Short-range Forecasting Research

Forecasting Research Division
Technical Report No. 37

A COMPARISON OF WIND OBSERVATIONS FROM A FLIGHT OF THE DRA(B) BAC 1-11 RESEARCH AIRCRAFT OVER HEMSBY,11 JUNE 1991, WITH OBSERVATIONS FROM THE HEMSBY RADIOSONDE

by
R.J. Graham

January 1993

Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ
United Kingdom

Forecasting Research Technical Report No.37

A COMPARISON OF WIND OBSERVATIONS FROM A FLIGHT OF THE DRA(B) BAC 1-11 RESEARCH AIRCRAFT OVER HEMSBY, 11 JUNE 1991, WITH OBSERVATIONS FROM THE HEMSBY RADIOSONDE

by

R.J.GRAHAM

Forecasting Research Division
Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ

January 1993

A comparison of wind observations from a flight of the DRA(B) BAC 1-11 research aircraft over Hemsby, 11 June 1991, with observations from the Hemsby radiosonde

Abstract

Observations of wind, temperature and height made during a single flight of the Bedford Defense Research Agency's BAC 1-11 research aircraft near Hemsby are compared with observations from a dedicated radiosonde launch from the Hemsby radiosonde station. Winds derived from the Racal RNS5000 system (RNS) and the Inertial Navigation System (INS) are analysed for a number of straight flight sectors, each sector being separated by a relatively sharp aircraft turn. Both level and ascending flight are addressed. The RNS winds are found to fit the radiosonde winds more closely than do the INS winds. On individual flight sectors typical standard deviations of aircraft-radiosonde u-component differences were 0.75ms^{-1} for the RNS and 1.4ms^{-1} for the INS. However, for both the RNS and INS, biases were found to vary considerably between different flight sectors and as a result the standard deviations calculated over all sectors are somewhat larger. This effect is particularly marked for the INS for which the standard deviation over all sectors is 6.17ms^{-1} - a factor ~4 that for the individual sectors. This suggests that for detailed analysis of aircraft data in terminal areas it may be advantageous to address the observation bias separately for individual flight sectors. There is evidence to suggest that for both INS and RNS winds biases are smallest in level, headwind flight.

Temperature observations from the Digital Airdata Computer (DADC) system were found to be cool, on average, compared to the radiosonde temperatures (by 0.67K). Aircraft based GPS measurements of height were found to read low, on average, compared to the radiosonde measurements (by 17.9m), however it was not possible to attribute the difference to bias in either the GPS or radiosonde measurements.

1. Introduction

Wind, temperature and height observations made during a single flight of the Bedford Defense Research Agency's (DRA(B)) BAC 1-11 research aircraft near Hemsby are compared with observations from a dedicated radiosonde launch from the Hemsby station at 0837GMT 11 June 1991. The main purpose of the comparison is to investigate the error structure of the aircraft's wind observations - as derived from three onboard systems - using the radiosonde data as "truth". The work is in support of the WAFTAGE research programme (WAFTAGE is an acronym for Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe), and is motivated by the need for a better understanding of the observation errors associated with aircraft data. Wind and temperature observations from commercial aircraft will form the main data input to WAFTAGE and an improved understanding of the observation errors is required in order to make best use of the data. The results of the comparison will be used to help determine strategies and parameter tuning in the WAFTAGE quality control and analysis schemes. The study follows on from a similar exercise documented by Lunnon *et.al.* (1991).

Wind observations derived from three on board navigation systems were available to the study; a Ferranti Inertial Navigation system (INS), the Racal RNS5000 system (RNS) and an Attitude and Heading Reference Unit (AHR). The navigation systems give the aircraft location which, together with the aircraft air speed and heading information, may be used to derive the wind vector. The two systems of main interest are the INS and RNS: the INS system is that used in the derivation of most current aircraft reports (e.g. AIREPS, ASDARS, ACARS); the RNS is a new system developed by Racal and not as yet deployed on commercial aircraft. A full description of the INS and RNS systems is beyond the scope of this report, however it is worth noting the fundamental differences: the INS works by integrating the aircraft accelerations in order to continually update the aircraft position, a disadvantage of the INS is that problems with the integration can result in "drifting" of the INS positions and consequent errors in the calculation of the wind vector (personal communication - D.Forrester); the RNS system uses ground beacons to locate position, and should therefore be less prone to drift, however its field of operation is limited by the number of ground beacons in range of the aircraft.

Details of the aircraft flight path, which consisted of a series of loops in order to remain in the vicinity of the radiosonde, are given in section 2. The ambient synoptic scale flow pattern which, through differences in spatial (and temporal) location of the radiosonde and aircraft, will contribute to differences in the observations, is discussed in section 3. Differences in the representativeness and processing of the aircraft and radiosonde data which will affect the comparison are outlined in section 4. A graphical comparison of the differences in wind observations is given in section 5, and is complemented by a statistical comparison in section 6.

In addition to wind observations, aircraft and radiosonde measurements of temperature and height are also compared, and are presented in section 7 and 8, respectively. The temperature observations were made by a Digital Air Data Computer (DADC) system, and the height measurements by a Navstar global positioning system (GPS). A summary and recommendations for future research are given in section 9.

2. The flight path

The aircraft flight path described a series of loops in order to remain in the vicinity of the ascending radiosonde. Figures 1a-d show details of the flight path for each of 5 legs executed by the BA-111. Aircraft positions at 10sec intervals are shown; on level portions of the flight, position is indicated by pluses; on ascending portions by triangles; and on descending portions by squares. The aircraft pressure observation is also shown every 100secs. The position of the radiosonde at the lowest and highest pressures recorded by the aircraft on the leg are also shown. For clarity of presentation the latitude scale has been stretched; this causes some distortion of bearing and to aid interpretation a line oriented NW-SE has been drawn in the lower left of the figure. The location of Hemsby has been added.

For purposes of reference the flight path has been divided into 11 approximately straight sectors flown approximately up and down the wind direction, which had a strong westerly component.

Leg 1 (Fig.1a)

Consists of headwind and tailwind sectors (1&2) at ~902mb. A climbing turn then leads into a headwind climb (3) to 573mb.

Leg 2 (Fig.1b)

Consists of a tailwind sector (4) mainly level but with a short climb to 528mb. A level turn then leads into a headwind climb (5) to 365mb.

Leg 3 (Fig.1c)

Begins with a climbing turn to 345mb. This is followed by tailwind and headwind sectors (6&7) at ~345mb.

Leg 4 (fig.1d)

A level turn at 345mb leads into a climb to ~238mb, comprising tailwind and headwind sectors (8&9) and linked by a climbing turn.

Leg 5 (Fig.1e)

A level tailwind sector at 238mb (10) is followed by a level turn and a headwind sector (11) which begins level, then descends to 678mb. The descent is interrupted by a short level stretch at 526mb. The descending part of sector 11 corresponds with the return of the BAC 1-11 to Bedford, and observations from the lower part of the flight are likely to be unrepresentative of the radiosonde observations at the same level (they differ by some 100km in location and 1hr 20mins in time). For this reason, and because no INS data were available on descent, analysis of the the descending part of the flight is not included.

3. Discussion of the ambient upper air flow, 06Z 11 June

The 06Z wind flow analyses (produced by the Met. Office's local area prediction model) for the UK and North Sea are shown in figures 2a-e for the 850mb, 700mb, 500mb, 300mb and 250mb levels respectively. The analyses give an idea of how horizontal gradients in the synoptic-scale wind field are likely to affect the comparison. The sides of the rectangular area shown represent the maximum and minimum latitude and longitude coordinates of the aircraft during the ascending and level legs of the flight. As figures 1a-e show, the aircraft remains fairly close to the radiosonde during the ascending and level legs, and therefore the variation of wind speed and direction within the area shown should give an idea of the maximum difference that can be expected between the radiosonde and aircraft observations as a result of gradients in the synoptic-scale wind flow.

At all levels, the area is downwind of an anticyclonic ridge in the flow field. This is particularly evident at 850mb, and will give rise to a backing in the wind direction as the experiment area is traversed from east to west. The variation in low-level wind direction across the area is likely to have increase by the radiosonde release time, 0837GMT (~2.5hrs after the valid time of the charts shown), as the ridge axis moved into the experiment area. There is very little gradient in wind speed at 850mb, 700mb and 250mb. At 500mb and 300mb there is very little north-south gradient in wind speed, however west-east gradients give rise to a difference of $4ms^{-1}$, $6ms^{-1}$ at 500mb and 300mb respectively.

4. Data pre-processing and representativeness

Pre-processing

To obtain some uniformity in the vertical spacing of the aircraft and radiosonde observations the frequency of the aircraft data, available at 16Hz, was reduced to a rate of 1 observation every 10sec. This gives a vertical spacing, during ascending sectors, ranging between 30m and 100m, which compares with a vertical spacing of ~10m for the radiosonde. To distinguish between level, ascending and descending portions of the flight the height increment between consecutive 10sec intervals was recorded; if the increment was greater than 20m, the phase of flight at the later observation was set as ascent; similarly descent was defined as a height increment less than -20m, and level flight as an absolute height difference less than 20m.

Throughout this report aircraft track angle is defined according to the meteorological convention (i.e. the direction from which the aircraft is approaching). The modulus of the difference between aircraft track angle and radiosonde wind direction was used to distinguish between headwind and tailwind sectors; headwind for differences exceeding 90°; tailwind for differences less than 90°.

Representativeness

Three factors will contribute to differences between the observations;

1) differences in location (in space and time).

2) differences in representativeness

3) differences in instrument performance.

We wish to assess (3), so it is clearly desirable to minimise differences associated with (1) and (2). Differences due to (1) have been discussed qualitatively in the previous section and will be referred to where it is thought that they may contribute significantly. No attempt was made to allow for the effects of ambient wind field gradients in the statistical analysis.

Differences in representativeness depend on the aircraft phase of flight and on differences in the processing of the aircraft and radiosonde data. The radiosonde winds used in the comparison are averages over a 60sec interval, and are therefore representative of depth of ~300m (the ascent rate of the sonde is ~5ms^{-1}), and a horizontal scale of order ~1km (assuming a mean wind speed of ~15ms^{-1}). The RNS winds are effectively weighted means over a period totalling 60secs (the actual meaning period is longer - but the average is heavily weighted to the last 60secs). In the experiment described here, ascent rates were of similar order to that of the radiosonde (~5ms^{-1}), the radiosonde and RNS winds will therefore be representative of a similar depth (~300m). However, the horizontal scale associated with the RNS winds will be an order of magnitude larger (~10km, assuming a ground speed of ~150ms^{-1}).

During level flight the vertical scale associated with the RNS observations will be much smaller than that of the radiosonde, and we may expect differences in the observations to contain a larger contribution from representativeness effects.

Two factors which further complicate the comparison between radiosonde and RNS winds should be borne in mind. The first concerns a difference in the way the two data types are averaged. The radiosonde winds are a post-processed centred mean, whereas the RNS means are derived from prior data and will either be assigned to the top or bottom of the layer traversed according to whether the aircraft is ascending or descending. The second factor concerns the RNS practice of excluding, from the data averaging, and data recorded when the aircraft roll angle was greater than a threshold value. This may have the result that RNS output immediately after exiting from a roll may be influenced by data recorded prior to the roll (even if the duration of the roll is greater than the effective averaging period of 60secs).

In contrast to the RNS winds, the INS and AHR winds are essentially spot observations, and comparison with radiosonde winds is therefore likely to be more prone to differences in representativeness. To address this problem a mean INS wind was calculated for each time by taking the mean of the previous 60secs of data. However, although radiosonde-INS differences for the meaned data were slightly smaller than for the raw data, the statistics were essentially very similar, and therefore only results for the raw INS winds will be discussed here.

Initial inspection of the AHR data suggested that there had been some malfunction of the AHR system resulting in unrealistic winds. For this reason the AHR data were not included in the statistical analysis.

5. Wind profiles

Profiles of wind direction and speed plotted from the radiosonde observations and from the RNS, INS and AHR winds over all ascending sectors are shown in figures 3a&b. As mentioned above, it is clear that the AHR data is unrealistic; the wind directions are erratic and the wind speeds are far too large and are constant above about 600mb. The AHR wind directions appear closely linked to the aircraft heading (see figure 5a). Because of these errors the AHR data are not included in further analysis.

5.1 Ascending sectors

Direction differences

Figures 4a&b show the wind direction and speed profiles as in figures 3a&b, but on an expanded scale and without the AHR profiles. The ascent has been divided into the tailwind, headwind, and climbing turn sectors described in section 2. The typical angular difference between the wind direction and the aircraft track are given. The aircraft track and roll angle are shown for reference in figures 5a&b. The wind profiles are discussed below with reference to the different flight sectors.

Referring first to the wind direction (figure 4a), it may be seen that the radiosonde profile (solid line) records a general veering of direction with height from 260° at 900mb to 300° at 240mb. As expected from consideration of representativeness (section 3) the radiosonde and RNS profiles show a similar representation of small scale structure, while the INS data shows rather more fine structure than the other two.

The aircraft ascent begins with a climbing turn prior to sector 3. Over this interval the radiosonde data indicates a wind direction veering with height from 260° to 270°. The corresponding INS direction backs unrealistically from ~290° to ~260°; the RNS directions, in contrast, are constant, reflecting the fact that no updating of direction information recorded prior to the turn has taken place because of the large roll angle (cf. figure 5b). The same sort of behaviour, i.e. large swings in the INS directions and constant RNS directions may be seen in the other climbing turns after sectors 5 and 8.

During sector 3 (headwind), both the INS and RNS data show similar profiles, however, both are backed by about 10° from the radiosonde direction. The greater backing of the aircraft winds is likely to be due, at least in part, to the gradient in the direction of the synoptic-scale wind. During much of sectors 3&4 the aircraft was located west of the radiosonde towards more backed wind directions. The fact that both the INS and RNS directions are backed from the radiosonde directions, and agree with each other is further evidence that the horizontal gradients of wind direction were important. In this respect the direction biases are likely to be more reliable above 500mb - where the gradients in wind direction were less marked.

