Numerical Weather Prediction

Accuracy of forecasts of geopotential height in the proposed European Civil Aviation Conference (ECAC)

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ACCURACY OF METEOROLOGICAL MODEL

IN THE PROPOSED ECAC HMU AREAS

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1. INTRODUCTION

This document describes the study undertaken by the United Kingdom Meteorological Office (UKMO) into the determination of the accuracy of the meteorological model in the areas covered by the proposed HMU sites within the ECAC area, namely Nattenheim, Oyonnax, Linz and Sollenau. The area of coverage is assumed to be a square 90nm by 90nm (about 165km by 165km) centred on the HMU site.

The report covers three topics. Firstly, an investigation into the accuracy of the T+0 (0 hour) and T+3 (3 hour) forecasts from the Limited Area Model (LAM) verified using radiosondes. Secondly, an investigation into the occurrence of mountain waves and turbulence in the proposed HMU areas. Thirdly, a recommendation is made on the use of Numerical Weather Prediction (NWP) model forecast height data over the proposed HMU areas.

2. RADIOSONDE VERIFICATION

Comparisons are carried out with reference to Aberporth (Wales) (52°08′N 04°34′W) (134 metres altitude) which has already been the subject of an exhaustive study (Ref 1)

(i) NATTENHEIM

Nattenheim (Germany) (50°01′N 06°32′E) is about 30km north of Trier.

The nearest radiosonde stations are:

- St Hubert (Belgium) (50°02′N 05°24′E) (557 metres) in the Ardennes is about 80km to the west.
- Nancy (France) (48°41′N 06°13′E) (217 metres) is about 140km to the south.
- Stuttgart (Germany) (48°50′N 09°12′E) (315 metres) is about 230km to the south-east.

(ii) OYONNAX

Oyonnax (France) (46°17′N 05°40′E) is about 35km to the west of Geneva.

The nearest radiosonde stations are:

- Lyon (France) (45°44′N 05°05′E) (240 metres) is about 90km to the south-west.
- Payerne (Switzerland) (46°49′N 06°57′E) (491 metres) is about 120km to the north-east near Fribourg.

(iii) LINZ

Linz (Austria) (48°14′N 14°06′E) is on the Danube.

The nearest radiosonde stations are:

- Wien (Austria) (48°15′N 16°22′E) (200 metres) is about 150km to the east.
- Praha (Czech) (50°00′N 14°27′E) (304 metres) is about 180km to the north.
- München (Germany) (48°15′N 11°33′E) (489 metres) is about 200km to the west.

(iv) SOLLENAU

Sollenau (Austria) (47°53′N 16°17′E) is 35km to the south of Wien near Wiener Neustadt.

The nearest radiosonde station is:

- Wien (Austria) (48°15′N 16°22′E) (200 metres) is about 40km to the north.

(v)

Other radiosonde stations in the vicinity of the Alps are:

- Hohenpeissenberg (Germany) (47°48′N 11°01′E) is at an altitude of 986 metres near Garmisch-Partenkirchen on the northern fringe of the Alps.
- Milano (Italy) (45°26′N 09°17′E) (103 metres) is about 100km to the south of Alpine peaks in excess of 3,000 metres.
- Udine (Italy) (46°02′N 13°11′E) (94 metres) is about 50km to the south of Alpine peaks in excess of 2,000 metres.

Radiosonde and LAM model forecast data were extracted from the Observation Processing Database (OPD) for the above 12 radiosonde stations, for 12 months (July 1996 to June 1997), for 4 times of day (00, 06, 12 and 18 UTC), and for 3 pressure levels (300, 250 and 200 hPa, approximately flight levels FL 300, 340 and 390). Almost 30,000 radiosonde measurements were used to generate statistics of mean and standard deviation (SD) of the radiosonde measurements, and the mean, root mean square (RMS) and standard deviation (SD) of the radiosonde (called observation, O) minus forecast differences for 0 hour forecasts (called analysis, A, hence O-A differences) and for 3 hour forecasts (called background, B, hence O-B differences).

Note that the (O-A) and (O-B) differences are calculated only at radiosonde times (ie 00, 06, 12 or 18 UTC) at which times an analysis and a background are both available. For example, the analysis at 12 UTC has made use of the radiosonde observations made at 12 UTC. However, the background valid at 12 UTC is a 3-hour forecast based on the analysis made at 09 UTC and is therefore independent of the radiosonde observations made at 12 UTC. Because of the lack of radiosonde observations at 09 UTC, the analysis at 09UTC is based almost entirely on the background valid at 09UTC which itself is a 3-hour forecast based on the analysis made at 06 UTC. Thus the background valid at 12 UTC is almost the same as the 6-hour forecast based on the analysis at 06 UTC.

These statistics were produced on a monthly basis for each radiosonde station, for each month, for each time of day, and for each level. However, the statistics were also summarised in various ways by accumulating results over all radiosonde stations and/or over all months and/or over all times of day and/or over all levels.

A few problems were encountered with the data. Some corrupt measurements from the Udine radiosonde had to be removed (200 hPa at 06 UTC in August 1996 and 250 hPa at 12 UTC in January 1997). Four months of data were missing from Nancy (Jul 1996, Feb, May, Jun 1997), and three months were missing from Praha (Feb, Mar, Apr 1997). Whilst some stations routinely report 4 times a day at 00, 06, 12 and 18 UTC (Aberporth, Praha, Udine and Milano), others routinely report 2 times a day at 00 and 12 UTC (Nancy, Lyon, Stuttgart and München). Payerne and Wien report mainly at 00 and 12 UTC, and sometimes at 06 and 18 UTC. St Hubert reports at 06 and sometimes 18 UTC. Hohenpeissenberg reports only (and only sometimes) at 06 UTC.

Consider firstly the overall accumulated statistics for all stations, all months, all hours, and all levels.

		Mean		SD	
O		10467.3 m	34341.1 ft	130.3 m	427.5 ft
O - B		1.6 m	5.2 ft	14.6 m	47.9 ft
O - A		3.4 m	11.2 ft	13.7 m	44.9 ft
No of obs	=	29966			

Thus the mean forecast errors are small (5 or 10 feet), but the standard deviation of the forecast errors approach 50 feet. The 0 hour forecast error (O-A) has a slightly smaller SD (45 feet), but a slightly larger mean (11 feet) than the 3 hour forecast error (O-B) (48 feet and 5 feet respectively). The positive sign of the mean error implies that the model forecast heights are slightly lower than the radiosonde heights, in other words, the model forecast temperatures are slightly colder than the radiosonde measured temperatures. It should be remembered that both forecast model heights and radiosonde heights are geopotential heights and are calculated from forecast model temperatures and radiosonde measured temperatures respectively.

Figures 1(a),(b),(c),(d) show the variations of the mean errors and the SD errors of (O-B) and (O-A) as a function of hour, level, month, and station respectively.

