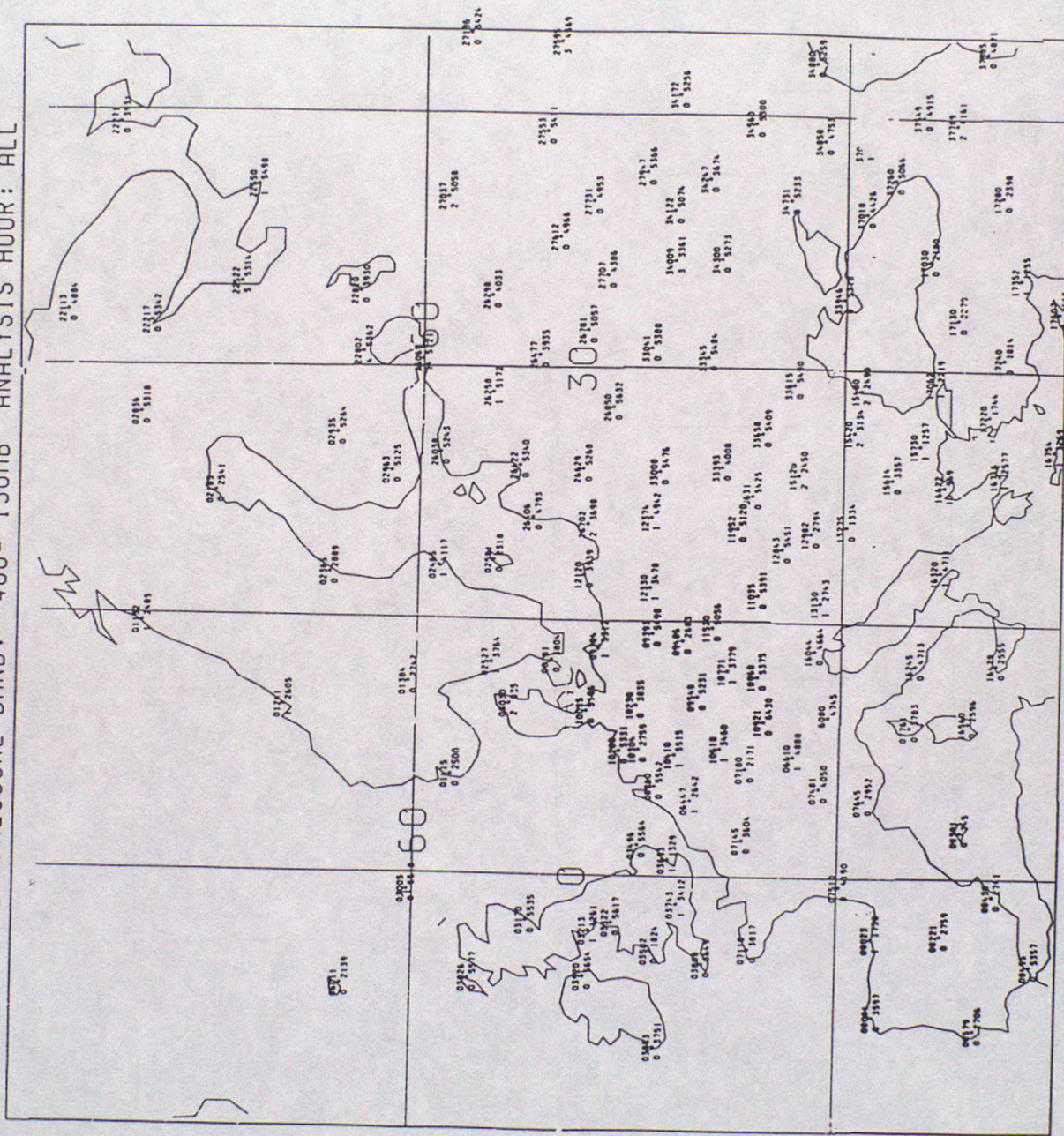


Fig. 4

OVERFLOW PLOTS FOR DATA DERIVED FROM CM OPD 1 JAN 1988- 30 DEC 1988 & PLOTTED
OBSERVATION AND FLAG COUNTS FOR MODEL DATA TYPE TMP.DAT UNUSUED:NONE
PLOT IS: TOP:IDENTIFIER,LEFT:% FINAL FLG,RIGHT:N. OBS USED FOR STATISTICS
VARIABLE:VT WD PRESSURE BAND: 150- 40MB ANALYSIS HOUR: ALL

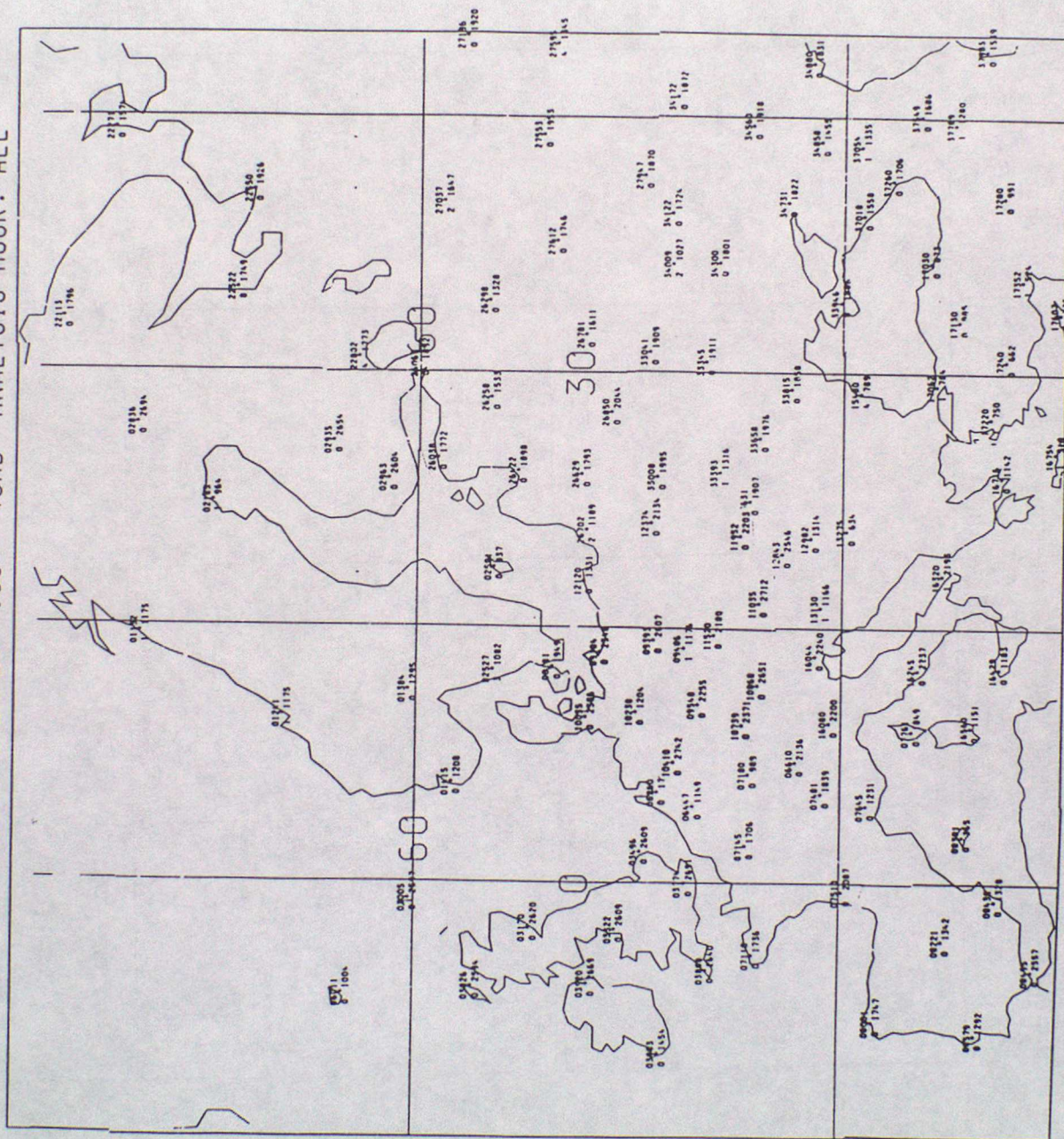
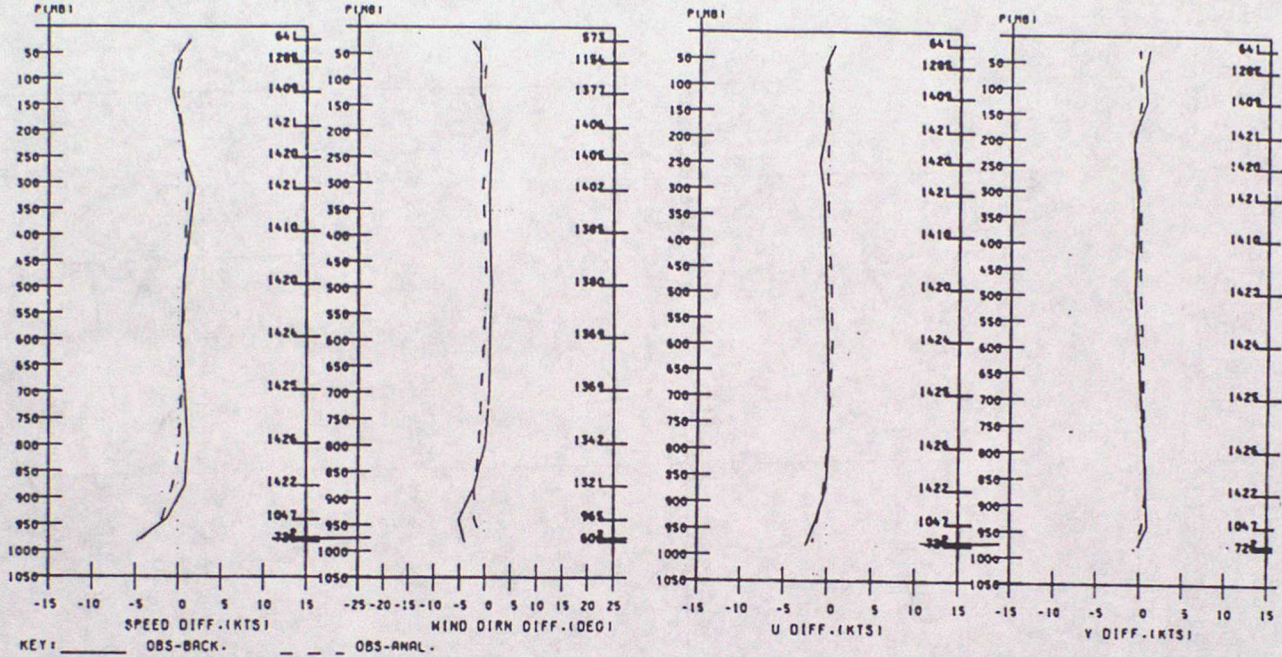


Fig. 5

MEAN AND RMS WIND DIFFERENCES FROM BACKGROUND
JANUARY TO DECEMBER 1988
CRAWLEY 51N 0W
ALL ANALYSIS HOURS

MEAN OF DIFFERENCES FROM BACKGROUND AND ANALYSIS FIELDS



RMS OF DIFFERENCES FROM BACKGROUND AND ANALYSIS FIELDS

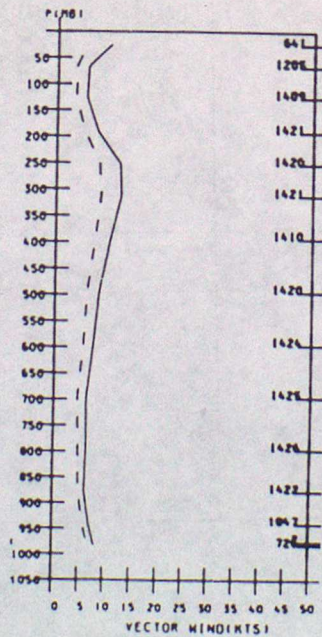


Fig. 6

DATA DERIVED FROM CM OPD 1 JAN 1988- 30 DEC 1988 & PLOTTED BY BAND(SIGMA DTA)
 MEAN VECTOR WIND (O-B) ARROWS. MODEL DATA TYPE: TMP DATA UNUSED:NONE
 PLOT SHOWS STN ID & MEAN VECTOR WIND BIAS. NO PLOT IF U AND/OR V STATS MISSING
 PRESSURE BAND: 400- 150MB ANALYSIS HOUR: ALL

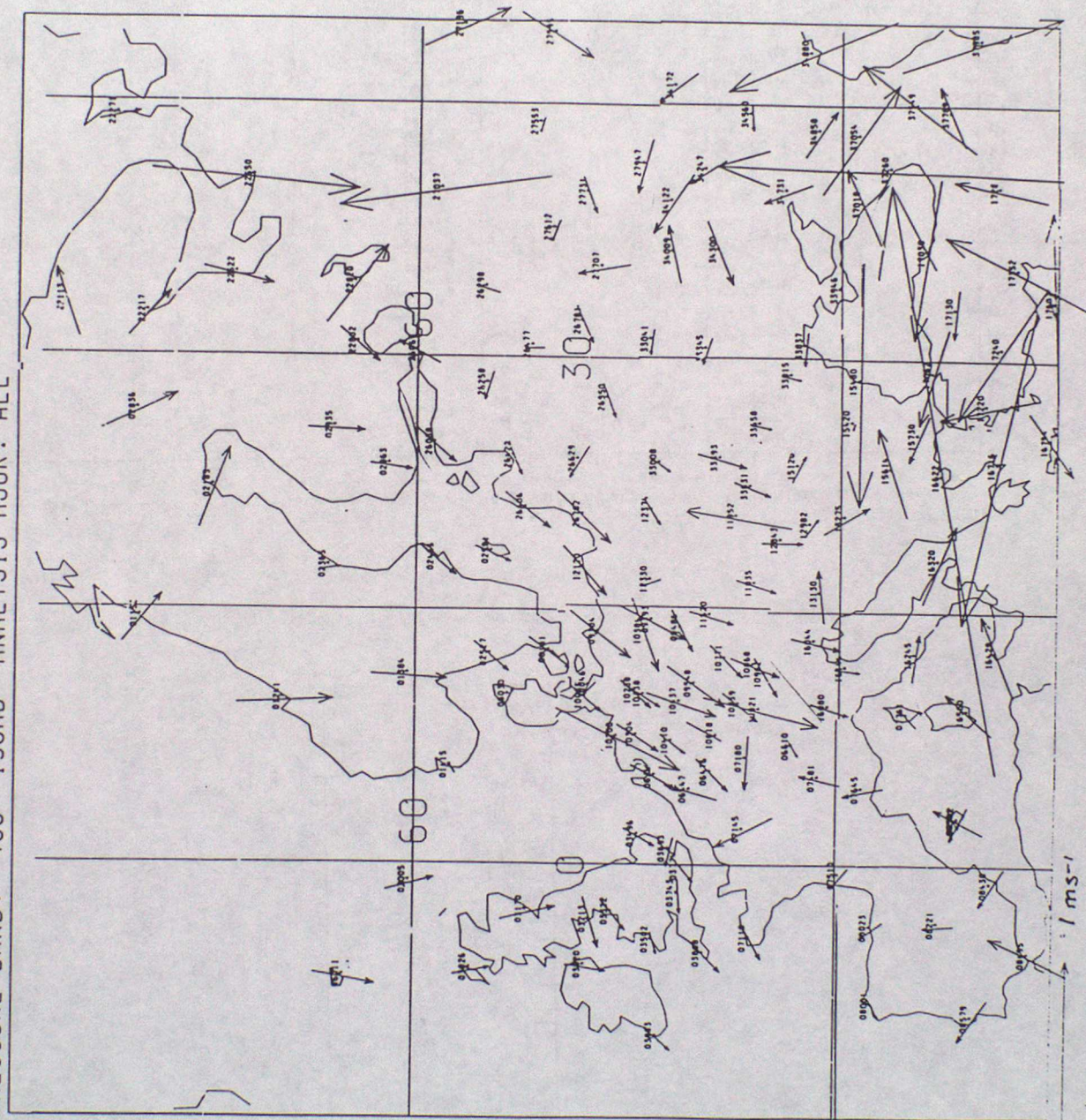


Fig. 7

DATA DERIVED FROM CM OPD 1 JAN 1988- 30 DEC 1988 & PLOTTED BY BAND(SIGMA DTA)
 MEAN VECTOR WIND (0-8) ARROWS. MODEL DATA TYPE: TMP DATA UNUSED:NONE
 PLOT SHOWS STN ID & MEAN VECTOR WIND BIAS. NO PLOT IF U AND/OR V STATS MISSING
 PRESSURE BAND: 150- 40MB ANALYSIS HOUR: ALL

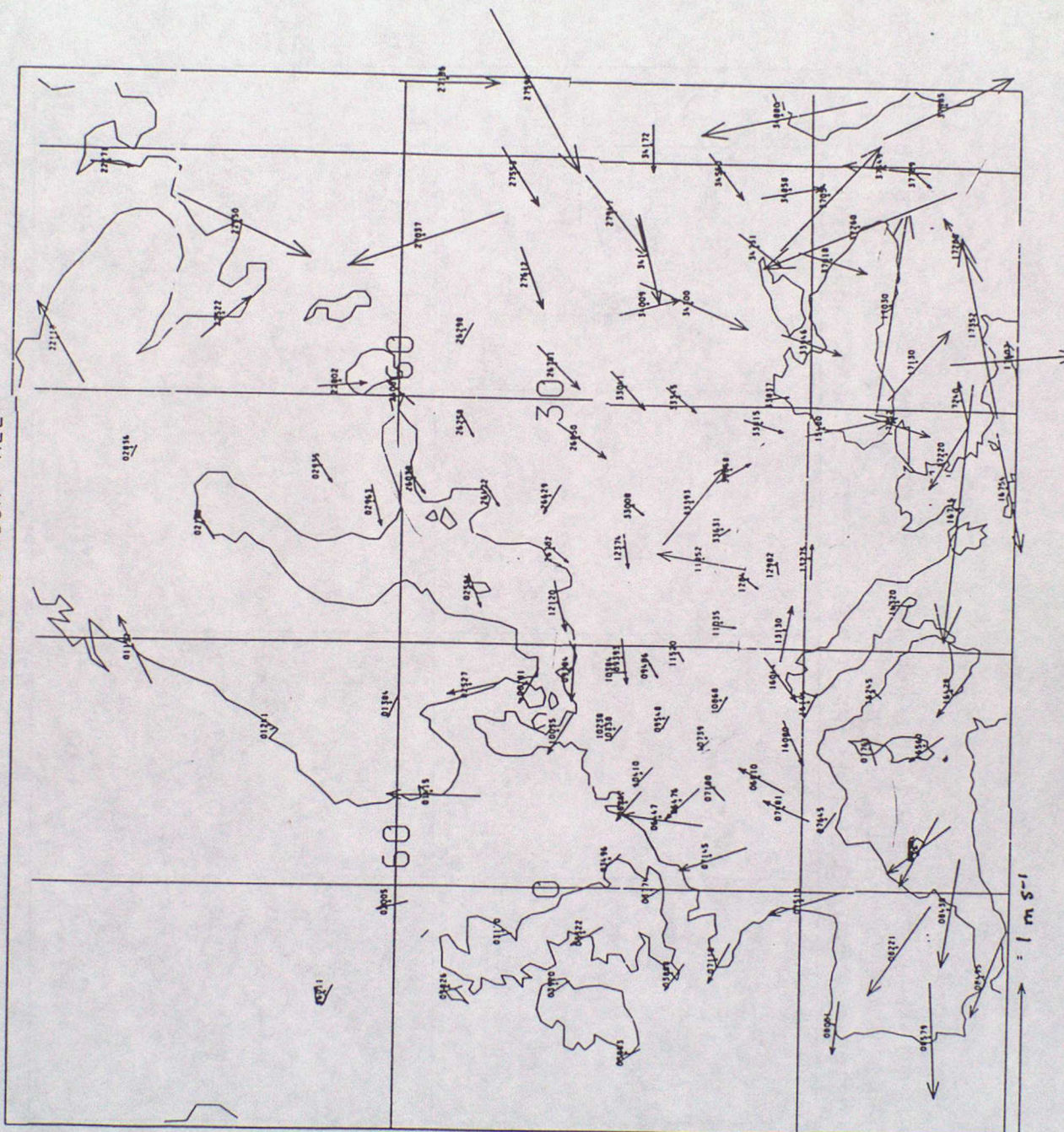


Fig. 8 DATA DERIVED FROM CM OPD 1 JAN 1988-- 30 DEC 1988 & PLOTTED BY BAND(SIGMA DTA)
MEAN AND RMS OF 0-8 DIFFERENCES FOR MODEL DATA TYPE TMP.DATA UNUSED:NONE
VARIABLE:VT WD PRESSURE BAND: 400- 150MB ANALYSIS HOUR: ALL

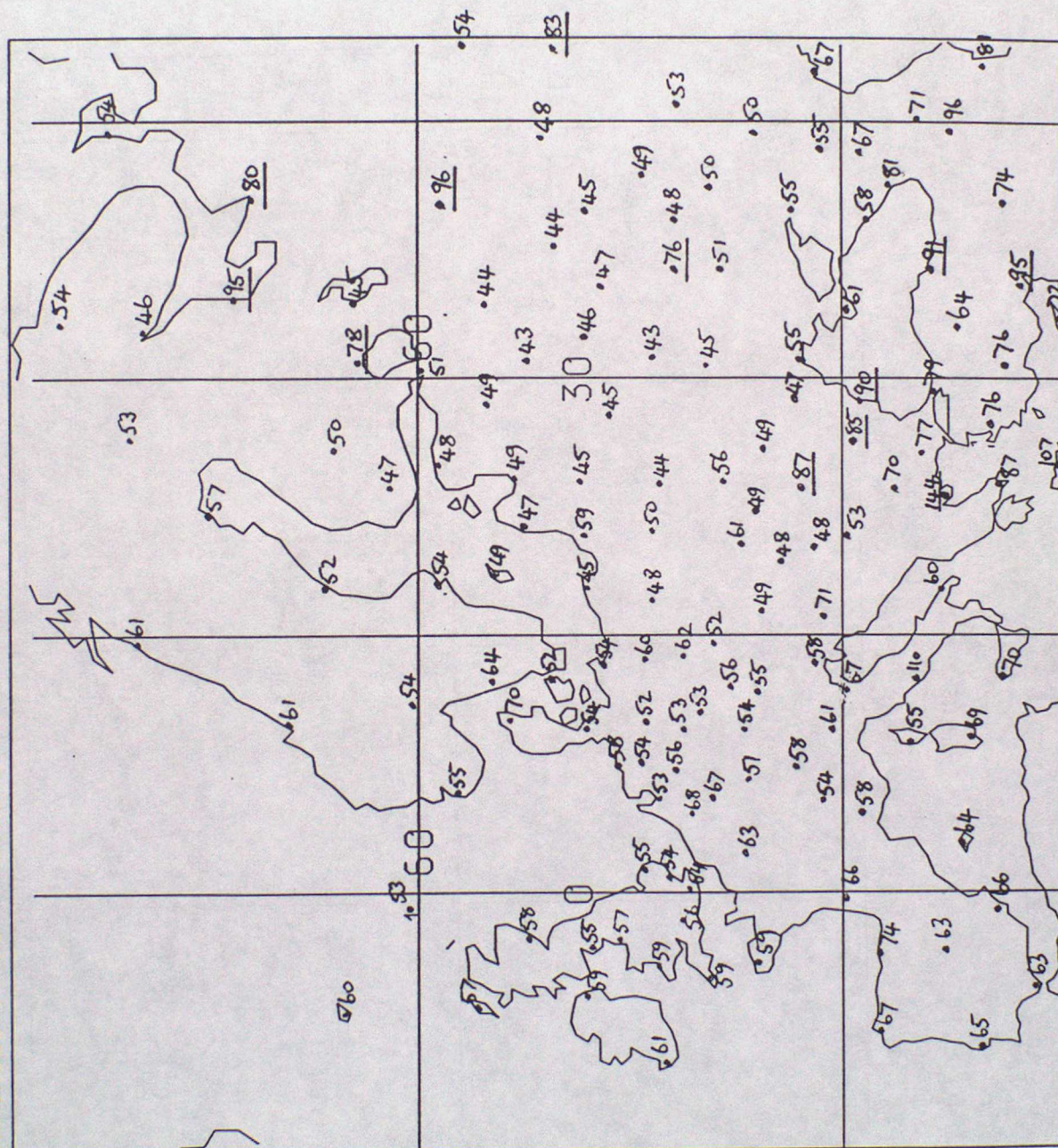


Fig. 9 DATA DERIVED FROM CM OPD 1 JAN 1988- 30 DEC 1988 & PLOTTED BY BAND(SIGMA DTA)
 MEAN AND RMS OF O-B DIFFERENCES FOR MODEL DATA TYPE IMP.DATA UNUSED:NONE
 VARIABLE:VT WD PRESSURE BAND: 150- 4UMB ANALYSIS HOUR: ALL