Despite the bias, the general trends in the profile correspond well; note the "nose" at **a** and the smaller scale detail at **b** and **c**. In sector 4 (tailwind) the INS and RNS directions are again very similar and remain backed from the radiosonde directions, with a slight trend for backing with height exhibited by all three profiles. In sector 5 (headwind) the INS and RNS profiles diverge progressively, with the INS directions coming more into line with those of the radiosonde. A brief direction swing to around 310° in the INS profile near 430mb appears to be associated with an increase in the roll angle to 7° at this level (cf. figure 5b). In contrast to sector 5 the best agreement in sectors 8 and 9 is between the radiosonde and RNS directions. In sector 8 both the RNS and INS directions are backed relative to the radiosonde, while in sector 9 both are veered. The INS profile in sectors 8 and 9 gives the impression that the directions take some time to recover from the marked swings which appear to affect the data during the preceding turning manoeuvres when the roll angle is large.

Speed differences

The wind speed profiles for ascending sectors are shown in figure 4b. The radiosonde profile shows a low level wind speed maximum near 850mb above which the wind speed increases with height from 14ms^{-1} to 20ms^{-1} at 500mb. Above 500mb wind speeds increase more quickly with height to 45ms^{-1} at 240mb. The climbing turn prior to sector 3 corresponds with the shear zone below the aforementioned low-level wind maximum. In this zone the INS speeds increase more rapidly than do the radiosonde speeds, while the RNS speeds, like the directions described above, remain constant. As a result the maximum in the INS profile is at the correct level but is too strong, while in the RNS profile the maximum is displaced upwards and is too weak. Similar behaviour, i.e. constant RNS speeds and rapidly varying INS speeds, may be seen in the climbing turns after sectors 5 and 8.

Below 500mb there is little horizontal gradient in wind speed, and over much of sector 3 the INS, RNS and radiosonde speeds are in broad agreement. The INS speeds are at first stronger than the radiosonde speeds (by about 3ms^{-1}) but lose strength relative to the radiosonde speeds with increasing height. The RNS speeds, in contrast, reproduce the shape of the radiosonde profile more faithfully but are consistently weaker by around 1-3ms^{-1}.

INS wind speeds in sector 4 (tailwind) are considerably stronger than those in the adjacent headwind sectors (3&5), and stronger than the radiosonde speeds (by about 3ms^{-1}). This behaviour gives rise to an apparent jet-like structure in the INS profile near 550mb. Comparison with the radiosonde profile, which indicates wind speeds approximately constant with height in this region, suggests that this feature is unrealistic. A similar jet-like feature, though of much smaller amplitude, may also be discerned in the RNS profile for sector 4. In contrast INS winds for sector 5 (headwind) are weaker (by about $8ms^{-1}$) than the corresponding radiosonde speeds. RNS speeds in this sector are also weaker than the radiosonde speeds, but by a smaller margin. Over the later part of sector 8 and in sector 9 the RNS speeds are quite similar to the radiosonde speeds, although slightly weaker. In contrast the INS speeds show a tendency to be too strong over sector 8 (tailwind) and too weak over sector 9 (headwind).

5.3 Level sectors

The radiosonde, RNS and INS winds for the level sectors of the flight path are shown in figures 6a&b. There were five level sectors in all at, approximately, 902mb, 527mb, 345mb, 238mb and again at 527mb. The radiosonde wind interpolated to the aircraft pressure level is shown in solid line and the scatter of the RNS and INS wind observations about the radiosonde values are shown by crosses and pluses respectively. For clarity the radiosonde data has been plotted as continuous with time, however, only that portion of the continuous line adjacent to the plotted aircraft data is relevant. It is clear from both figures 6a&b that in general the RNS observations are more closely grouped around the radiosonde values than are the INS data. The greater scatter in the INS data is not only a reflection of the fact that they represent "spot" observations - since a similar plot using the 60sec mean INS data showed similar characteristics.

Biases in INS wind direction and wind speed may be seen from figures 6a&b. Referring first to wind direction (figure 6a), the flight sectors at 902mb and 345mb suggest that INS winds tend to be backed in tailwinds and veered in headwinds. A similar pattern is visible in the RNS data for the 238mb sector (for which there was no INS data). Moreover, a similar pattern is evident in the RNS data at 345mb, although at this level the pattern is superimposed on a general bias towards backing.

Referring to figure 6b, it may be seen that INS speeds at 902mb were biased too strong in the headwind section and too low in the tailwind section. At 345mb, however, the trend is reversed with speeds biased high in the tailwind section and low in the headwind. Apart from the sector at 902mb, where RNS speeds show a small positive bias, and the later of the two sectors at 527mb (sector 11), where a large positive bias may be seen (~10ms,$^{-1}$) the RNS speeds tend to be biased too low.

In summary, we draw the following points from the above comparisons.

Ascending flight

- There is a problem with the AHR data which makes it unsuitable for further analysis.
- INS direction and speed data are unreliable during turning manoeuvres (i.e. when the roll angle is large). Both directions and speeds show marked swings about the radiosonde direction.
- The RNS strategy of not updating the wind observation when the roll angle exceeds a threshold value can result in significant wind speed errors (~10ms^{-1}) when the aircraft is climbing through a region of marked vertical shear. This may lead to a vertical displacement in the observed level of wind maxima.
- Both INS and RNS directions are backed from the radiosonde direction by about 10° over the lower half of the ascent. The backing may be attributed, at least in part, to horizontal gradients in the ambient flow. For this reason the comparisons at levels above 500mb are likely to give the most reliable estimates of observation bias.

Level flight

- Relative to the radiosonde winds INS winds are backed in tailwinds and veered in headwinds. A similar, but much damped, pattern is visible in the RNS winds.
- On most level sectors the INS wind speeds show a large bias (~8ms^{-1}) relative to the radiosonde wind speeds. Examples of both negative and positive bias are seen and, unlike the direction biases, the sign of the bias is not consistently related to whether the observation was made in headwind or tailwind flight. Similar, but much damped, patterns are evident in the RNS output. RNS wind speeds are generally too weak - by about 3ms^{-1}.

6. Statistical analysis

6.1 Direction and speed differences

A statistical analysis of the differences between the aircraft observations (RNS and INS) and the radiosonde observations is given in tables 1-8, observations made when the aircraft roll angle exceeded 5° are not included in the calculations. The tables confirm the general trends evident from figures 3-6 discussed in the previous sections.

Mean differences

Table 1 shows the mean direction differences for the four level and four ascending legs, where possible a mean value is given for both the headwind and tailwind parts of each leg. A negative mean indicates aircraft wind directions backed with respect to radiosonde directions. We first note that for both the RNS and INS measurements the direction bias may vary markedly both between different legs and between the headwind and tailwind portions of the same leg. As may be seen from the legs with both tailwind and headwind flight, RNS and INS observations of wind direction made in tailwind flight are backed relative to those made in headwind flight. This is particularly evident for the INS winds, which show differences of up to $\sim 20^{\circ}$ between the headwind and tailwind means. The large variations in the bias found on consecutive flight sectors suggests that bias in the observations contributes much more to the mean differences than do the effect of gradients in the ambient wind field (the likely effect of horizontal gradients in wind direction on the biases at low levels (i.e. the 902-573mb leg) has been discussed in section 3).

For both RNS and INS measurements the absolute mean difference is largest, in most cases, for the tailwind part of the leg. There is some evidence to suggest that biases are smallest in level, headwind flight. The mean speed differences are shown in table 2. Typical values of wind speed bias are $1\text{-}3ms^{-1}$ for the RNS; and $4\text{-}5ms^{-1}$ for the INS. Overall the RNS speeds are biased low, apart from the level leg at 902mb - where there was a small positive bias. The INS speeds show a tendency to be biased low in headwind flight and high in tailwind flight - apart from the level leg at 902mb where the pattern is reversed. For the INS winds the absolute value of the wind speed bias is largest in headwind flight, RNS absolute values are similar in both headwind and tailwind flight.

There is no firm evidence to suggest that the direction and speed biases may be significantly different between level and ascending portions of the flight.

Standard deviations

The standard deviations of direction differences are shown in table 3. RNS and INS standard deviations are generally similar, and are in the range 0.5 - 6.0° (apart from INS tailwinds in the level leg at 902mb, where an extreme value of 18.58° occurs). In the main, the RNS standard deviations are smaller that the INS standard deviations in headwind flight, whilst the reverse is true in tailwind flight. The standard deviations of wind speed difference are shown in table 4. The largest standard deviation is 1.95ms^{-1} for the RNS and 2.3ms^{-1} for the INS. For the most part the RNS standard deviations for speed difference are smaller than those for the INS (apart from the tailwind case in the leg 527-344mb, and the headwind case in the leg 344-238mb). This is to be expected bearing in mind the fact that no averaging has been performed on the INS data. As was found for the direction measurements, there is no evidence to suggest that the standard deviations are significantly different in tailwind or headwind flight.

The fact that the standard deviations in level and ascending flight are not significantly different suggests that the dependence of representativeness on phase of flight is small - and does not significantly affect the comparison.

6.2 Differences in U and V components

Tables 5&6 give a summary of the mean and standard deviation of the differences in *u* and *v* components. Because the flow was predominantly westerly the *u*-component mean speed differences (table 5) show similar characteristics to the differences in total wind speed (table 2). RNS *u*-components are biased low in the main, the maximum absolute magnitude of the bias being 3.41ms^{-1}; INS *u*-components show biases of opposite sign in head and tailwind flight and are much larger in magnitude than the RNS biases - exceeding 8ms^{-1} on four of the sectors. The RNS *v*-components are, in the main, biased high, with the largest bias seen in tailwind flight (7.72ms^{-1} in ascent between 527-344mb - although this is from a sample of only 5 observations). The INS mean *v*-components are biased high in tailwinds, while in headwinds the bias is as often negative as positive. For both RNS and INS the absolute magnitude of the

v-component biases are larger in tailwinds, with the INS values larger than the RNS. By contrast the bias for headwind measurements is most often largest for the RNS.

Standard deviations

U-component standard deviations (table 6) for the RNS are all less than 1.7ms^{-1}, with 9 of the 13 sectors showing standard deviations of less than 1ms^{-1}. Standard deviations for the INS u-component are generally in the range 1-2ms^{-1} (with only one sector having an SD below 1ms^{-1}). Standard deviations for the v-component are generally of similar order for the INS and RNS.

Tables 7&8 show mean and standard deviation of aircraft-radiosonde differences for all level and ascending legs, and illustrate how the standard deviations of the differences increase markedly when data from all legs is combined. The combined standard deviations for headwind and tailwind flight are larger than that for any of the individual legs, most notably in the differences for INS u-component for which the standard deviations are in the range ~1-2ms^{-1} for individual legs, but rise to 5.22 and 5.45 in combined headwind and combined tailwind flights respectively. If headwind and tailwind sectors are combined the standard deviation rises to 6.17 (table 8). The larger standard deviations for the combined data is a consequence of the variation in bias between separate legs (individual observations with a small deviation about the "leg" mean may deviate markedly from the overall mean). The same effect is evident in the v-component winds, but with rather less difference between the RNS and INS observations.

The above result suggests that to maximise the assumed accuracy of the observation (and thereby to give maximum weight to the observations in the analysis) it will be advantageous to estimate the bias separately for each individual leg of the available flight path.

6.3 The effect of roll angle

Table 9 shows rms wind component differences for data obtained when the aircraft roll angle was within three ranges. The less-than-5^{o} range corresponds to the mean and standard deviation data given in table 8. Since RNS winds are held constant when the roll angle exceeds a threshold value we expect to see more roll-angle dependence in the INS winds. This is the case for the INS v-component, for which an rms error of 3.75ms^{-1} for roll angles less than 5^{o} increases to $5.11ms^{-1}$ for roll angles greater than 25^{o}. The RNS rms differences for both *u*- and *v*-components also increase slightly with increasing roll angle. However, rms errors for the INS *u*-component show a decrease with increasing roll angle; this is likely to be due to the exclusion of data with large biases (present in the INS *u*-component during some straight legs cf. table 5) when only observations taken at roll angles greater than 5^{o} are considered.

7. Comparison of temperature observations.

The difference between the static temperature measurements recorded by the on board Digital Air Data Computer (DADC) system and the radiosonde temperatures interpolated to the aircraft pressure are shown in figure 8 for all ascending legs. Both the DADC and radiosonde temperature measurements are essentially "spot" values, so their representativeness should be similar. The aircraft temperatures are for the main part cooler than the radiosonde temperatures, with the exception of two layers centred near 700mb and 430mb where DADC temperatures are warmer. The difference statistics corresponding to figure 8 confirm a negative bias of 0.67K; the standard deviation from the mean was 0.59K, and the maximum absolute difference 1.85K.

8. Comparison of aircraft GPS heights and radiosonde heights

Aircraft observation of the height of pressure surfaces made by an onboard Global Positioning System (GPS) have been compared with heights derived from the radiosonde data. No pressure information was available on the GPS dataset, so it was necessary to use the observations of flight level recorded by the DADC system in an intermediary step. The DADC flight level data are observations of pressure converted to height using the ICAO standard atmosphere. The following procedure was followed; GPS heights as a function of time (from the GPS dataset) and pressure as a function of time (from DADC dataset) were combined to obtain GPS heights (Z_g) as a function of pressure. The radiosonde height observations of the corresponding pressure levels were then obtained by interpolation. Two measurements of height were available from the radiosonde data; that derived from radar measurements of the radiosonde range and elevation (Z_r); and that derived by integration of the hydrostatic equation using the radiosonde temperature measurements (Z_h). The Z_g, Z_r and Z_h heights are shown in figure 8 as differences from the corresponding ICAO standard heights (Z_r and Z_h have been converted to geometric metres from geopotential metres). The best agreement is between Z_g and Z_h, particularly above 400mb. Below 400mb Z_g reads low compared to Z_h - by ~30m (no GPS data was available between about 350 and 450mb). At 500mb a 1mb pressure interval is equivalent to ~15m, so the discrepancy between the Z_g and the Z_h could be explained by a ~2mb negative bias on the aircraft pressure sensor. The large discrepancy seen between the Z_r and Z_h observations are not uncommon (personal communication, John Elms). For the whole ascent the mean Z_g - Z_h difference was -17.9m with a standard deviation of 10.9m.