Figure 1(b) shows a slight increase in the SD errors by about 3 feet between 300 hPa (FL300) and 200hPa (FL390). The mean errors have a slight peak at 250hPa (FL340). The total number of observations at 300, 250 and 200 hPa are 10023, 9982 and 9961 respectively.

Figure 1(a) shows a decrease (from positive towards negative values) in the mean error through the daytime, but a small increase in the SD error. This suggests that the adjustments applied to the radiosonde measurements to take account of solar heating are not quite correct. The total number of observations at 00, 06, 12 and 18 UTC are 9803, 5365, 9648 and 5150 respectively.

Figure 1(c) shows some variation in both the mean error and the SD error throughout the year. The SD error displays peaks in July and November 1996 and March 1997. The mean error (O-A) is reasonably flat, but the mean error (O-B) diverges from (O-A) in the summer months. The total number of observations in each month ranges from 2109 in Feb 97 to 2716 in Dec 96.

Figure 1(d) shows considerable variation in the mean error and some variation in the SD error from station to station. Aberporth, Stuttgart and Hohenpeissenberg have mean errors very close to zero, whereas Payerne, Nancy and Praha have rather large positive mean errors, and Udine has a significant negative mean error. The SD errors are less variable with Praha and Lyon having the smallest, and Stuttgart and Hohenpeissenberg the largest. The total number of observations for each station ranges from 321 for Hohenpeissenberg to 4333 for Aberporth.

Figure 2 shows plots against months for each station individually. This allows the identification of problems in specific months at particular stations. Note that the vertical scales run from -15m to +35m.

Aberporth has larger than average SD errors in Oct 96 and Feb 97. During both these months the weather pattern was particularly changeable with strong winds leading to larger than normal errors in the forecasts.

St Hubert has a dramatically large SD error in Jul 96. Examination of the data suggests that this is most likely to have been caused by corruption of the data from one or more of the 18 UTC radiosonde reports. The SD error for 06 UTC in this month is about 14m.

Payerne has large mean errors in Feb, Mar and Apr 97. Possible contributory factors are: firstly, Payerne radiosonde exhibits a large radiation adjustment factor which may need to be revised, and secondly, there was some irregularity in the availability/use of Payerne radiosonde data at 06 and 18 UTC and this could be biasing some of the results.

Nancy displays fairly consistent errors throughout the year (although four months are missing), but with a large positive mean error.

Lyon is less consistent with the mean error decreasing from positive to negative values through the year. The SD error also decreases slightly through the year.

Stuttgart has a peak SD error in Nov 96 and Mar 97. In both months the radiosonde heights were more variable than usual (SD of Os about 200m), and this due to changeable weather patterns./suggesting corruption of some of the data.

München also has a peak SD error in Nov 96 and a small peak in Mar 97, with corresponding higher SD of Os. Changeable weather pattern.

Hohenpeissenberg has considerable variability with a particularly large peak in SD error in May 97. This may be due partly to changeable weather patterns, and partly to the relatively small number of radiosonde observations.

Wien displays a peak in the mean errors in Feb, Mar and Apr 97 but fairly steady SD errors. This is attributable to the characteristics of the radiosonde data because 06 and/or 18 UTC data was available only during those months. Apart from Jul 96, the SD errors are very constant.

Praha displays fairly constant errors, the SD being quite small, but the mean being quite large and positive.

Udine also displays fairly constant errors, with the mean error being negative.

Milano displays considerable variation in the mean error throughout the year (positive in winter, negative in summer)

Figures 3, 4, 5, 6 show results similar to Figure 2, but for the individual hours 00, 06, 12 and 18 UTC. These show considerable variation during the day at individual sonde stations. As with Aberport (Ref 1) this is mainly attributable to variations in the characteristics of the radiosondes and in particular to the effect of solar heating which is a maximum at midday. However, the possibility of a contributary effect from the NWP model due to the diurnal oscillation cannot be entirely ruled out.

Conclusions. It is concluded that there is some variability in both mean errors and SD errors at different radiosonde stations, but that this variability is not obviously linked to mountainous features. Much of the variability can be attributed either to problems with the radiosonde measurements or to changeable weather patterns.

The mean errors vary much more from station to station than do the SD errors. However, at least part of this mean error is attributable to local radiosonde characteristics, in particular to uncertainty in the solar heating adjustment factor.

Apart from an excursion up to +20m at Payerne in Spring 97, the monthly mean errors for the individual sonde stations all lie between +15m and -10m (and mostly lie between +10m and -5m) with an average of +2.5m.

The monthly SD errors are rarely less than 10m, but generally (after removal of the extreme peaks) do not exceed 20m, and indeed are less than 15m during most months at most stations.

3. WEATHER

Three phenomena which may have an influence on aircraft within the HMU areas are:

- Mountain waves
- Clear air turbulence
- Convective turbulence

3.1. MOUNTAIN WAVES

A literature survey was undertaken to examine the evidence for the known occurrence of mountain waves in the upper troposphere and/or lower stratosphere in the vicinity of the HMU areas.

Queney (Ref 2) describes early observations and the theory of mountain waves. He also discusses flying aspects and points out that, if aircraft are not flying on autopilot, or if the autopilot is not able to maintain a constant flight level, then the motion of aircraft flying in opposite directions will be out of phase with each other.

The Alpine Experiment (ALPEX) was an international collaboration carried out during March and April 1982 covering the Alps, Pyrenees and Balkans. (See Refs 3 and 4.) Stankov (Ref 5) found that there were few occasions of lee waves over the Alps during ALPEX, and those that did occur were comparatively weak and confined to the lower and middle troposphere (up to about 9km = FL295). Hafner (Ref 6) found evidence of strong lee waves at both low levels (lower and middle troposphere) and at high levels (upper troposphere and lower stratosphere) over the Pyrenees. The high level waves had a wavelength of about 35km. Both Hoinka (Ref 7) and Cox (Ref 8) further analysed this event. Vertical velocities were 1 to 3m/s.

Using a set of 3 wind profilers during April-May 1982 in the Rhone delta, Ecklund et al (Ref 9) and Carter et al (Ref 10) provide evidence of wave motion in the troposphere (3.1-6.1km) and in the lower stratosphere (11.4-13.6km) on days when the Mistral wind is blowing from the north. The wavelengths of these waves range from 7 to 20kms, and the vertical velocities are 1 to 3m/s. However, most of the observed wave activity was restricted to the lower troposphere, and only occasionally did weak activity penetrate into the stratosphere.

Hoinka (Ref 11) and also Seibert (Ref 12) studied a foehn on 8 November 1982 which produced lee waves in the troposphere and lower stratosphere to the north of the Alps. The strongest waves were confined to levels below 6km, but a high level double wave with an amplitude of about 1km was observed at 12km (=FL390). According to Hoinka, these so-called “south foehns” occur on about 50 days a year when the wind is blowing across the Alps from a SW-ly direction. However, the one under study was described as “one substantially strong event of the last decade”. [The foehn is a warm and dry, but strong and gusty downslope wind.]