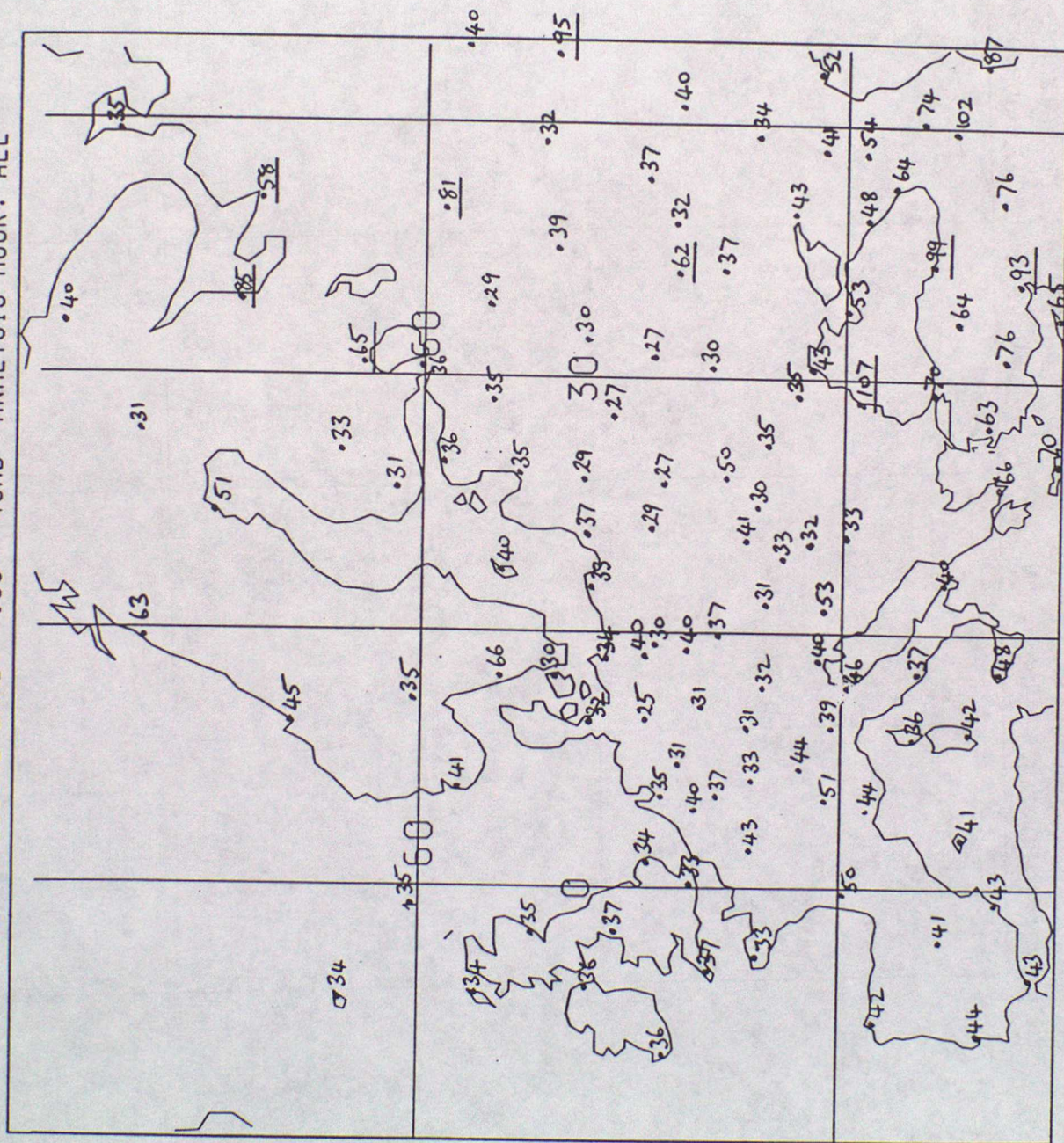


Fig. 10

DATA DERIVED FROM CM OPD 1 JAN 1988- 30 DEC 1988 & PLOTTED BY BAND(SIGMA DIA)
 MEAN AND RMS OF O-B DIFFERENCES FOR MODEL DATA TYPE TMP.DAT UNUSED:FINAL FLAGS
 VARIABLE:VT WD PRESSURE BAND: 400- 150MB ANALYSIS HOUR: ALL

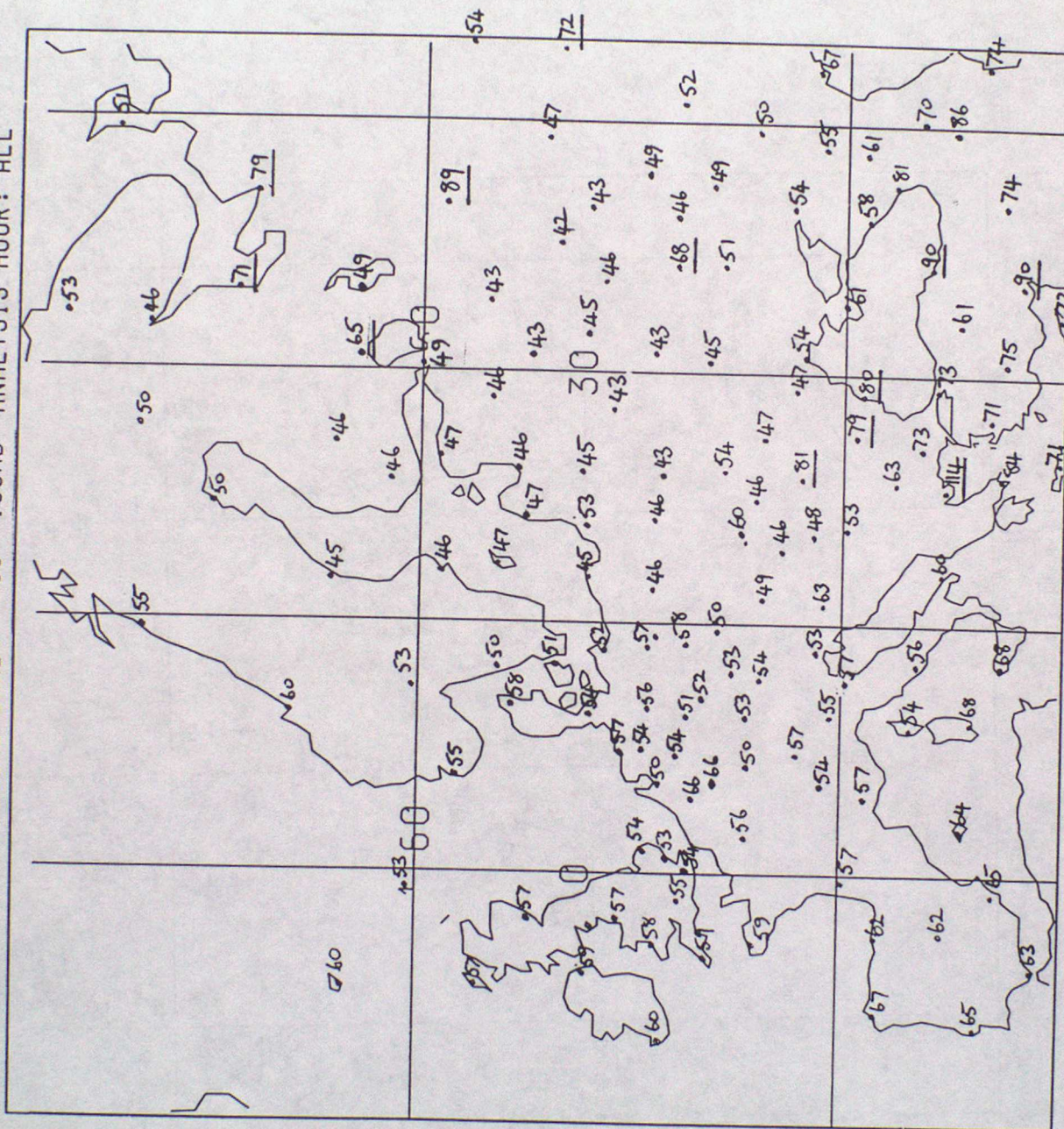
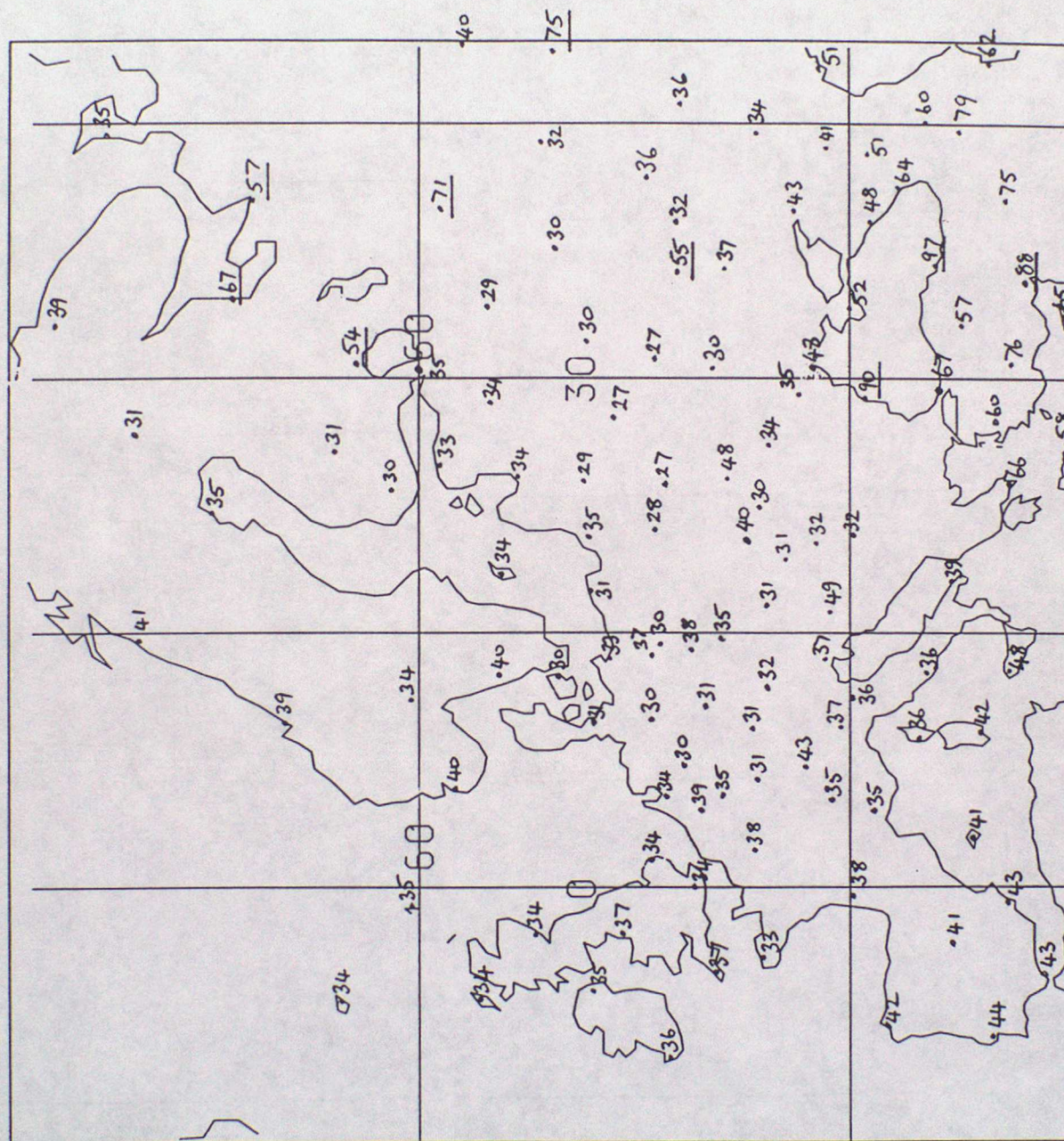


Fig. 11

DATA DERIVED FROM CM OPD 1 JAN 1988- 30 DEC 1988 & PLOTTED BY BAND(SIGMA DTA)
 MEAN AND RMS OF 0-8 DIFFERENCES FOR MODEL DATA TYPE TMP.DAT UNUSUED:FINAL FLAGS
 VARIABLE:VT WD PRESSURE BAND: 150- 40MB ANALYSIS HOUR: ALL



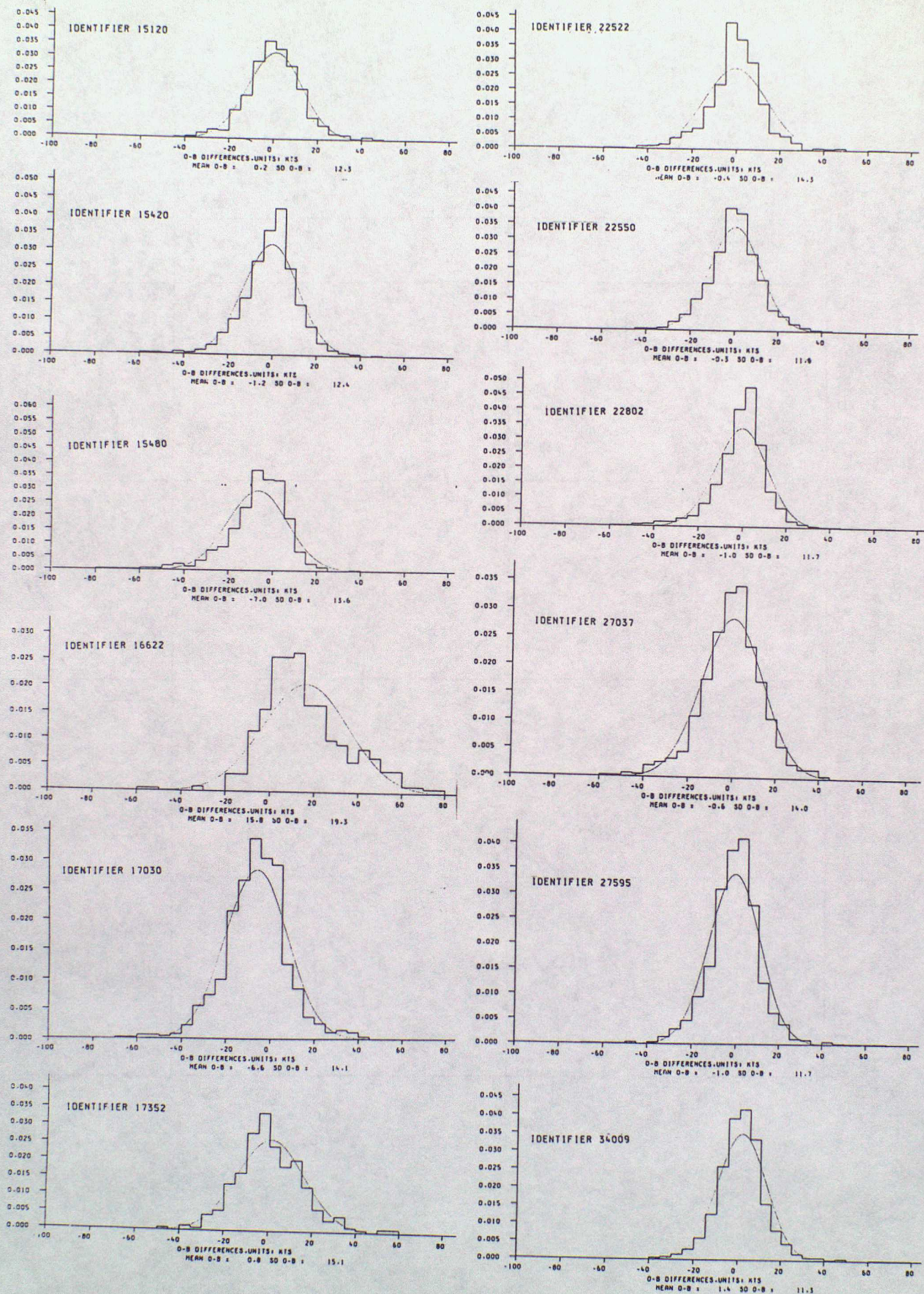
HISTOGRAMS OF U-COMPONENT DIFFERENCES FROM BACKGROUND

JANUARY TO DECEMBER 1988

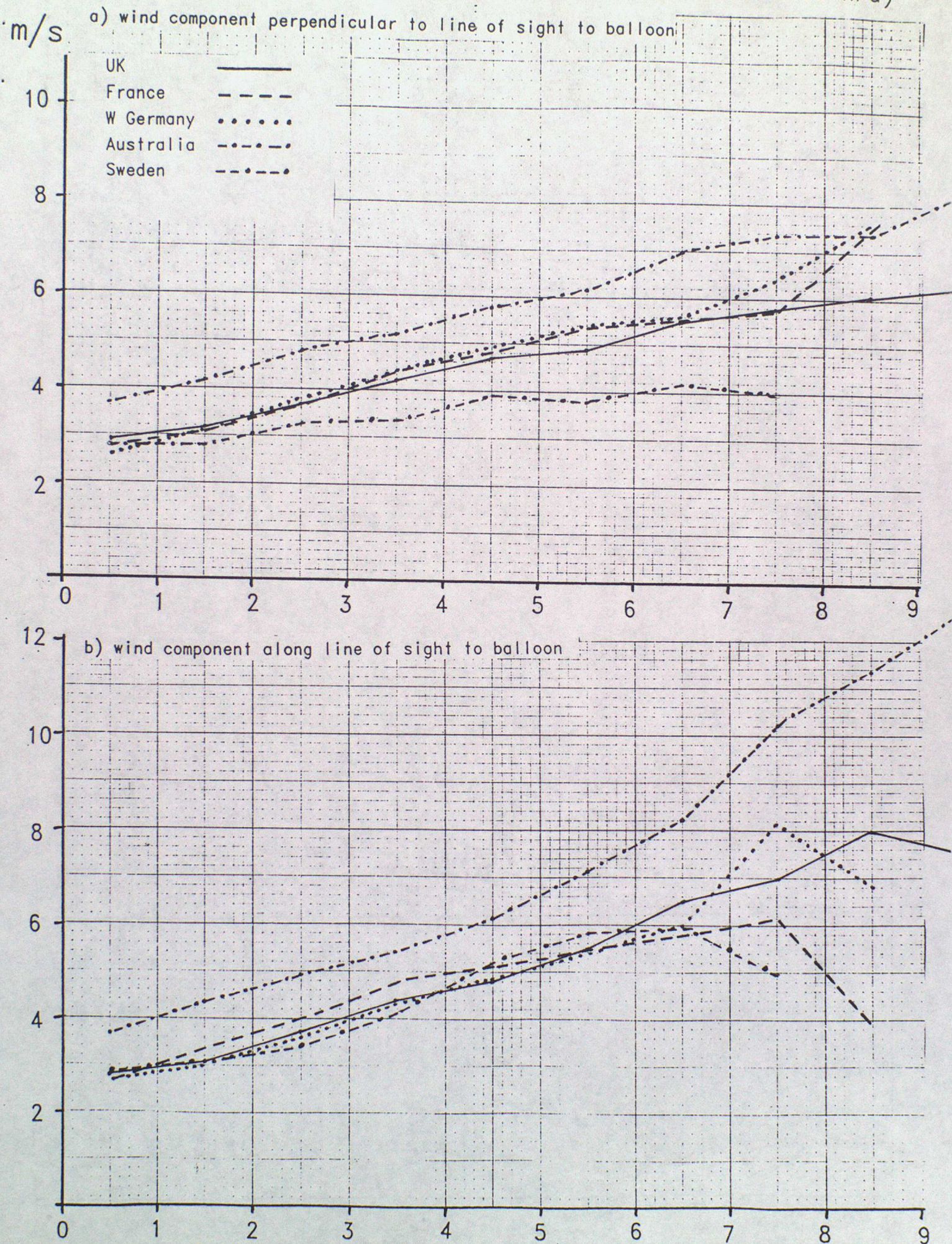
ALL ANALYSIS HOURS

GAUSSIAN DISTRIBUTION WITH SAME MEAN AND SD ALSO SHOWN

Fig. 12

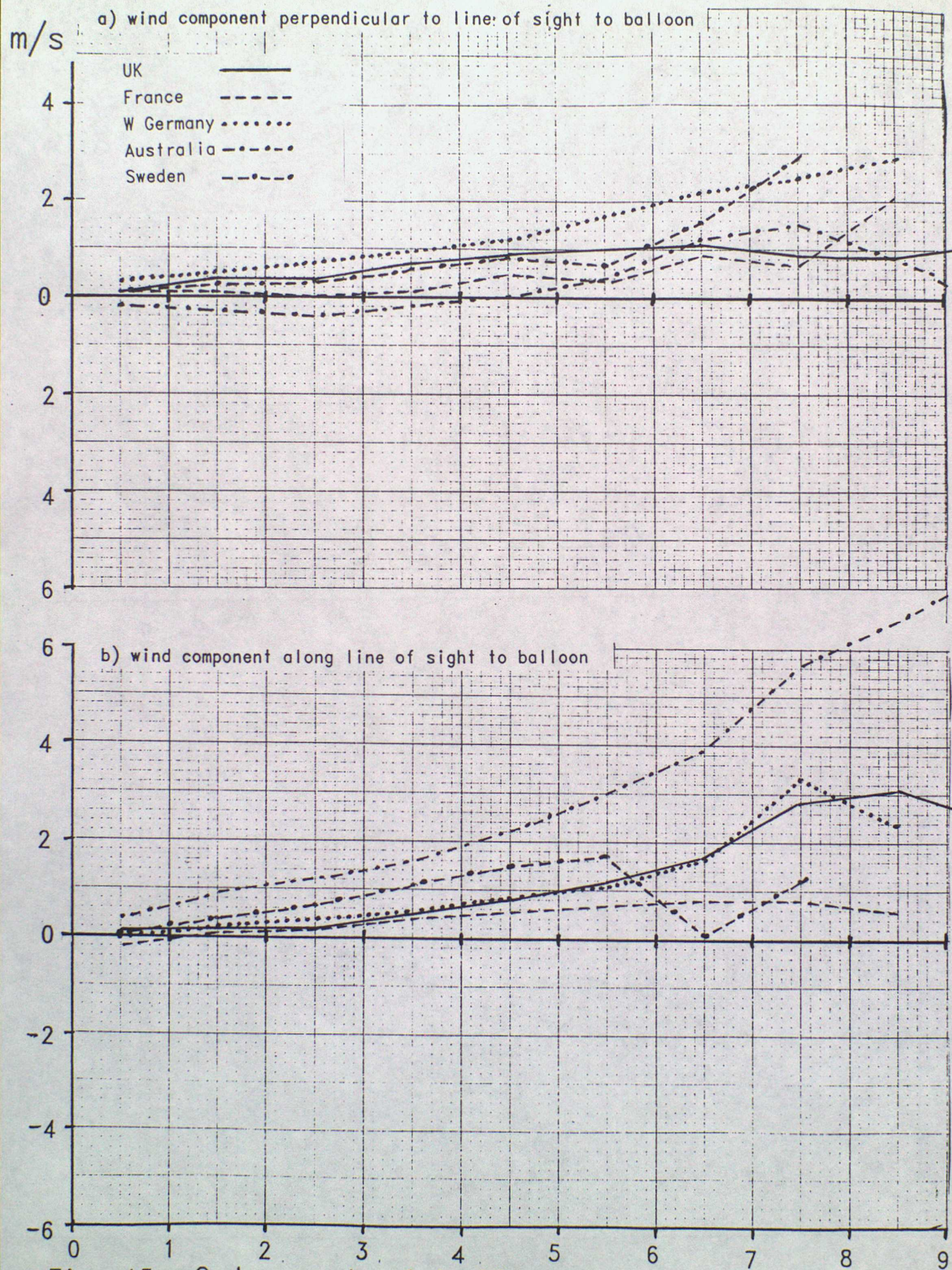


RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988
 Mean over sigma layers 9 to 12 (approximately 400 to 150 hPa)



