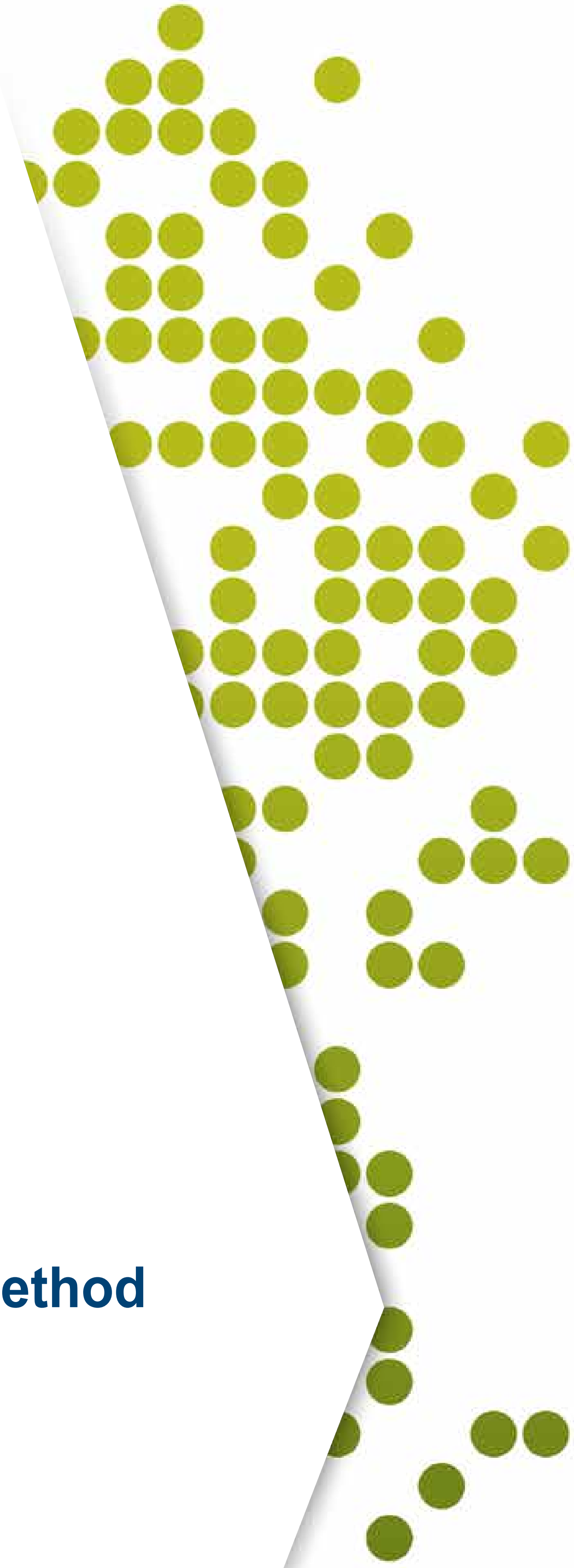

Discussion Paper

Validation of Inversion Strength Estimation Method

www.epa.nsw.gov.au

This project has been assisted by the New South Wales Government through its Environmental Trust (project 2009/RD/0014).

Published by:
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ISBN 978 1 74359 372 1
EPA 2014/0011
March 2014

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Acknowledgements

This project has been assisted by the New South Wales Government through its Environmental Trust.

The kind permission of the West Australian Department of Industry and Resources to use the data from the Collie Basin Study is gratefully acknowledged.

Sincere thanks to the Parish of Singleton for their assistance and kind permission to undertake measurements from the grounds of the Camberwell Church.

Ashton Coal Pty Ltd unconditionally provided meteorological data, permission to undertake measurements from land under their ownership or control, and accommodation in Camberwell for the Access MQ team during the second campaign.

Note

This project was commenced by the Department of Environment, Climate Change and Water NSW, continued by the Office of Environment and Heritage, and completed by the NSW Environment Protection Authority.

1. Background

The Environmental Trust project ‘Validation of Inversion Strength Estimation Method’ is directly relevant to the NSW Industrial Noise Policy (INP; EPA 2000). This document is the EPA report to the Environmental Trust project.

The INP includes an expectation that noise limits will apply under weather conditions characteristic of an area, including atmospheric temperature inversions (atmospheric conditions where temperatures increase with height above ground level), known as surface inversions. (There are also inversions that occur in layers of the atmosphere above the earth’s surface, known as ‘upper inversions’. Upper inversions are not relevant to this study and all references to inversions in this report relate to surface inversions.)

Inversions can ‘trap’ air pollutants and cause deaths during fumigation or severe smog events, and are therefore very important to air quality studies. Much of the research into measuring and predicting inversions has been primarily in relation to air pollution, which has subsequently been adopted and adapted for environmental noise application.

The temperature of the atmosphere affects its density, which affects the speed at which sound travels through it. When an inversion occurs there is a temperature gradient of cooler air close to the ground and warmer air above. This causes sound waves passing through to be bent (refracted) back down towards the ground. A location (such as a house) at distance from a noise source (such as a factory) receives noise that travels in a straight line from the source when there is no inversion. When an inversion occurs, the same location receives both the noise that travels in a straight line from the source and the noise that is refracted by the inversion back down towards the ground. This can result in noise levels at a house being noticeably greater under inversion conditions compared to what they would be if no inversion was present. Inversions are strongest and more common at night, which is also the time when most people are trying to sleep and are therefore most sensitive to noise.

In the INP, surface inversion strengths are expressed in terms of the change in temperature of the atmosphere, in degrees Celsius (°C) over the first 100 metres, from ground level vertically up (degC/100m, or °C/100m). The vertical temperature gradient is also known as the lapse rate. Measuring temperature at ground level is not difficult but in order to obtain the change in temperature up to 100m above ground level (agl) it is necessary to know, or have an estimate of, the temperature at 100m agl. Direct measurement at this height can be relatively costly and difficult, usually requiring installation of a tower with automatic instrumentation or manual data collection using balloon-borne instrumentation.

Because of the cost and difficulty of measuring temperature at 100m agl, a number of methods have been proposed as alternatives to direct measurement, from which reasonable estimates can be obtained.

The simplest alternative is to measure at a height less than 100m agl and, assuming that the change in temperature is constant throughout the entire 100m, extrapolate to obtain a value for 100m. This method is described in Section E2 of the INP:

> *‘The temperature gradient measurement involves measuring temperature at two elevated levels (1.5 to 10m and 50 to 60m) over a 50-m height interval to determine the temperature difference.’*

For example: temperatures of 8°C at 2m agl and 10°C at 52m agl are measured. The temperature difference is 2 degrees, over 50m vertically; therefore, an inversion strength (or temperature gradient) per 100m can be calculated as 2 * (100 / 50) = 4°C.

Another method proposed is to:

- measure at elevated terrain some distance from a ground level measuring location
- assume that the temperature of the atmosphere at this location is the same as the temperature of the atmosphere at the same height directly above the ground level temperature measurement location and
- extrapolate to obtain a value for 100m.

For example, suppose temperatures are measured as:

- 8°C at 2m agl and
- 10°C at 2m agl on a nearby hill that is 65m higher in elevation.

The temperature difference is 2 degrees, over 65m vertically; therefore, an inversion strength per 100m is calculated as 2 * (100 / 65) = 3.1°C.

The second method relies on the terrain having no, or no significant, effect on the vertical atmospheric temperature profile.

Both of these methods rely on there being a linear relationship between temperature and height. If this is assumed to be the case then the temperature gradient in °C up to 100m above ground level could be calculated by measuring at any two heights less than 100m and extrapolating to obtain a value for 100m. (Values could also be obtained by interpolating between a temperature measured at more than 100m and one measured at less than 100m, but this is not encountered usually and is not considered further in this report.)

Presumably because of this assumption of linearity, some environmental noise reports, including compliance assessments, have sought to quantify inversion strengths by linear extrapolation of measured temperatures at heights considerably less than 100m, for example, 2m and 10m agl.

2. Project aims

This project's primary aim was to investigate whether temperature inversion strengths over the lower 100m of the atmosphere could be reasonably accurately estimated by extrapolation of temperatures measured at:

- 2m and 10m agl and
- 10m and 60m agl.

Further aims, if adequate data could be obtained, included investigating whether temperature inversion strengths over the lower 100m of the atmosphere could be reasonably accurately estimated by extrapolation of temperatures measured:

- with less than 50m elevation difference and
- at different elevations that were spatially separated.

3. Method

The method used was to calculate lapse rates (particularly for inversion conditions) using the different estimation methods, and to compare the results against the actual lapse rates (determined from measurements made of air temperatures at various heights from ground level to 100m agl).

Herring Storer evaluated some approaches for estimating inversion strengths in their report on atmospheric temperature profile measurements from the Collie Basin in Western Australia

(Herring Storer Acoustics 2010). Although the Herring Storer report utilised data collected for another project with different objectives to this one, the project methodology and presentation of results were considered and led to key elements of the design and data processing of a subsequent field study by Access MQ in NSW (Access MQ, 2011).

Both the Herring Storer (2010) and the Access MQ (2011) studies used tethersondes – measurement instrumentation (sensors or ‘sondes’) suspended at intervals along a cable, or ‘tether’, attached to a helium-filled balloon used to raise or lower the sondes.

There are essentially two ways of measuring temperature profiles using a tethersonde:

§ continuously raise and lower the balloon and sensor(s) to obtain a number of profiles of temperature comprising a number of measurements at many heights between ground level and 100m, or greater (the method used by Herring Storer) or

§ measure at a number of heights fixed for the duration of each balloon ascent.

The second alternative, with sensors at 100m, 60m and 10m agl (and manual temperature observations nominally at 2m agl) was chosen as it aligned better with the aims of this project and the policy background, and environmental noise measurement practice in NSW. Measurements were made by Access MQ in two campaigns, nominally of 3 days each, in 2010 and 2011, at Camberwell in the Hunter Valley of NSW.

The original project scope envisaged one campaign in winter and a second in summer, for comparison. Inversions are generally considered to be stronger and more prevalent in winter. A useful project outcome depended on collecting data during inversions, and therefore the winter campaign was considered to be the most important. Inversions occur under calm, clear conditions and do not occur during cloudy or windy conditions. Helium and other supplies for the field campaign had to be ordered in advance, and the project budget did not incorporate a standby component for personnel: therefore the dates for each campaign had to be committed to some time in advance. This allowed the field work timing to be adjusted only by postponement due to forecasts of continuing rain or continuing strong winds. During the first campaign, some ascents did not measure inversion conditions because of overcast conditions at the time. Therefore it was decided to exchange the summer comparison campaign for a second winter campaign to try and increase the data set for inversion conditions.

On each day of each campaign the instruments were raised to their measurement height above ground level by the balloon (a balloon ‘ascent’): nominally around sunrise, midday and sunset. The sunrise and sunset times were chosen as most likely to return data for the greatest range of conditions: from stable, inversion conditions prior to sunrise through inversion breakup to stable daytime conditions, and vice versa for sunset. The midday ascent was expected to provide data for unstable, well mixed atmospheric conditions.