9. Summary and recommendations

Observations of wind, temperature and height made from instrumentation on board the DRA(B) BAC 1-11 have been compared with those made by a nearby radiosonde released at Hemsby. Comparison of INS and RNS winds show the RNS winds to be the more reliable, with smaller biases and standard deviations from the radiosonde observations. Biases on observations made during different sectors of the flight were found to vary considerably. In particular the INS wind direction biases vary by up to ~20^{o} between flight sectors and are frequently of different sign. The variation in bias between different sectors results in standard deviations calculated for all the observations being much larger than the typical standard deviation for an individual sector. For example, typical standard deviations for the INS *u*-component on individual sectors are ~1.5ms^{-1} while the standard deviation for all sectors combined is 6.17ms^{-1}. If this result is typical of INS performance then it will be advantageous for the WAFTAGE quality control/analysis scheme to attempt to remove the bias on individual sectors of a given flight, in order that the assumed error of the observation be minimised. However, it must be said that the variation in bias may be due to INS drift induced by the sharp nature of the aircraft turns in this experiment. Turning manoeuvres in commercial aircraft, even in terminal areas, are likely to be less sharp - and consequently less demanding of the INS.

A tendency for wind direction measurements during tailwind flight to be backed relative to those during headwind flight was found for both the INS and RNS systems. There is evidence to suggest that biases are smallest in level, headwind flight. RNS wind speeds were biased low, in general with respect to the radiosonde winds; while for the INS both positive and negative biases were found with a predominance of positive biases in tailwinds and negative biases in headwinds.

INS winds were found to be unreliable at large roll angles (i.e. during turning manoeuvres) when marked swings in the INS wind direction and speed are observed. The RNS system does not update the wind speed and direction output when the roll angle is above a given threshold, and this can give rise to significant error when the aircraft is climbing through a region of marked wind shear.

For this flight the DADC temperature observations were found to be biased low relative to the radiosonde temperatures (by -0.67 K). GPS height measurements were found to read low, on average, relative to the radiosonde heights by 17.9m. Unfortunately, it was not possible to attribute the source of the difference to bias in either the GPS or radiosonde measurements (a small negative bias (of 1-2mb) in the aircraft pressure observations would also give rise to similar differences).

Recommendations for future work

Clearly, comparisons based on a single flight do not provide a basis with which to draw firm conclusions, and further comparisons experiments are required. As is evident from sections 3&4 of this report, comparisons with radiosonde observations have the disadvantage that factors related to the ambient wind gradients and to the different representativeness of radiosonde and aircraft data are difficult to separate from the true observation differences. Similar problems are likely to occur if the experiment were performed using a wind profiler rather than a radiosonde. For these reasons it is proposed that the next study should entail a comparison of raw and "corrected" INS winds (such as the corrected INS data available from Meteorological Research Flight tapes). Comparing observations made from the same platform at the same resolution will avoid the aforementioned problems.

The greater stability of the RNS measurements compared to the INS measurements suggest that winds derived using GPS data may be more reliable than those derived using INS. The next study should include an evaluation of GPS-derived winds.

Acknowledgements

The author would like to thank the BAC 1-11 team at RAE Bedford and the radiosonde team at Hemsby, without whose cooperation the experiment would clearly not have been possible. Helpful discussions with Reg Harlow (RAE Bedford) and also with John Elms (Met. OB(2p)) are gratefully acknowledged. Thanks are due to R.Luunon and D.Forrester for useful comments on an earlier draft of this report.

References

Lunnon,R.W. 1991: *Short range forecasts for air traffic control using high resolution aircraft data.* Fourth international conference on aviation weather systems.

Lunnon,R.W., Lowe,D.A. and Marklow,A.D. 1991: *A comparison of a Hemsby radiosonde ascent with a dedicated flight of the RAE Bedford BAC-111 on 31st October 1991.* S-division technical note No.56, UK Meteorological Office.

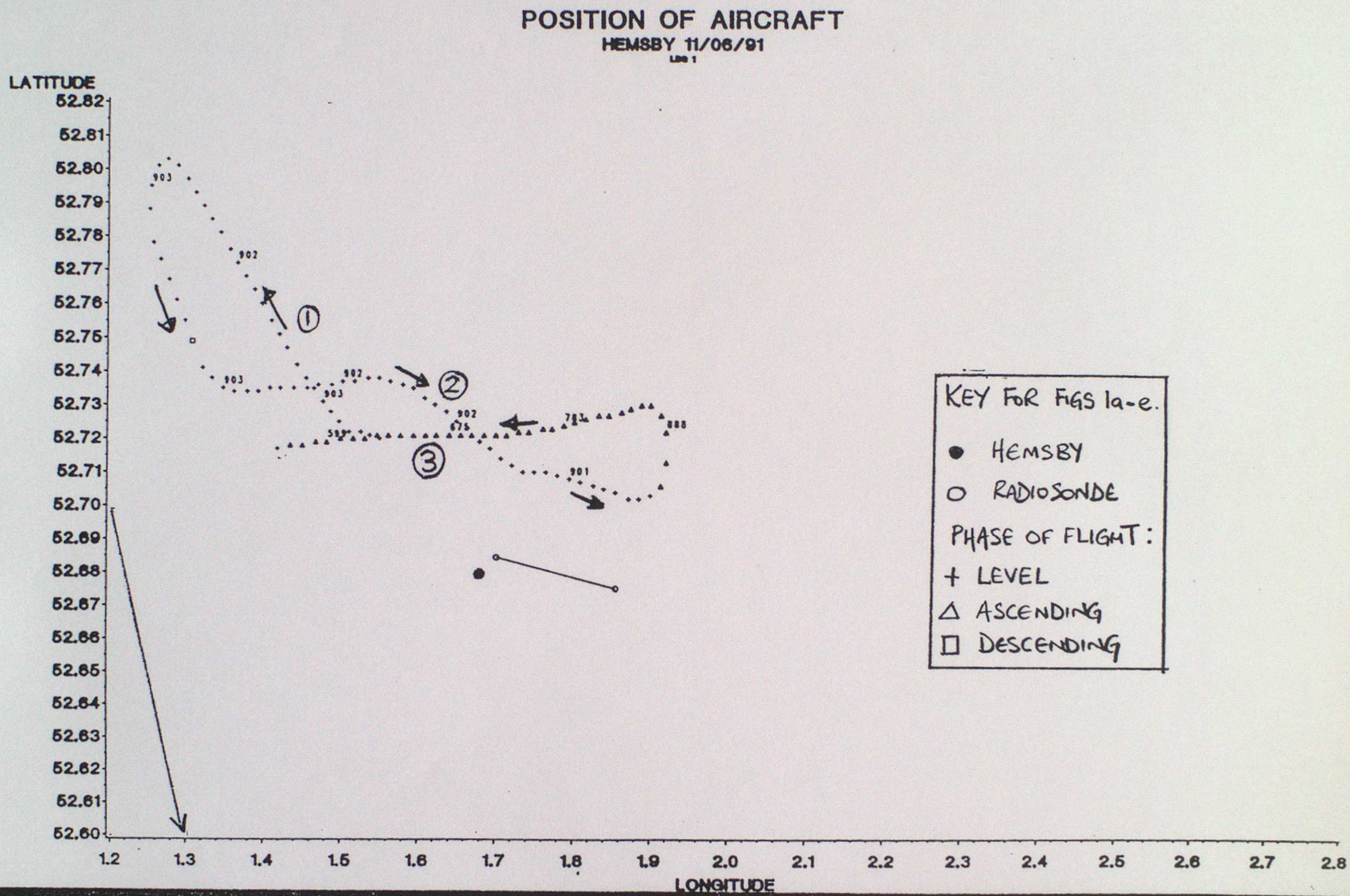
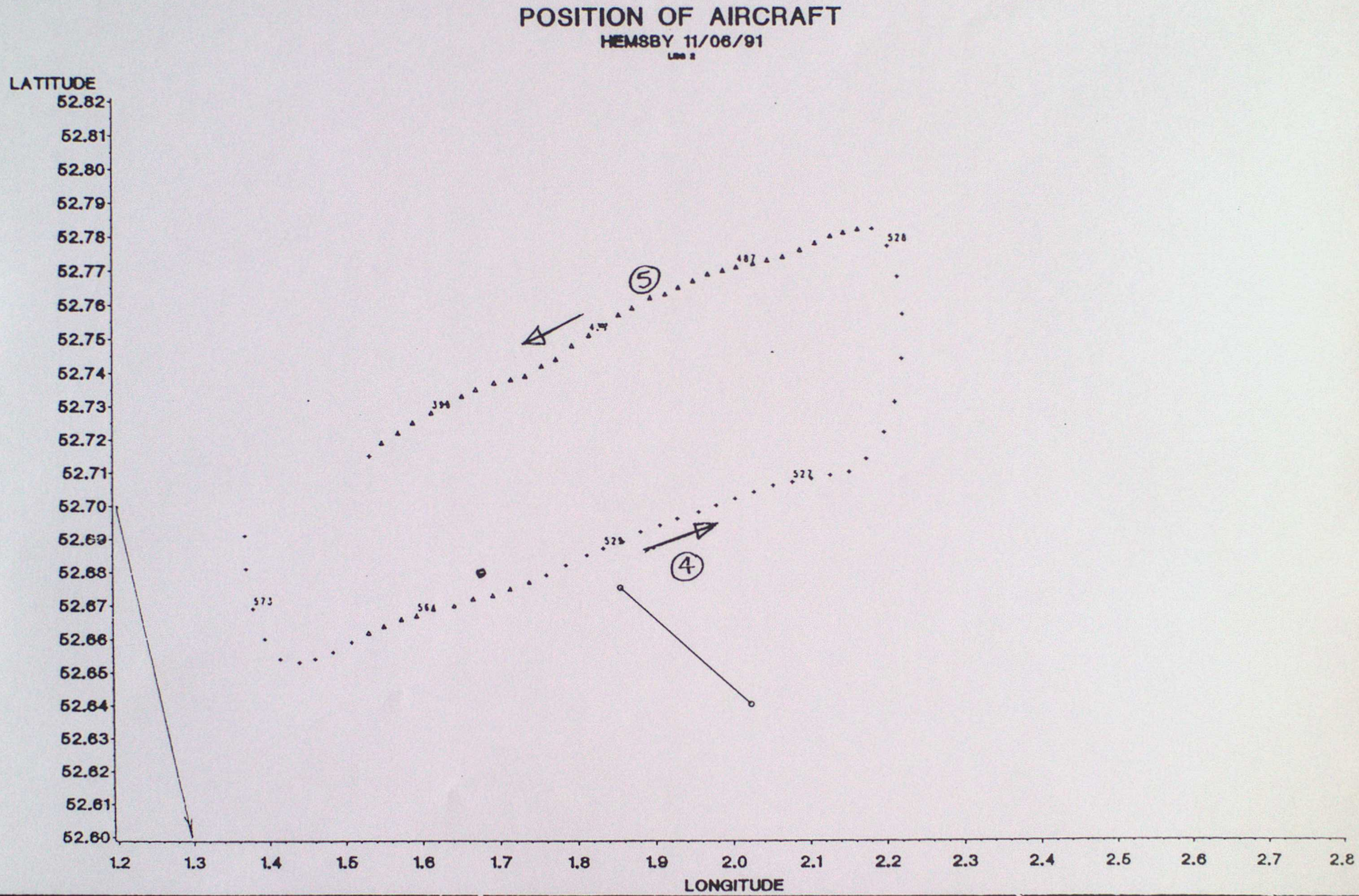

POSITION OF AIRCRAFT
HEMSBY 11/06/91
LATITUDE
52.82
52.81
52.80
52.79
52.78
52.77
52.76
52.75
52.74
52.73
52.72
52.71
52.70
52.69
52.68
52.67
52.66
52.65
52.64
52.63
52.62
52.61
52.60
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
LONGITUDE
903
902
901
①
②
③
KEY FOR FIGS 1a-e.
● HEMSBY
○ RADIOSONDE
PHASE OF FLIGHT:
+ LEVEL
△ ASCENDING
□ DESCENDING

Figure 1a



POSITION OF AIRCRAFT
HEMSBY 11/06/91
LATITUDE
52.82
52.81
52.80
52.79
52.78
52.77
52.76
52.75
52.74
52.73
52.72
52.71
52.70
52.69
52.68
52.67
52.66
52.65
52.64
52.63
52.62
52.61
52.60
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
LONGITUDE
5
4