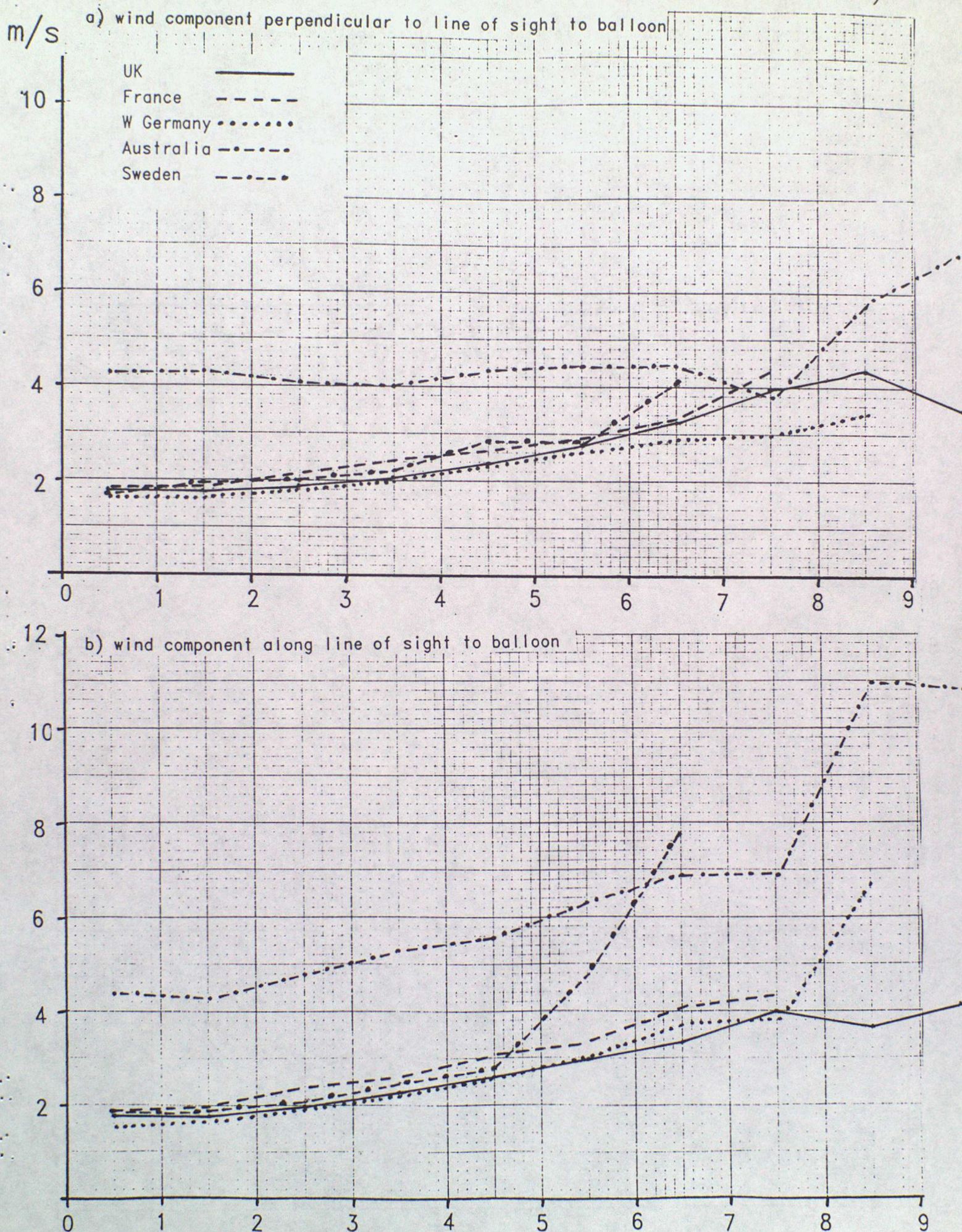
MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 (approximately 400 to 150 hPa)



RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

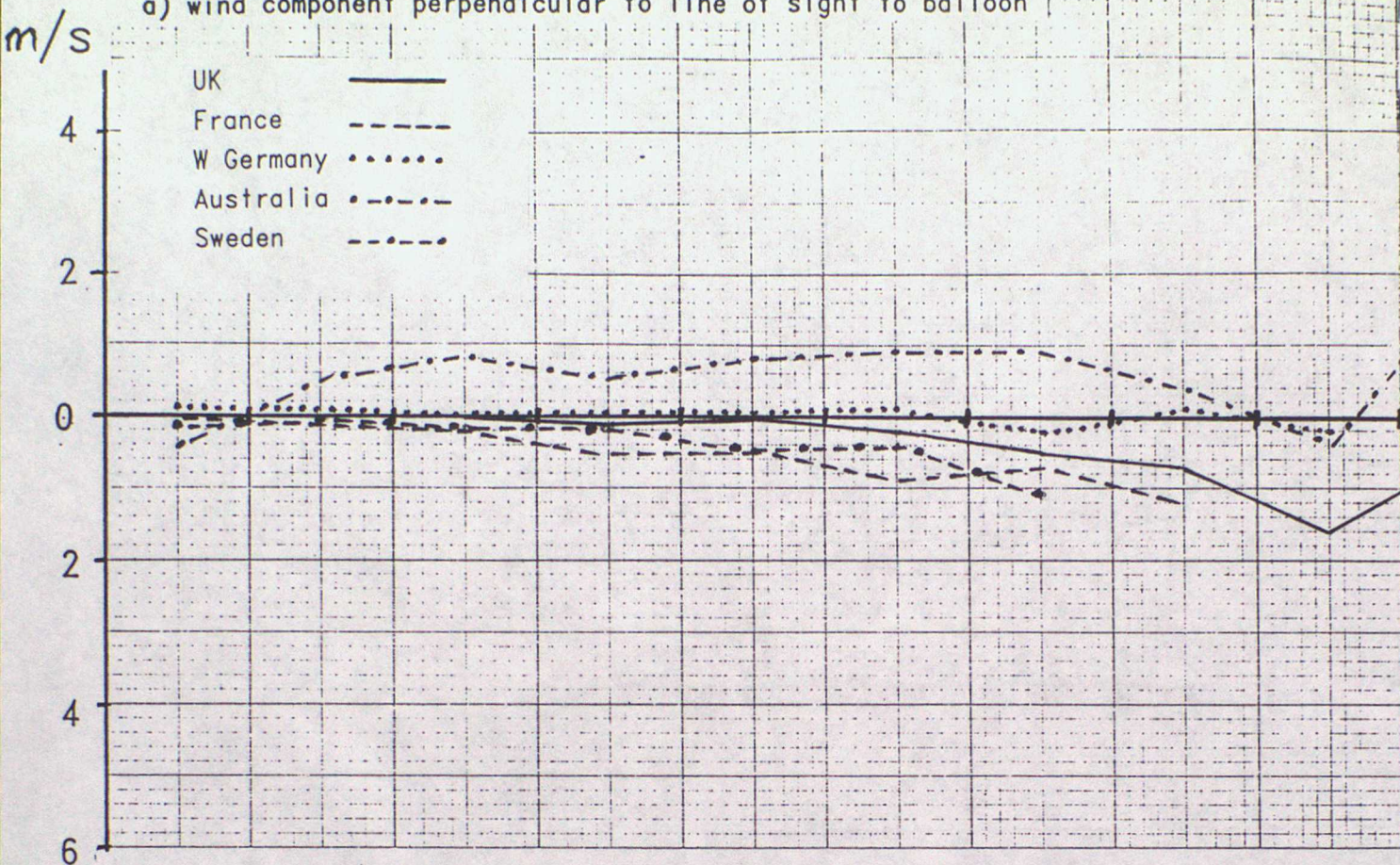
Mean over sigma layers 13 to 14 (approximately 150 to 40 hPa)



MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 13 to 14 (approximately 150 to 40 hPa)

a) wind component perpendicular to line of sight to balloon



b) wind component along line of sight to balloon

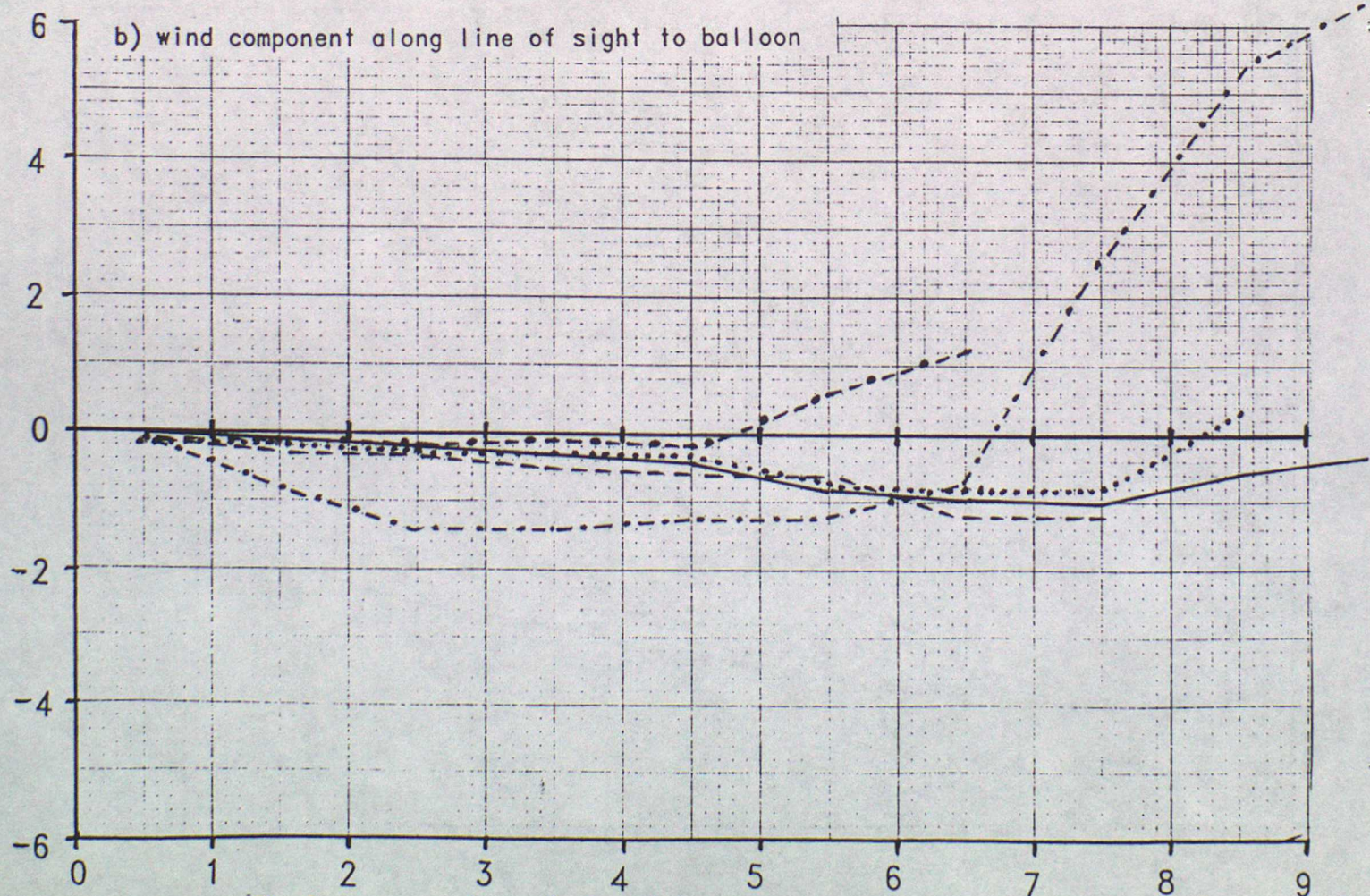
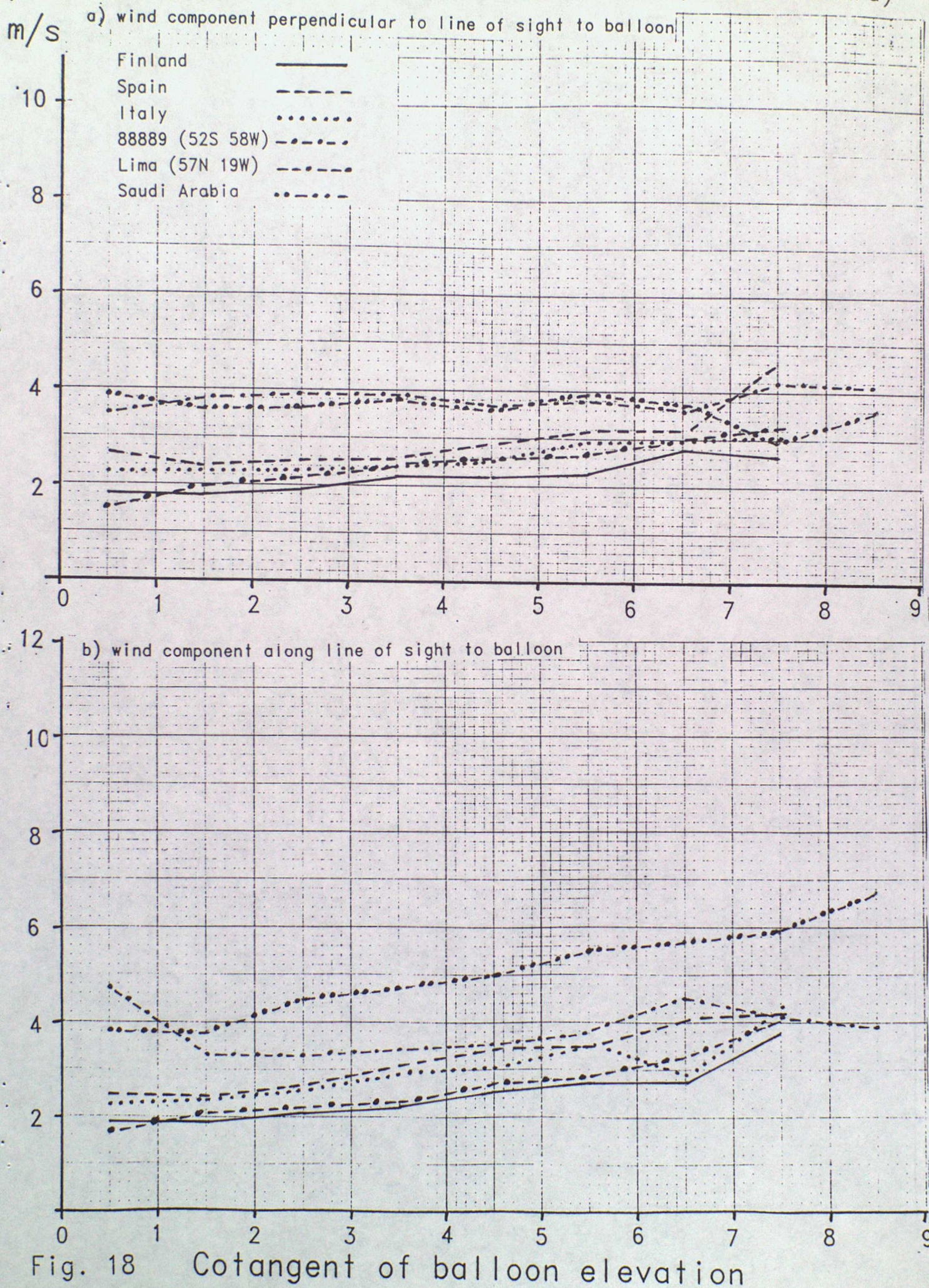


Fig. 17 Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988
 Mean over sigma layers 13 to 14 (approximately 150 to 40 hPa)

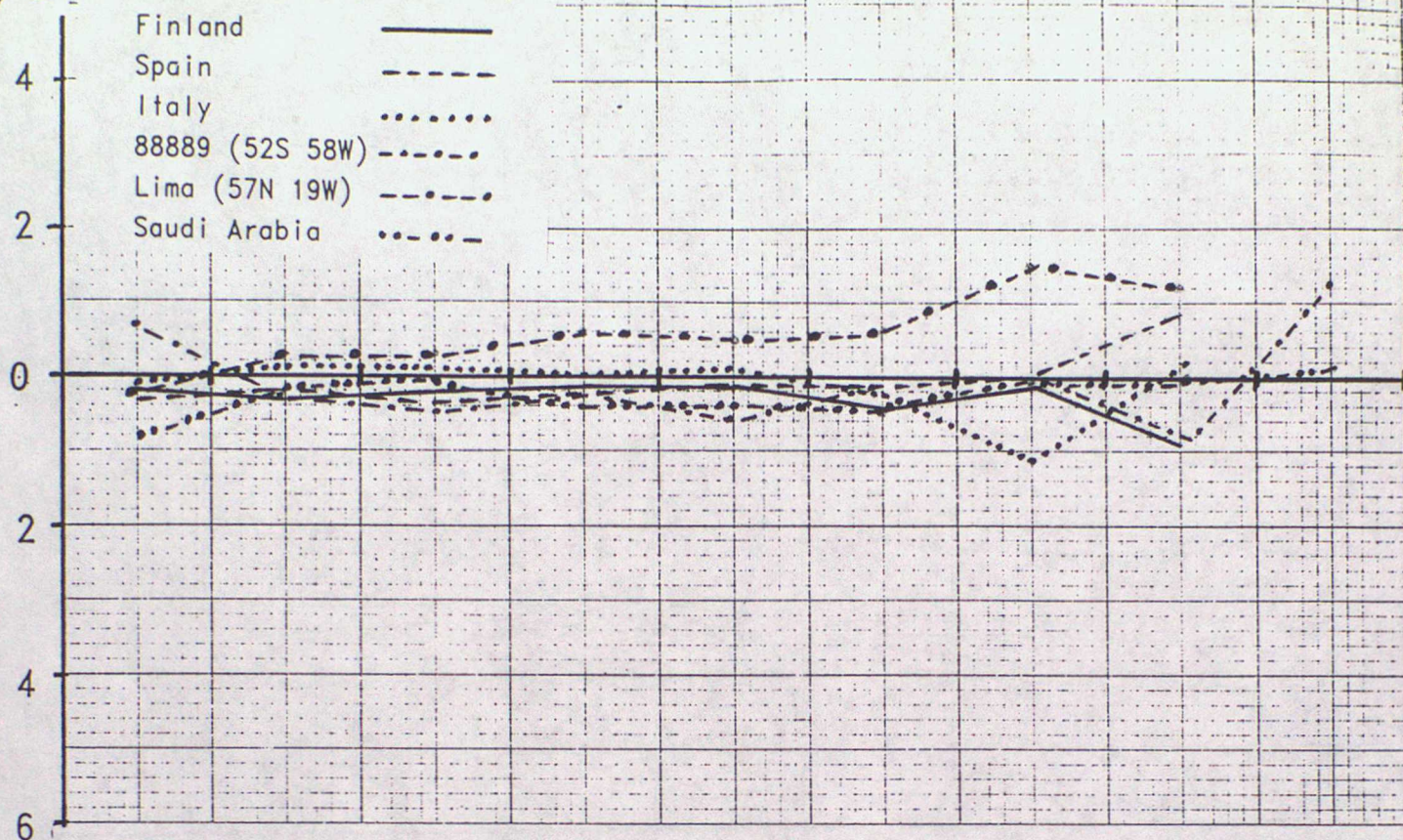


MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 13 to 14 (approximately 150 to 40 hPa)

a) wind component perpendicular to line of sight to balloon

m/s



b) wind component along line of sight to balloon

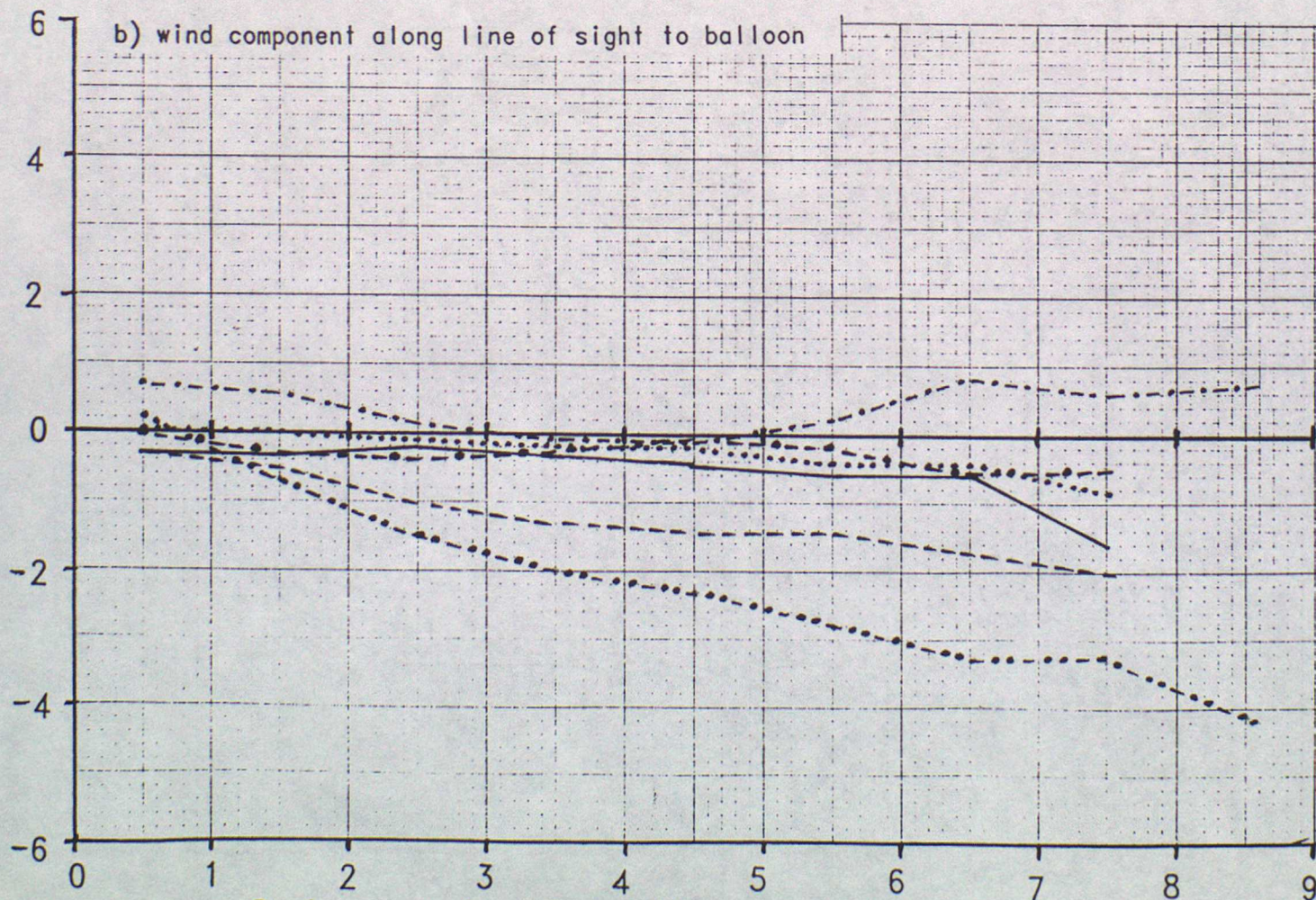


Fig. 19 Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988
 Mean over sigma layers 9 to 12 (approximately 400 to 150 hPa)