For each ascent, measurements continued for the battery life of the instrumentation. Measurements were not made, or discontinued, during strong winds or rainfall because of health and safety risks to personnel or equipment. The measurements provided a baseline. Against this baseline were compared:

§ estimates obtained by extrapolating from the lower elevation measurements and

§ measurements from two nearby weather stations.

The temperature and other parameters, reported by the sensors every 5 seconds, were averaged over a 15-minute period; nominally at quarter-past, half-past, quarter-to and on the hour. This averaging approach was selected to best align with the policy background and environmental noise measurement practice in NSW. Because the sensor batteries lasted around 3 hours only, this approach does limit the total potential data points to around twelve (4/h x 3 h) for each balloon ascent.

The data were analysed for assessment against the project aims.

Photo 1: Tethersonde balloon above Camberwell just before sunrise Tuesday 20 July 2010. *Photo*: Larry Clark, EPA

Photo 2: View from ground level up to the balloon showing sonde arrangement on the tether *Photo*: Larry Clark, EPA

4. Results

Herring Storer Acoustics (2010) presents the results of the desktop study by Herring Storer – atmospheric temperature profile data collected over short time periods on three nights, as part of a sound propagation study undertaken in the Collie Basin in southern Western Australia. The review used °C/100m atmospheric vertical temperature gradients (lapse rates) calculated from measurements in the vicinity of 100m agl, and compared them with lapse rates calculated by extrapolating measurements made at lower elevations.

Access MQ presents the results of field measurements of some atmospheric temperature profiles, made by Access MQ on behalf of the agency.

EPA's graphical presentations of Access MQ's raw temperature profile measurement results are in Appendix A. For ease of visual comparison the temperature range on the vertical axis of each graph has been normalised to a 10° range, and the measurement duration on the horizontal axis of each graph has been normalised to the longest measurement duration of 3h 15 min.

An electronic copy of the field measurement data is provided in Appendix B, in read-only format to preserve the integrity of the original data.

5. Discussion and conclusions

5.1 Herring Storer desktop study

One of the key outcomes of this project is the observation that the method of inversion strength calculation is potentially very important, and should be described in detail when presenting measured or predicted values. This is not a criticism of Herring Storer's approach: nowhere in the literature (albeit limited) consulted during the preparation for, and the progress of, this project was found consistent explicit instructions, or a consistent, common standardised approach, for measuring or specifying atmospheric lapse rates to 100m agl. It seems that whatever approach was used was assumed to be what all other investigators also used.

This becomes apparent when considering, for example, the first part of Herring Storer's analysis (2010, section 4.2, pages 7 and 8). A lapse rate of 5.5°C/100m is calculated by extrapolating from the temperature of 11.4°C measured at 10m agl and the temperature of 12.5°C at 30m agl. Both temperatures were measured on a tower, at the same geographic location. The formula for extrapolating to give a calculated lapse rate over 100m is given as:

(upper height temperature – lower height temperature) × [100/(upper height – lower height)]

This formula can be rearranged, to give an estimated temperature of 16.4°C at 100m, based on:

- the lapse rate of 5.5°C/100m and
- either the temperature of 11.4°C measured at 10m, or the temperature of 12.5°C measured at 30m agl.

The 'actual' temperature at 100m agl was measured as 13.3°C using a tethersonde, albeit at a geographic location quite removed from the tower. If we assume, however, that the atmospheric temperature profile is the same at the tethersonde location as at the tower location, then using the 100-m temperature of 13.3°C the lapse rate is calculated as:

- 1.1°C/100m using the 30-m temperature of 12.5°C but
- 2.1°C/100m using the 10-m temperature of 11.4°C.

(Note that Herring Storer have inadvertently given this last value as 1.9°C/100m, which is the difference in the temperature between 100m and 10m (delta T, or ΔT) and could be considered to represent the lapse rate over 90m, not 100m.) This observation becomes more significant when considering guidance on measuring lapse rates, and particularly inversions, which is discussed further below.

The calculated lapse rates above, using temperatures measured at different heights, range in value from 5.5 to 1.1°C/100m. Noise limits specified in Environment Protection Licences in NSW may not apply for inversion conditions greater than a specific lapse rate, usually 3°C/100m. If this had been a scheduled premises in NSW, with the tower measurements being made on the premises and the 100m agl temperature measurement being made at a licence assessment location (usually a residence), any noise emissions greater than licence limits, which applied under inversions up to 3°C/100m, would have been considered either non-compliances or not, dependent entirely on which method was used to calculate the inversion strength.

Thus, the method for calculating the lapse rate can be very important for licence holders, the EPA and the community, because it can mean the difference between a noise emission being considered in, or out of, compliance with the licence limit. Recommendations in relation to this are made below.

Conclusions of Herring Storer's review (2010) included that:

- Calculation of lapse rates by extrapolation (in this case by use of temperatures measured at 10m and 30m agl) required careful evaluation.
- Extrapolation showed an over prediction in the thermal inversion by up to 5°C, when an inversion was present.

Herring Storer also concluded, based on the results of their measurements and analyses, that not less than 80m was the appropriate upper height to calculate the 100-m lapse rate by comparison against the temperature measured at 10m – measured levels beyond 80m remained static with little variation.

Herring Storer's conclusions were based on the best data available to them, but these data were obtained from two spatially separated locations, which introduces the potential for the results to be significant influenced by variation in atmospheric conditions between the two locations. The field work conducted by Access MQ was designed to remove this variable for the first two project aims, and to minimise it as far as possible for the further aims.

5.2 Access MQ field measurements

The Access MQ (2011) field measurements provided simultaneous atmospheric temperatures at various heights to 100m agl above the same single geographical location. This removed the variable of lateral variation in the atmosphere, which had to be assumed to be non-existent or not significant for the Herring Storer data.

The field measurements highlighted a key conceptual consideration, which is that there is really no absolute or 'true' atmospheric lapse rate value for the first 100m of the atmosphere above ground level: the value is definitional and depends on the calculation method.

For example, for the first ascent for which inversion conditions were present and temperatures obtained at 10m (the evening of 19 July 2010), the average temperatures between 6:30pm and 6:45pm are presented in Table 1 below, together with calculated lapse rates and temperature differences.

Table 1 Atmospheric temperatures measured at four heights above ground level, calculated lapse rates and temperature differences between two heights (ΔT).

Height agl (m)	Temperature (°C)	Lapse rate; re 100m (°C/100m)	ΔT; re 100m (°C)
2	7.8	5.6	5.5
10	10.0	3.6	3.3
60	12.6	5.2 (re 10–60m)	2.6 (re 10–60m)
100	13.3		

Notably the lapse rate and ΔT values are all different (yet it is the same atmosphere). Presumably the temperature at actual ground level (i.e. 0m agl) was less than the temperature at 2m agl, and therefore would have returned a lapse rate greater than 5.6.

Figure 3 in Access MQ's report (2011) graphically illustrates this issue: a straight line representing the lapse rate over 100m will have a different slope from the top of each profile, depending on where the line intersects the profile close to the ground. The important point is that actual temperature profiles for inversion conditions are rarely linear.

Which is the 'correct' lapse rate depends on the height of the lower temperature measurement. The question of which is the correct lower height is fundamental to establishing a reference or benchmark against which to evaluate other approaches, particularly where values must be obtained to a tenth of a degree.

Theoretically, measurement at ground level would appear at first glance to be most appropriate, because comparison of this temperature with that at 100m would directly provide the true °C/100m value.

In meteorological practice, the surface air temperature refers to free air at a height between 1.25 and 2m above ground level (BOM 1975). This probably has its origins in being the most relevant height to most human activities and for a human observer.

The *Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales* (DEC 2005) specifies, in relation to siting and operating meteorological monitoring equipment, use of the Australian Standards 2922-1987 and 2923-1987, and the US EPA (2000) *Meteorological Monitoring Guidance for Regulatory Modeling Applications* (US EPA guidance). The USEPA guidance specifies that:

> *'Ambient temperature should be measured at 2m, consistent with the World Meteorological Organization (WMO) standards for ambient measurements. Probe placement for temperature difference measurements depend on the application…the temperature difference should be measured between* $20z_0$ *and* $100z_0$ *… for temperature difference measurements for use in estimating the Pasquill–Gifford stability category using the solar radiation delta-T method.'*

Atmospheric stability is very important to environmental noise applications because, mainly for air quality applications, the industry standard in NSW has become to estimate atmospheric stability using measurements of wind variables at 10m agl and the sigma-theta estimation method (which uses the standard deviation of wind direction in combination with the scalar mean wind speed). Appendix E (Methods for determining the frequency of temperature inversions) of the INP (EPA 2000) discusses different approaches for assigning atmospheric stability and presents published relationships between stability category and vertical temperature gradients. This is discussed more below.

The solar radiation delta-T (SRDT) method mentioned above requires that the vertical temperature gradient be resolved as either less than zero, or greater than or equal to zero, only. That is, the method does not intend that the temperature difference measurements resolve an absolute value for an inversion, only whether one is present or not.

Classification of atmospheric stability is a key factor in air quality dispersion modelling, to facilitate estimates of lateral and vertical dispersion. The preferred stability classification scheme is that based on proposals by Pasquill and Gifford.

Pasquill-Gifford (P–G) stability categories range from A to F, where A corresponds to warm, sunny clear conditions; D is neutral; and F is a moderate inversion. A seventh class, G, has also been defined to accommodate extremely stable conditions such as might be found in arid rural areas.

A number of methods have been proposed for deriving P–G stability categories, including sigma–theta. The accuracy of these methods is considered to be such that they will estimate the same stability category as the benchmark Turner method about 50 per cent of the time, and will be within one category about 90 per cent of the time. However, this performance may require adjustment of the turbulence criteria as a result of spot checks.

The US Nuclear Regulatory Commission's *Regulatory Guide 1.23 Meteorological Monitoring Programs for Nuclear Power Plants* was first issued in 1972. The latest (2007) version:

- includes in its definitions
  'Vertical Temperature Difference (ΔT): The measured difference in ambient temperature between two elevations on the same tower. It is defined as the upper level temperature measurement minus the lower level temperature measurement'.
- specifies that vertical temperature difference (delta T, or ΔT) should be measured between the 10-metre level and 60-metre levels, and provides a table defining Pasquill stability classes as a function of ΔT.

Table 2 is reproduced from the US NRC 2007 guide.

Table 2 Classification of atmospheric stability
(*Source*: Table 1, US NRC 2007)

Stability classification	Pasquill stability category	Ambient temperature change with height (°C/100m)
Extremely unstable	A	$\Delta T \le -1.9$
Moderately unstable	B	$-1.9 < \Delta T \le -1.7$
Slightly unstable	C	$-1.7 < \Delta T \le -1.5$
Neutral	D	$-1.5 < \Delta T \le -0.5$
Slightly stable	E	$-0.5 < \Delta T \le 1.5$
Moderately stable	F	$1.5 < \Delta T \le 4.0$
Extremely stable	G	$\Delta T > 4.0$

Ten metres was chosen as the appropriate lower temperature measurement height for this study having regard to:

- the US EPA Guidance that the probe placement for temperature difference depends on the application
- the US NRC Regulatory Guide (2007) specifying 10m as the lower height for temperature difference measurement
- consideration that most noise sources on mines (trucks, shovels, washeries, conveyors, etc.) and on other large industrial sites such as refineries are typically of heights 4–5m and up to 10–15m and

- conceptually, while the greatest temperature gradients per metre of atmosphere (which will cause the most refraction) typically occur close to the ground, it is likely to be the upper 90 per cent of the atmosphere (from 10m to 100m) that is more important in influencing the amount of enhancement of noise levels at relevant distances (in the order of kilometres).