Figure 1b

POSITION OF AIRCRAFT
HEMSBY 11/06/91

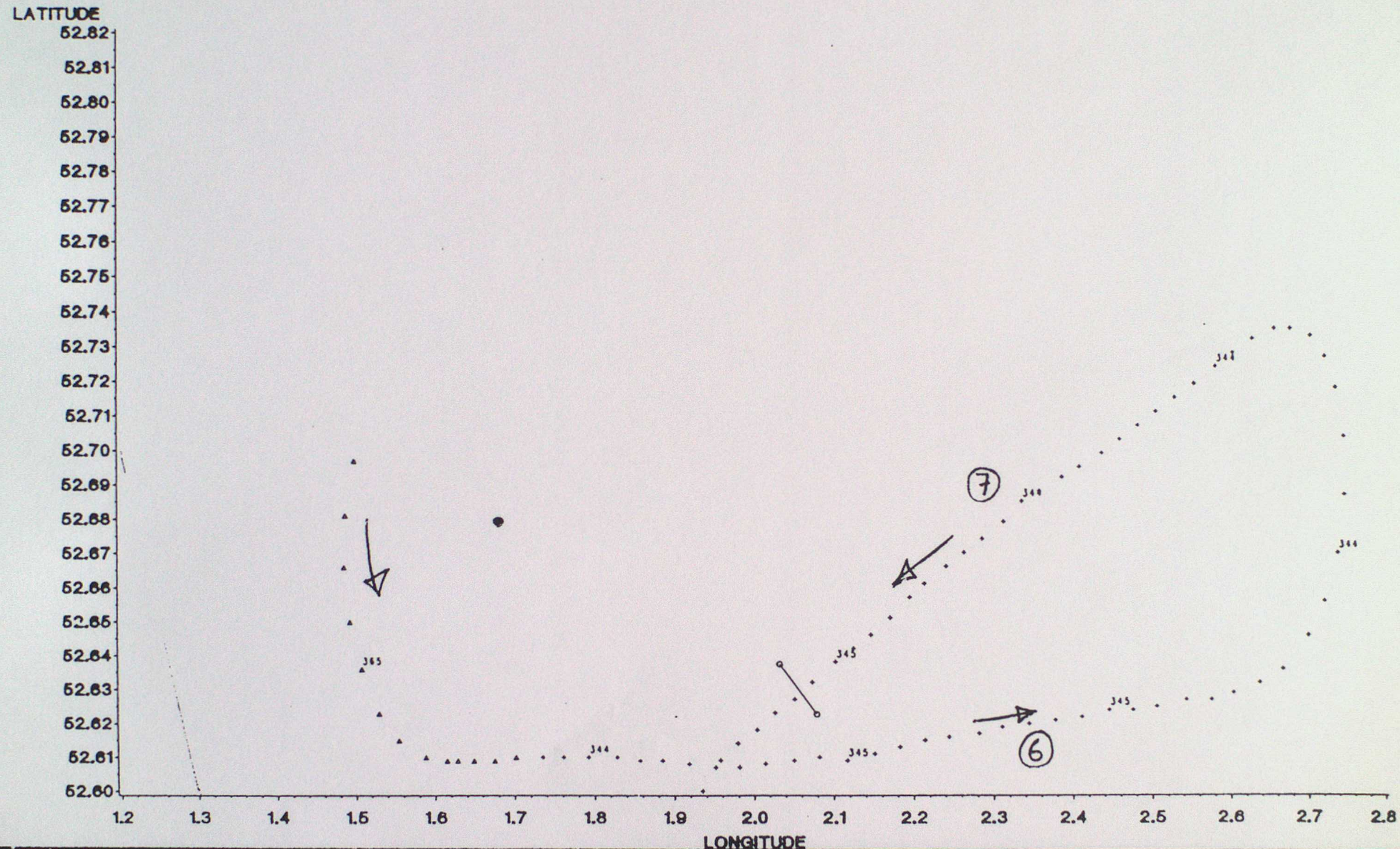


Figure 1c

POSITION OF AIRCRAFT

HEMSBY 11/06/91

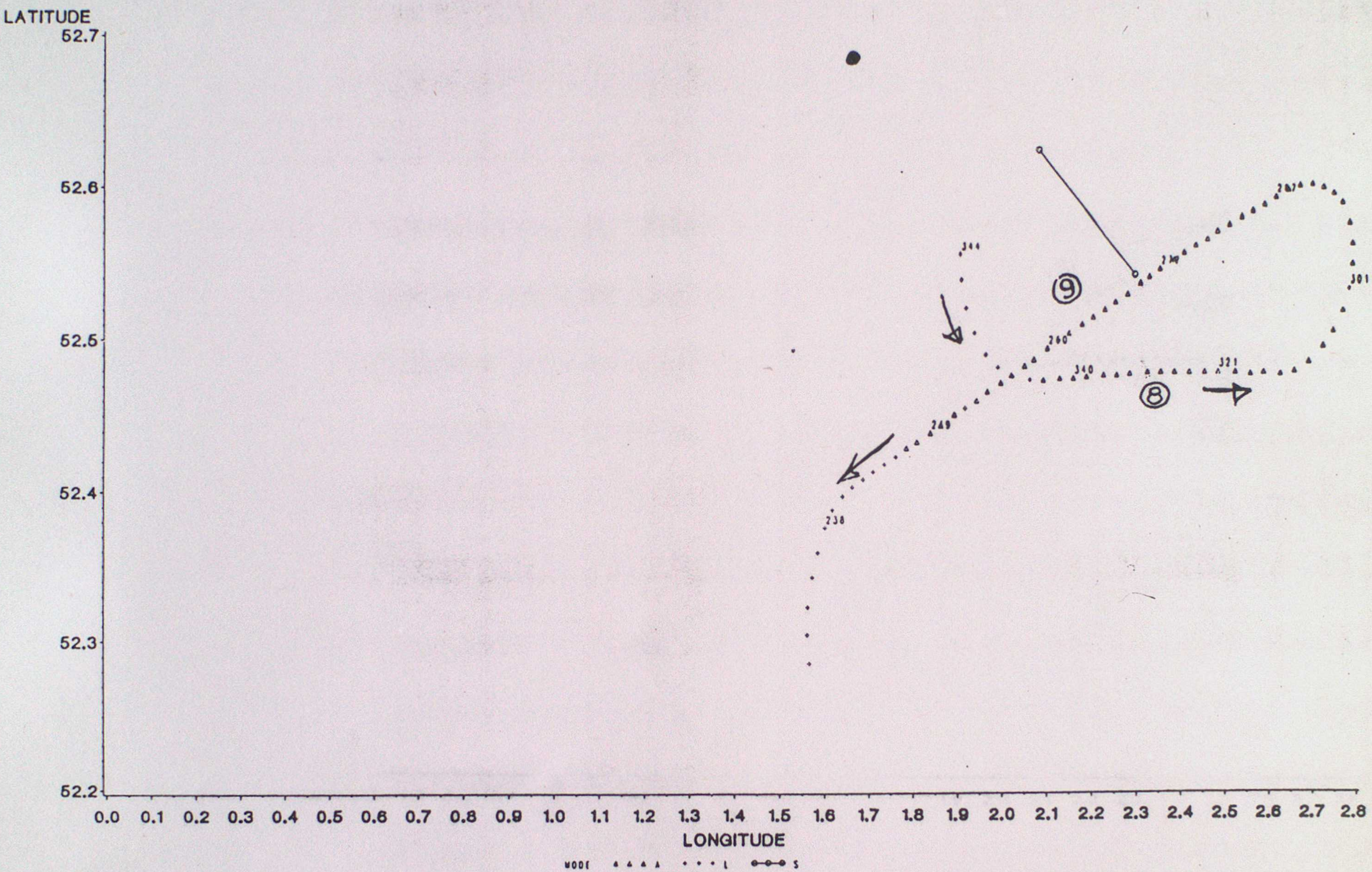
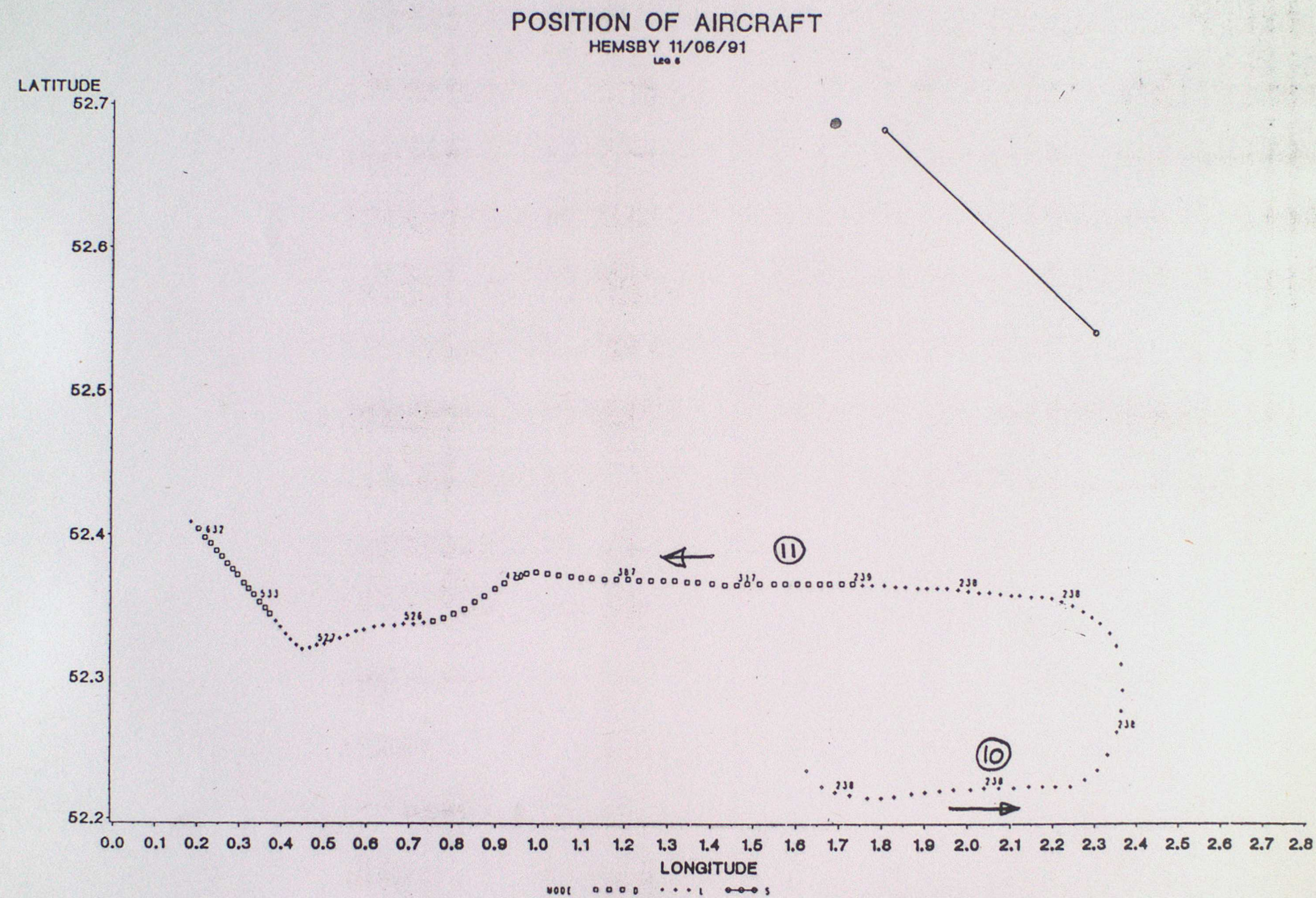
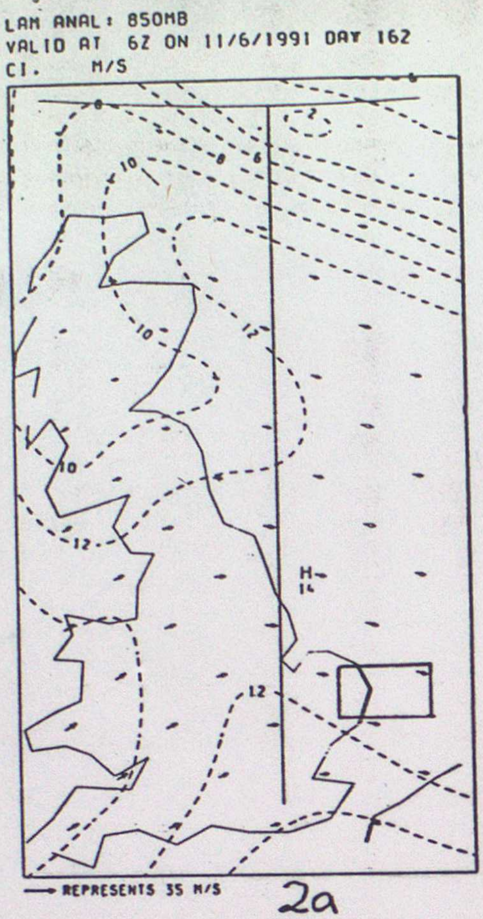


Figure 1d

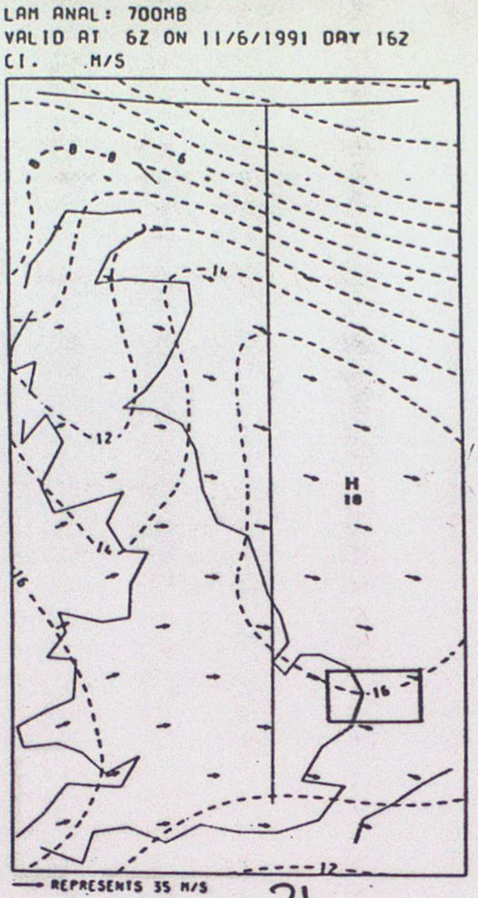


POSITION OF AIRCRAFT
HEMSBY 11/06/91
LATITUDE
52.7
52.6
52.5
52.4
52.3
52.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
LONGITUDE
11
10