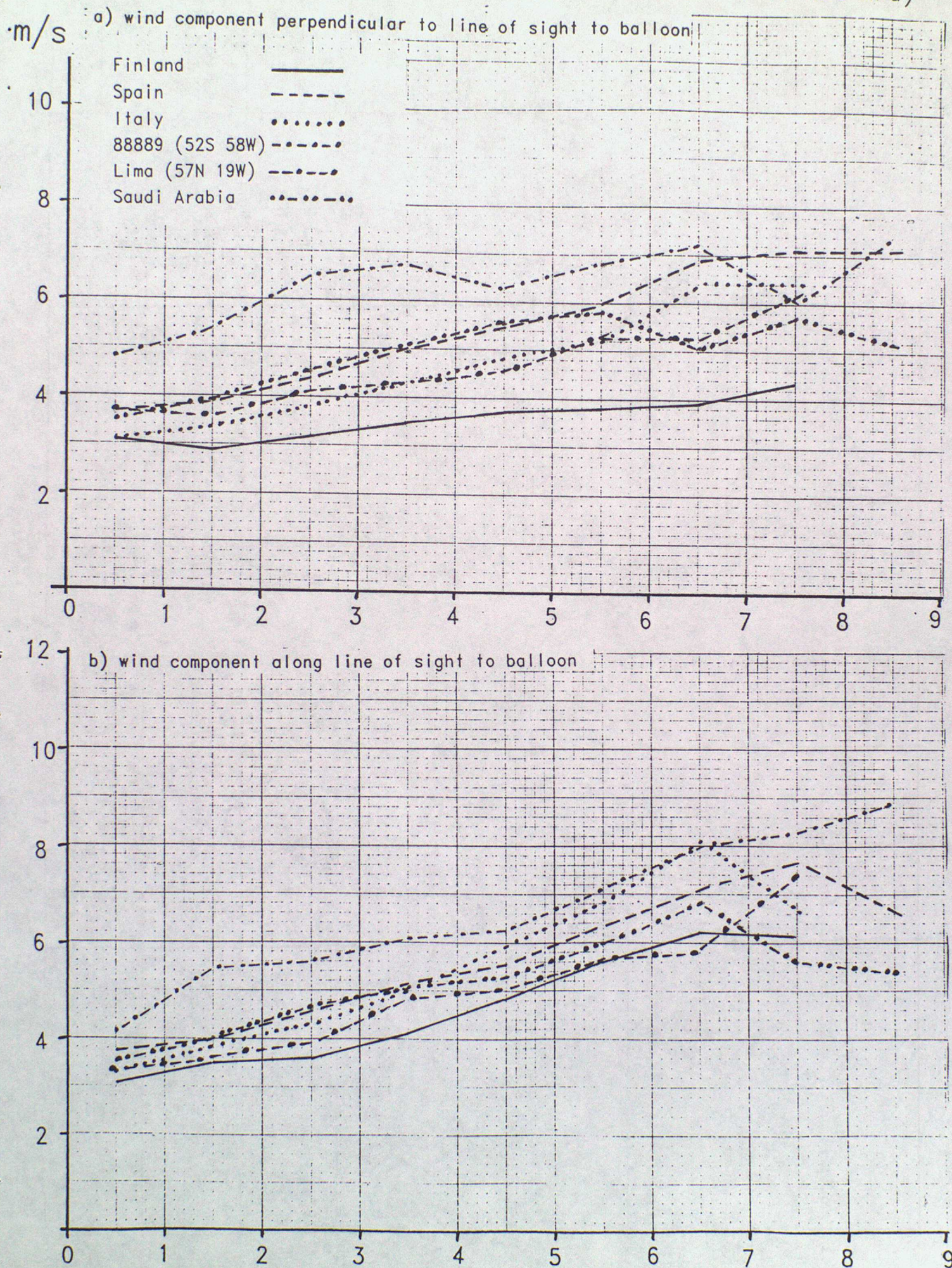
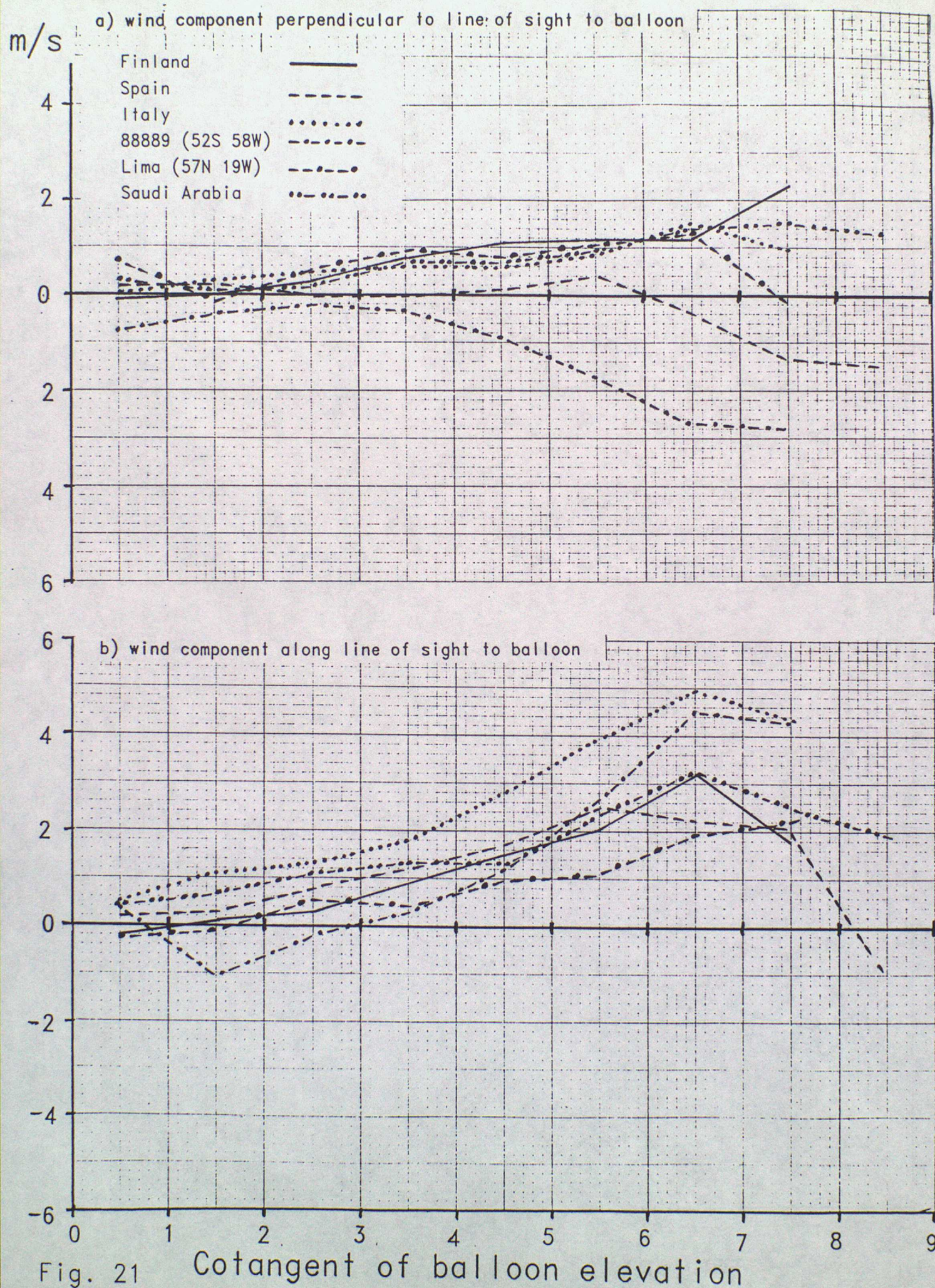


Fig. 20 Cotangent of balloon elevation

MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 (approximately 400 to 150 hPa)



RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 ——— ; 13 to 14 - - - -

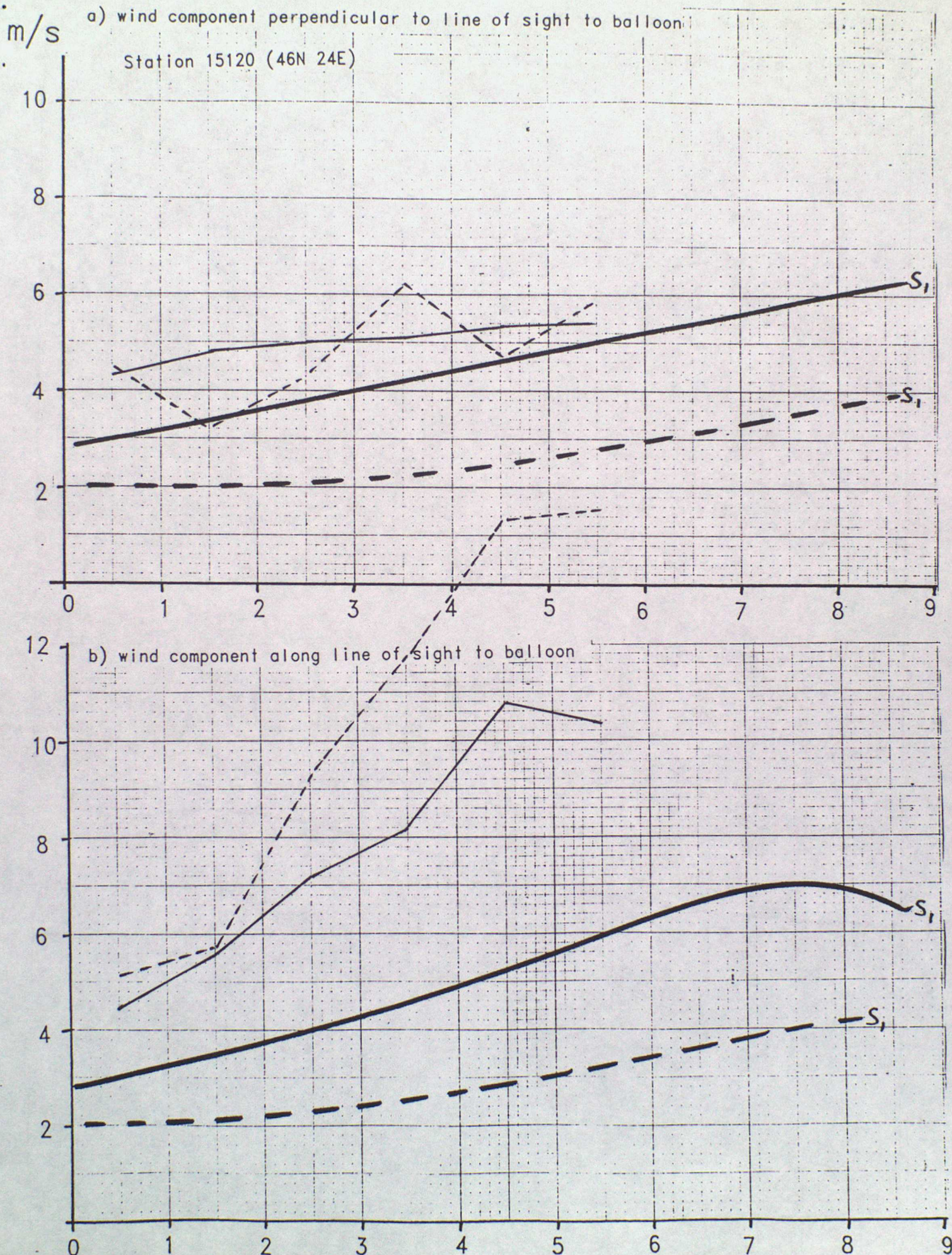


Fig. 22 a Cotangent of balloon elevation

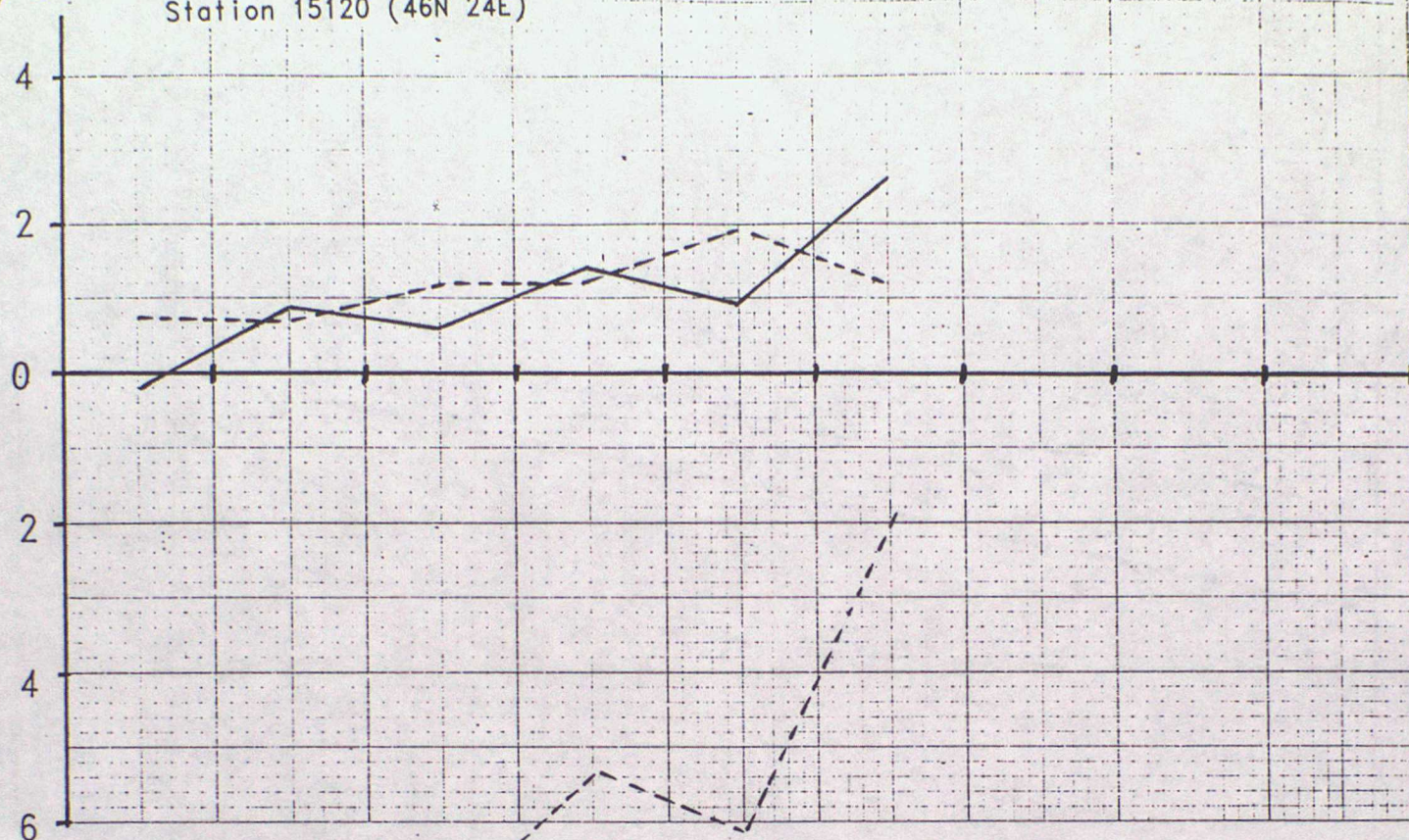
MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

a) wind component perpendicular to line of sight to balloon

Station 15120 (46N 24E)

m/s



b) wind component along line of sight to balloon

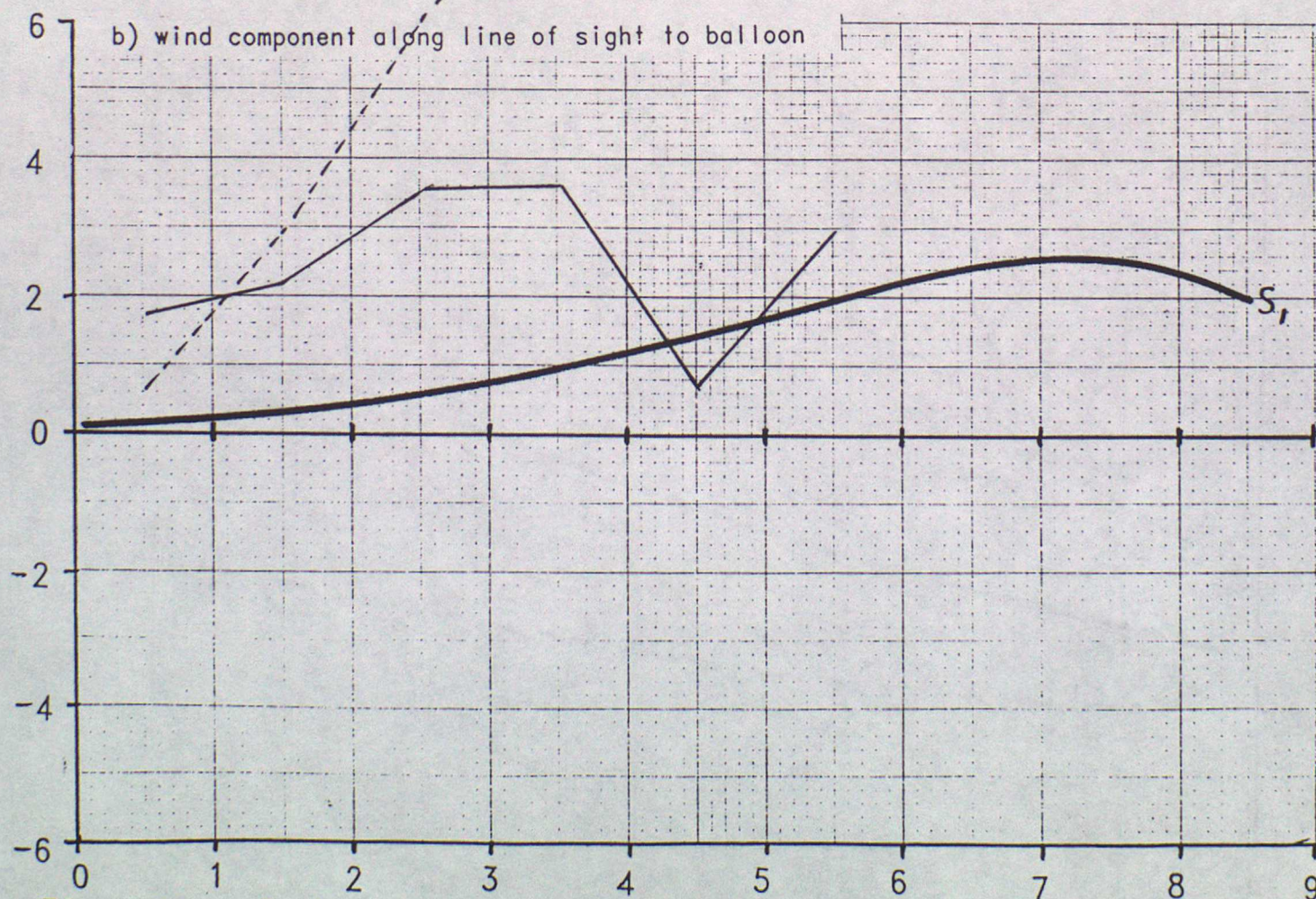
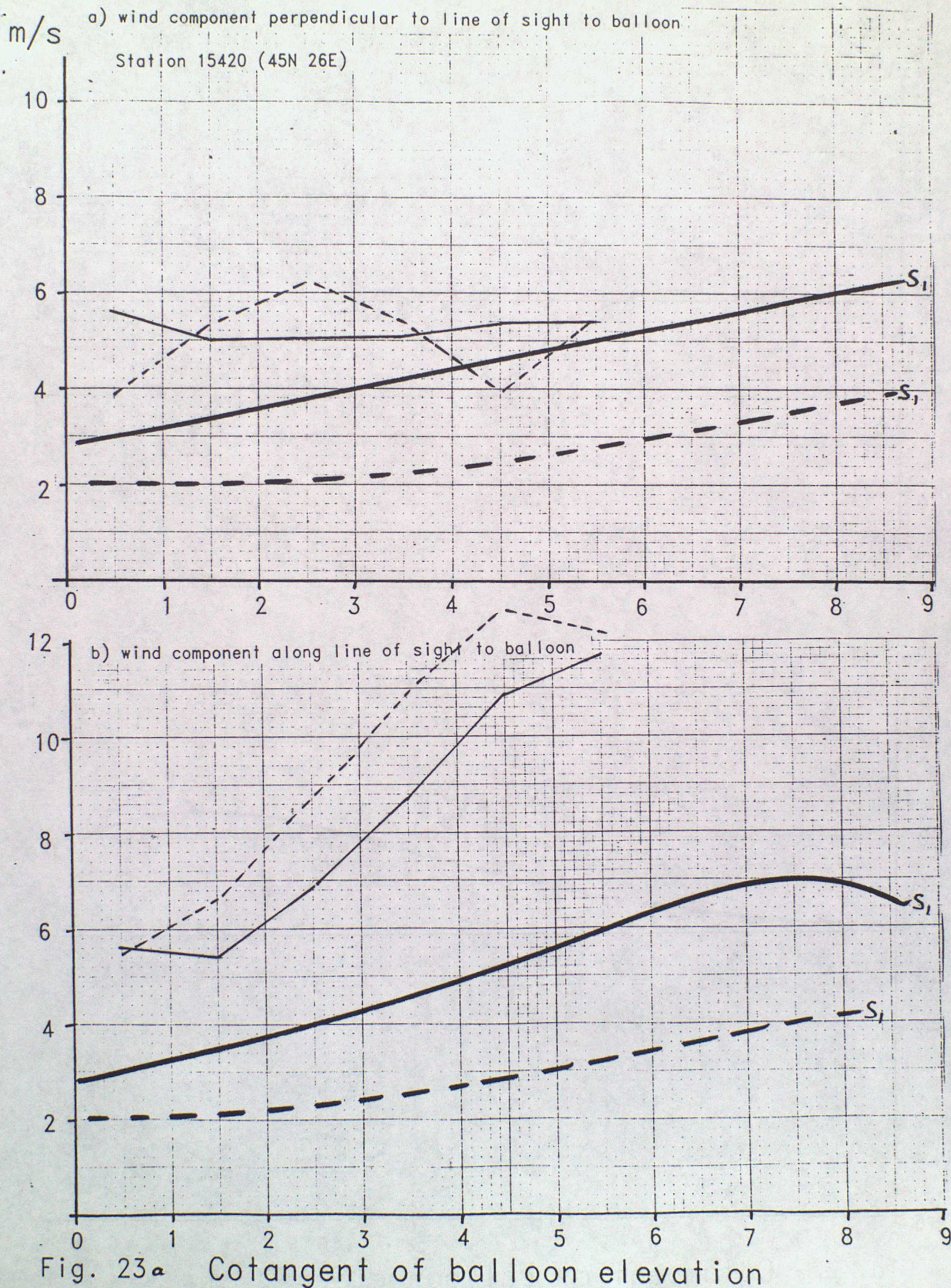