Tutis (Ref 13) describes a case of lee waves over the Dinaric Alps and the Carpathians on 22 October 1986, but these waves, which have a wavelength of 6-10km, are restricted to low levels (2-3km)

From the literature survey it is concluded that there is some evidence for the existence of mountain waves in the upper troposphere and lower stratosphere over the Alps. However, it seems likely that these are relatively infrequent events. Waves are more likely to occur in association with the Pyrenees, which, like the Sierre Nevada in the USA, forms a well-defined ridge.

Consultation. Because of the lack of knowledge of mountain wave activity, it was decided to consult expert meteorologists in the Alpine countries. A letter was sent to the Meteorological Services in four countries (Germany, France, Austria and Switzerland) requesting information on the local knowledge of the existence of wave activity in the upper troposphere and lower stratosphere.

Of the three replies received, Switzerland stated: “There is no doubt that mountain waves do occur in the alpine region several times a year and up to very high altitudes.” The reply from Austria was much more pessimistic and suggested that mountain wave activity could affect the upper troposphere and/or lower stratosphere up to 40 times a year with peaks in autumn (September to November) and spring (late February to mid April). The Linz HMU area would be affected in SW-ly flow and the Sollenau HMU area would be affected in W-ly flow. The reply from France stated that mountain waves caused by the Alps did occur, but that no detailed information was readily available.

Conclusions. There follows a short description of the likely situation at each of the HMU sites.

- Nattenheim

The highest peaks in the Ardennes to the west and the Eifel to the north are about 700 metres, whilst the Hunsruck to the south-east reach about 800 metres. Whilst these hills could produce lee wave activity in appropriate wind conditions, it is unlikely that these waves would penetrate into the upper airspace, but will be mostly confined to the lower levels.

- Oyonnax

Mont Blanc (4,807 metres) is about 100km to the south-east. The mountains in the Mont Blanc area form a “ridge” oriented NE-SW. In SE-ly winds mountain waves and possibly severe turbulence may affect at least the SE quadrant of the HMU area of coverage. However, winds blow from this direction only about 5% of the time, and these winds are sufficiently strong to produce waves (20 knots or more at mountain top) only about 1% of the time.

The Jura mountains form a “ridge” from Oyonnax towards the north-east, with peaks reaching 1,679 metres. In NW-ly winds mountain waves and turbulence could affect the eastern sector of the HMU area of coverage, whilst in SE-ly winds the northern sector could be affected. However, these waves and turbulence are likely to be far less intense than those caused by the Mont Blanc “ridge”.

- Linz

Mountain peaks in excess of 2,000 metres are within 70km to the south of Linz. Further afield are the Niedere Tauern with peaks up to 2,863 metres about 120km to the south of Linz. The Hohe Tauern with peaks up to 3,797 metres are about 180km to the south-west of Linz. In southerly, and possibly also SW-ly, wind conditions mountain wave activity could influence the southern part of the HMU area of coverage.

- Sollenau

Mountain peaks in excess of 2,000 metres are within 35km to the south-west of Sollenau. These peaks tend to form a “ridge” oriented roughly ENE-WSW. Thus winds from the directions around NNW or SSE might produce mountain wave activity, which could affect the SW quadrant of the HMU area of coverage. According to the meteorologist at Austro-Control, W-ly winds produce mountain wave activity which can reach Sollenau on occasions.

3.2. CLEAR AIR TURBULENCE

Clear air turbulence (CAT) occurs mainly in association with strong vertical wind shear and hence often close to jet streams. The vertical shears can be enhanced by the flow of air over mountains giving rise to an increased frequency and increased intensity of CAT over mountains.

Dutton (Ref 14) reports that, of the total distance flown by civil aircraft over both the N Atlantic and W Europe, about 10% is in light CAT, 1% is in moderate CAT, and 0.01% is in severe CAT. It is to be expected that the frequency of CAT over the HMU areas will be similar, but possibly slightly increased over mountainous areas.

CAT can occur at any time of year. However, the frequency is likely to be higher in winter due to the general increase in wind speed and hence wind shear.

Mountain waves may break to form moderate or severe turbulence.

3.3. CONVECTIVE TURBULENCE

Although convection can occur under favourable conditions at any time of year, deep convection reaching the tropopause is most likely over the continent in summer on an afternoon following intense solar heating. Instability in the air can easily be released by uplift over hills and mountains, particularly in association with fronts or troughs, producing convective cloud, rain, hail, thunder/lightning, icing and turbulence.

The annual frequency of thunderstorms reported at met stations is about 1% in all four of the HMU areas. In summer this increases to 2% in the Nattenheim and Sollenau areas, 2.5% in the Linz area, and 3% in the Oyonnax area. The corresponding figures for the Preseli area are 0.2% (annual) and 0.5% (summer).

4. USE OF FORECAST HEIGHTS OVER ENHANCED HMU AREA

Reference 1 recommended the use of a 9 point specification of forecast heights over the 90nm by 90nm enhanced area covered by the HMU. This should provide adequate information from current NWP models to allow the use of 4-point bilinear interpolation to any point within one of the four sub-areas defined by the 9 points.

Situations with strong height gradients (ie high wind speeds) should be catered for by this interpolation. There is an increased likelihood of error due to the strong gradient, but this can be dealt with by using a suitable confidence factor. The Met Quality Indicator (MQI) function developed for Preseli could be applied to the new HMU sites, on either a grid-point basis or an area basis.

It might be possible to extend the confidence factor to try to alert to likely mountain wave or turbulence situations. However, this would involve a detailed investigation.

Situations with a sharp change in wind direction (eg upper front or trough) should be covered satisfactorily by the 4-point bilinear interpolation, although 16-point bicubic interpolation might provide slightly better accuracy under certain circumstances. However, this would entail using a larger number of points eg 25 instead of 9, and boundary effects would necessitate extending the area of coverage outside the 90nm by 90nm area.

Note that the UKMO has recently enhanced its global NWP model (GM) by decreasing the horizontal grid length from about 90km (50nm) to about 60km (33 nm). Thus an enhancement of the previously recommended 9 points (45nm grid) to 16 points (30nm grid) might be justifiable, although a significant improvement in accuracy is not expected.

The Limited Area Model (LAM), which has a grid length of about 50km (26nm), will soon be discontinued. The Preseli forecasts, which are currently taken from the LAM, will then move to the GM. The mesoscale model (MES), which has a grid length of about 17km (9nm), could be used for Preseli, but does not cover the whole of Europe so could not be used for all the proposed ECAC HMU sites. Moreover, its use for Preseli might lead to confusion as the GMS relies on the UKMO GM.