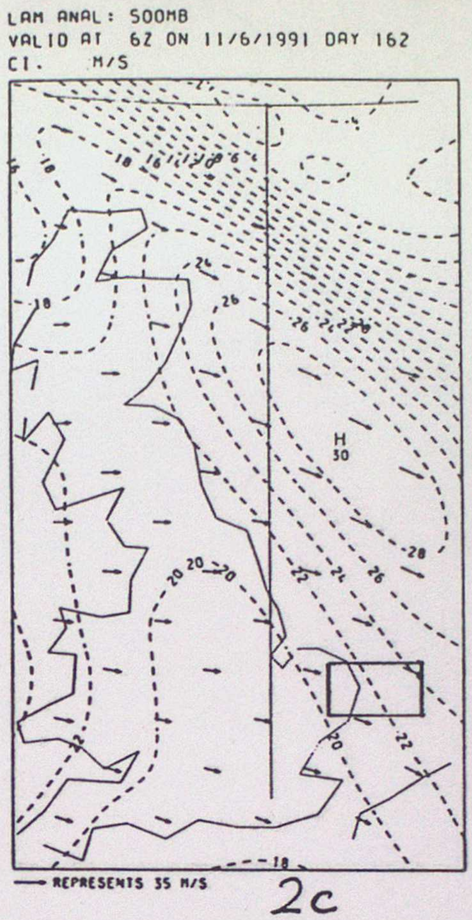
Figure 1e


LAM ANAL: 850MB
VALID AT 6Z ON 11/6/1991 DAY 162
CI. M/S
REPRESENTS 35 M/S

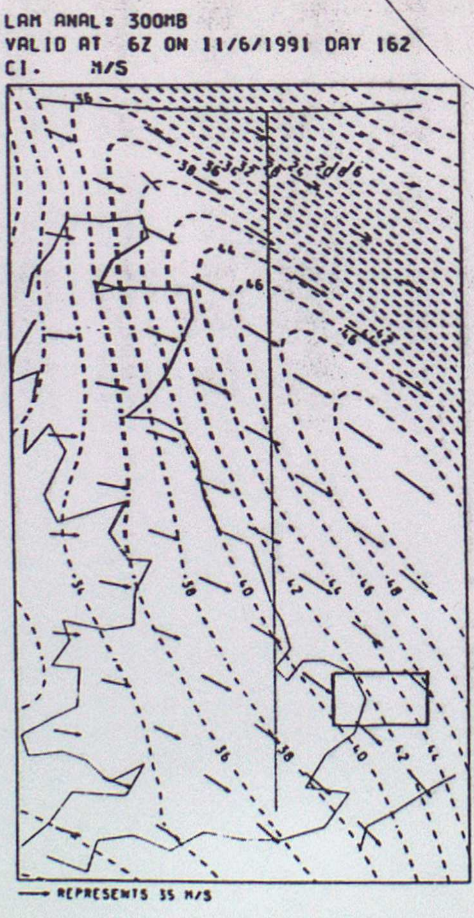
2a


LAM ANAL: 700MB
VALID AT 6Z ON 11/6/1991 DAY 162
CI. M/S
REPRESENTS 35 M/S

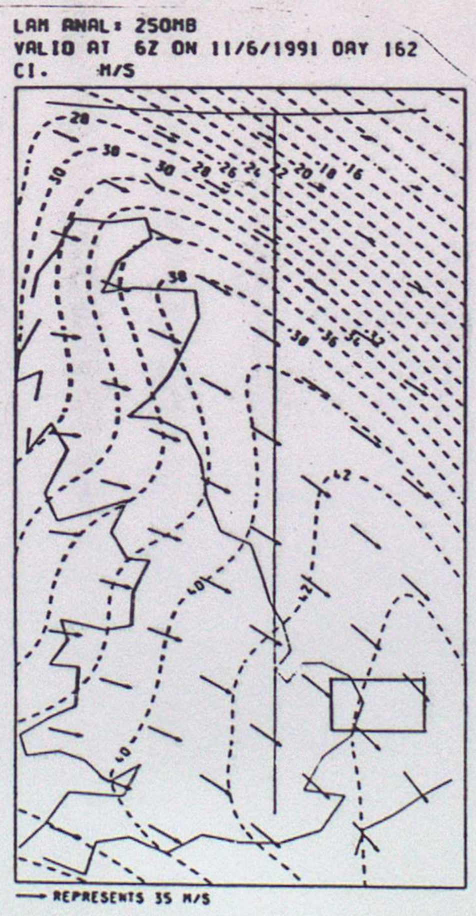
2b


LAM ANAL: 500MB
VALID AT 6Z ON 11/6/1991 DAY 162
CI. M/S
REPRESENTS 35 M/S

2c


LAM ANAL: 300MB
VALID AT 6Z ON 11/6/1991 DAY 162
CI. M/S
REPRESENTS 35 M/S

2d


LAM ANAL: 250MB
VALID AT 6Z ON 11/6/1991 DAY 162
CI. M/S
REPRESENTS 35 M/S

2e

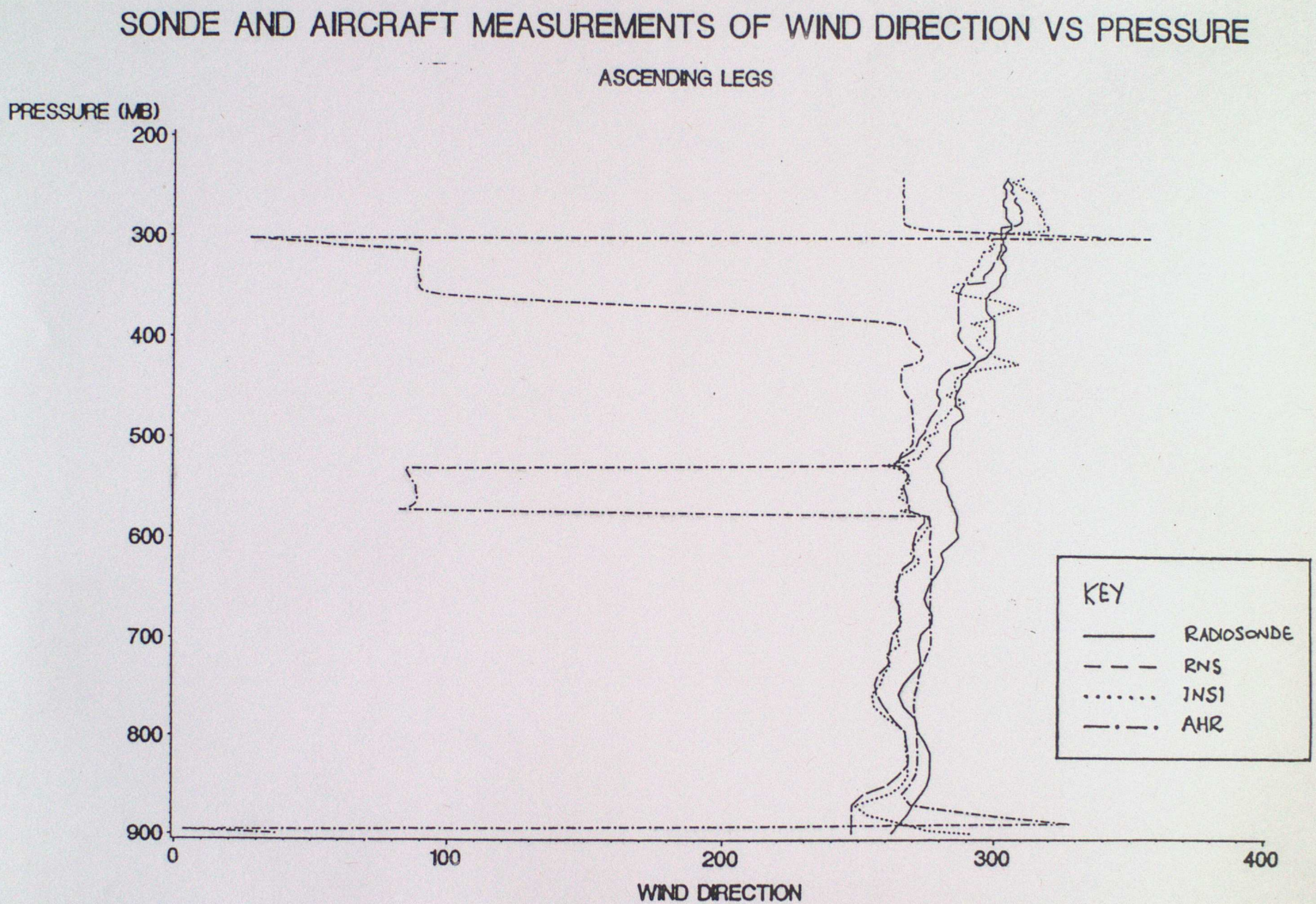

SONDE AND AIRCRAFT MEASUREMENTS OF WIND DIRECTION VS PRESSURE
ASCENDING LEGS
PRESSURE (MB)
200
300
400
500
600
700
800
900
0
100
200
300
400
WIND DIRECTION
KEY
RADIOSONDE
RNS
INS1
AHR