The lapse rate in °C/100m, calculated by extrapolating using the formula given in section 5.1 and the 10m and 100m temperature values, was chosen as the benchmark (or 'gold standard') for this project, against which lapse rates calculated by other methods were evaluated.

To evaluate the prediction methods, calculated lapse rates were compared to the values in Table E1 of the INP (essentially Table 2 above) to 'back calculate' a stability category. A method was considered adequately accurate if it predicted the same stability category as the benchmark method 50 per cent, and within one stability category 90 per cent, of the time.

Access MQ concluded that temperatures measured simultaneously at:

- 2m and 10m agl could be used to predict the occurrence of inversions but were not useful for predicting actual inversion strengths
- 10m and 60m agl are needed for reasonable estimates of the lapse rate to 100m agl
- 10m agl, but with one measurement separated vertically and horizontally, can provide reasonable estimates of the lapse rate to 100m agl.

5.3 Project Insights

In completing this project it has become apparent that care has to be taken when comparing the results of direct measurement of temperature gradients over the lower 100m of the atmosphere. The lower measurement height, which can have a significant influence on the result, may be implied or inferred in guidance material but is not consistently explicitly standardised or specified, and is usually not reported with results.

Table E1 of the INP is reproduced here as Table 3, and is the equivalent of Table 1 from the US NRC Guide, except that the use of '<' (less than) and '≤' (less than or equal to) is reversed in the two documents and G Class is given as '4.0 ≤ /DT/DZ' in the INP Table E1. Establishing which of the two documents aligns with the original classification and the significance of the difference between the documents is beyond the scope of this report.

Table 3 Stability categories based on DT/DZ (*Source*: NSW INP)

Stability category	Range of vertical temperature gradient (°C/100m)
A	DT/DZ < -1.9
B	-1.9 ≤ DT/DZ < -1.7
C	-1.7 ≤ DT/DZ < -1.5
D	-1.5 ≤ DT/DZ < -0.5
E	-0.5 ≤DT/DZ < 1.5
F	1.5 ≤ DT/DZ < 4.0
G	4.0 ≤ DT/DZ

Section E2 of the INP: Direct measurement of temperature lapse rates, specifies that:

> *'The temperature gradient measurement involves measuring temperatures at two elevated levels (1.5 to 10m and 50 to 60m) over a 50-m height interval to determine the temperature difference. The temperature gradient is then the temperature difference (that is, the temperature at the higher elevation minus the temperature at the lower elevation) divided by the height difference.'*

The second sentence appears to be incorrect and should read: *'The temperature gradient is then the temperature difference … multiplied by a fraction that is calculated as 100 divided by the height difference.'*

There appears to be an ambiguity in the US NRC guide in that the text states that '*Table 1 provides a definition of Pasquill stability classes as a function of ΔT*'. Temperature values in Table 1 are specified relative to ΔT, however the relevant column is headed '*Ambient temperature change with height (°C/100m)*'. This is potentially very significant and needs to be clarified because the lapse rate in °C/100m should be twice the ΔT measured between 10 and 60m (For example if ΔT is 2°, the lapse rate is 4°C/100m). The INP would have referenced an earlier version of the NRC Guide, which may have been different to the current 2007 issue. It is beyond the scope of this project to clarify these issues.

These ambiguities and discrepancies may have lead to differences in the way °C/100m has been calculated in various studies. This makes it difficult to make meaningful comparisons between different sets of direct measurements with confidence, and reduces confidence in comparing direct measurement results against results of other schemes for classifying atmospheric stability. This is important for making noise predictions with reasonable accuracy but is particularly important for regulatory and compliance matters.

Because the first 100m is a relatively small interval and the temperature in the first few metres closest to the ground can vary considerably, a standardised approach is necessary for describing a lapse rate to 100m agl. Otherwise:

- meaningful comparisons with the measurement results of others are difficult or cannot be made and
- attempts at regulatory action could fail through claims of unfairness due to a lack of clarity and consistency.

The heights at which temperatures are measured for specifying atmospheric lapse rates to 100m agl should be explicitly standardised, and certainly need to be explicitly stated when reporting results. This would appear to be particularly necessary for regulatory purposes, to ensure:

- consistency between conditions under which noise level predictions are made and those under which compliance is assessed
- consistency across licences and regulated premises and
- reproducibility of results for licensees and regulators.

These points are relevant not only for EPA but also for Environmental Assessment (EA), Environmental Impact Statements (EIS) and the like.

6 Policy, technical and regulatory recommendations

The following recommendations arising from this project are proposed for consideration by the EPA. These recommendations need to be peer reviewed and any cost implications for industry considered prior to any policy change.

6.1 Policy recommendations

1. Section E2 of the INP should be amended to state:

   'The temperature gradient measurement involves measuring temperature at two elevated levels (10m and 60m) to determine the temperature difference. Where temperature is not measured at 10m and 60m the actual measurement levels need to be stated; the lower level should not be less than 10m and the height interval should not be less than 50m. The temperature gradient is then the temperature difference (that is, the temperature at the higher elevation minus the temperature at the lower elevation) multiplied by a fraction that is calculated as 100 divided by the height difference.'

2. The INP should be modified where relevant to specify that lapse rates in °C/100m, for the purposes of the INP, are:

   - defined as the difference between the temperatures at 100m and 10m above ground level, multiplied by 1.1 (1.1 being the fraction obtained by dividing 100m by the difference between 100m and 10m).

3. The EPA should confirm with the US NRC that the values in Table 1 of the 2007 Guide are °C/100m values (as per the column header), and not ΔT values (as possibly implied by the text).

4. The INP default should be changed from 3°C/100m to F Stability Class. At the time of publication of the INP (2000) the principal noise prediction model used in Australia was the Environmental Noise Model (ENM), which allowed specification of lapse rate as a user-input variable in °C/100m. ENM is still in use but is no longer being sold or supported. Models currently commercially available typically allow specification of atmospheric conditions by stability category. Industry practice has become mostly standardised in reporting atmospheric conditions as stability category, determined by the sigma–theta method using measurements made at 10m agl.

   The INP default inversion strength for the majority of noise predictions is 3°C/100m. This is close to the upper limit for F Stability Class of around 4°C/100m. Changing the INP default from 3°C/100m to F Stability Class would align with the current generation of noise prediction models, and could be accommodated by ENM users by, for example, specifying an inversion strength of 4°C/100m. It would also align with the industry standard of monitoring and reporting atmospheric profile conditions in stability categories. Licence noise limits could be based on noise levels predicted for specific stability categories; and licence conditions could specify that the limits apply for the stability category that was used in the predictions. This would simplify compliance assessment for industry and regulators and improve clarity for the community. The difference in noise levels predicted for 3°C/100m compared with 4°C/100m is anecdotally reported as being around 1dB (Ishaac, pers comm.).

   A difficulty with this approach is how to deal with the INP default of 8°C/100m for arid regions because the obvious replacement of G Stability Class has no upper bound.

6.2 Technical recommendations

1. Inversion strengths to 100m agl:
   - calculated by extrapolation of the differences between temperatures measured at 2m and 10m agl should not be accepted because the method is prone to gross overprediction
   - calculated by extrapolation of differences between temperatures at two heights less than 100m can be estimated with reasonable accuracy provided the elevation difference is not less than 50m
   - should be standardised in measurement to a lower reference height of 10m agl, or at least not less than 10m agl
   - calculated or measured from direct measurements need to state the measurement heights together with the results
   - calculated or measured from direct measurements where the lower reference height is not 10m agl can be used for determining the frequency of occurrence of inversion strengths, but that frequency of occurrence will be specific to that method
   - calculated by extrapolation of the differences between temperatures measured at the same or different heights above ground level, but where one measurement is laterally displaced on elevated terrain may give reasonable accuracy. The accuracy should be established by comparison of the calculated values against measurements from a campaign of direct measurements, such as by tethersonde.
2. As stated by Access MQ (and shown in the graphical presentations in Appendix A), inversion formation and collapse can occur rapidly and highlights the importance of the temporal dimension (averaging period). Access MQ tested the sensitivity of their analysis based on 15-minute averages by comparing the results with hourly averages, and found that 15-minute averages gave reasonable resolution. Theoretically, there should be poor correlations between measured values and values predicted by extrapolation during periods of transition. Better correlations are expected for 15-minute consecutive averages if data collected during periods of transition were excluded from the analysis, or if the data set was increased (through more measurements or measurements of longer duration). If this project was replicated, or supplemented with further measurements, periods of transition should be avoided and measurements directed to times prior to sunrise and after sunset, when conditions should have stabilised.
3. The approach of averaging the 5-second raw data values over a 15-minute period; nominally quarter-past, half-past, quarter-to and on the hour was chosen as optimum for this study, being:
   - closest to current NSW industry practice for unattended and continuous environmental noise logging
   - close to the 10-minute averaging period of the nearby meteorological stations.

   The raw data could, however, provide additional data sets which could be further analysed by being processed for 15-minute (or other) periods commencing at any time, even displaced by one data point only (and overlapping for the remainder – ‘running’ 15-minute periods).
4. Ashton’s meteorological station is understood to measure and report sigma–theta, from which stability categories can be determined by the sigma–theta method. It was outside the scope of this study to compare tethersonde-derived stability classes with sigma–theta stability classes, but such comparisons could provide further insights and useful outcomes.

6.3 Regulatory recommendations

Environmental Protection Licences (EPLs) that specify a noise limit and an inversion strength in °C/100m under which the limits apply need to:

§ specify the measurement heights and calculation method for the inversion strength. For example:

  'The noise limits set out in condition L6.1 apply under all meteorological conditions except for the following:

  - *(a) wind speeds greater than 3 m/s at 10 metres above ground level or*
  - *(b) temperature inversion conditions up to 3°C/100m and wind speeds greater than 2 m/s at 10 metres above ground level or*
  - *(c) temperature inversion conditions greater than 3°C/100m.*

  The temperature inversion condition in °C/100m refers to the difference in temperatures at 60m and 10m above ground level, multiplied by 2.'