Fig. 22b Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -



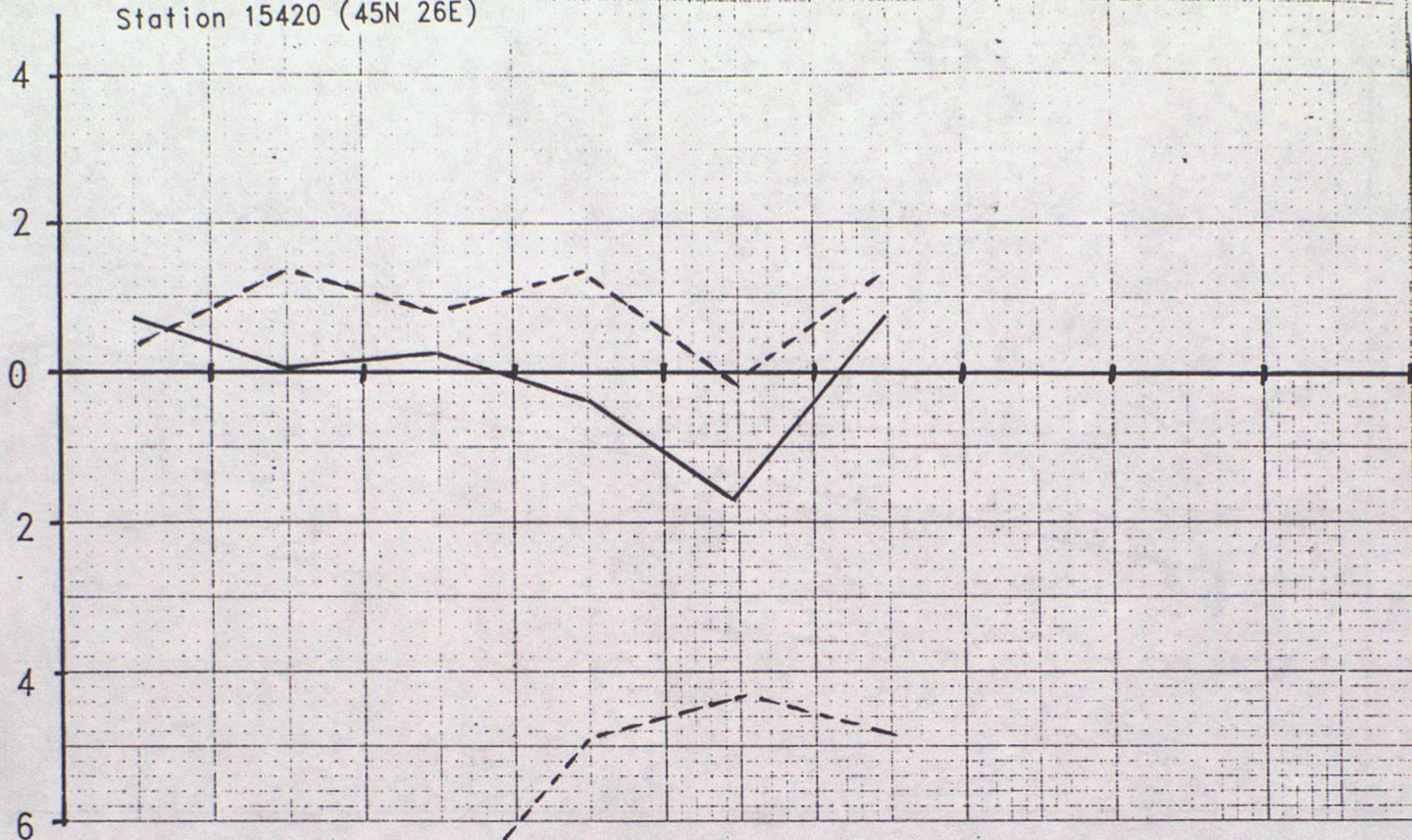
MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 ——— ; 13 to 14 - - - -

a) wind component perpendicular to line of sight to balloon

Station 15420 (45N 26E)

m/s



b) wind component along line of sight to balloon

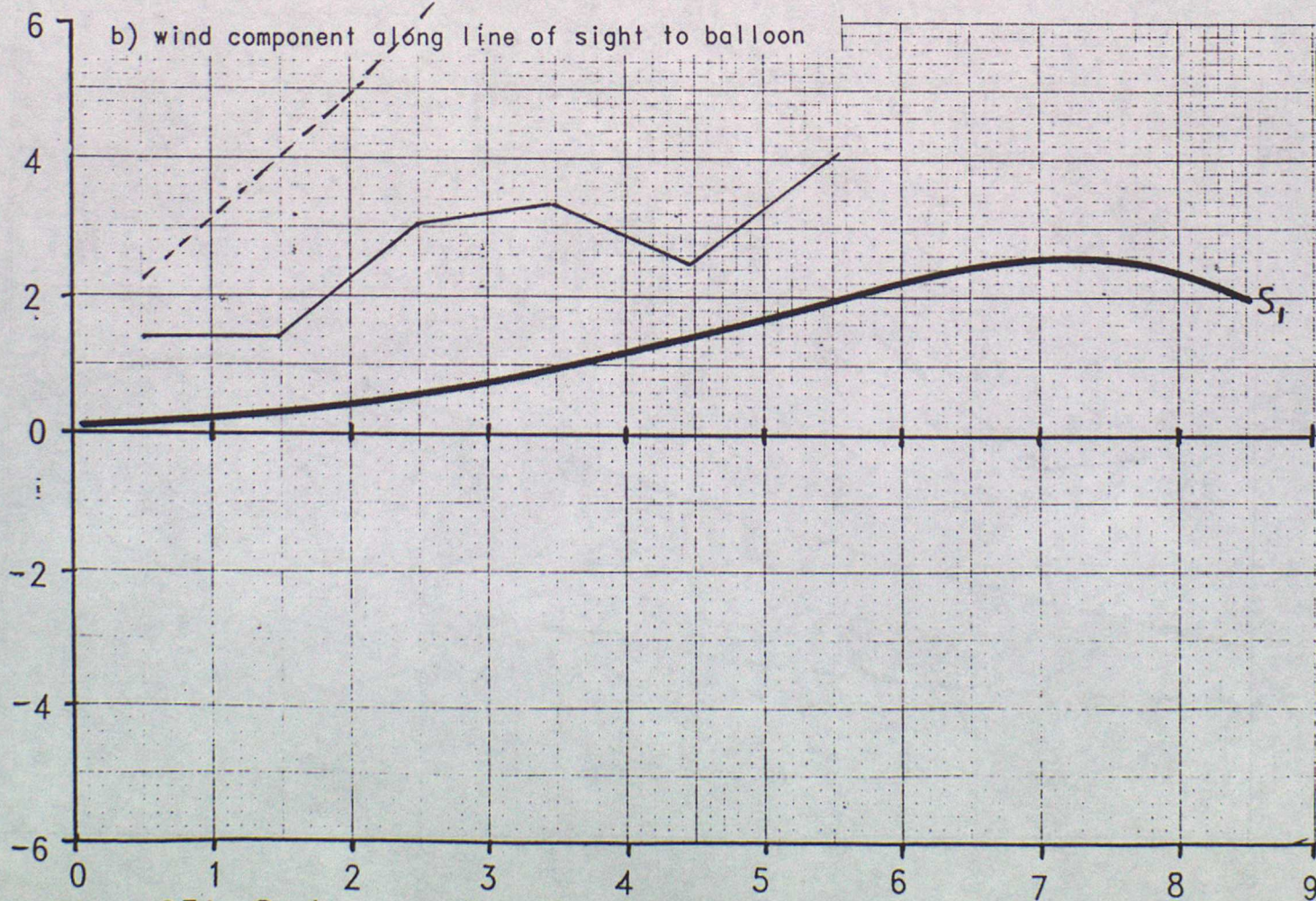


Fig. 23b Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 ——— ; 13 to 14 - - - -

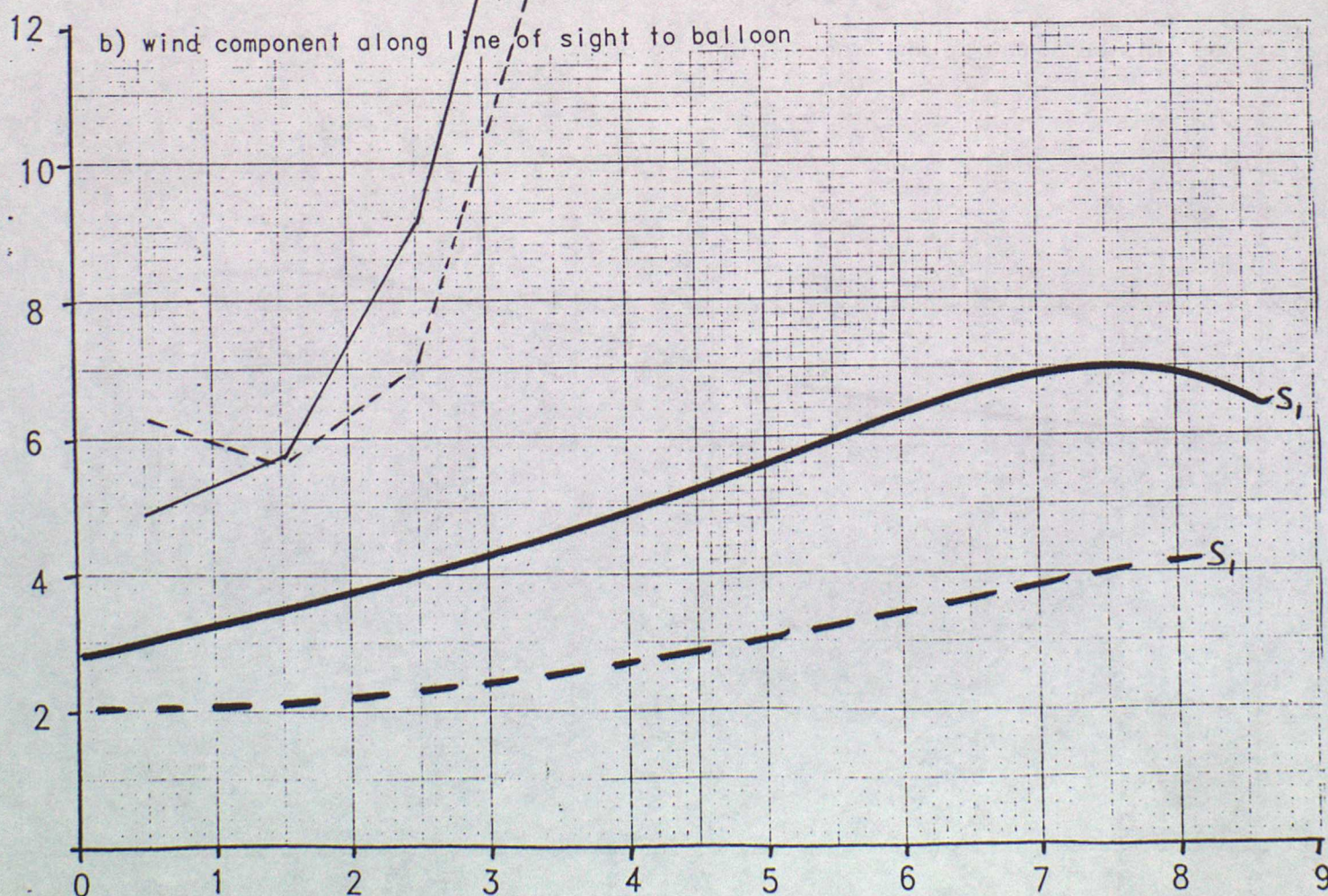
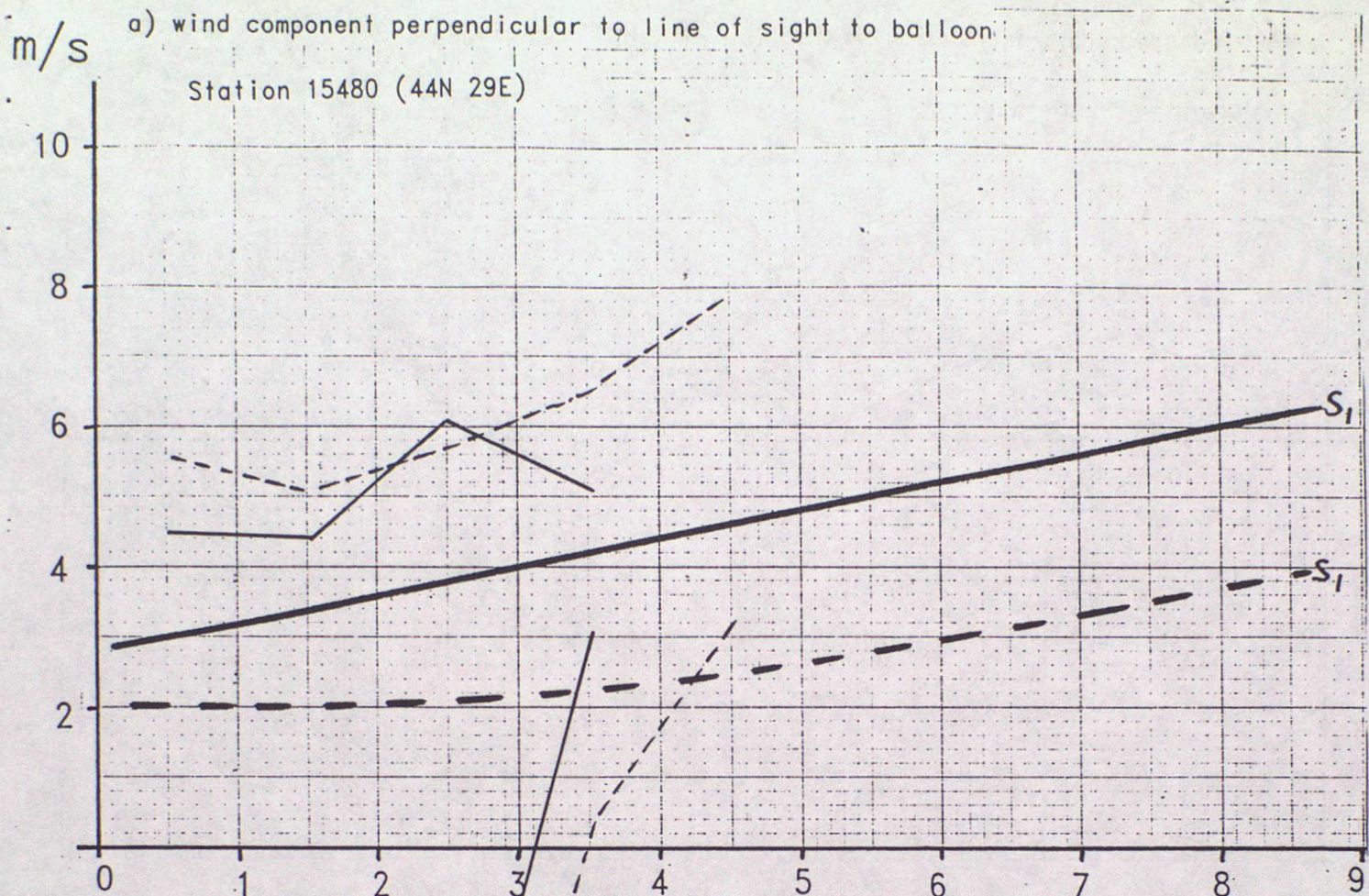


Fig. 24a Cotangent of balloon elevation

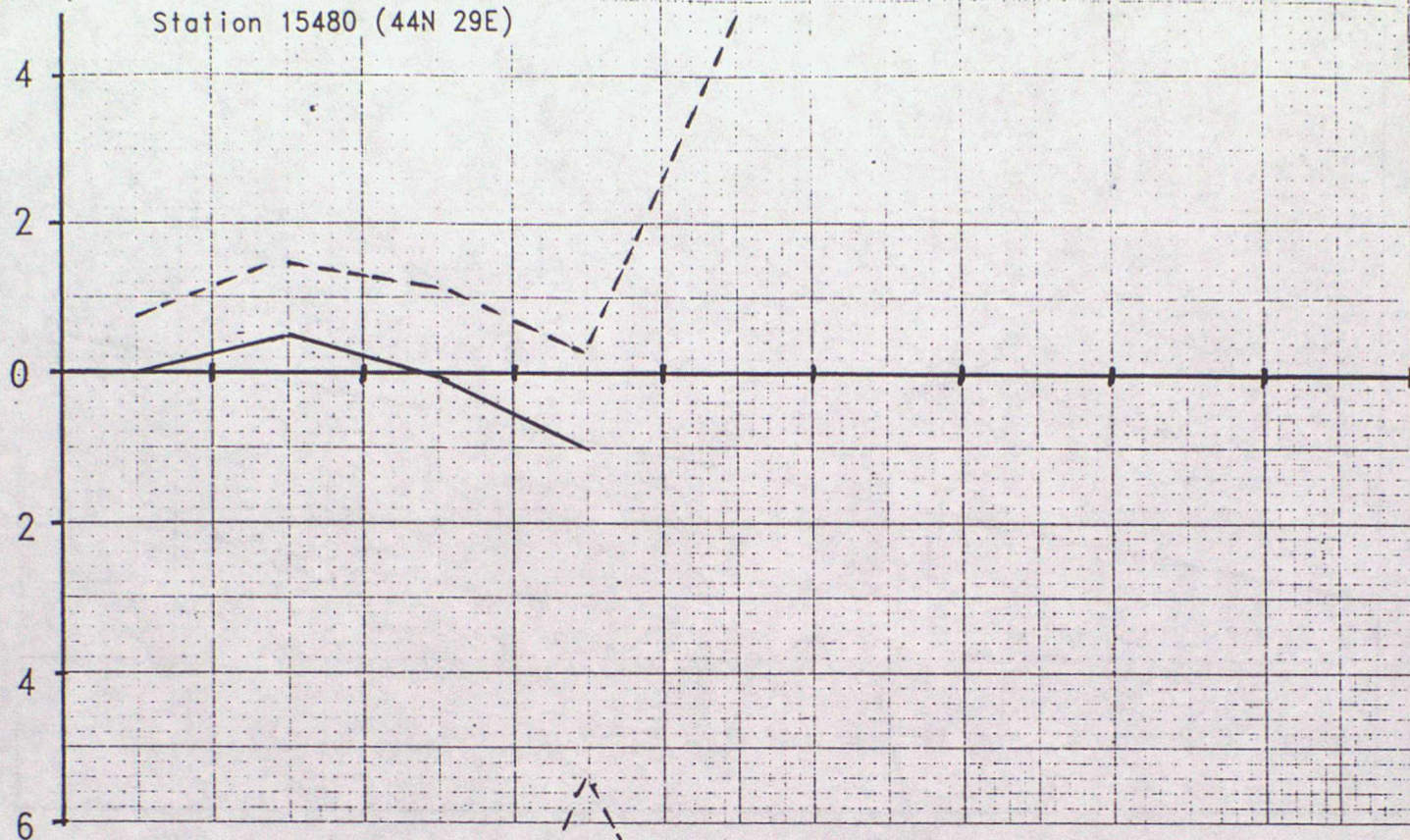
MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

a) wind component perpendicular to line of sight to balloon

Station 15480 (44N 29E)

m/s



b) wind component along line of sight to balloon

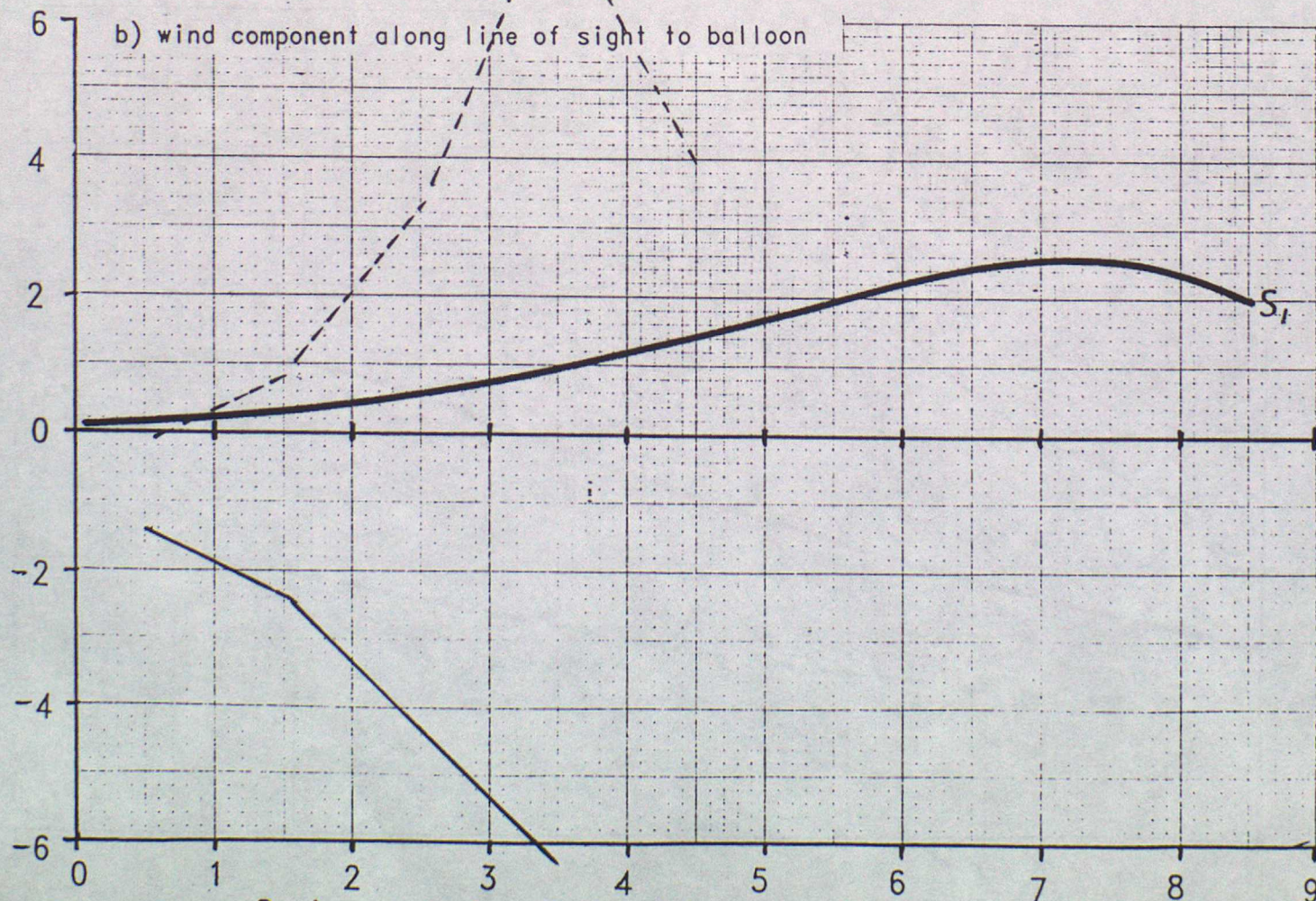
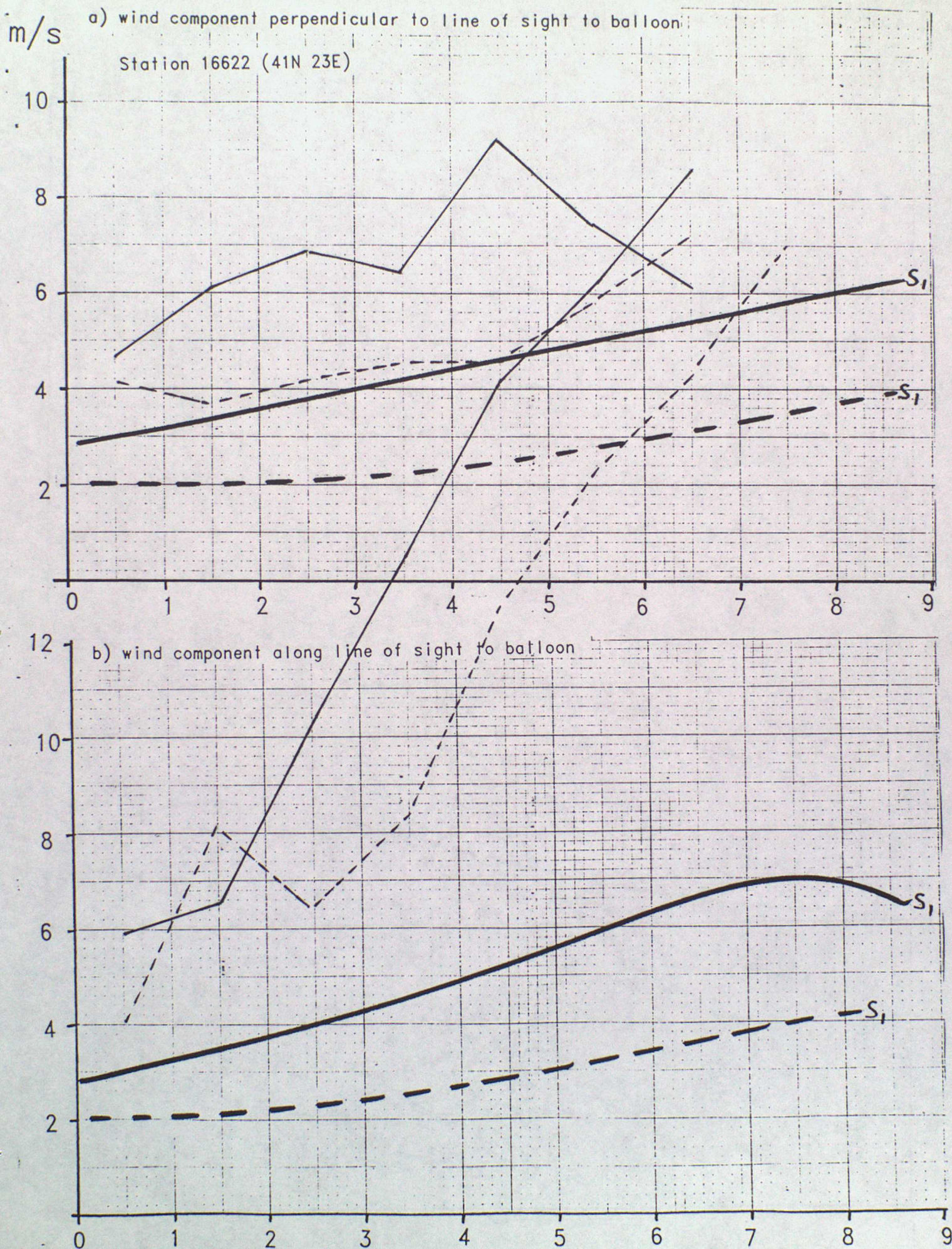