5. CONCLUSIONS

It is concluded that:

- The accuracy of the UKMO LAM height forecasts are not appreciably worse over the proposed ECAC HMU areas than they are over Preseli. In most cases the mean error lies between +10m and -5m (+33 feet and -17 feet). This mean error is probably a combination of a radiosonde bias and a model bias, in which case the likely mean model error lies between about +5m and -2.5m (say +20 feet and -10 feet) most of the time. The SD error lies between 10m and 15m (33 feet and 50 feet) most of the time. Removal of the radiosonde bias would reduce these errors to give a likely SD model error lying between about 7m and 10.5m (say 25 feet and 35 feet)

- Mountain waves may occur over parts of the Oyonnax, Linz and Sollenau HMU areas. The frequency is uncertain, but probably quite rare in the upper troposphere and lower stratosphere.

- Clear air turbulence can occur anywhere. However, severe turbulence is rare compared with light and moderate turbulence. Mountain waves may break to form moderate or severe turbulence.

- Convective turbulence can occur anywhere, but can be deep, severe and frequent over mountainous areas.

6. RECOMMENDATIONS

It is recommended that:

- To enhance the HMU coverage to 90nm by 90nm, it is recommended that an array of at least 3 by 3 grid points be chosen to represent the forecast heights over the enlarged area, and that 4-point (bilinear) interpolation be used to compute values within any of the sub-areas.
  It is also recommended that relevant software should be able to cope with possible enhancements eg to 4 by 4 or 5 by 5 grid points if improvements to meteorological modelling allows for more detail at higher resolution.

- The MQI (confidence) function should be reviewed for each of the ECAC HMU sites individually. Consideration should be given to introducing an alert for occasions of mountain wave activity and/or turbulence as well as strong winds.

- Consideration should be given to the requirements for and the feasibility of reporting HMU measurements of aircraft in wave or turbulence to meteorological centres in either real-time or non-real-time.

7. REFERENCES

1. Forrester, D. A., McNair, I. J. and Sanders, J. E. “Comparison and Enhancement of Meteorological Models for Height Monitoring” Report for Eurocontrol, 10 June 1997.

2. Queney, P. “The Airflow Over Mountains” WMO Technical Note No 34, WMO-No 98.TP.43, Geneva, 1960

3. “ALPEX: The Alpine Experiment” Meteorological Magazine vol 111, no 1323, pp 262-270, October 1982.

4. “ALPEX completed” Meteorological Magazine vol 111, no 1323, pp 270-272, October 1982.

5. Stankov, B. B. et al “A preliminary analysis of lee waves over the Alps as observed by aircraft during ALPEX” pp 205-217 of “ALPEX Preliminary Scientific Results” edited by Kuettner, J. P., GARP - ALPEX No 7, ICSU and WMO, Geneva, 1982.

6. Hafner, T. A. “Lee waves over the Pyrenees” pp 218-226 of “ALPEX Preliminary Scientific Results” edited by Kuettner, J. P., GARP - ALPEX No 7, ICSU and WMO, Geneva, 1982.

7. Hoinka, K. P. “Observations of a mountain wave event over the Pyrenees” Tellus vol 36A, pp 369-383, 1984 and vol 38A, pp 93-94, 1986.

8. Cox, K. W. “Analysis of the Pyrenees lee wave event of 23 March 1982” Monthly Weather Review vol 114, no 6, pp 1146-1166, 1986.

9. Ecklund, W. L. et al “Observations of vertical motion in the troposphere and lower stratosphere using three closely spaced ST radars” Radio Science vol 20, no 6, Nov-Dec 1985, pp 1196-1206.

10. Carter, D. A. et al “Investigation of internal gravity waves using three vertically directed closely spaced wind profilers” Journal of Geophysical Research vol 94, no D6, pp 8633-8642, 1989.

11 Hoinka, K. P. “Observations of the airflow over the Alps during a foehn event” Quarterly Journal of the Royal Meteorological Society vol 111, pp 199-224, 1985.

12. Seibert, P. “South foehn studies since the ALPEX experiment” Meteorology and Atmospheric Physics vol 43, pp 91-103, 1990.

13. Tutis, V. “Lee waves - a case study” XIIIth international conference on Carpathian meteorology, Sept 14-19, 1987, Proceedings, vol 1, pp 27-35, 1987.

14. Dutton, M. J. O. “Performance of conventional operational forecasts of clear-air turbulence during the 1976 Turbulence Survay” Meteorological Magazine vol 108, no 1280, pp 61-76, March 1979.

8. ACRONYMS

A	(model) analysis (T+0)
B	(model) background (T+3)
CAT	Clear Air Turbulence
dam	decametre (=10 metres)
ECAC	European Civil Aviation Conference
FL	Flight Level
GM	Global Model
GMS	GPS Monitoring System
HMU	Height Monitoring Unit
hPa	hectoPascal (=millibar)
km	kilometre(s)
LAM	Limited Area Model
m	metre(s)
MES	Mesoscale Model
MQI	Met Quality Indicator
nm	nautical mile(s)
NWP	Numerical Weather Prediction
O	(radiosonde) observation
O-A	observation minus analysis
O-B	observation minus background
OPD	Observation Processing Database
RMS	Root Mean Square
SD	Standard Deviation
UKMO	United Kingdom Meteorological Office

9. LIST OF FIGURES

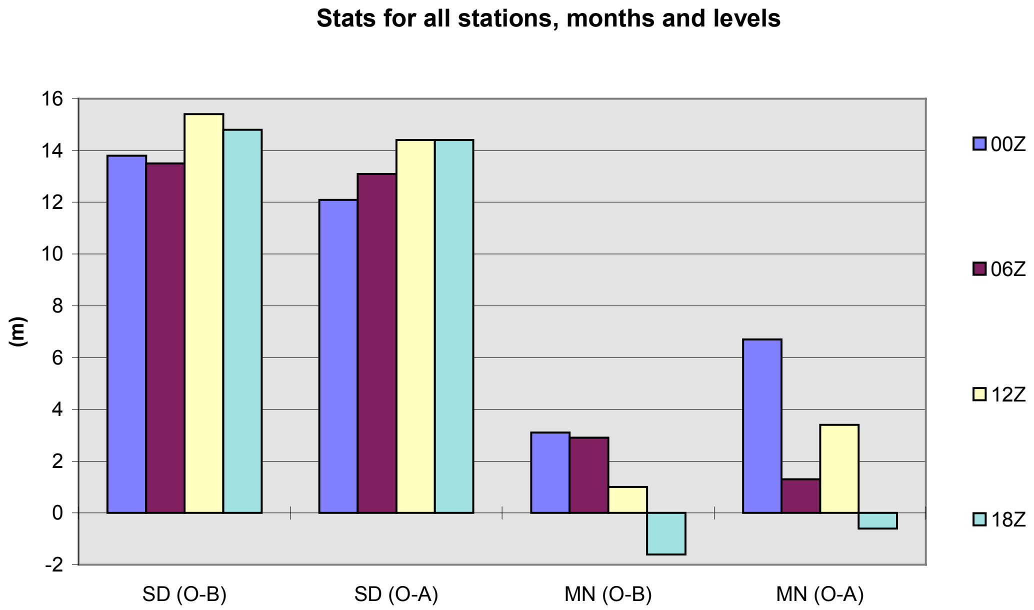

Figure 1(a) Mean, SD (O-B),(O-A) height difference summaries plotted for each hour.