§ specify the measurement method where that method is other than direct measurement at 10m and 100m agl, or extrapolation from two direct measurements: one at 10m agl and the second at no less than 60m agl. For example:

  A Noise Impact Assessment (NIA), forming part of an Environmental Assessment supporting a development application for a new industrial development, includes an assessment of the frequency of occurrence of temperature inversions, as required by the INP. The assessment is based on temperature measurements at 2m agl and 30m agl on the undeveloped development site. The measured levels are extrapolated to calculate lapse rates and the assessment finds that temperature inversion strengths of up 12°C/100m, as calculated by extrapolation of the measured temperatures at 2 and 30m agl, are a feature of the area. Temperature inversion strengths measured by this method are certain to be greater than (over predictions of) 'true' inversion strengths determined from measurements at 10m and 100m. Noise levels as a result of the proposed development are predicted for 12°C/100m temperature inversions, either with or without prediction calibration adjustments. Without calibration adjustments, the predicted noise levels should be conservative because the model algorithm is presumably accurate for a 'true' inversion strength. Any calibration adjustments would have to be adequately supported. If approved, the project approval and the Environment Protection Licence should include conditions limiting noise emissions to the levels predicted under a 12°C/100m inversion, **to be determined by extrapolating from measurements at 2m and 30m agl**. This way, compliance is related back to the predicted levels, for the inversion conditions under which the predictions were made and according to the measurement method used to establish the inversion strength.

7 Closing statement

The project aims have been met.

In addition:

§ significant insights have been gained in to the practicalities of measuring and reporting temperature inversions

§ policy, technical and regulatory recommendations have been made for consideration by EPA

§ valuable data has been obtained that could be useful in further analyses.

8 References

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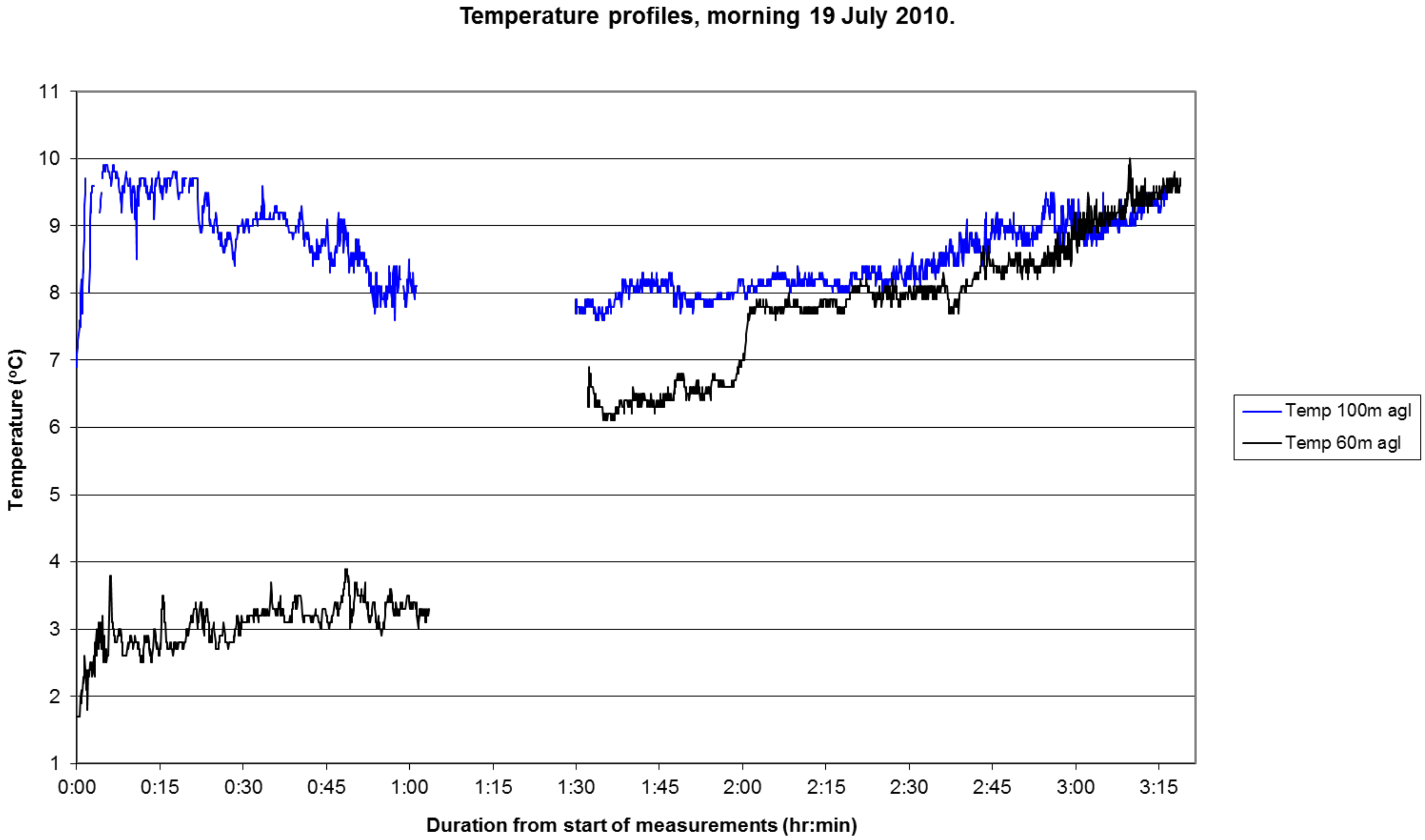
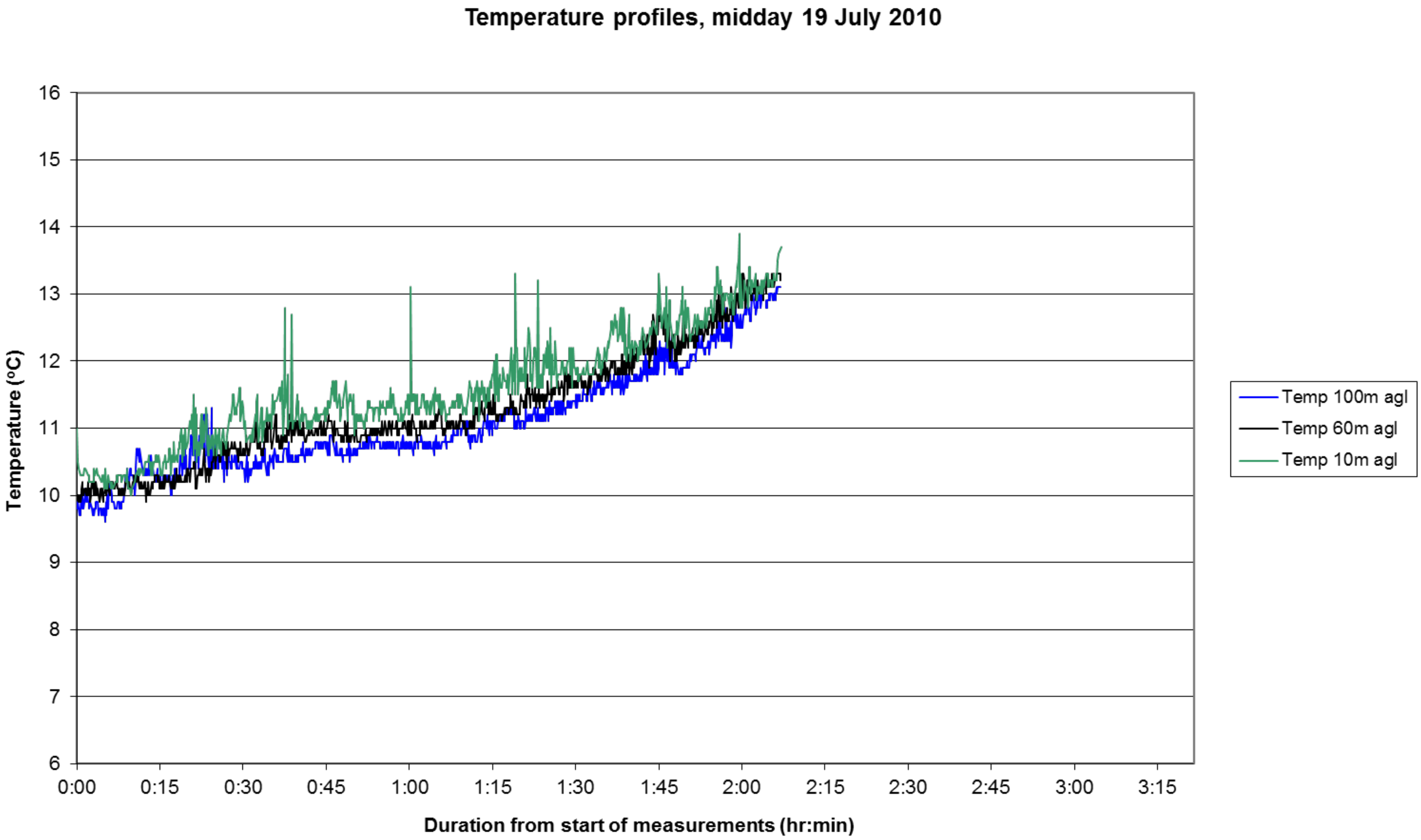
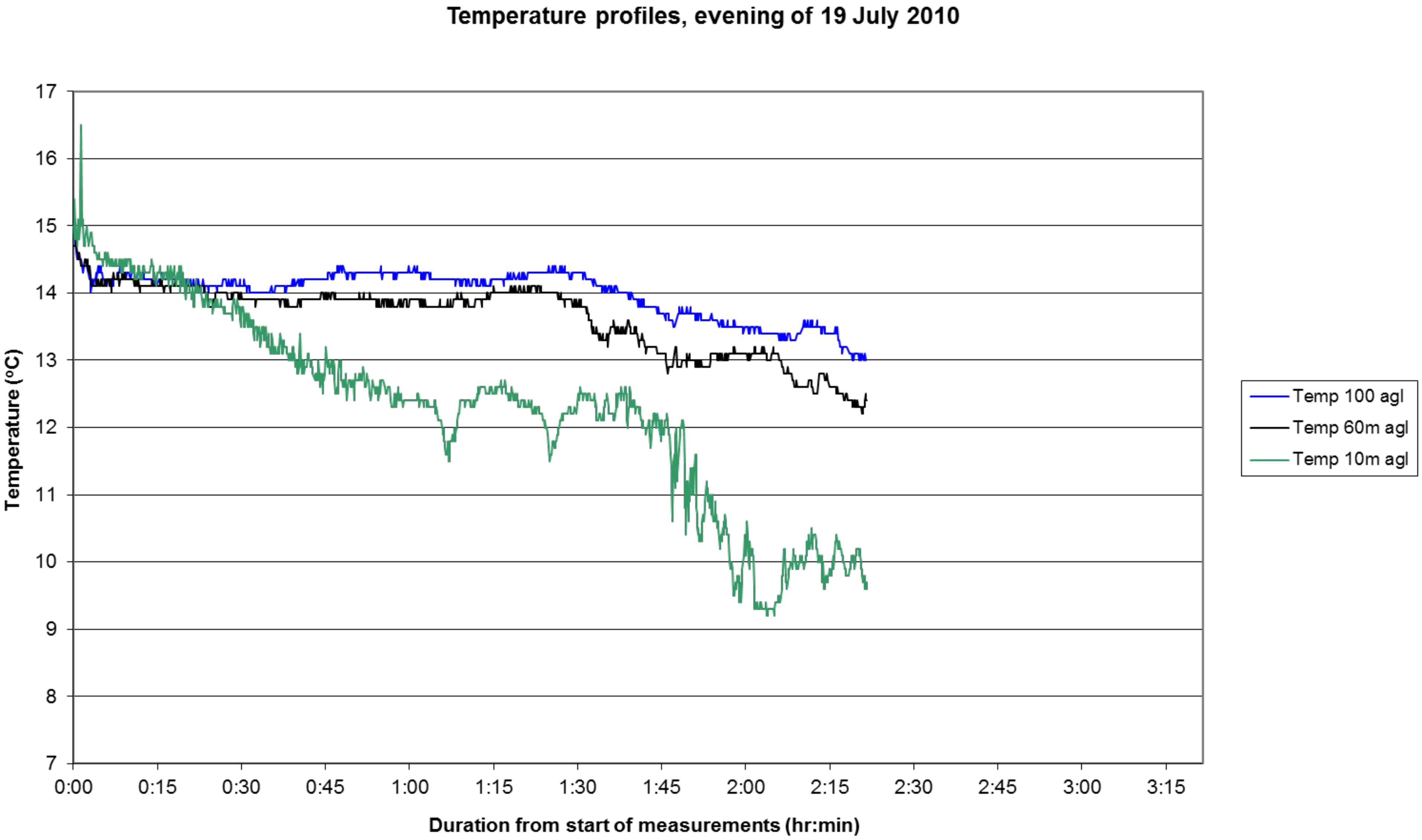
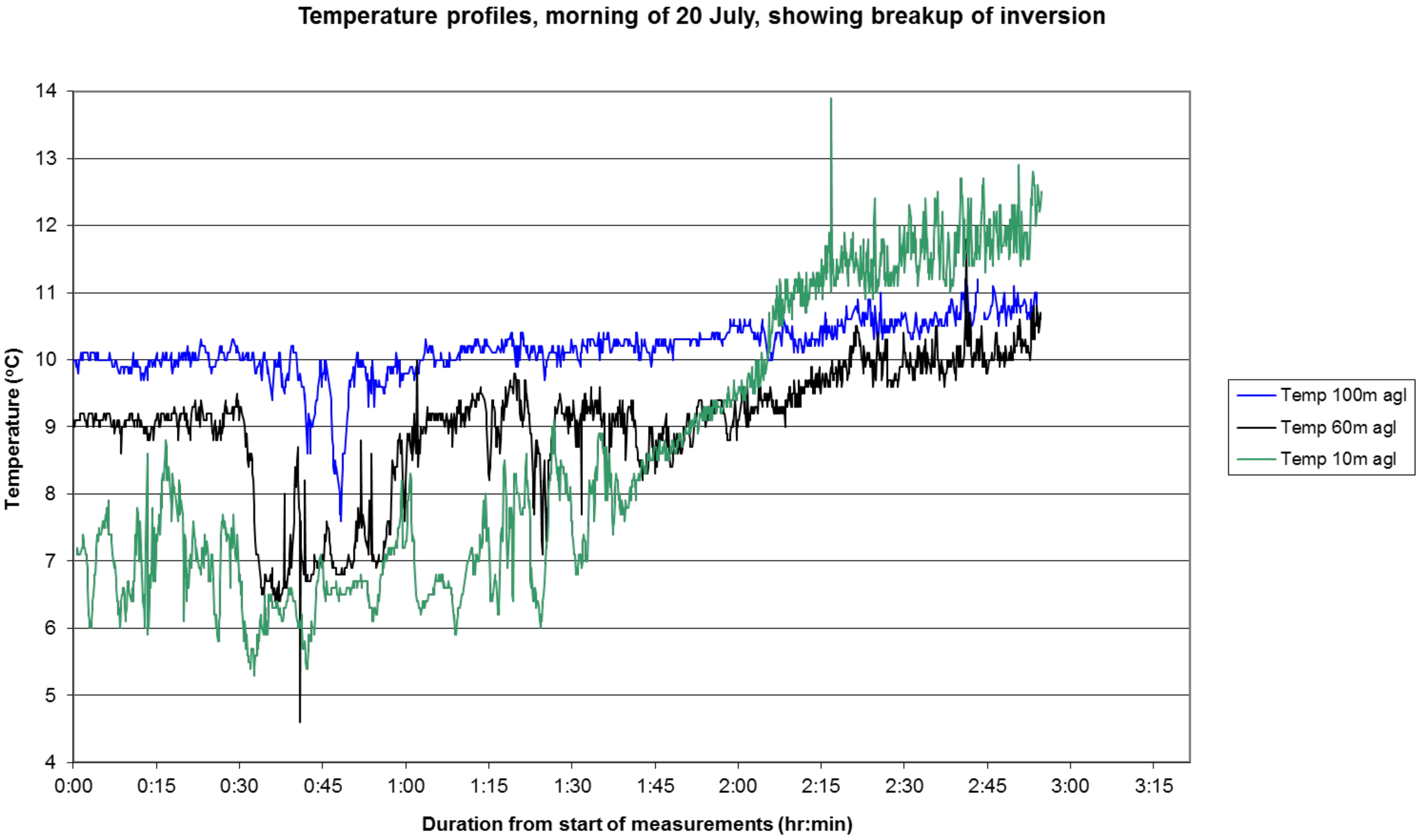
World Meteorological Organization 2006, *Guide to Meteorological Instruments and Methods of Observation WMO-8*, Secretariat of the World Meteorological Organization, Geneva, Switzerland