Fig. 24 b Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -



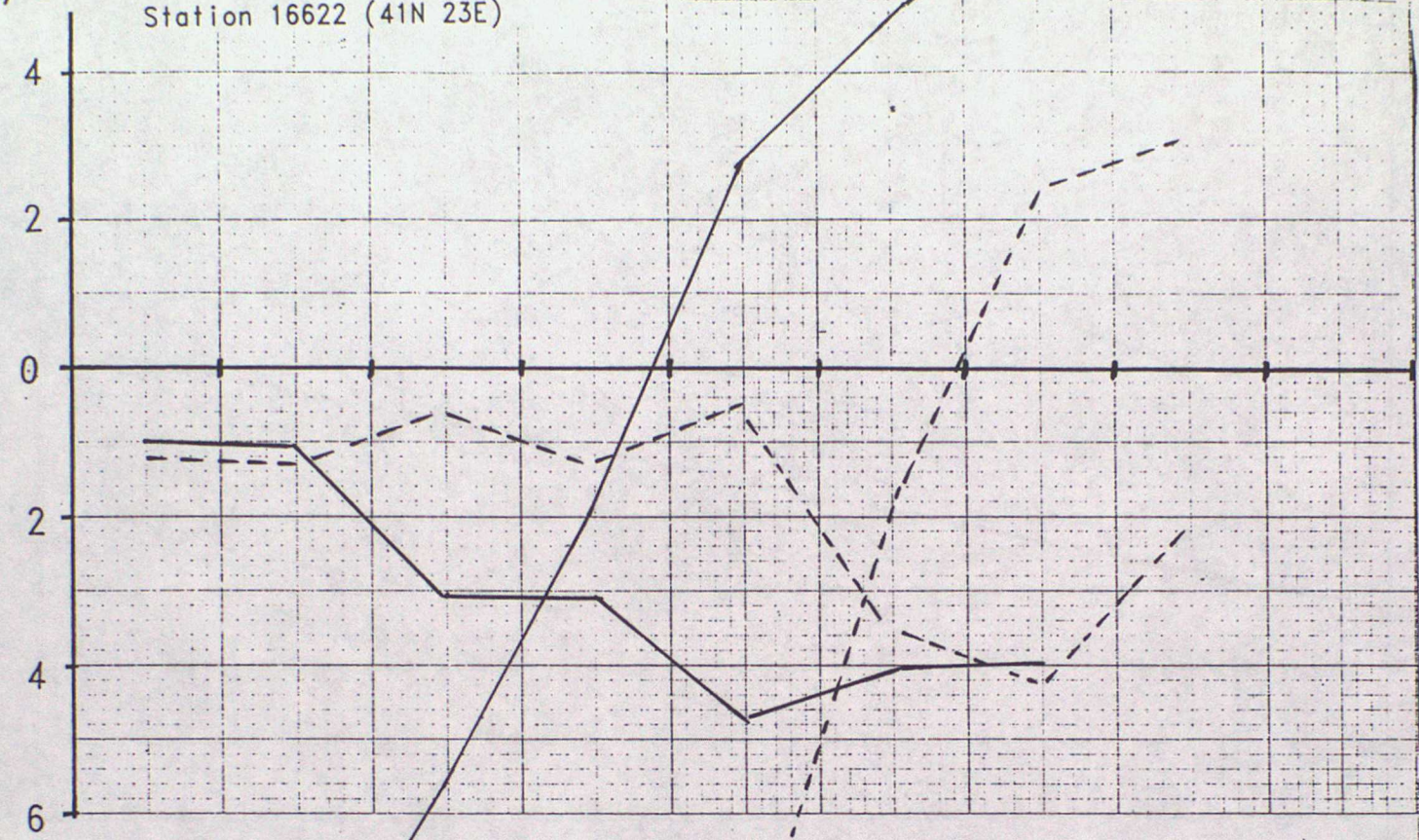
MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

a) wind component perpendicular to line of sight to balloon

m/s

Station 16622 (41N 23E)



b) wind component along line of sight to balloon

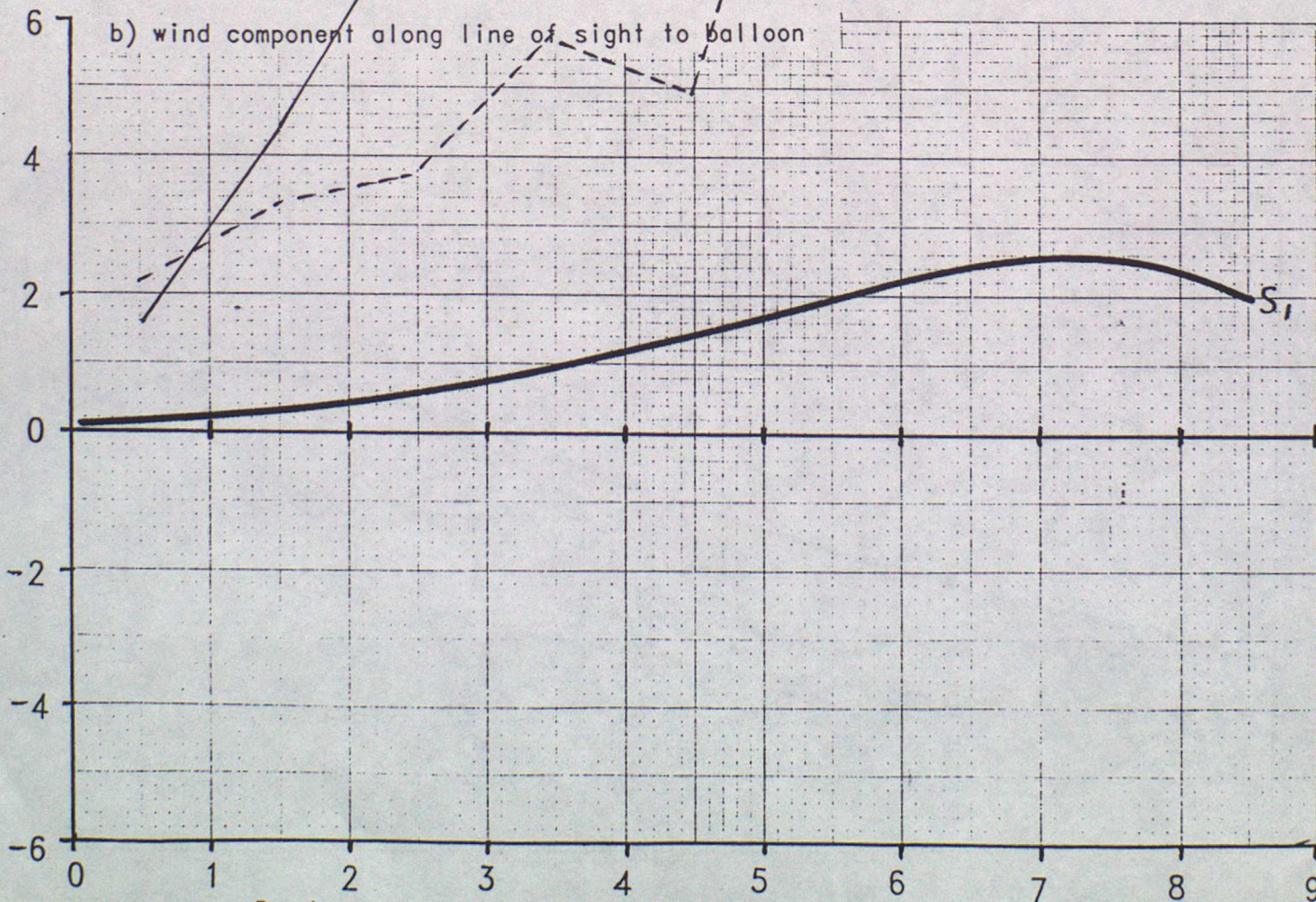


Fig. 25 b Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

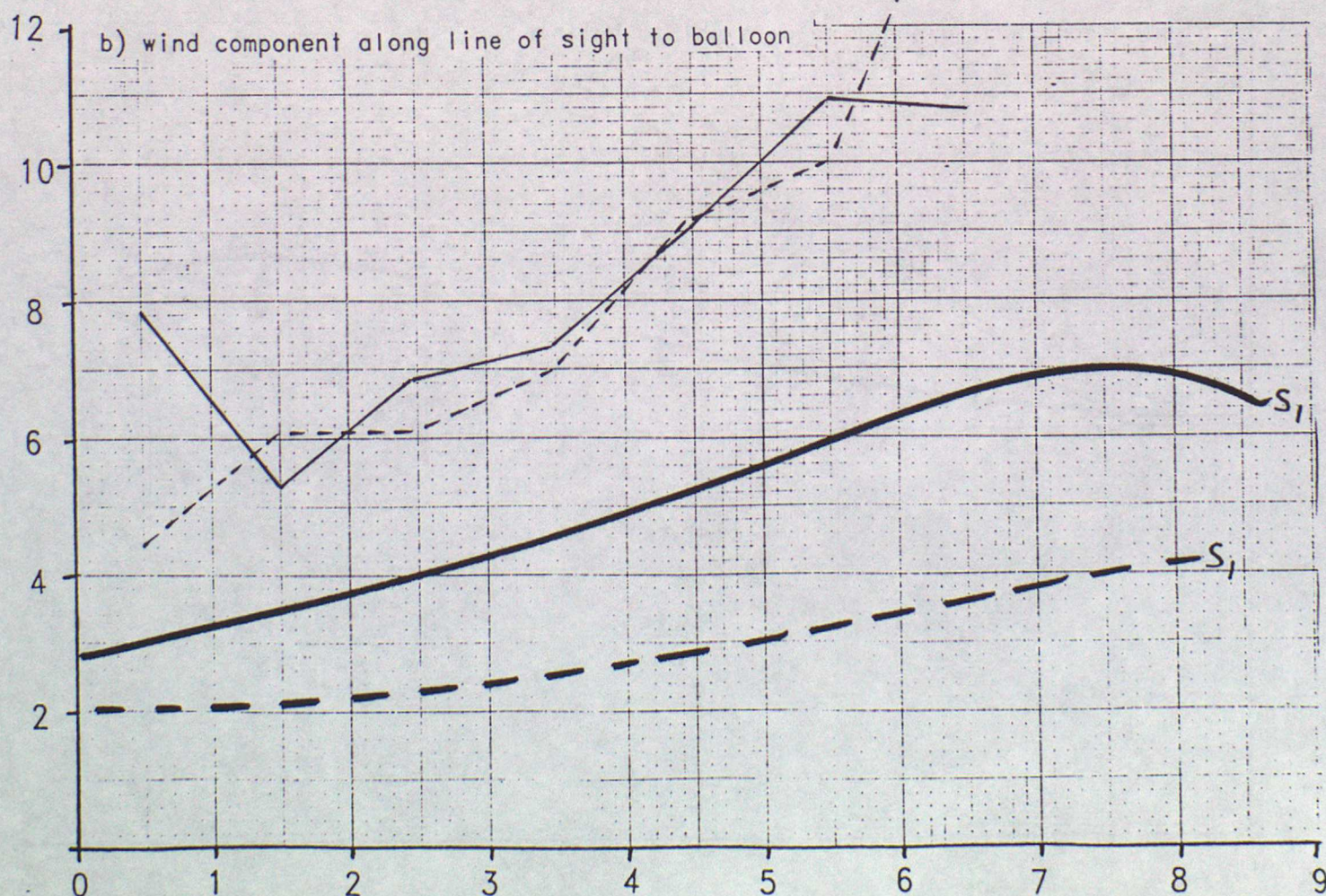
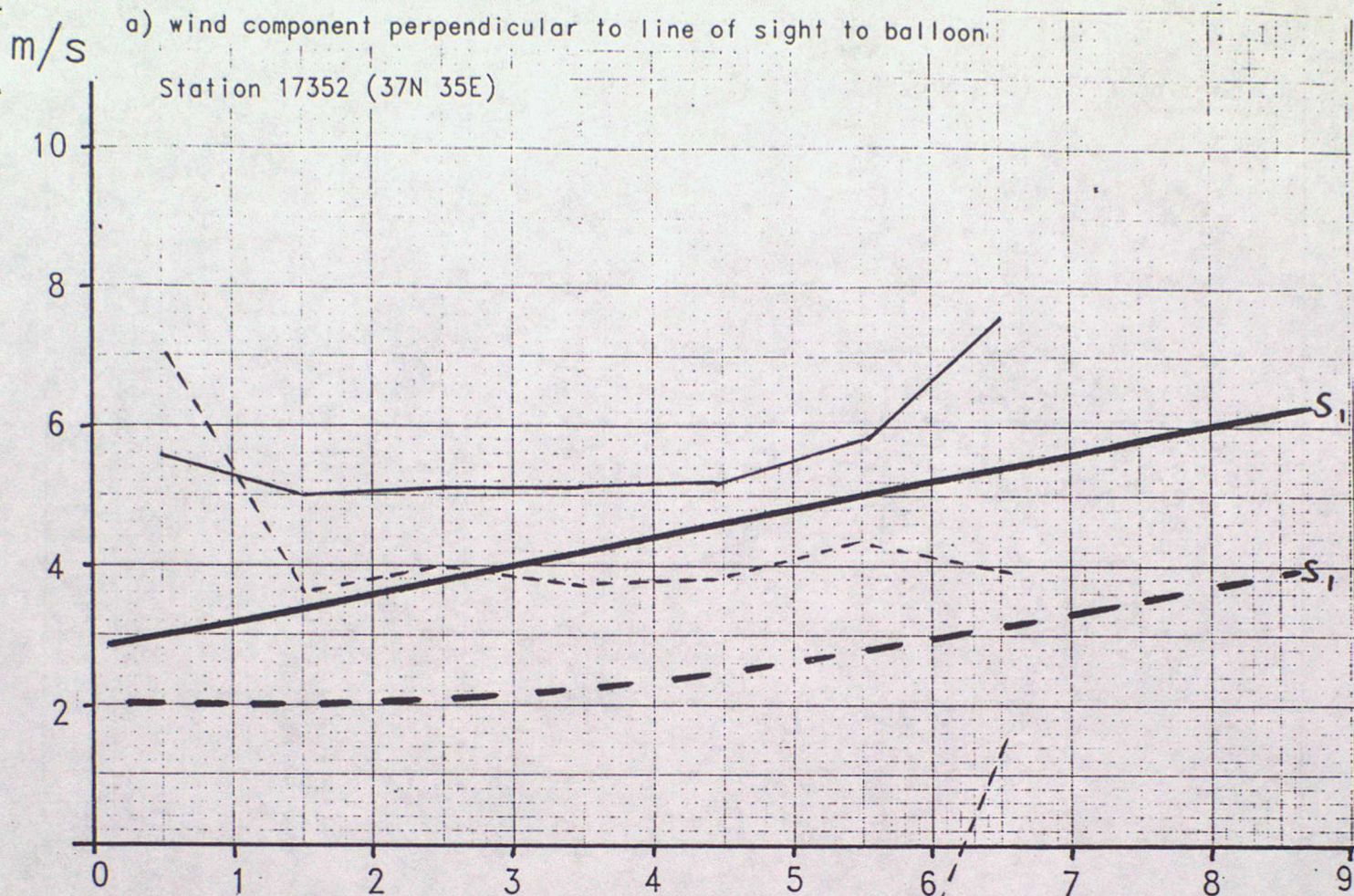


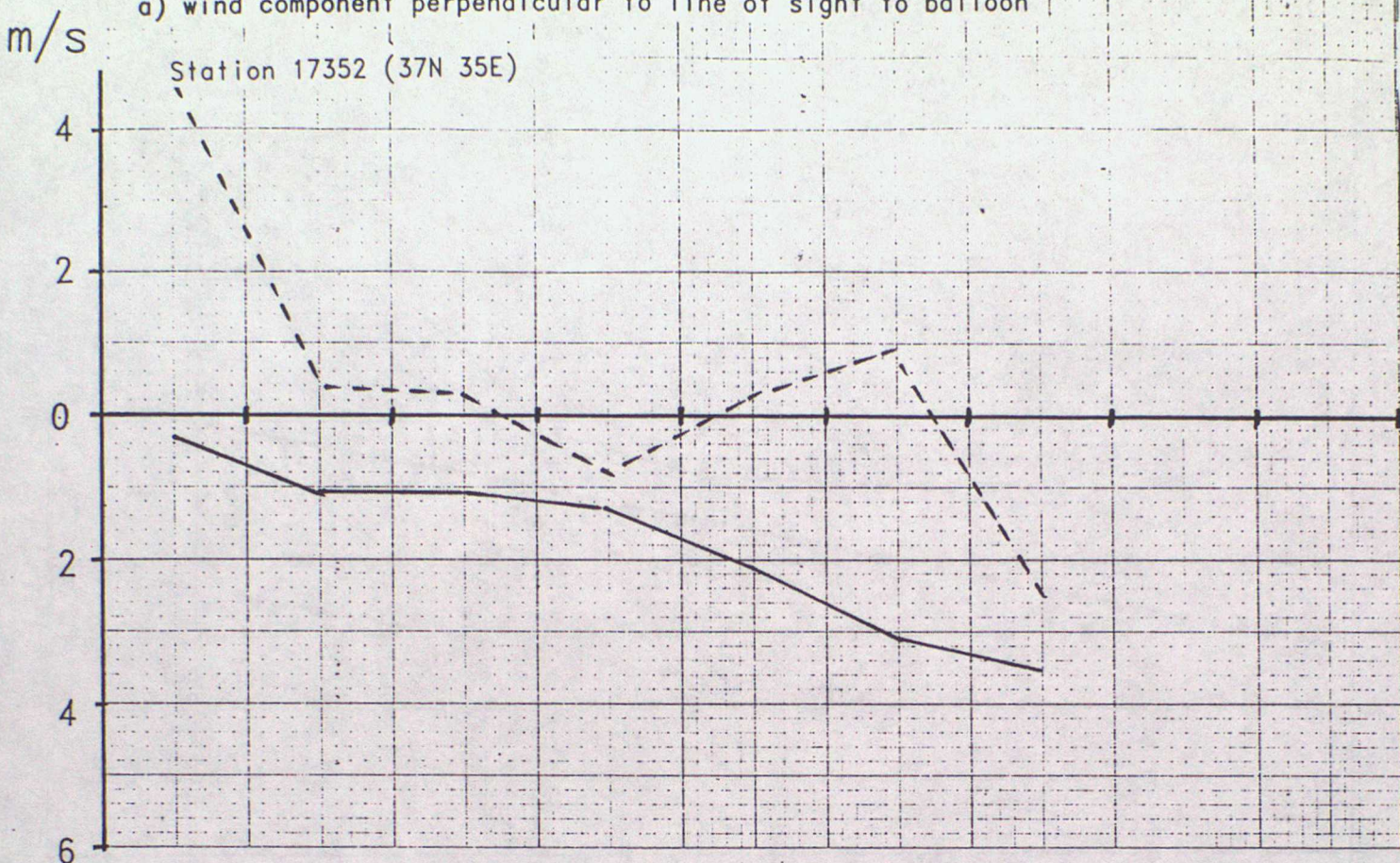
Fig. 26 a Cotangent of balloon elevation

MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

a) wind component perpendicular to line of sight to balloon

Station 17352 (37N 35E)



b) wind component along line of sight to balloon

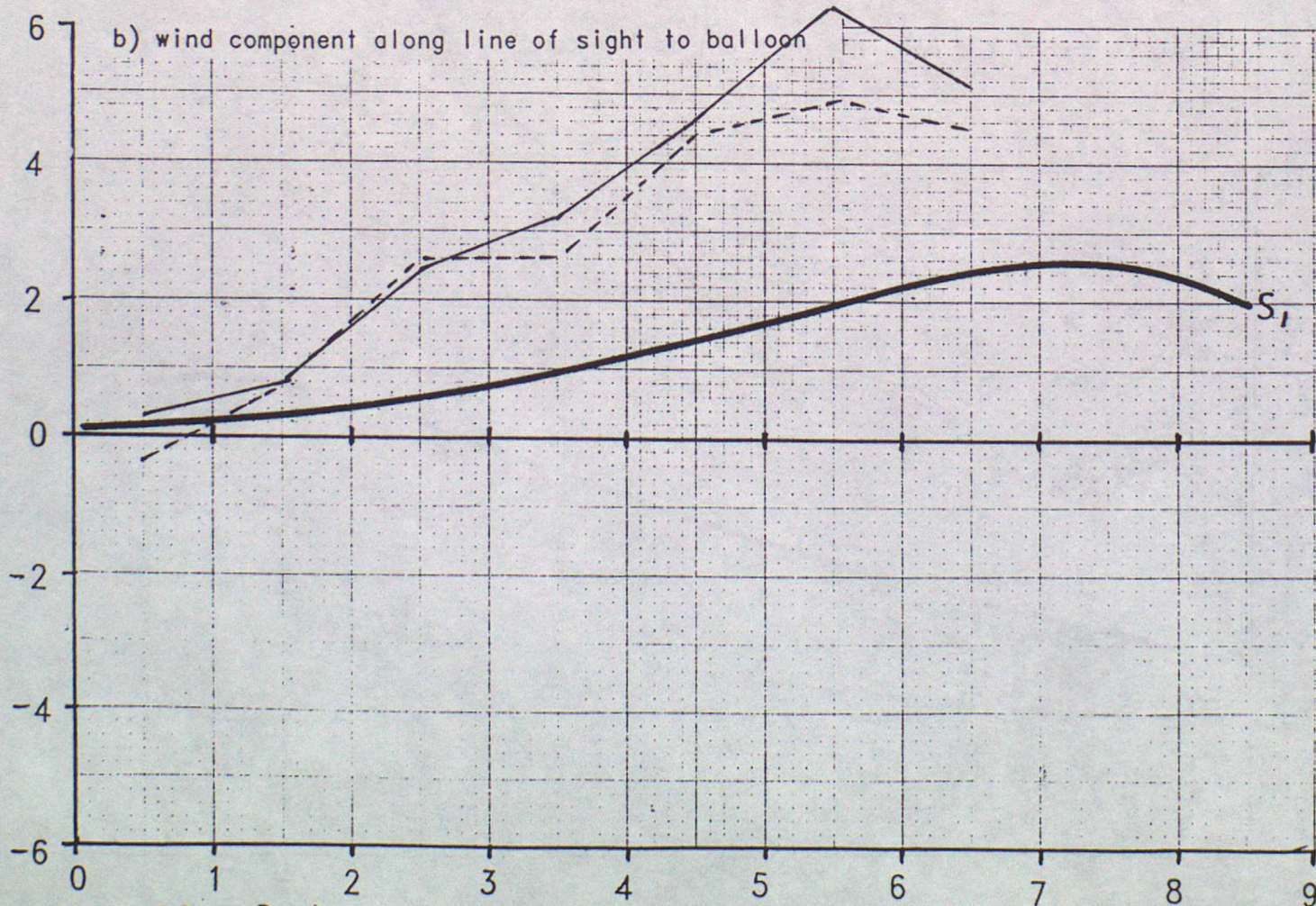


Fig. 26 b Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 ——— ; 13 to 14 - - - -