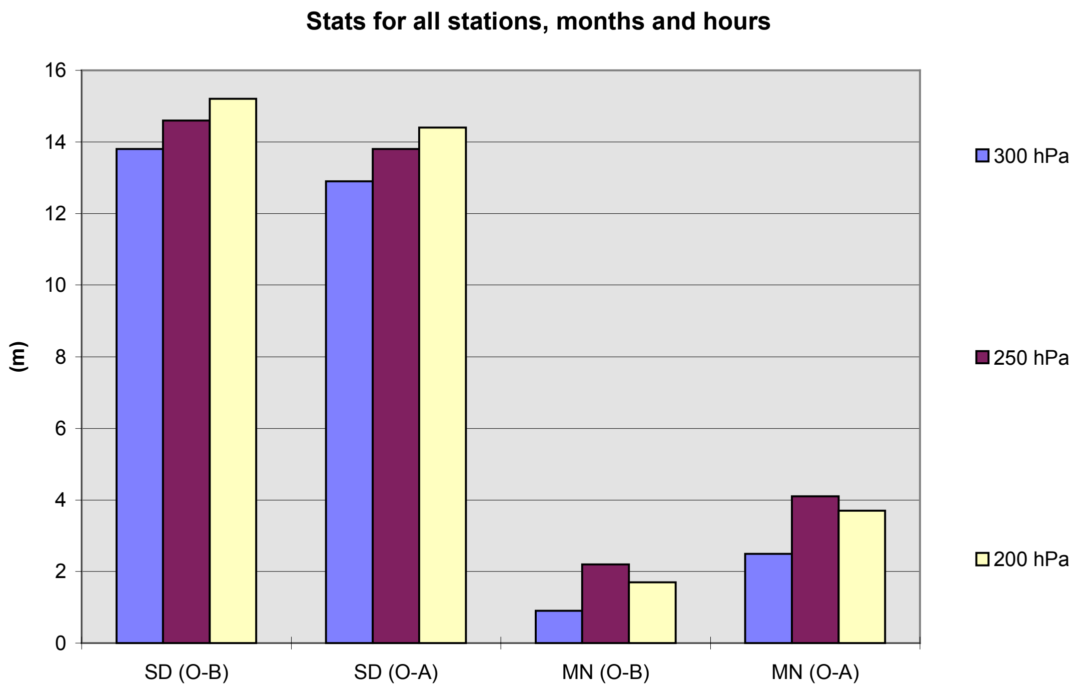

Figure 1(b) Mean, SD (O-B),(O-A) height difference summaries plotted for each level.

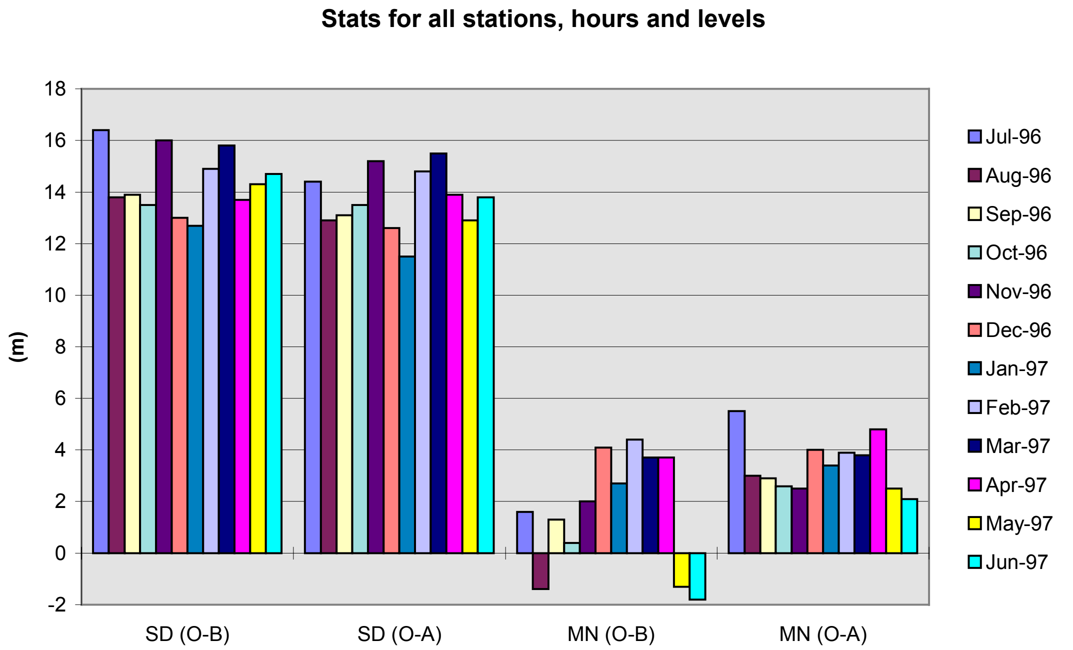

Figure 1(c) Mean, SD (O-B),(O-A) height difference summaries plotted for each month.

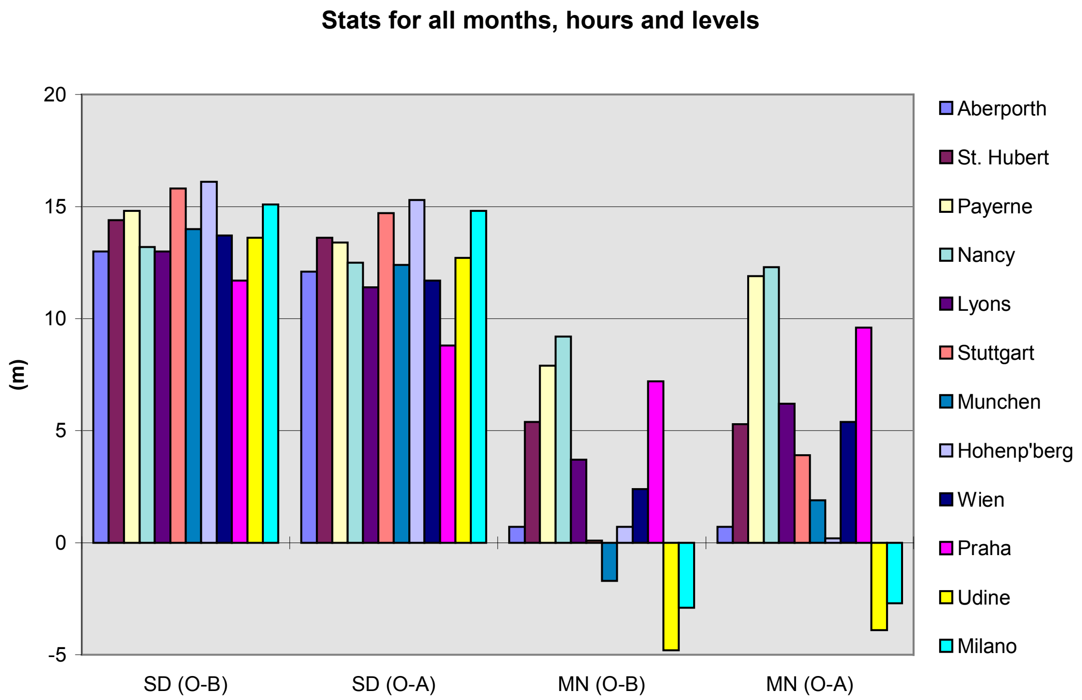

Figure 1(d) Mean, SD (O-B),(O-A) height difference summaries plotted for each station.