Figure 3a

SONDE AND AIRCRAFT MEASUREMENTS OF WIND SPEED VS PRESSURE

ASCENDING LEGS

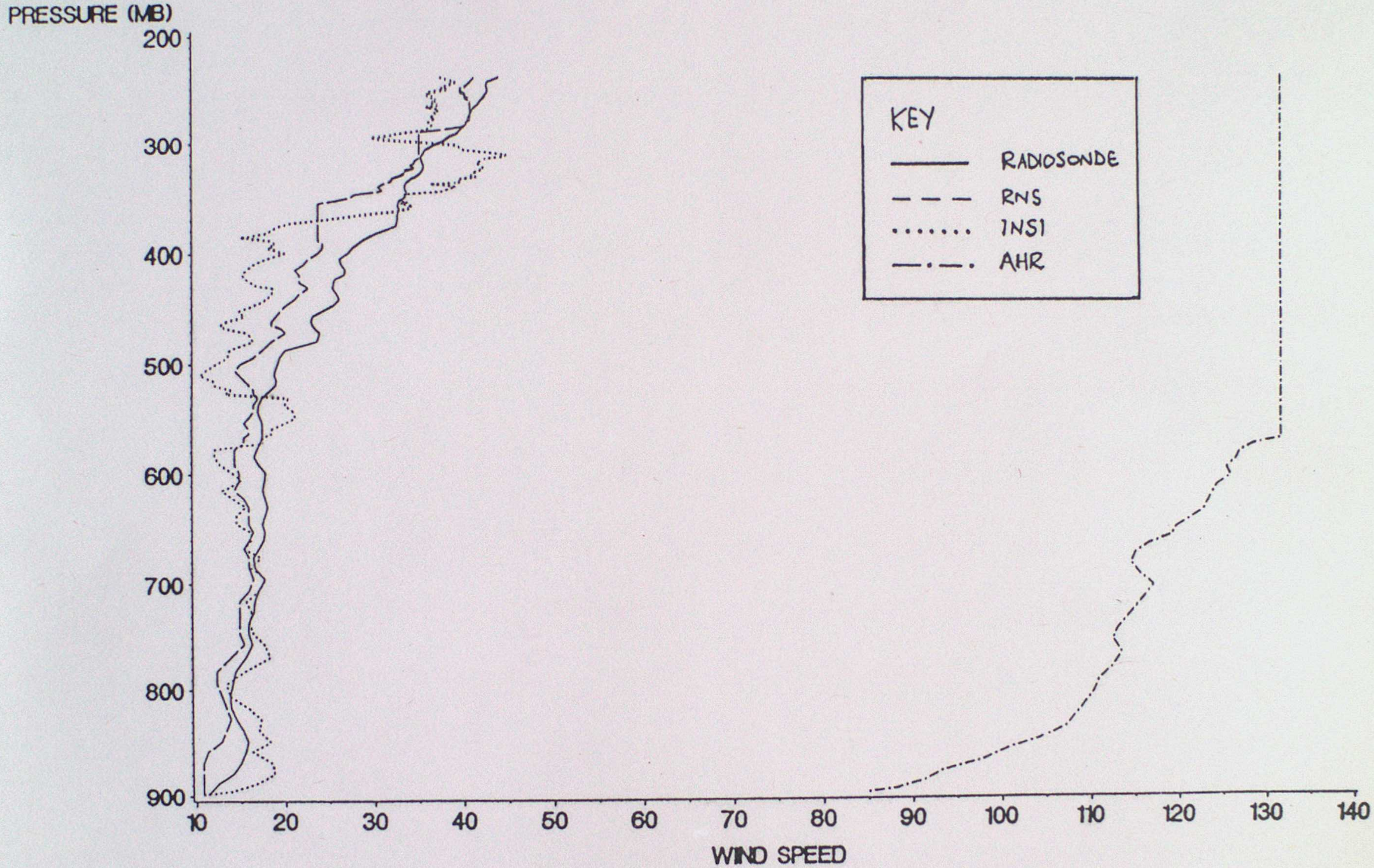


Figure 3b

SONDE AND AIRCRAFT MEASUREMENTS OF WIND DIRECTION VS PRESSURE

ASCENDING LEGS

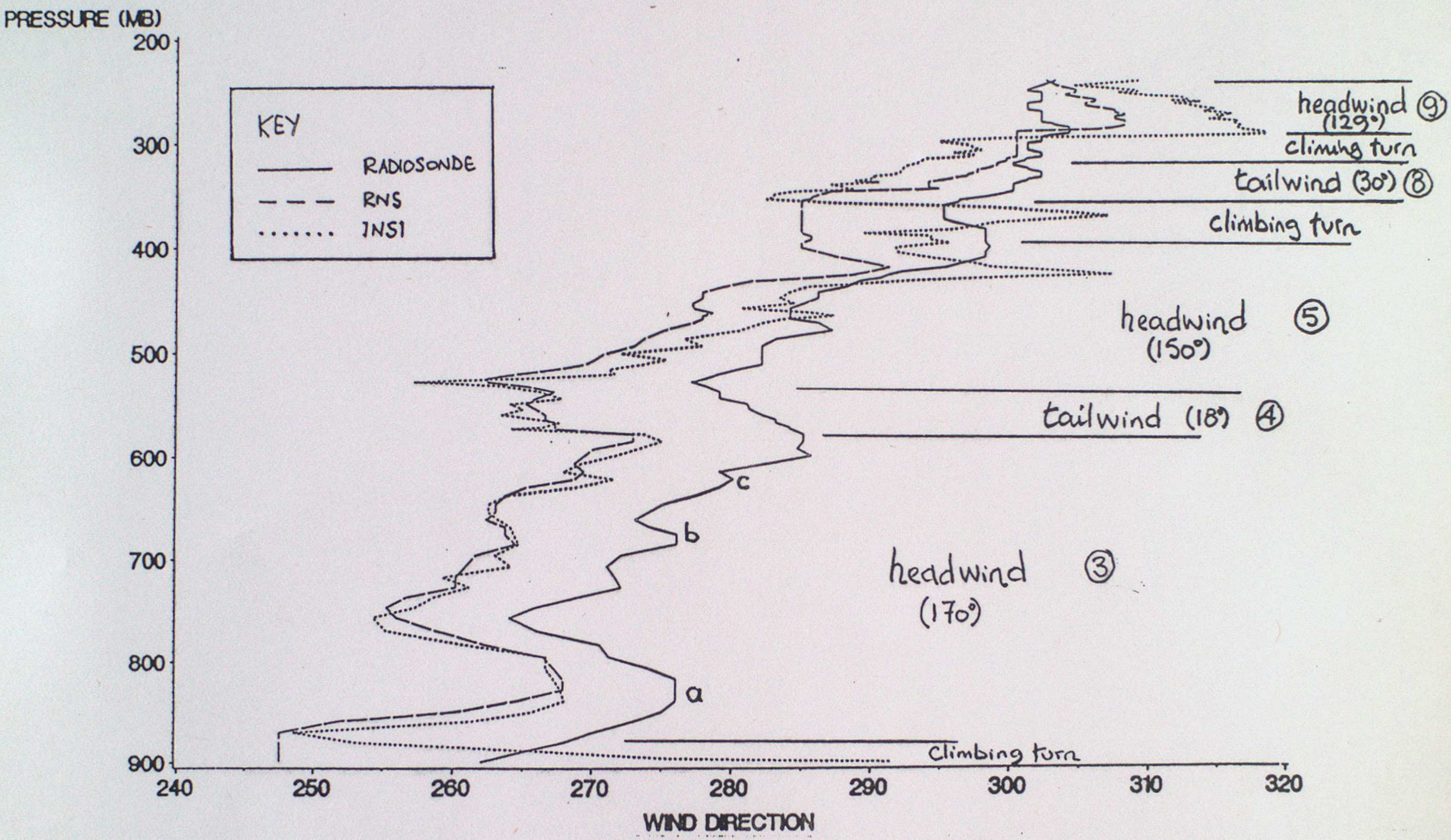


Figure 4a

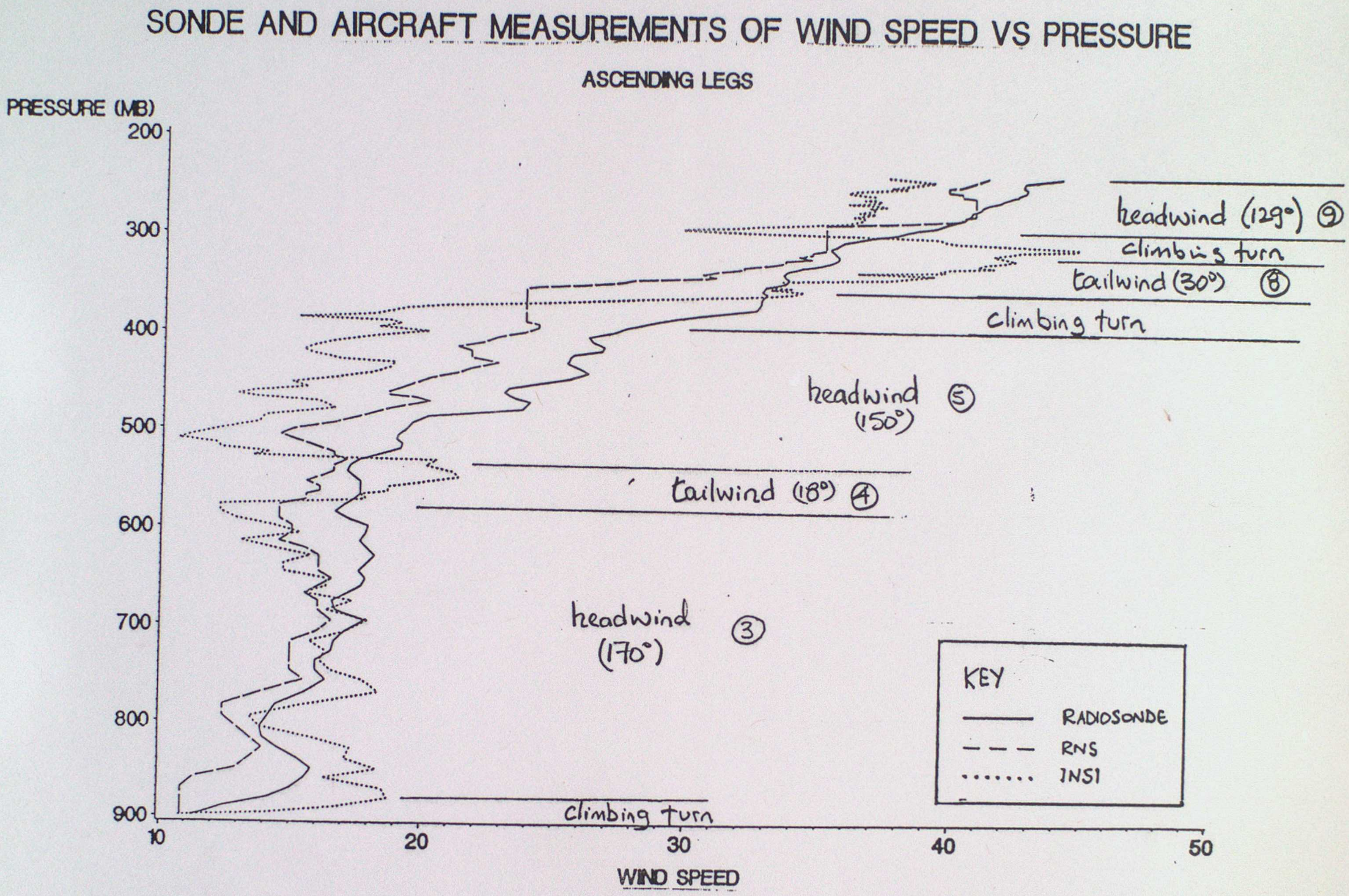

SONDE AND AIRCRAFT MEASUREMENTS OF WIND SPEED VS PRESSURE
ASCENDING LEGS
PRESSURE (MB)
200
300
400
500
600
700
800
900
10
20
30
40
50
WIND SPEED
headwind (129°) 9
climbing turn
tailwind (30°) 8
climbing turn
headwind (150°) 5
tailwind (18°) 4
headwind (170°) 3
climbing turn
KEY
RADIOSONDE
RNS
INS1

Figure. 4b

AIRCRAFT TRACK VS PRESSURE

(ASCENT)

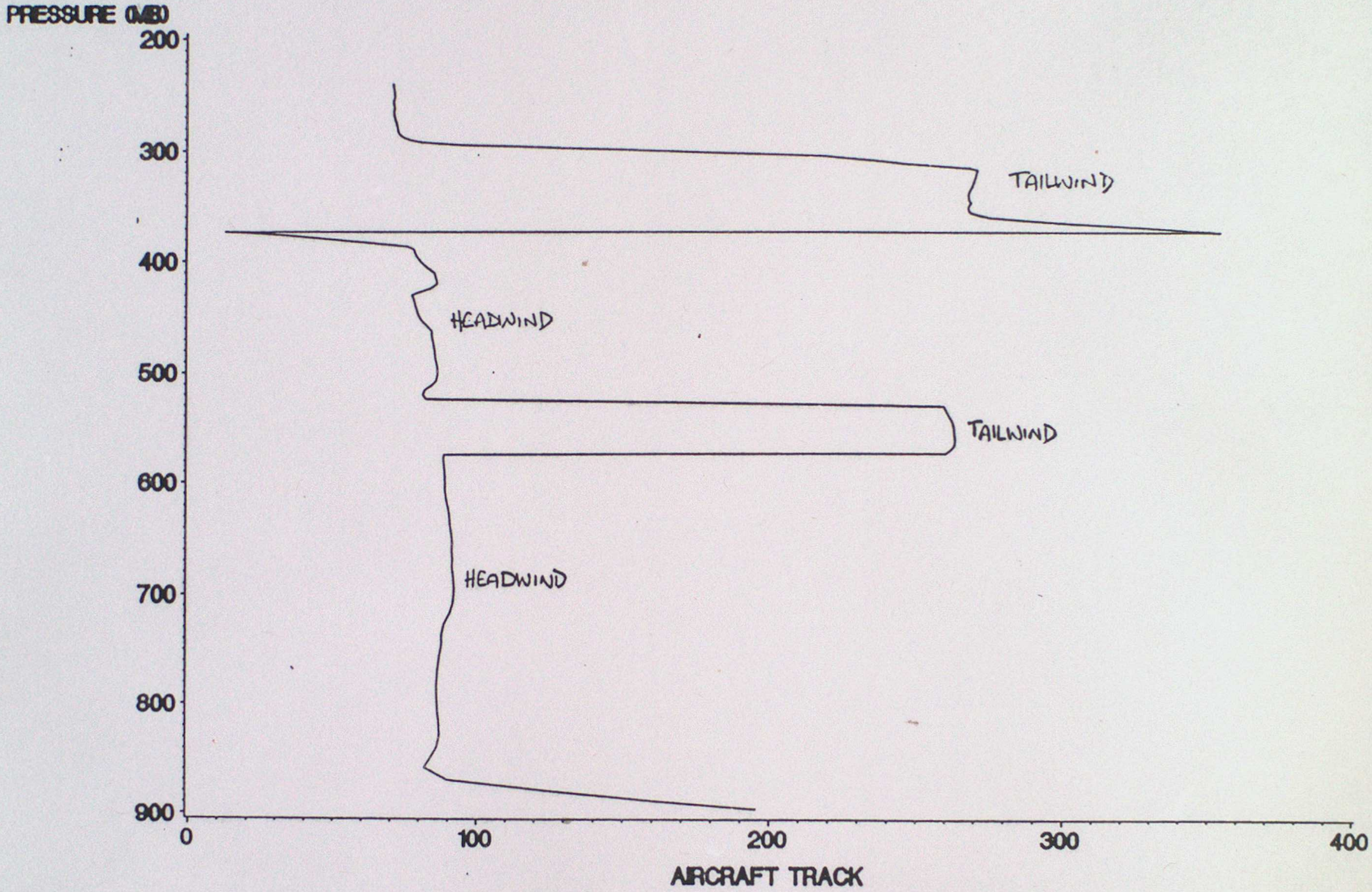


Figure 5a

AIRCRAFT ROLL VS PRESSURE

(ASCENT)