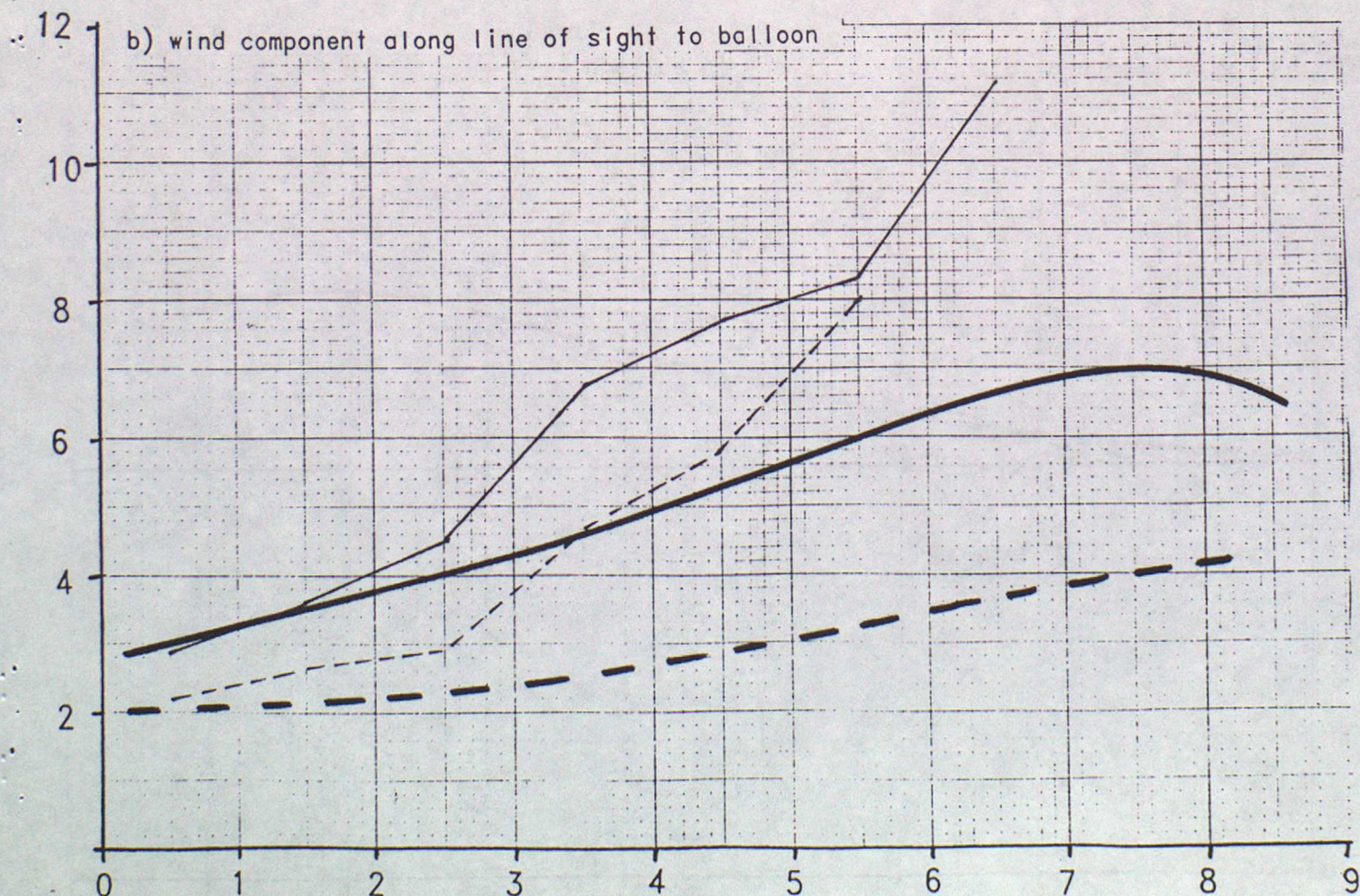
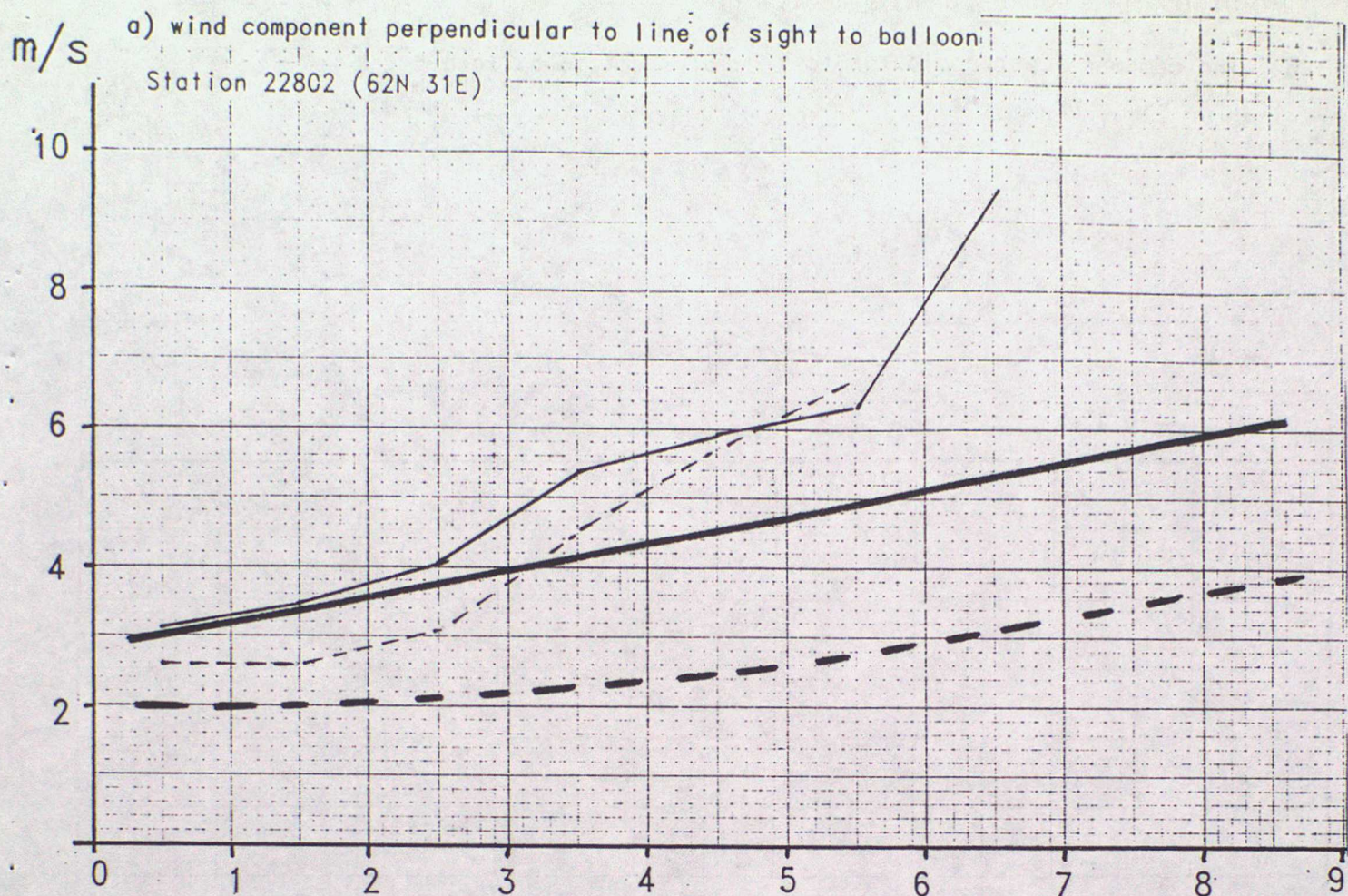


Fig. 27_a Cotangent of balloon elevation

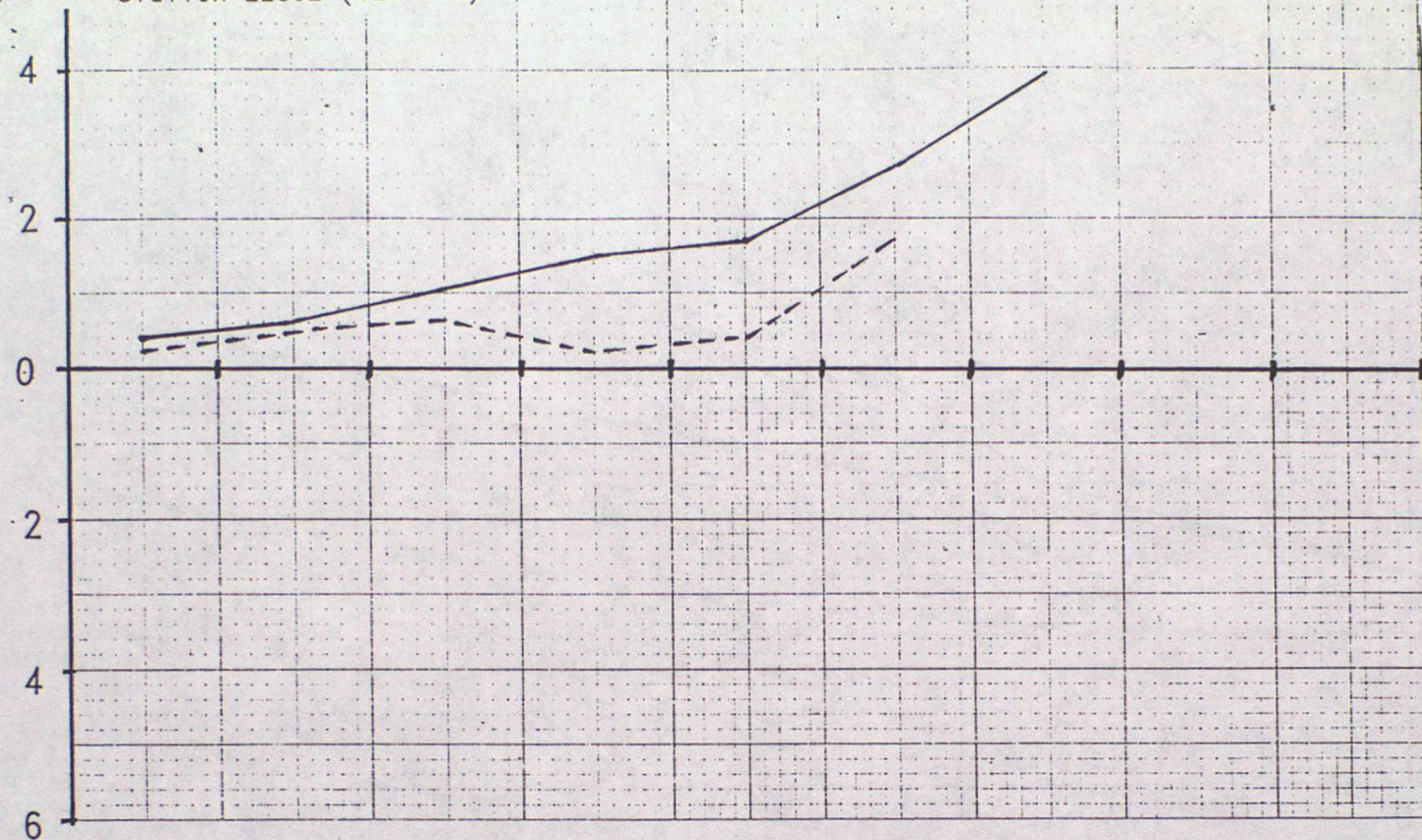
MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

a) wind component perpendicular to line of sight to balloon

Station 22802 (62N 31E)

m/s



b) wind component along line of sight to balloon

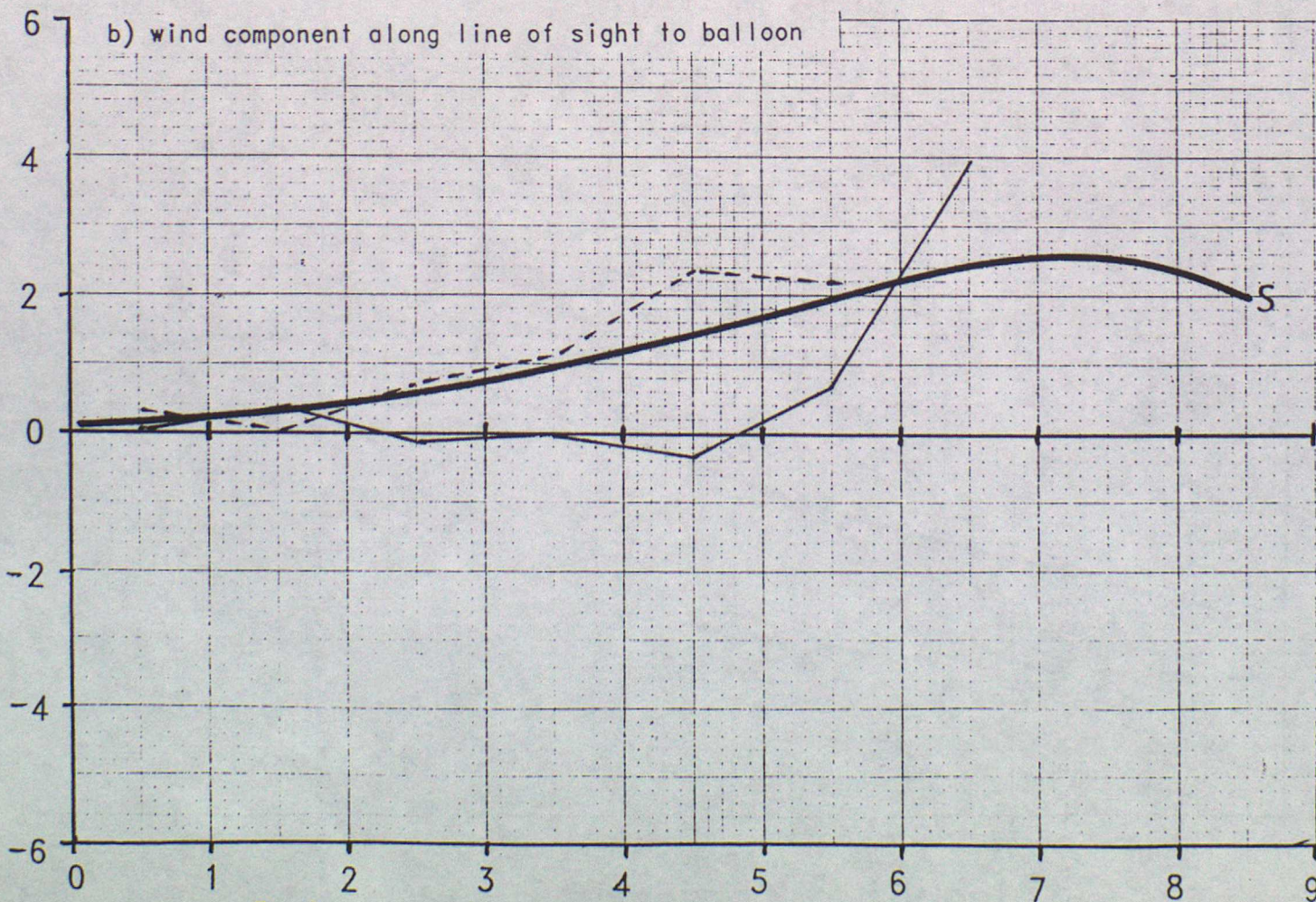


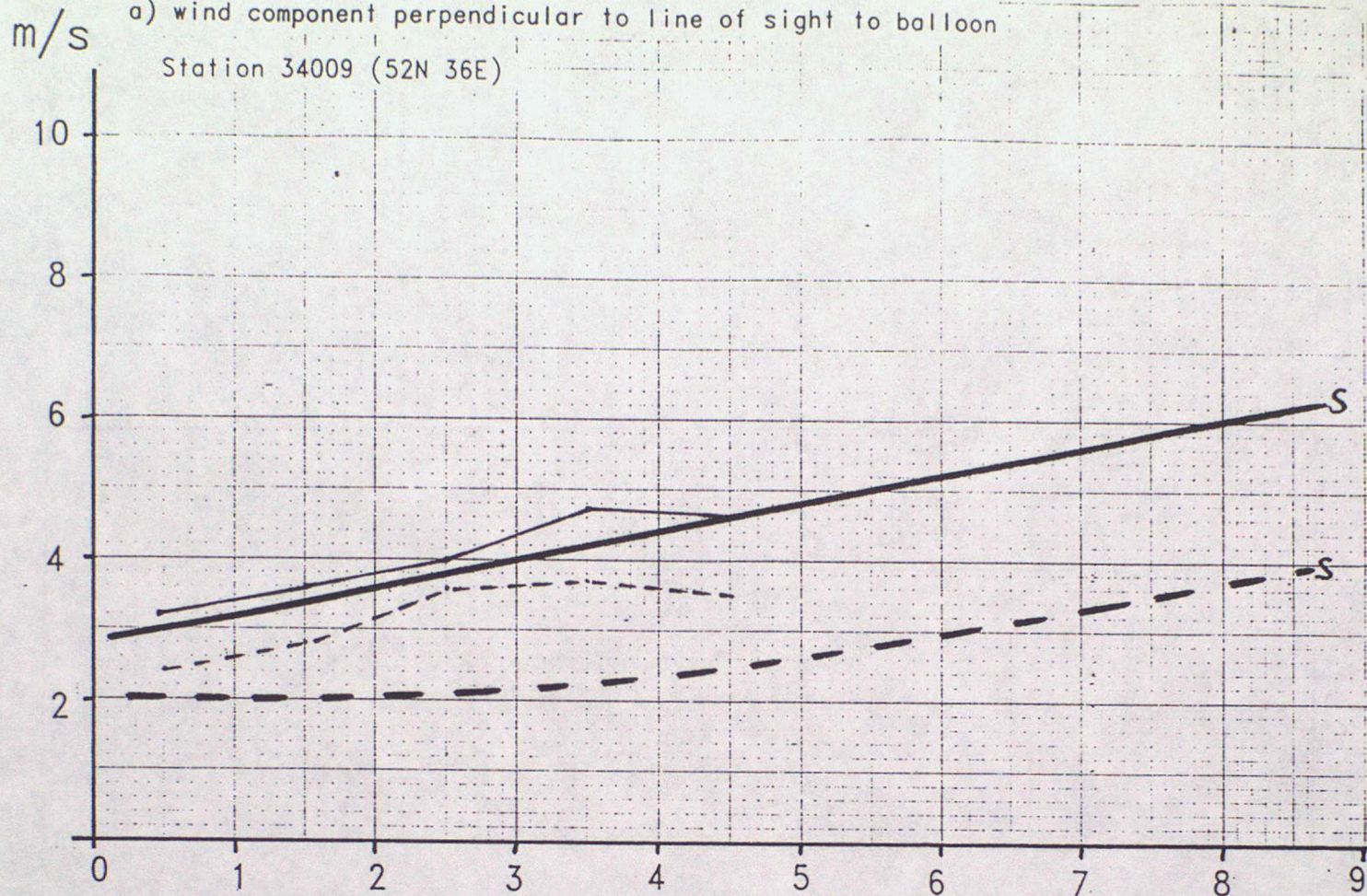
Fig. 27_b Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

a) wind component perpendicular to line of sight to balloon

Station 34009 (52N 36E)



b) wind component along line of sight to balloon

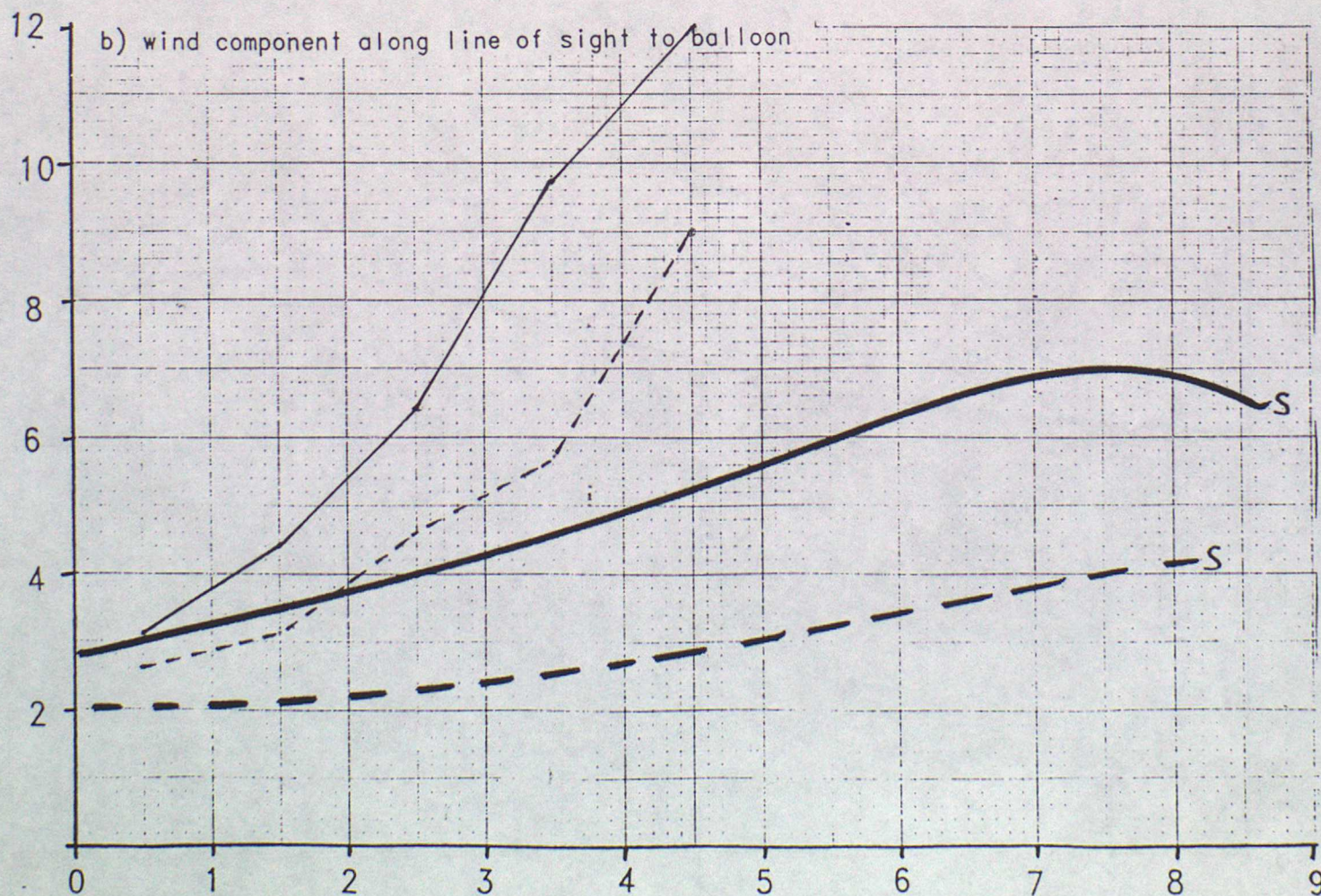


Fig. 28a Cotangent of balloon elevation

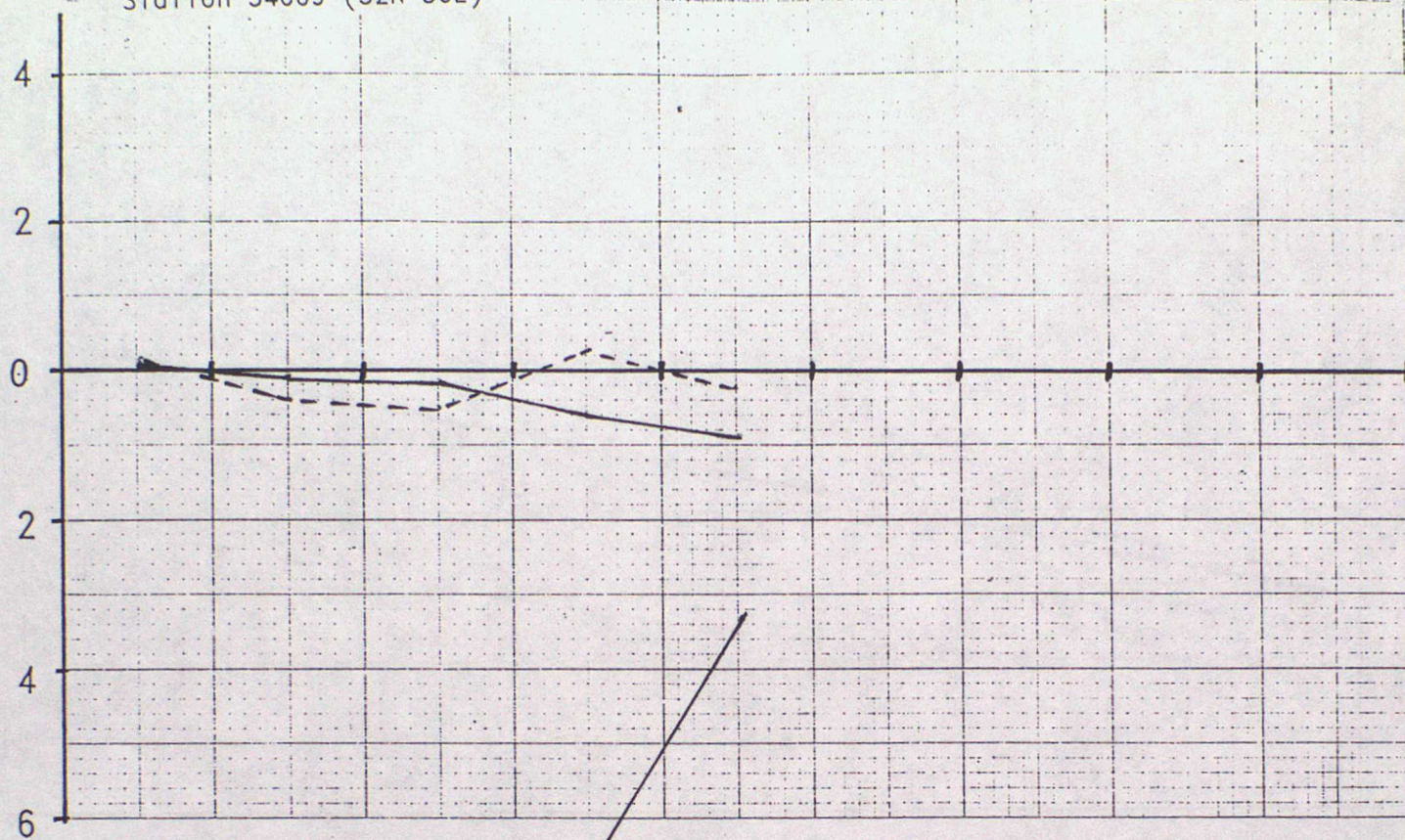
MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