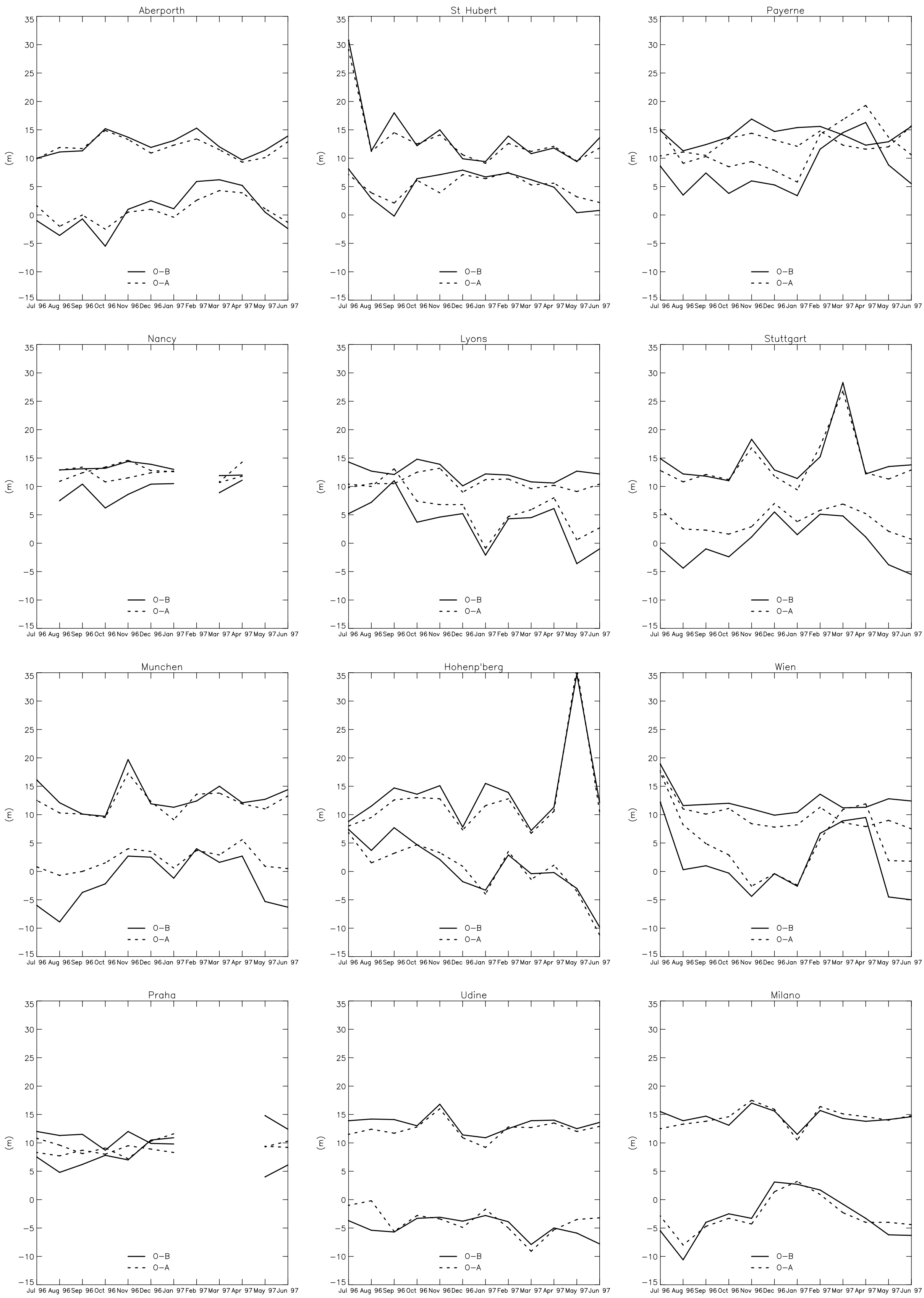

Figure 2 Mean, SD (O-B),(O-A) height difference summaries for each station plotted against months.