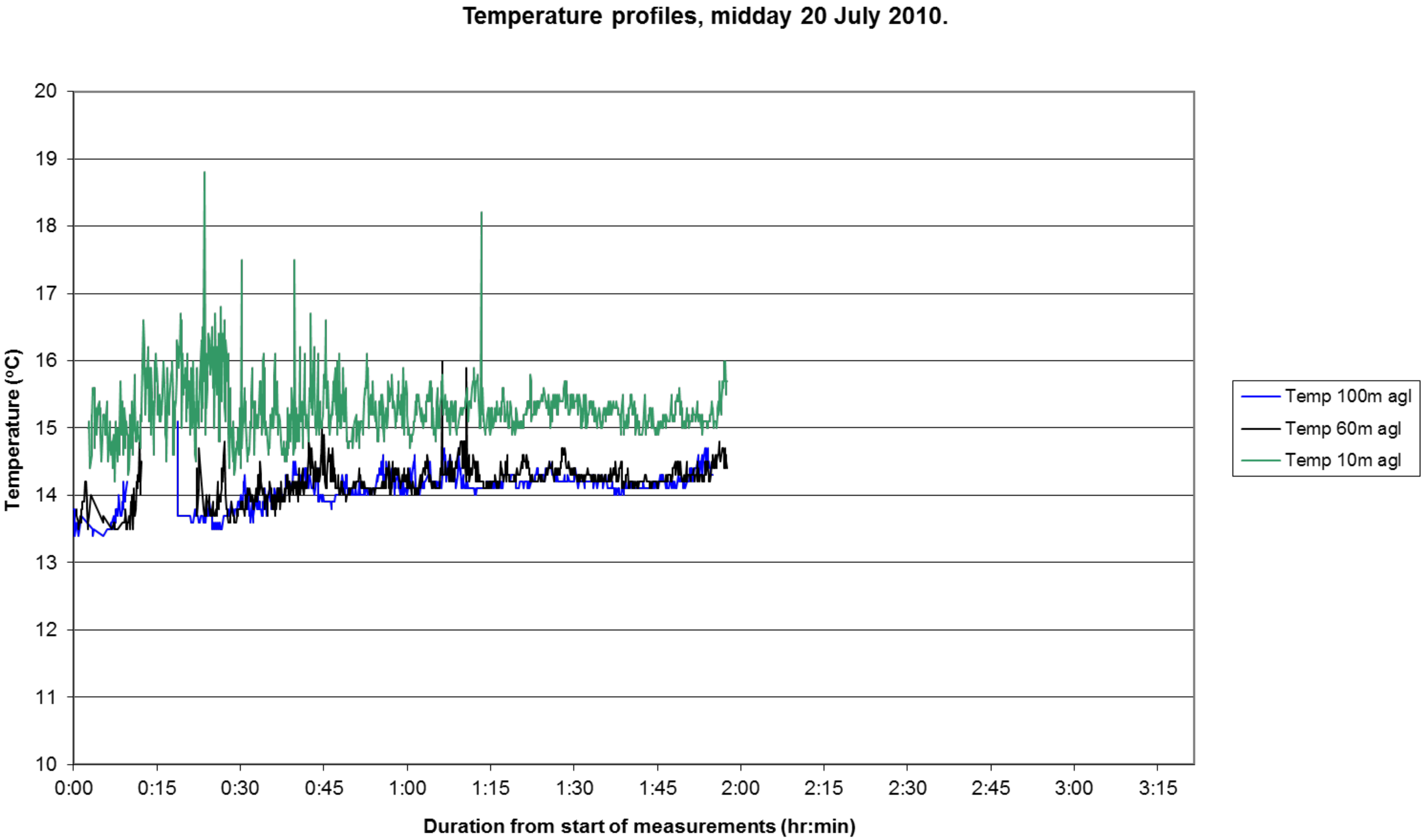
Appendix A Graphical presentations of inversion measurement results