a) wind component perpendicular to line of sight to balloon

Station 34009 (52N 36E)

m/s



b) wind component along line of sight to balloon

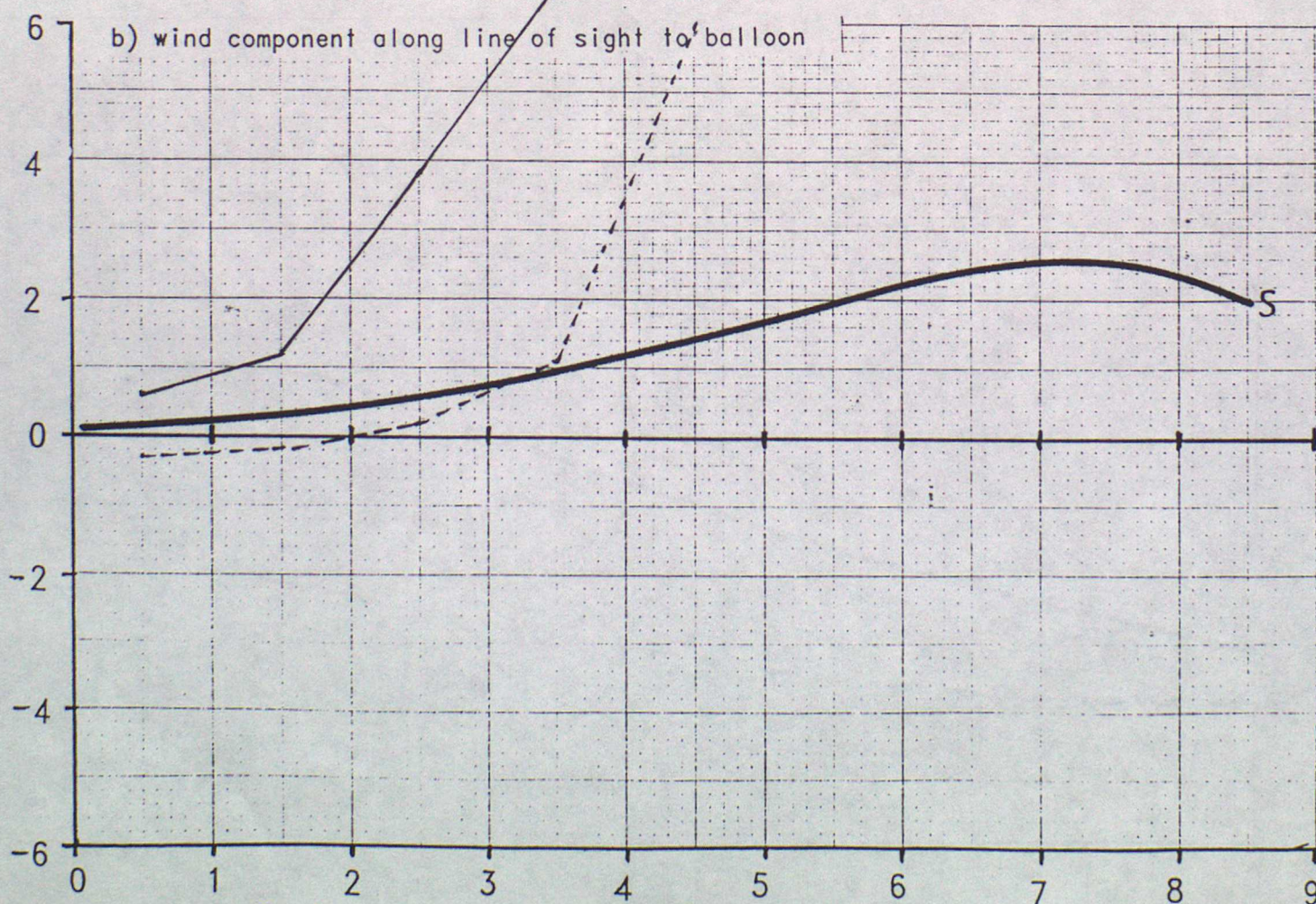


Fig. 28_b Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 400-150 hPa ——— ; 150-40 hPa - - - -

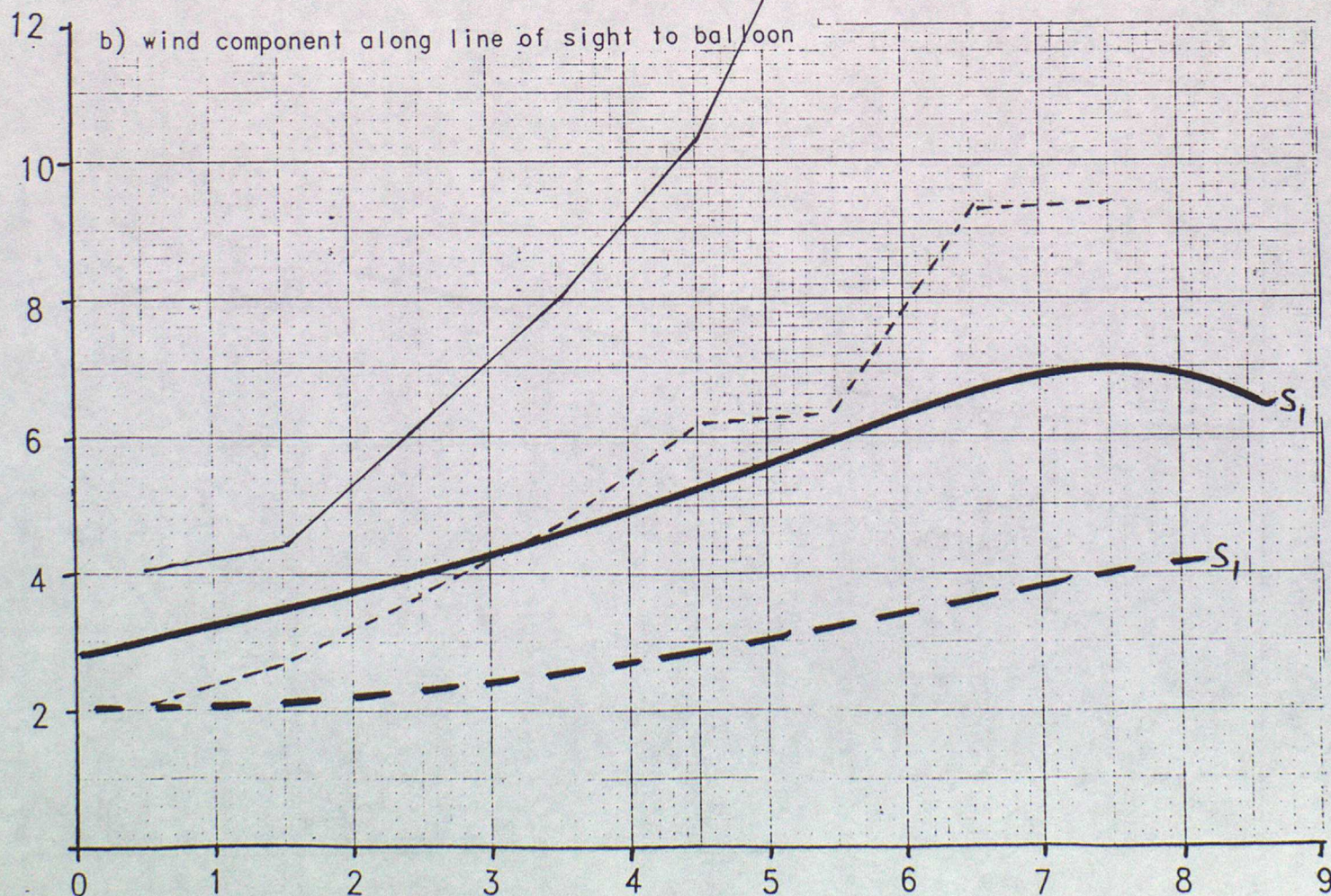
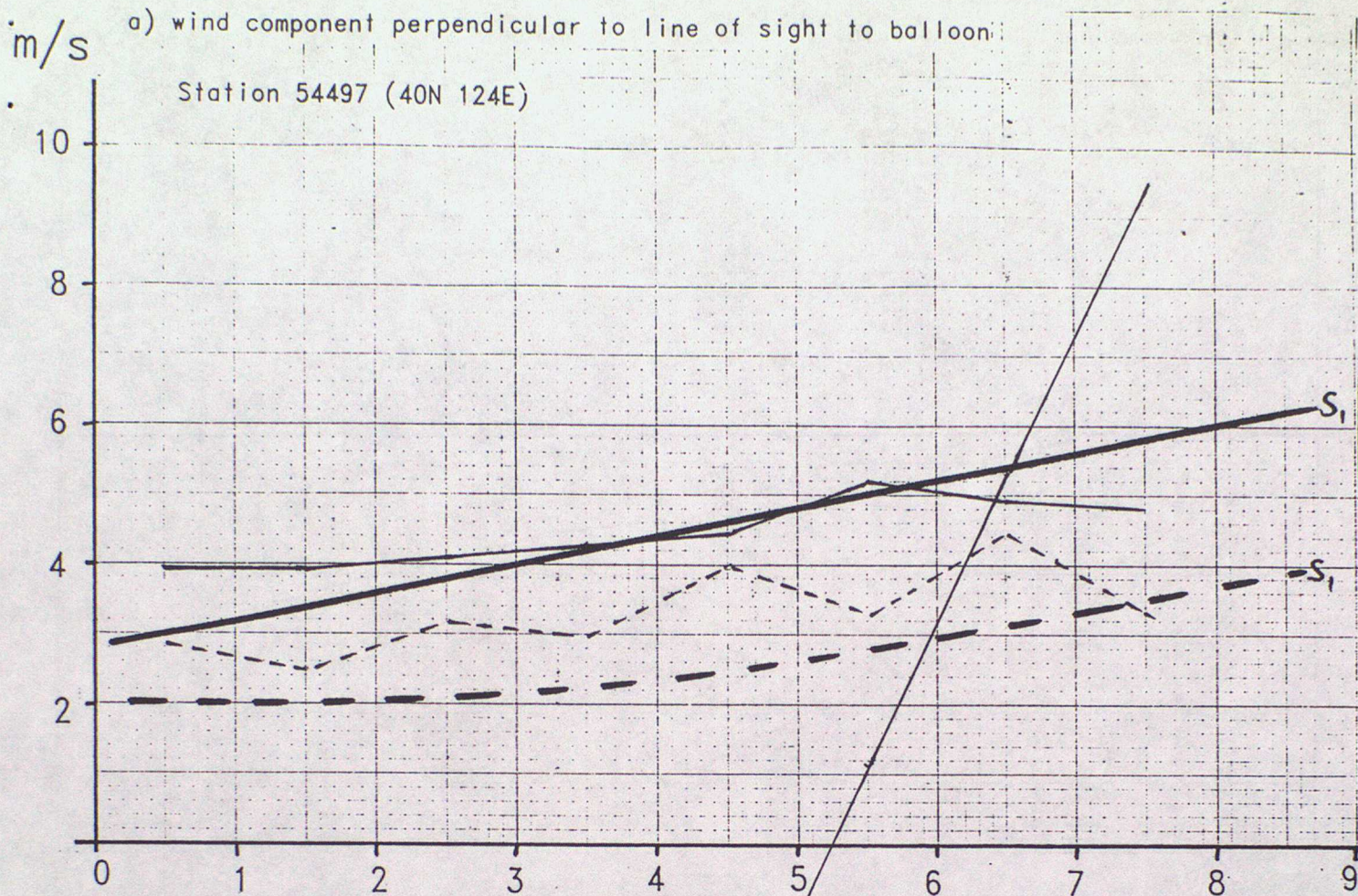


Fig. 29_a Cotangent of balloon elevation

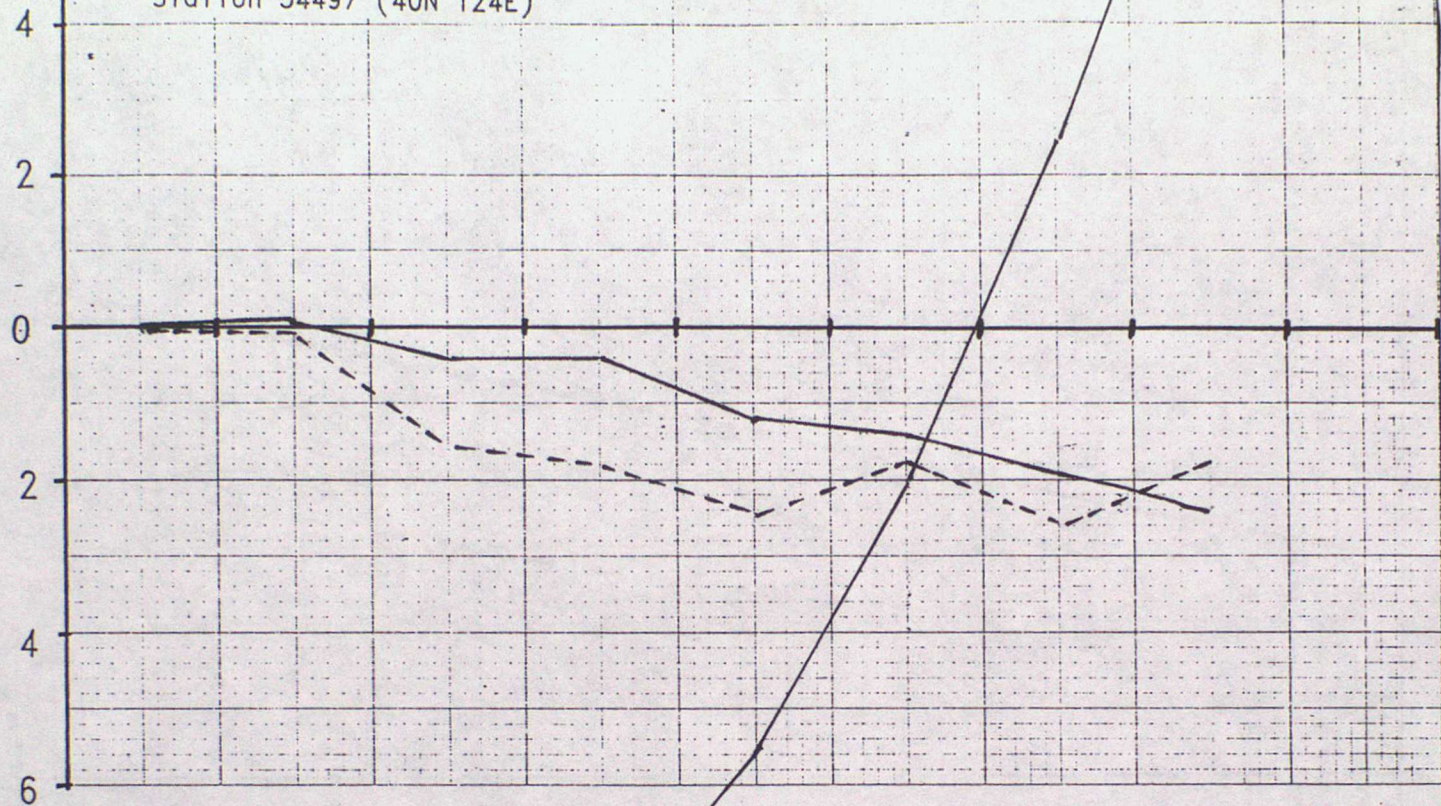
MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 400-150 hPa ——— ; 150-40 hPa - - - -

a) wind component perpendicular to line of sight to balloon

m/s

Station 54497 (40N 124E)



b) wind component along line of sight to balloon

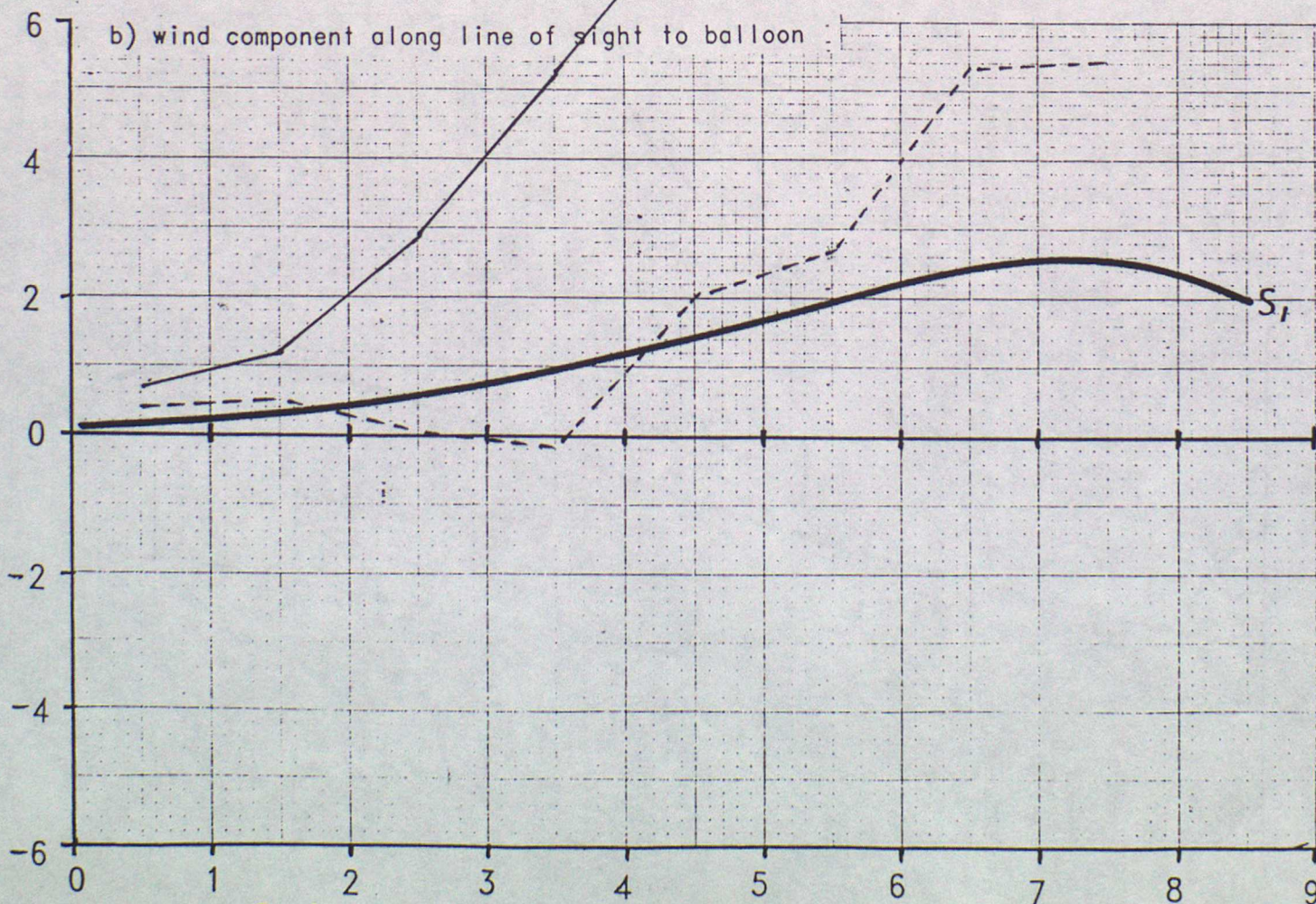


Fig. 29_b Cotangent of balloon elevation

RMS DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 ——— ; 13 to 14 - - - -

a) wind component perpendicular to line of sight to balloon

Station 68816 (34S 19E)

m/s

10

8

6

4

2

0

1

2

3

4

5

6

7

8

9

S_2

S_2

b) wind component along line of sight to balloon

12

10

8

6

4

2

0

1

2

3

4

5

6

7

8

9

S_2

S_2

Fig. 30 a Cotangent of balloon elevation

MEAN DIFFERENCES FROM BACKGROUND. JANUARY TO DECEMBER 1988

Mean over sigma layers 9 to 12 — ; 13 to 14 - - -

a) wind component perpendicular to line of sight to balloon

Station 68816 (34S 19E)

m/s

4

2

0

2

4

6

6

4

2

0

-2

-4

-6

0 1 2 3 4 5 6 7 8 9

b) wind component along line of sight to balloon

S_2

Fig. 30 Cotangent of balloon elevation

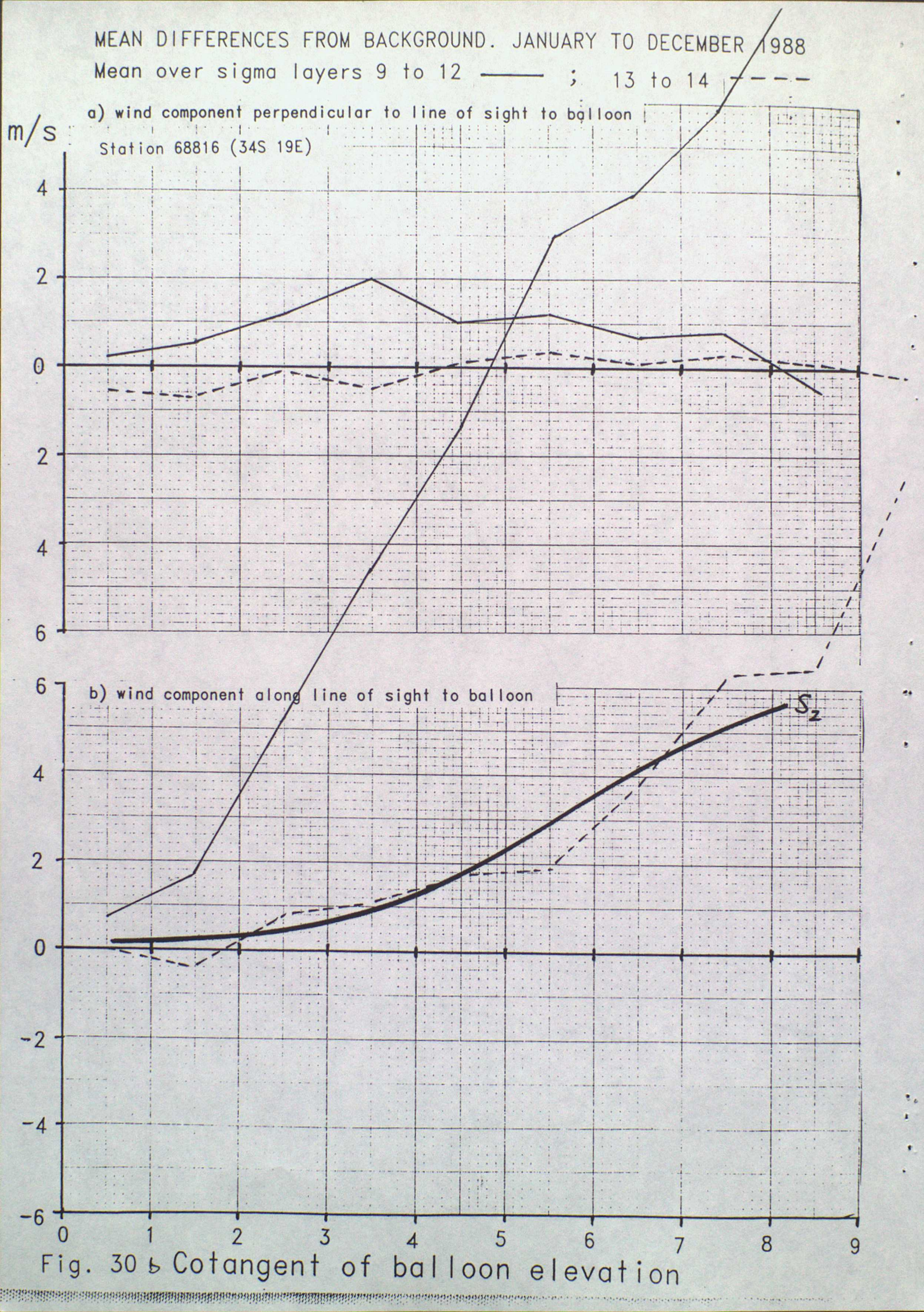


Fig. 31

MEAN AND RMS TEMPERATURE DIFFERENCES FROM BACKGROUND
JANUARY TO DECEMBER 1988
STATIONS 34300 (50N 36E) and 26422 (57N 24E)
ALL ANALYSIS HOURS