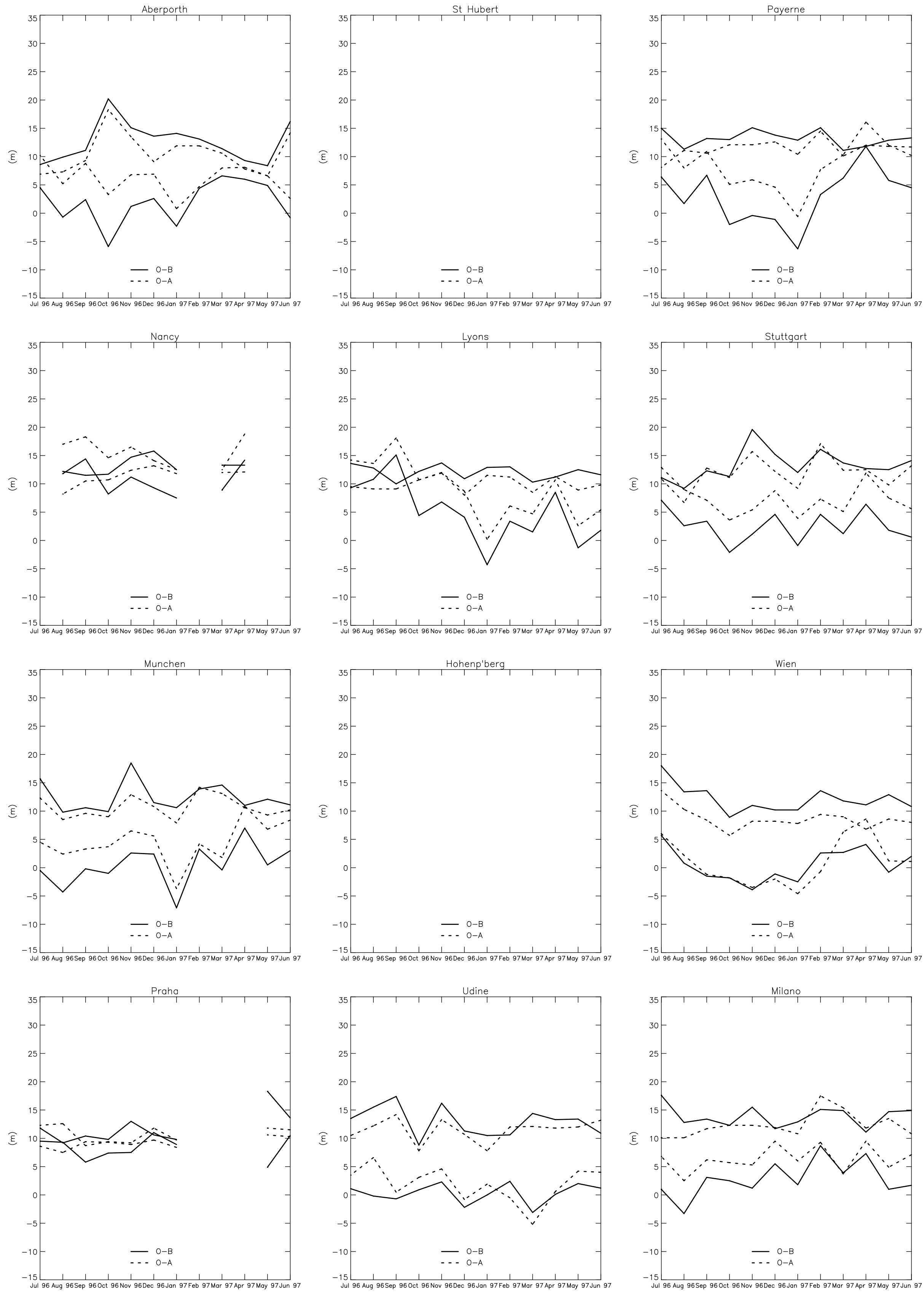

Figure 3 Mean, SD (O-B),(O-A) height difference summaries for each station for 00 UTC plotted against months.

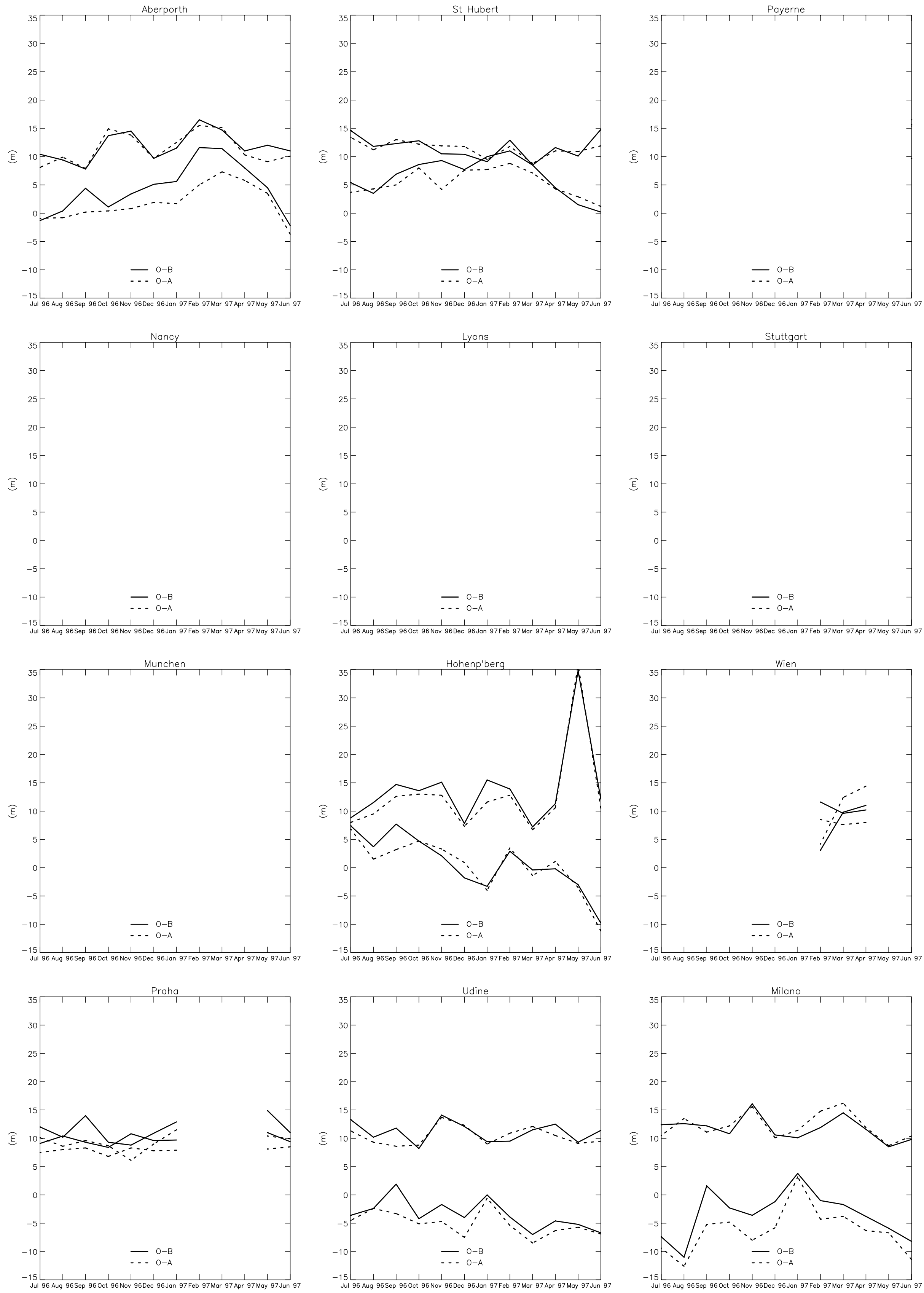

Figure 4 Mean, SD (O-B),(O-A) height difference summaries for each station for 06 UTC plotted against months.