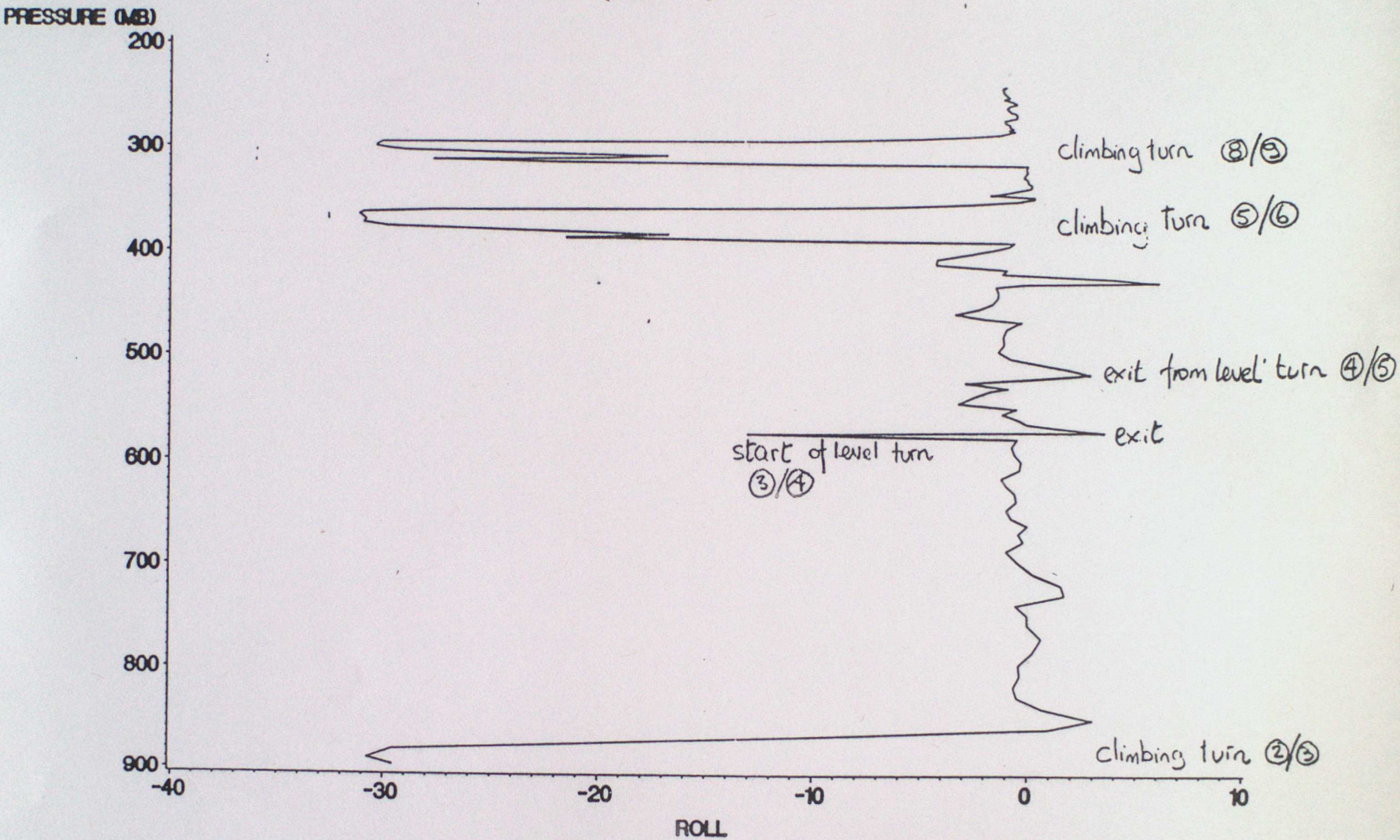
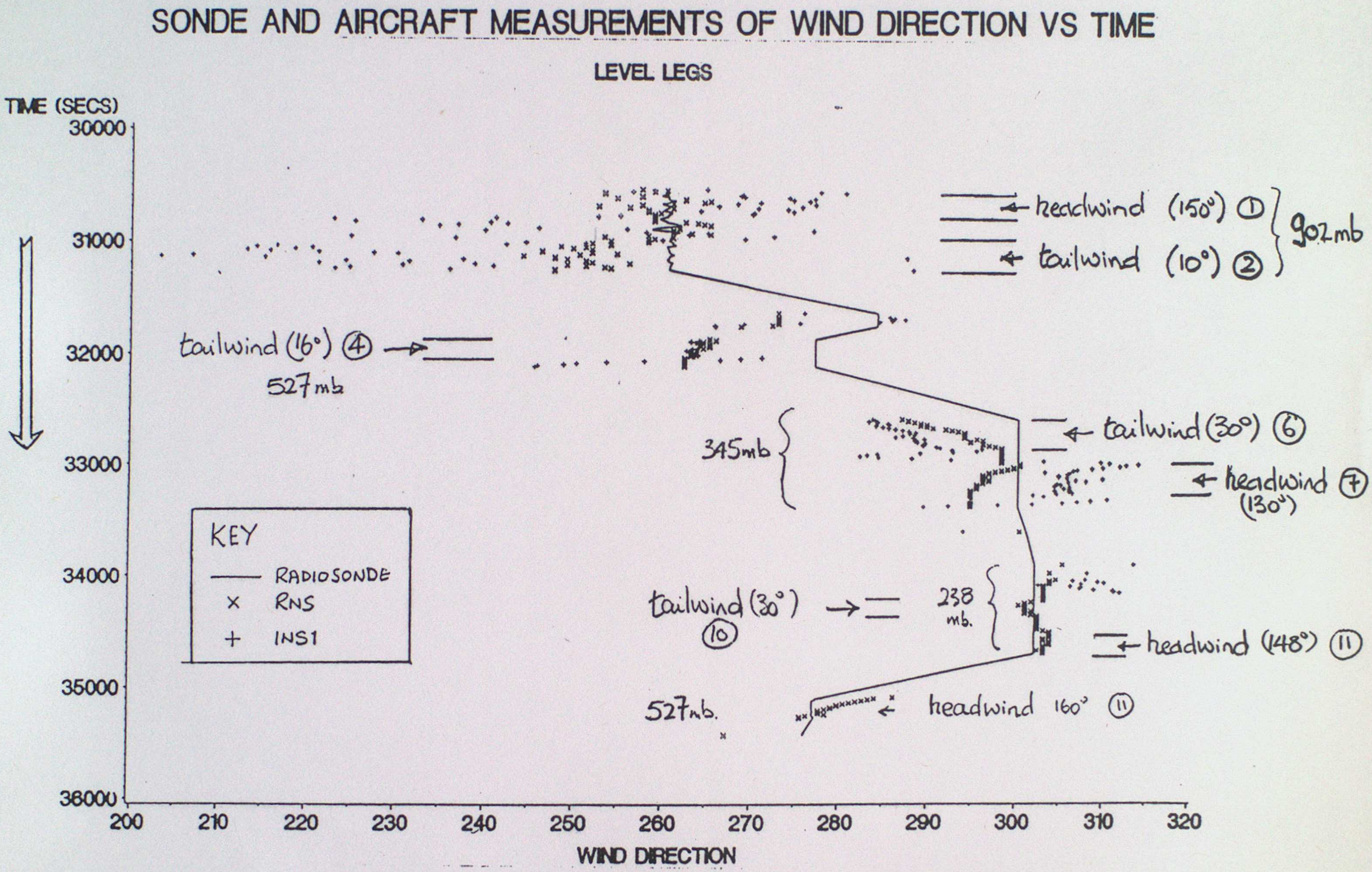


Figure 5b



SONDE AND AIRCRAFT MEASUREMENTS OF WIND DIRECTION VS TIME
LEVEL LEGS
TIME (SECS)
30000
31000
32000
33000
34000
35000
36000
200
210
220
230
240
250
260
270
280
290
300
310
320
WIND DIRECTION
headwind (150°) 1
tailwind (10°) 2
902mb
tailwind (16°) 4
527mb
tailwind (30°) 6
345mb
headwind 7 (130°)
KEY
RADIOSONDE
× RNS
+ INS1
tailwind (30°) 10
238 mb.
headwind (148°) 11
527mb.
headwind 160° 11

Figure 6a

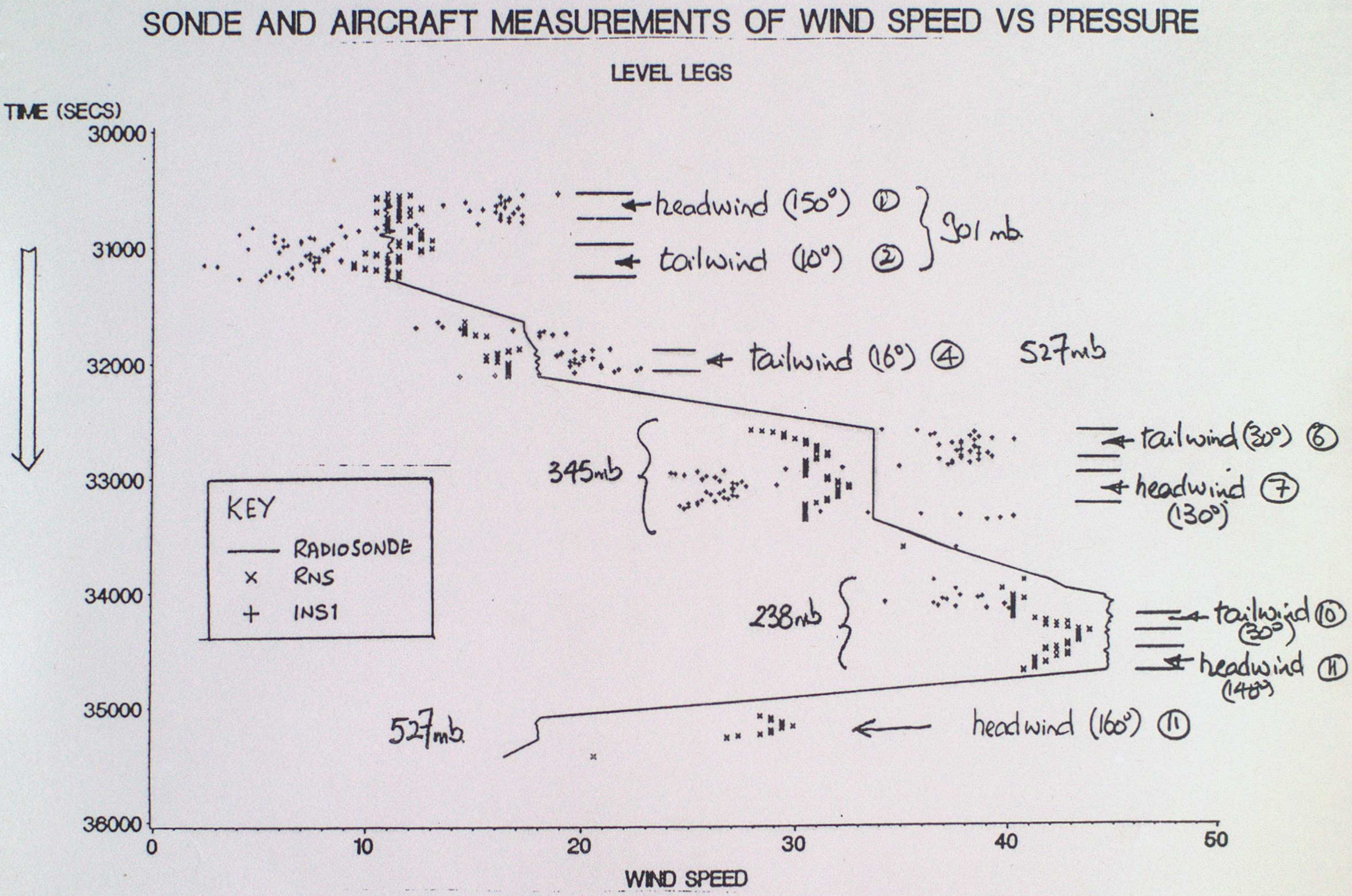

SONDE AND AIRCRAFT MEASUREMENTS OF WIND SPEED VS PRESSURE
LEVEL LEGS
TIME (SECS)
30000
31000
32000
33000
34000
35000
36000
0
10
20
30
40
50
WIND SPEED
headwind (150°) 1
tailwind (10°) 2
901 mb.
tailwind (16°) 4
527mb
345mb
tailwind (30°) 6
headwind (130°) 7
238mb
tailwind (30°) 10
headwind (140°) 11
527mb.
headwind (160°) 11
KEY
RADIOSONDE
× RNS
+ INS1

Figure 6b

DIFFERENCE BETWEEN AIRCRAFT AND SONDE TEMPERATURE MEASUREMENTS

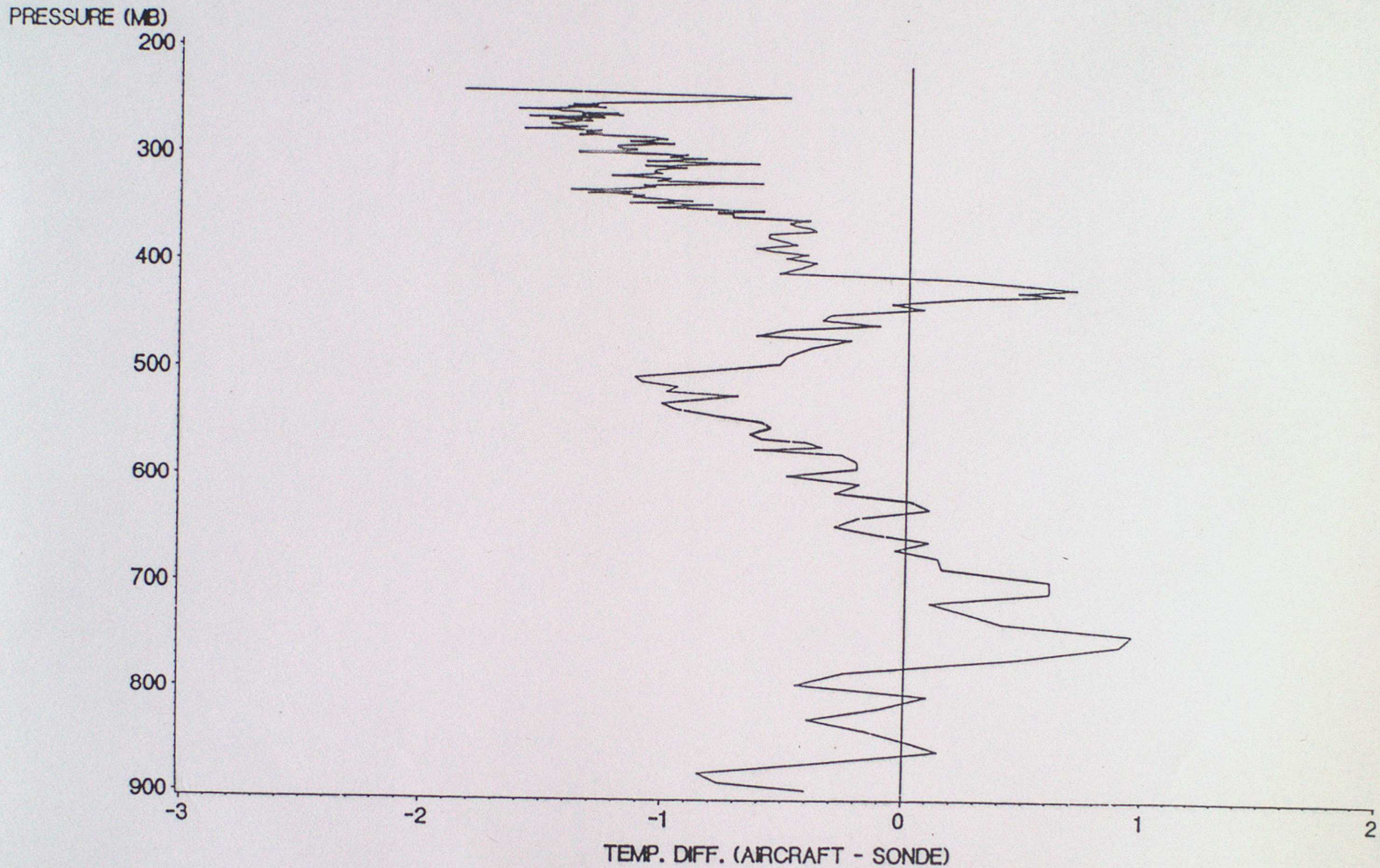


Figure. 7

Sonde converted to meters.