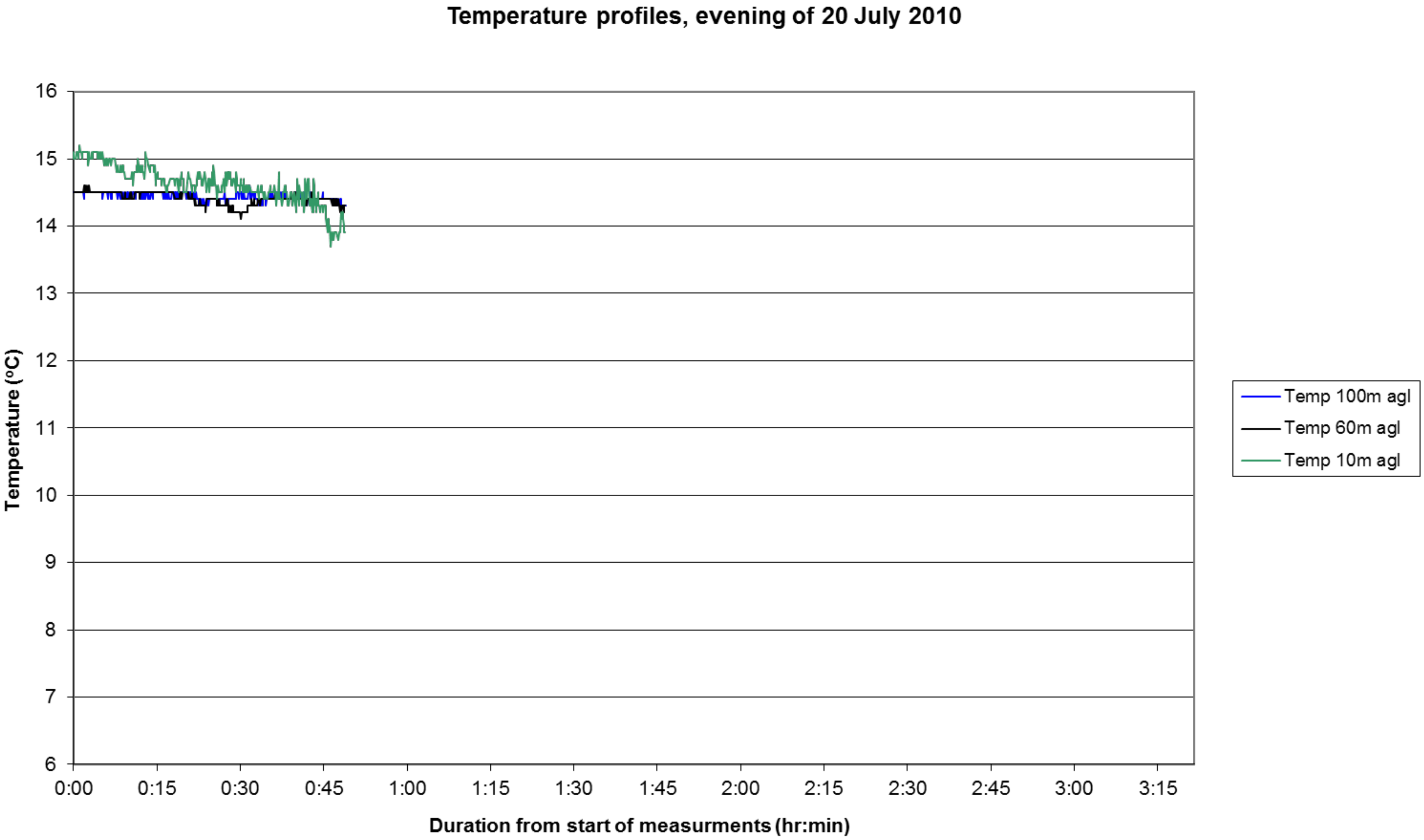

Temperature profiles, morning 19 July 2010.
Temperature (ºC)
11
10
9
8
7
6
5
4
3
2
1
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl

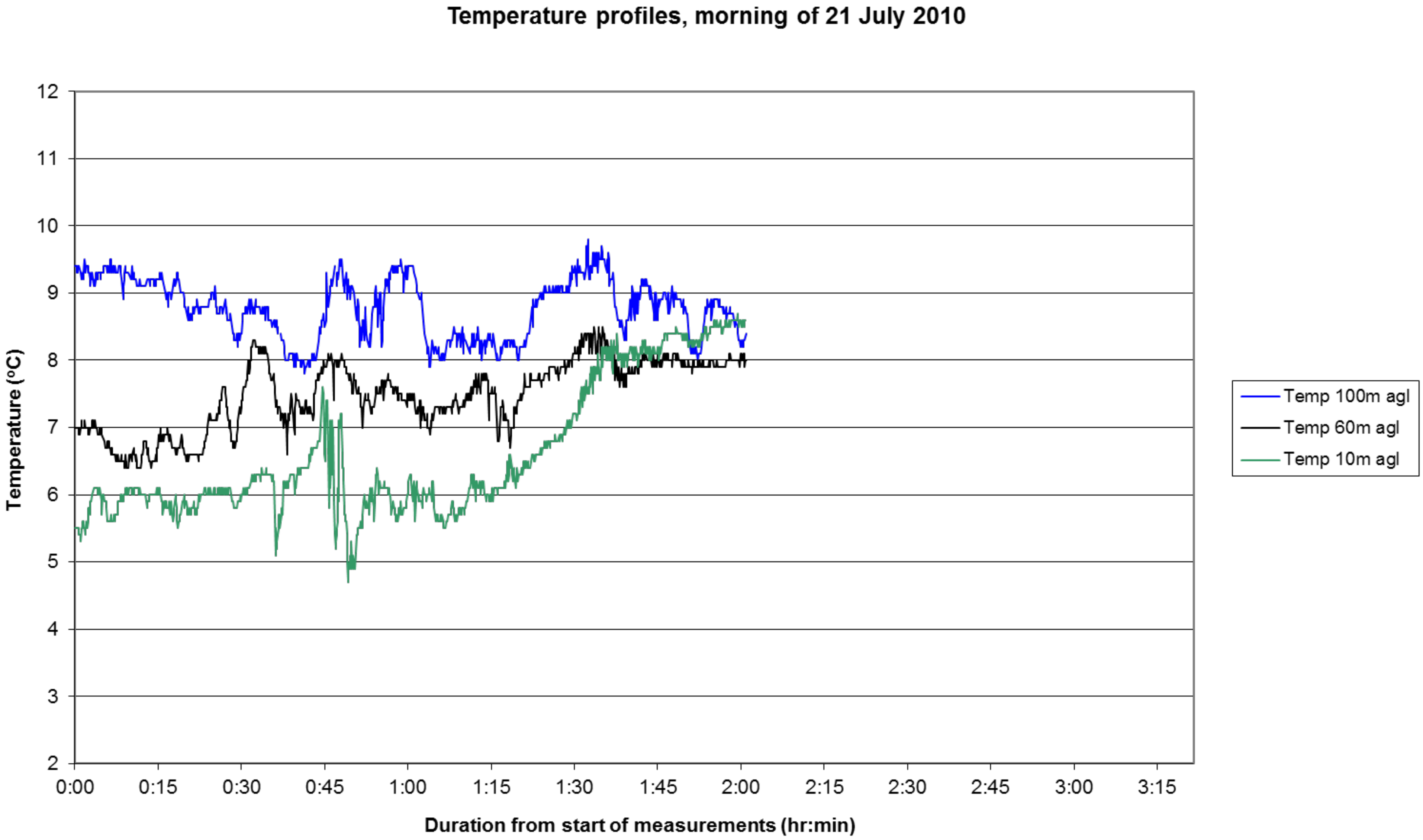

Temperature profiles, midday 19 July 2010
Temperature (ºC)
16
15
14
13
12
11
10
9
8
7
6
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl


Temperature profiles, evening of 19 July 2010
Temperature (ºC)
17
16
15
14
13
12
11
10
9
8
7
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100 agl
Temp 60m agl
Temp 10m agl

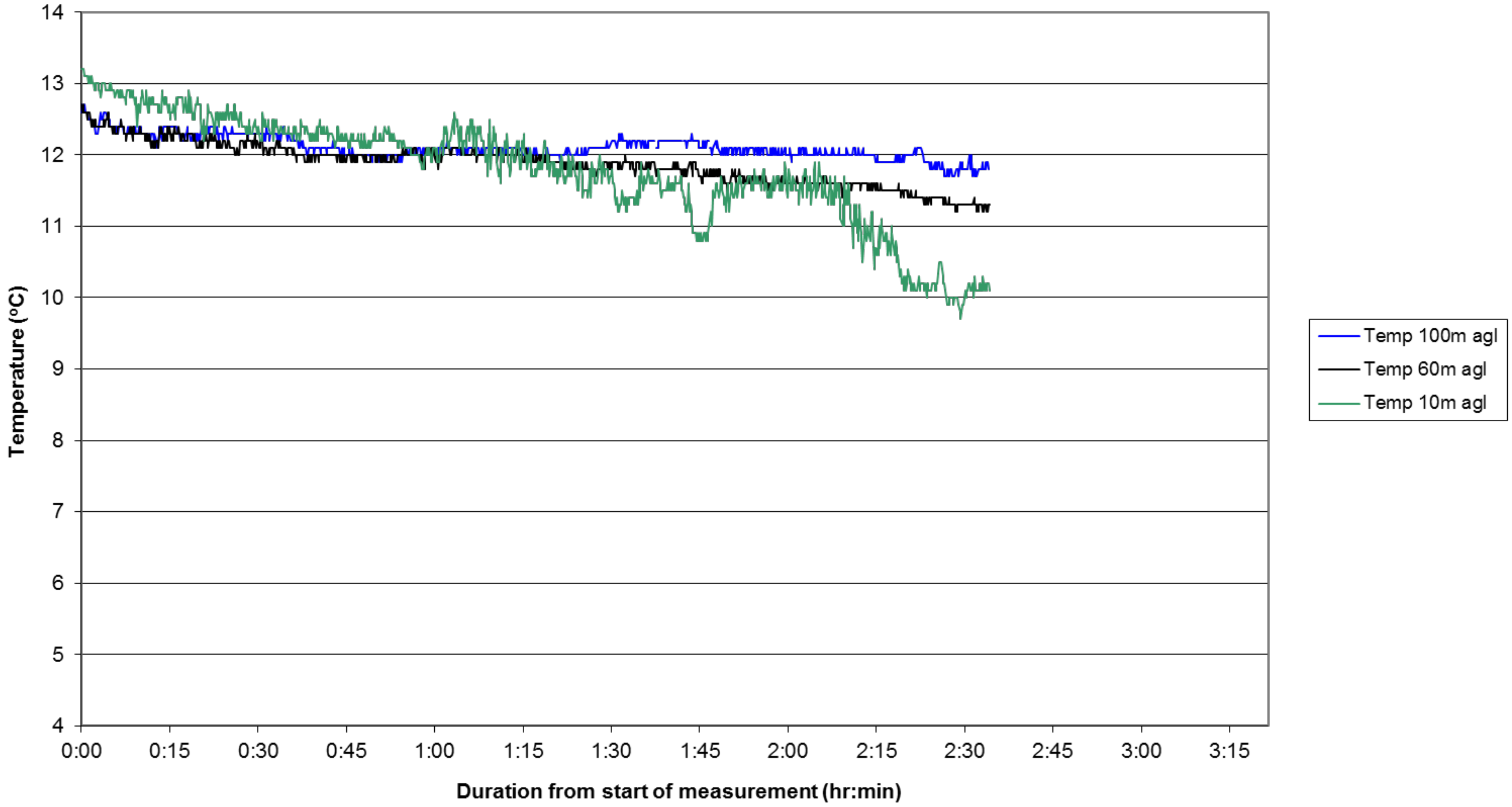

Temperature profiles, morning of 20 July, showing breakup of inversion
Temperature (°C)
14
13
12
11
10
9
8
7
6
5
4
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl