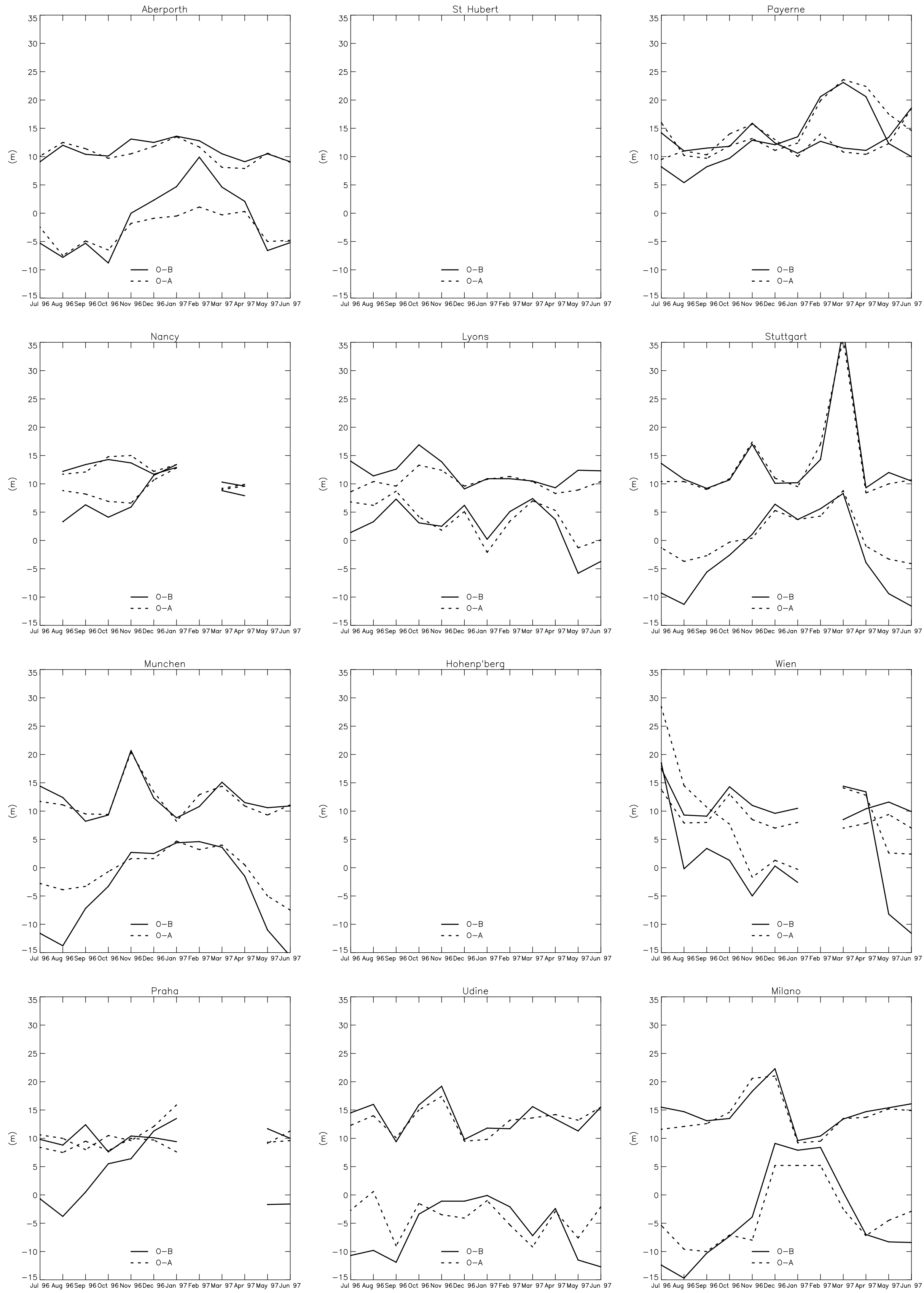

Figure 5 Mean, SD (O-B),(O-A) height difference summaries for each station for 12 UTC plotted against months.

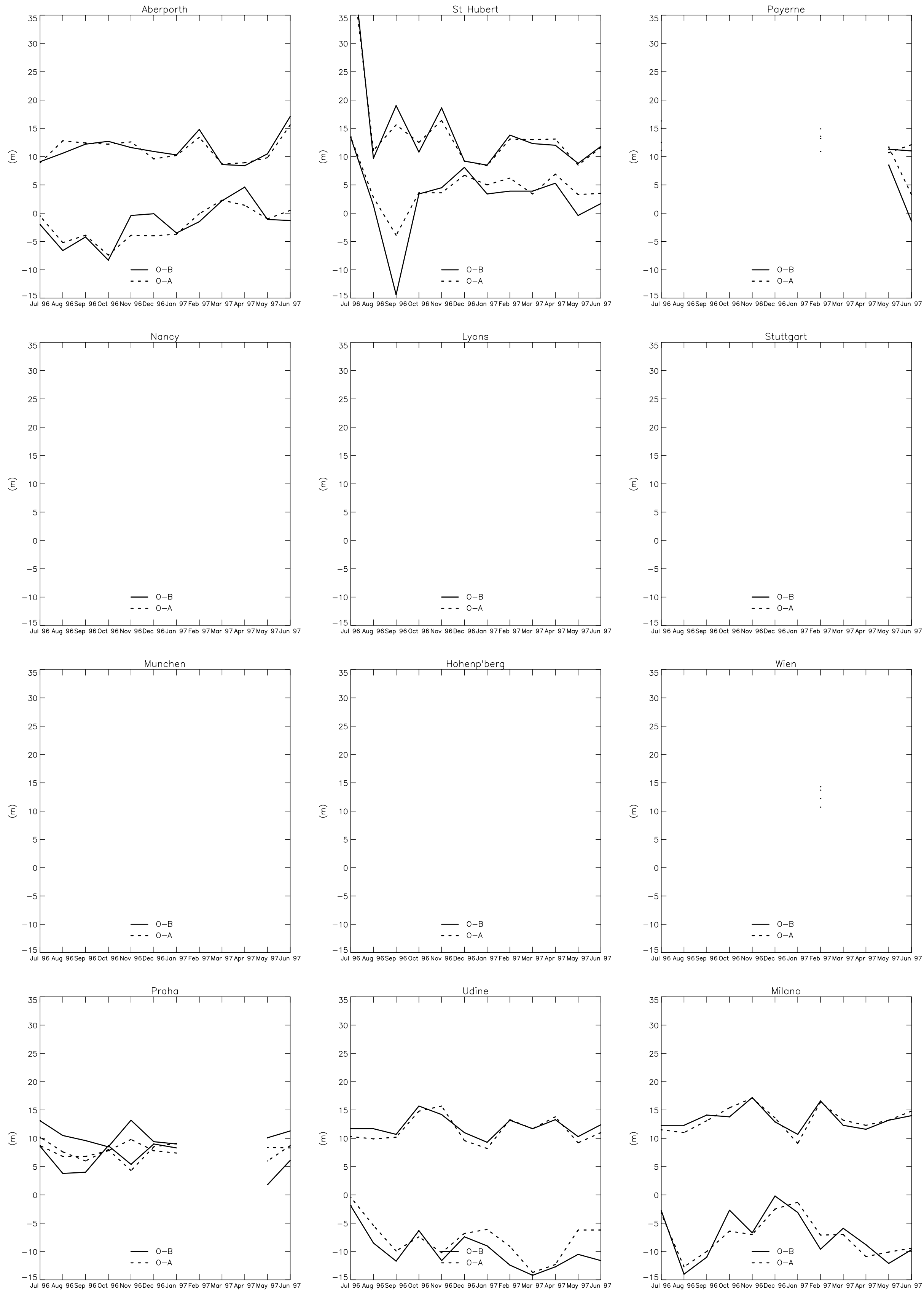

Figure 6 Mean, SD (O-B),(O-A) height difference summaries for each station for 18 UTC plotted against months.