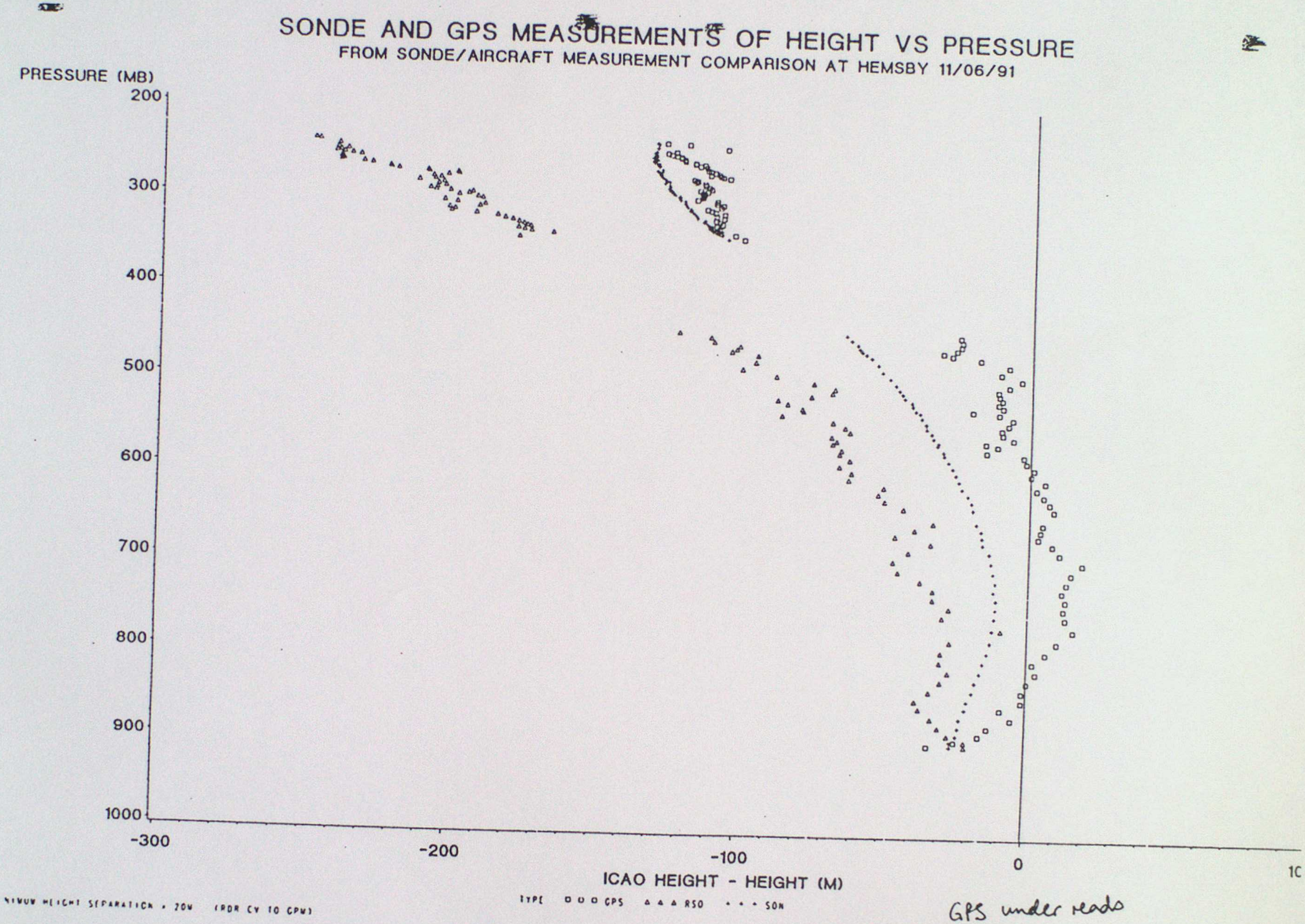


Figure 8

	RNS		INS1	
	head	tail	head	tail
Level				
902mb	-1.23	-5.72	9.60	-25.60
528mb	-	-12.93	-	-13.36
344mb	-3.13	-7.27	6.88	-12.94
238mb	1.33	-0.79	6.57	-
Ascending				
902 - 573mb	-11.34	-	-10.24	-
573 - 528mb	-	-14.88	-	-15.66
527 - 344mb	-9.58	-11.13	-2.90	-14.75
344 - 238mb	4.04	-4.24	10.83	-10.08

Table 1: Mean aircraft-radiosonde difference: wind direction

	RNS		INS1	
	head	tail	head	tail
Level				
902mb	0.45	0.47	5.30	-3.74
528mb	-	-1.69	-	1.89
344mb	-1.97	-3.34	-7.22	4.15
238mb	-3.09	-2.44	-6.46	-
Ascending				
902 - 573mb	-1.77	-	-0.85	-
573 - 528mb	-	-1.33	-	2.08
527 - 344mb	-3.97	-6.17	-8.32	0.93
344 - 238mb	-1.17	-1.79	-4.69	5.85

Table 2: Mean aircraft-radiosonde differences: wind speed.

Level	RNS head	RNS tail	INS1 head	INS1 tail
902mb	3.01	5.72	5.53	18.58
528mb	-	0.96	-	0.72
344mb	1.83	3.29	2.74	2.28
238mb	0.42	0.68	1.89	-
Ascending				
902 - 573mb	3.15	-	2.07	-
573 - 528mb	-	1.77	-	2.36
527 - 344mb	3.38	3.27	5.50	1.94
344 - 238mb	1.69	2.11	2.91	2.09

Table 3: Standard deviation of aircraft-radiosonde differences: wind direction

Level	RNS head	RNS tail	INS1 head	INS1 tail
902mb	0.53	0.83	1.09	1.50
528mb	-	0.45	-	0.69
344mb	0.59	0.98	0.96	1.24
238mb	0.82	1.09	0.98	-
Ascending				
902 - 573mb	0.88	-	2.30	-
573 - 528mb	-	0.65	-	1.51
527 - 344mb	0.88	1.95	1.64	1.73
344 - 238mb	1.13	0.77	0.97	1.10

Table 4: Standard deviation of aircraft-radiosonde differences: wind speed.

	u-comp				v-comp			
	RNS		INS1		RNS		INS1	
Level	head	tail	head	tail	head	tail	head	tail
902 $^{21}_{35}$	0.39	0.18	5.38	-5.18	0.30	1.11	-1.75	2.16
528 $^{00}_{16}$	-	-1.65	-	1.90	-	3.84	-	4.35
344 $^{27}_{27}$	-0.90	-1.25	-8.01	6.96	2.51	5.08	1.00	5.72
238 $^{22}_{13}$	-3.14	-1.76	-8.00	-	0.82	1.80	-0.11	-
Ascending								
902-573 $^{31}_{00}$	-1.76	-	-0.83	-	3.08	-	2.99	-
573-528 $^{00}_{09}$	-	-1.03	-	2.35	-	4.40	-	4.89
527-344 $^{29}_{05}$	-2.98	-3.41	-7.72	3.99	4.38	7.72	3.36	7.76
344-238 $^{31}_{15}$	-2.59	-0.40	-8.20	8.08	-1.73	3.01	-2.98	3.35

Table 5: Mean aircraft-radiosonde wind component differences.

	u-comp				v-comp			
	RNS		INS1		RNS		INS1	
Level	head	tail	head	tail	head	tail	head	tail
902 $^{21}_{35}$	0.58	1.01	1.09	1.72	0.54	0.97	1.57	2.04
528 $^{00}_{16}$	-	0.45	-	0.69	-	0.28	-	0.26
344 $^{27}_{27}$	0.66	0.45	1.28	1.20	0.96	1.93	0.93	1.52
238 $^{22}_{13}$	0.70	1.08	1.42	-	0.51	0.52	0.71	-
Ascending								
902-573 $^{31}_{00}$	0.84	-	2.10	-	0.92	-	0.70	-
573-528 $^{00}_{09}$	-	0.54	-	1.39	-	0.52	-	0.73
527-344 $^{29}_{05}$	1.06	1.68	1.65	1.41	1.30	2.00	1.45	1.62
344-238 $^{31}_{15}$	0.50	0.38	1.12	1.01	1.54	1.36	1.64	1.43

Table 6: Standard deviations of aircraft-radiosonde wind component differences.

	u-comp				v-comp			
	RNS		INS1		RNS		INS1	
	head	tail	head	tail	head	tail	head	tail
All 164 123								
Mean	-1.93	-0.90	-4.52	1.83	1.59	3.19	0.58	4.08
S.D.	1.40	1.21	5.22	5.45	2.35	2.19	2.84	2.21

Table 7: Mean and standard devations of aircraft-sonde wind component differences: all headwind and tailwind sectors.

	RNS		INS1	
	u-comp	v-comp	u-comp	v-comp
All (287)				
Mean	-1.49	2.28	-1.78	2.09
S.D.	1.41	2.41	6.17	3.11

Table 8: Mean and standard deviations of aircraft-radiosonde wind component differences: combined legs.

	RNS		INS1	
	u-comp	v-comp	u-comp	v-comp
Roll angle				
LT 5 (287)	2.05	3.32	6.42	3.75
GT 15 (92)	2.85	3.56	6.17	4.69
GT 25 (68)	2.99	3.70	5.65	5.11

Table 9: Rms aircraft-radiosonde wind component differences as a function of aircraft roll angle.

Forecasting Research Division Technical Reports

Forecasting Research Division Technical Reports

1.	ON THE TIME SAVING THAT CAN BE ACHIEVED BY THE USE OF AN OPTIMISED COURSE IN AN AREA OF VARIABLE FLOW	R.W. Lunnon A.D. Marklow September 1991
2.	Treatment of bias in satellite sea surface temperature observations	R.S.Bell August 1991
3.	FINITE DIFFERENCE METHODS	M.J.P. Cullen August 1991
4.	Representation and recognition of convective cells using an object-orientated approach	W.H. Hand 30th September 1991
5.	Sea-ice data for the operational global model.	C.P.Jones November 1991.
6.	Tuning and Performance of the Atmospheric Quality Control.	N.B. Ingleby. December 1991.
7.	More satellite sounding data - can we make good use of it?	R.S.Bell January 1992.
8.	WAM/UKMO Wind Wave model Intercomparison Summary Report	Heinz Gunther ECMWF Martin Holt UK Met Office January 1992
9.	Spin up problems of the UKMO Mesoscale Model and moisture nudging experiments	Akihide Segami JMA February 1992
10.	A comparison of 2nd generation and 3rd generation wave model physics	M.W. Holt B.J. Hall February 1992
11.	RETRIEVAL AND ASSIMILATION: SYSTEM CONSIDERATIONS	Andrew C Lorenc March 1992
12.	Detection of Precipitation by Radars in the UK Weather Radar Network	M. Kitchen P.M. Brown April 1992
13.	THE VALUE OF WIND OBSERVATIONS FOR WEATHER FORECASTING AND CLIMATE STUDIES	Andrew C Lorenc April 1992
14.	An investigation into the parameters used in the analysis scheme of the Mesoscale Model	G. Veitch B.J. Wright S.P Ballard May 1992
15.	THE VERIFICATION OF MESOSCALE MODEL FORECASTS OF LIQUID WATER CONTENT USING HELICOPTER REPORTS OVER THE NORTH SEA DURING WINTER 1991	M. Ahmed R.W Lunnon R.J. Graham May 1992

Forecasting Research Division Technical Reports

16.	Simulations of the Diurnal Evolution of Marine Stratocumulus Part I: The sensitivity of the Single Column Version of the Mesoscale Model to Changes in the Turbulence Scheme.	S.D.Jackson S.P. Ballard May 1992
17.	Simulations of the Diurnal Evolution of Marine Stratocumulus Part II: A Comparison of Radiation Schemes Using the Single Column Version of the Mesoscale Model.	S.D.Jackson S.P. Ballard May 1992
18.	Quantifying the low level windshear aviation hazard for the UK: some research proposals	R.J. Graham R.W. Lunnon May 1992
19.	WAM/UKMO Wind Wave model Intercomparison Part 2 Running the UKMO wave model at higher resolution	M.W. Holt April 1992
20.	Sensitivity of Mesoscale Model forecasts of anticyclonic Statocumulus to the specifications of initial conditions and Boundary Layer mixing scheme.	B.J. Wright S.P. Ballard July 1992
21.	Evaluation of diffusion and gravity wave changes in the Global Forecast Model.	F. Rawlins O. Hammon 16 June 1992
22.	Background Errors for the Quality Control and Assimilation of Atmospheric Observations in the Unified Model - the situation in July 1992.	C.A. Parrett July 1992
23.	Estimation of the Mean and Standard Deviation of the Random Component of Data also Containing Non- random Errors.	B.R. Barwell July 1992
24.	Experiments in Nowcasting convective rain using an object- oriented approach.	W.H. Hand 15th August 1992
25.	Gravity Wave Speeds from the Eigenmodes of the Unified	I. Roulstone 28 July 1992
26.	A re-calibration of the Wave Model	M.W. Holt August 1992
27.	Evaluation of Koistinen's method of radar range and bright band correction	A.G. Davies August 1992
28.	A Study of the Boundary Layer in the Mesoscale Unified Model	Graham Veitch August 21,1992
29.	Profiles of wind using time-sequences of absorption channel imagery from geostationary satellites: proof of concept using synthetic radiances	R.W.Lunnon September 1992
30.	AN EMPIRICAL INVESTIGATION OF THE "WATER VAPOUR TEMPERATURE LAPSE-RATE FEEDBACK" TO THE GREENHOUSE EFFECT	K.F.A. Smith R.J. Allam J.S.Foot September 1992
31.	Observation needs for operational ocean modelling	S.J. Foreman September 1992

Forecasting Research Division Technical Reports

32.	Bright band correlations for layered precipitation; the comparison of Chilbolton radar data and Hardaker model output.	A.G. Davies November 1992
33.	Progress and performance of the operational mesoscale model	S.P. Ballard
34.	Assessment of the bias of significant wave height in the Met.Office global wave model	S.J. Foreman M.W. Holt S. Kelsall
35.	STUDY OF CIRRUS CLOUD WINDS: ANALYSIS OF I.C.E DATA FINAL REPORT FOR EUMETSAT CONTRACT ITT 91/16	R.W. Lunnon D.A. Lowe J.A. Barnes I. Dharssi December 1992
36.	Revisions to the operational data assimilation-Nov.92	R.S. Bell January 1993
37.	A comparison of wind observations from a flight of the DRA(B)BAC 1-11 research aircraft over Hemsby, 11 June 1991, with observations from the Hemsby radiosonde	R.J. Graham January 1993
38.	The Moisture Observation Pre-processing System	B.J. Wright January 1993
39.	Performance of the data assimilation scheme in the operational trial of the new mesoscale model.	B. Macpherson B.J. Wright A.J. Maycock January 1993
40.	Development and performance of the new mesoscale model.	S.P. Ballard B. Robinson January 1993