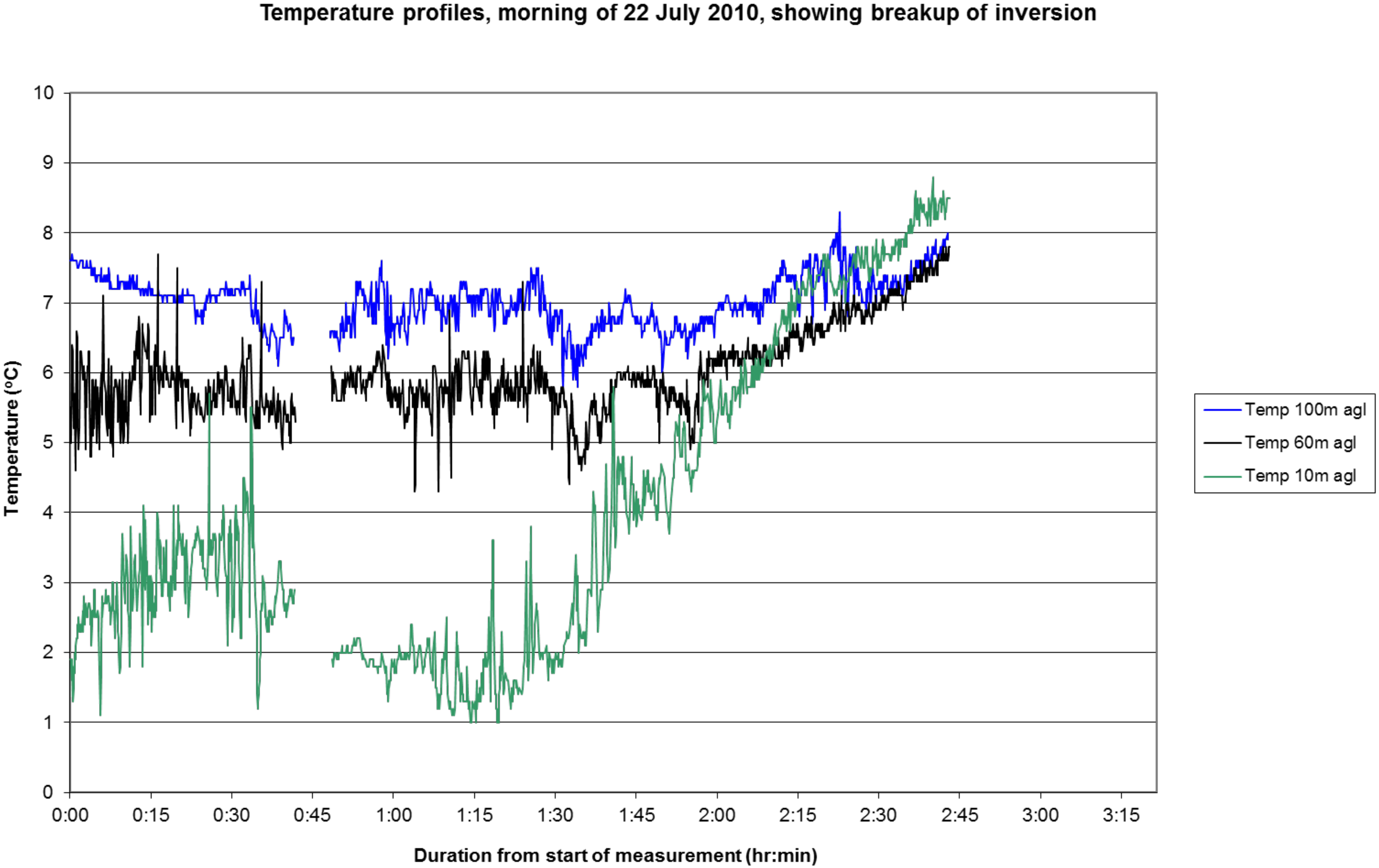

Temperature profiles, midday 20 July 2010.
Temperature (°C)
20
19
18
17
16
15
14
13
12
11
10
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl

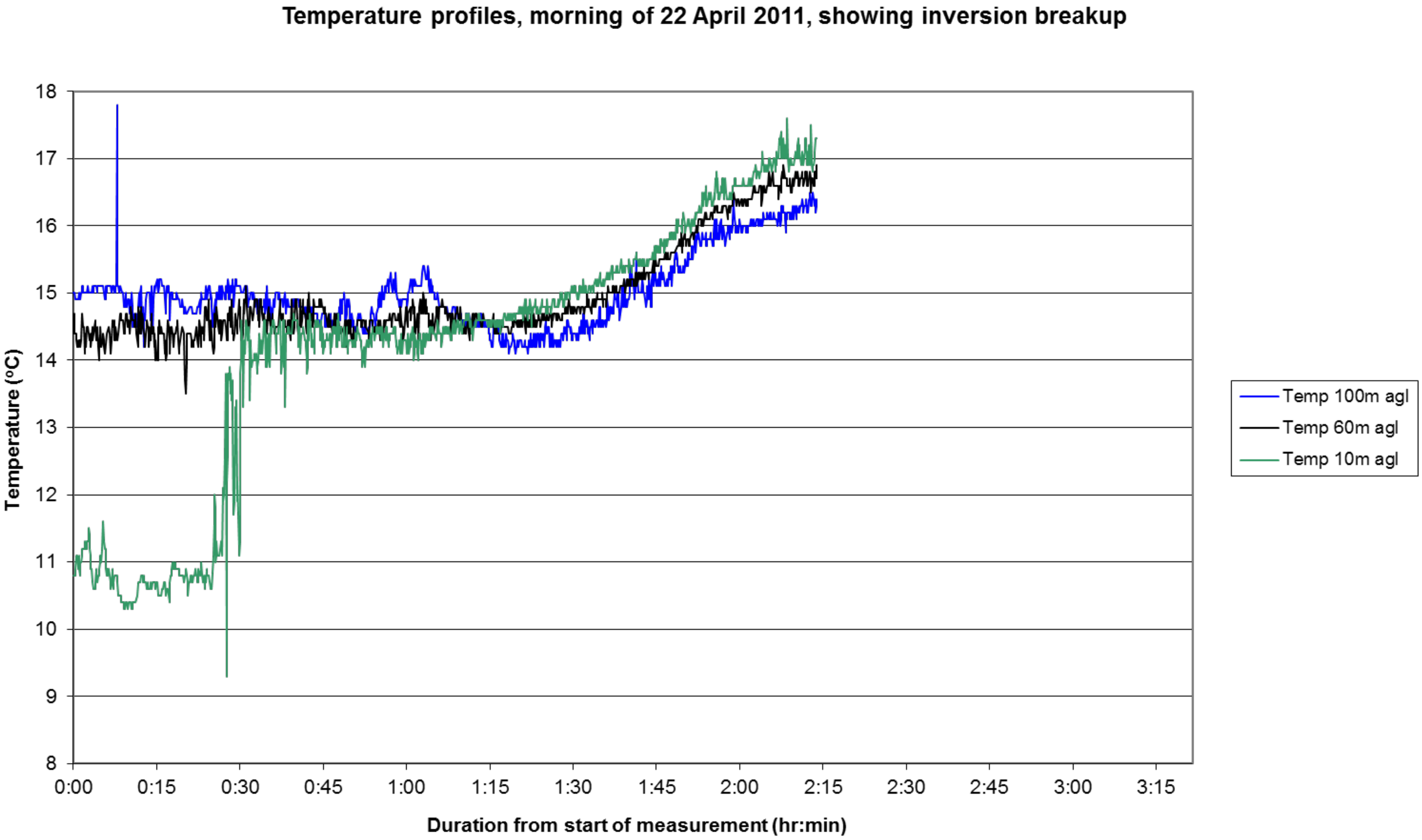

Temperature profiles, evening of 20 July 2010
Temperature (°C)
16
15
14
13
12
11
10
9
8
7
6
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurments (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl

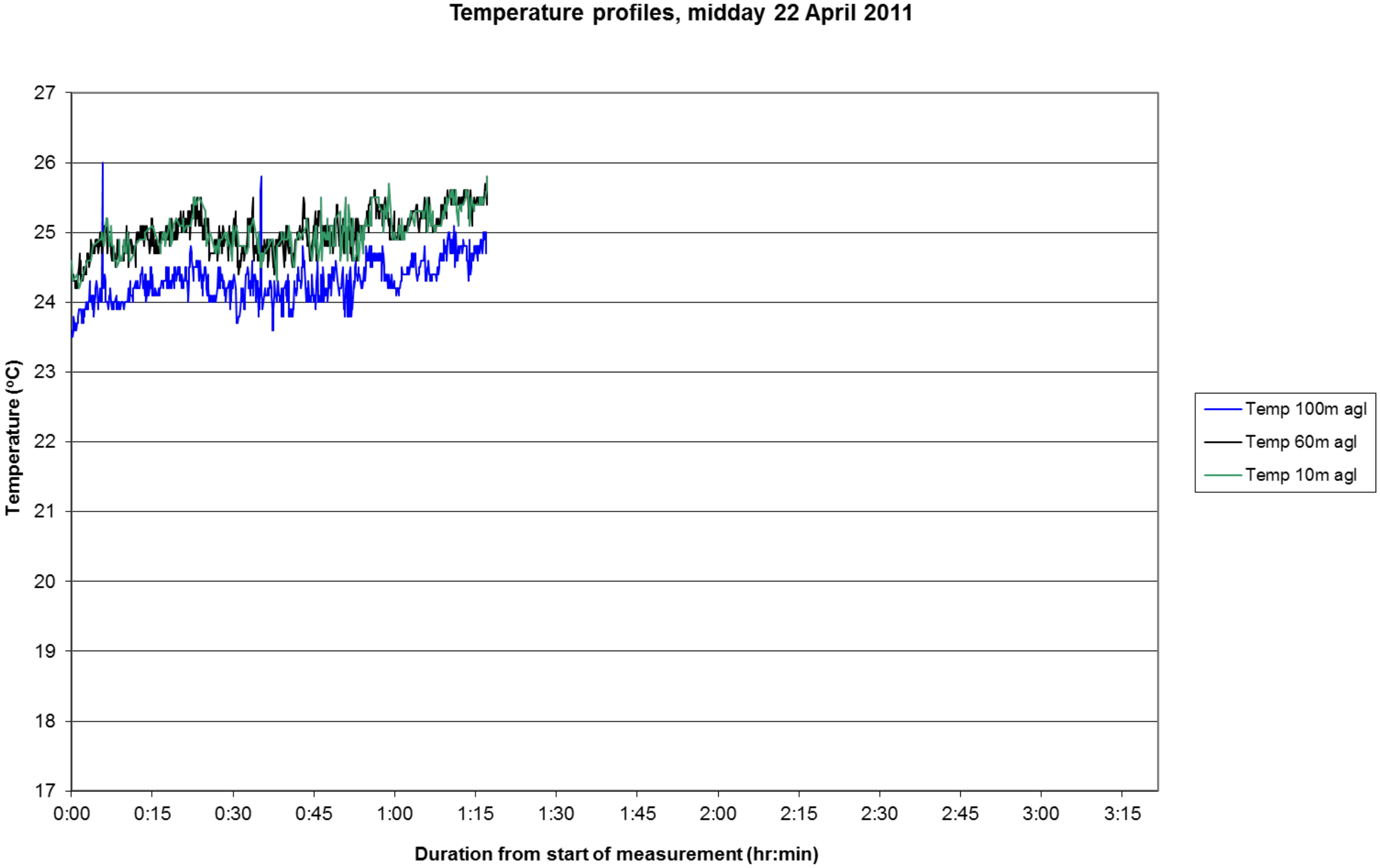

Temperature profiles, morning of 21 July 2010
Temperature (ºC)
12
11
10
9
8
7
6
5
4
3
2
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl

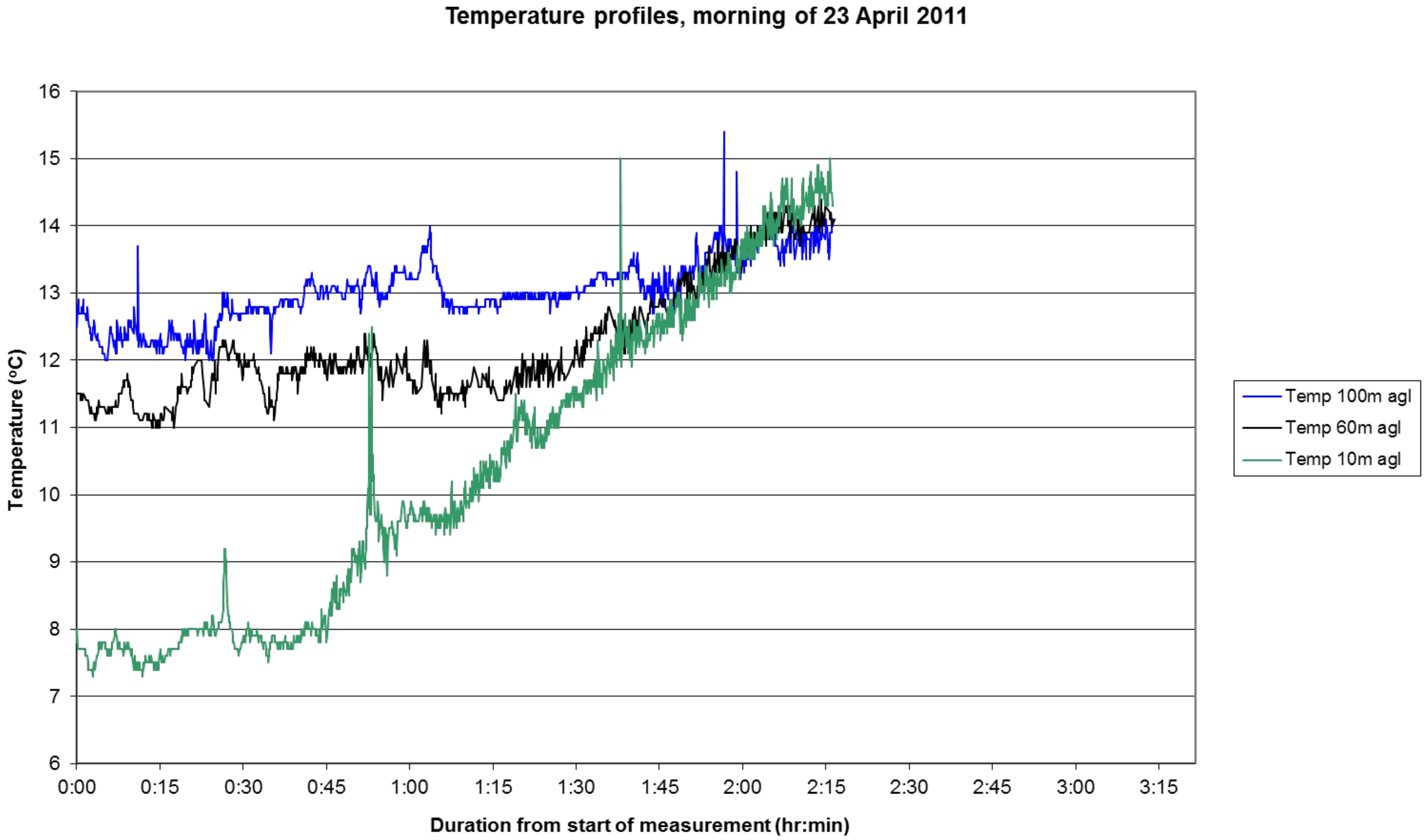
Temperature profiles, evening of 21 July 2010

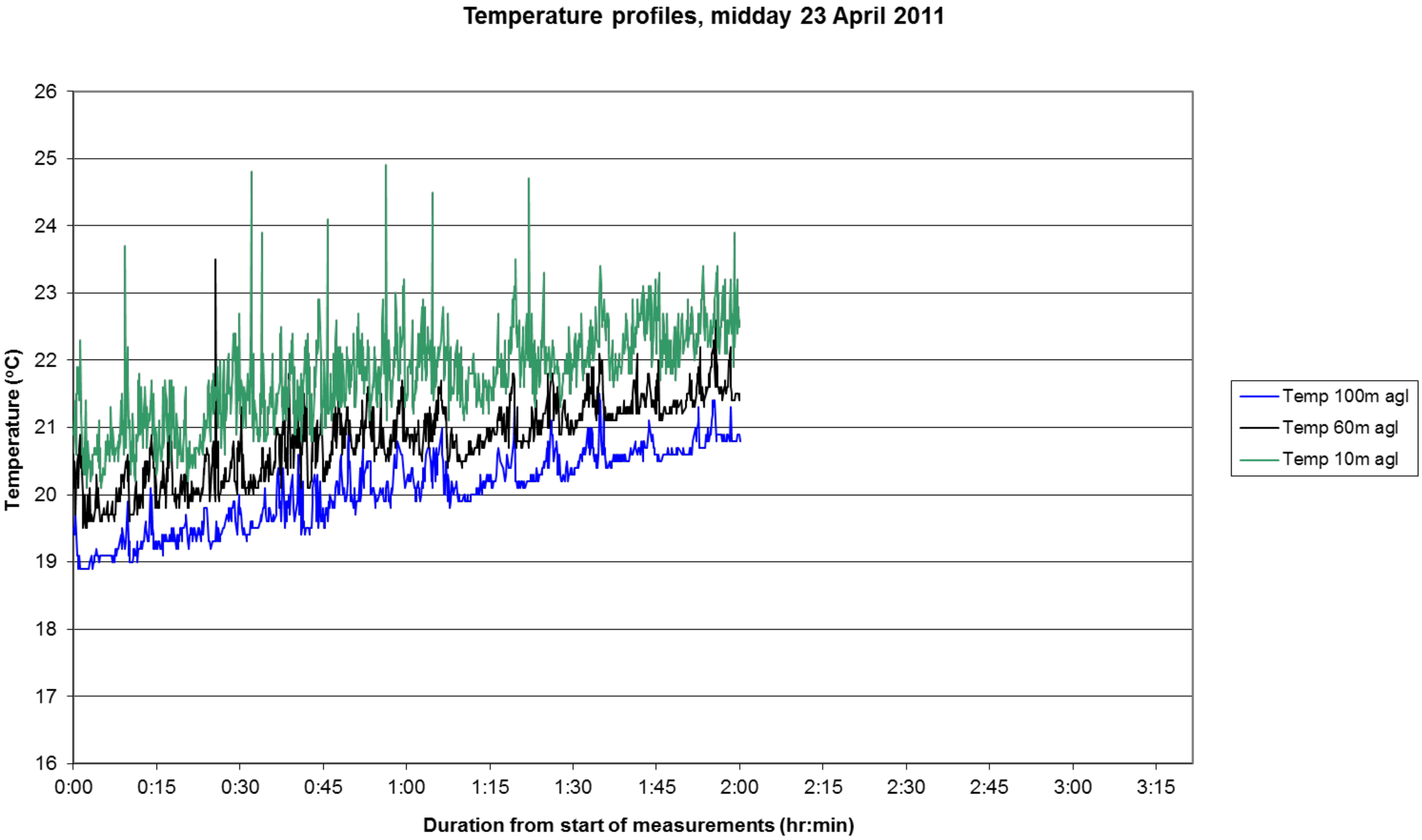


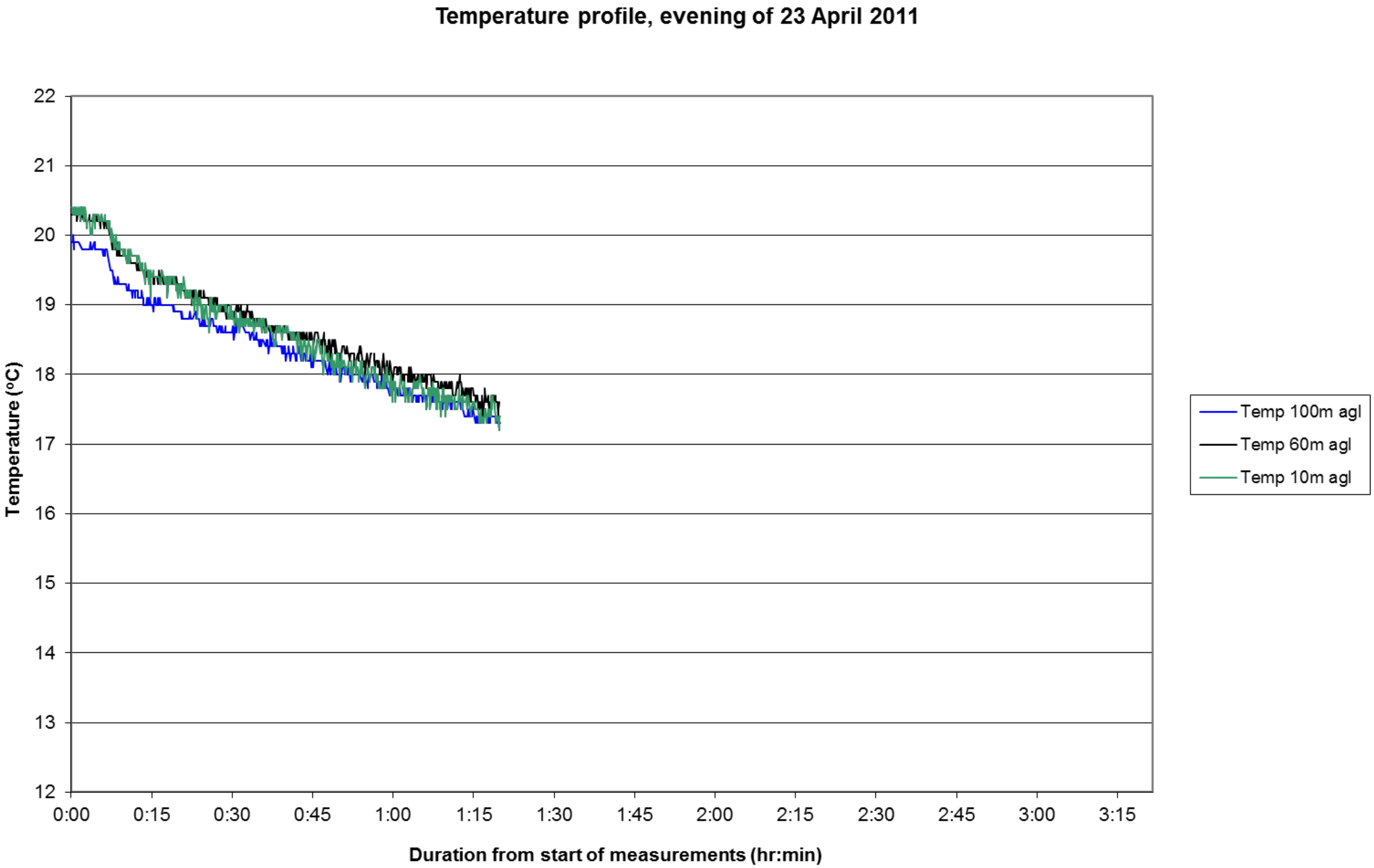

Temperature profiles, morning of 22 July 2010, showing breakup of inversion
Temperature (ºC)
10
9
8
7
6
5
4
3
2
1
0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurement (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl

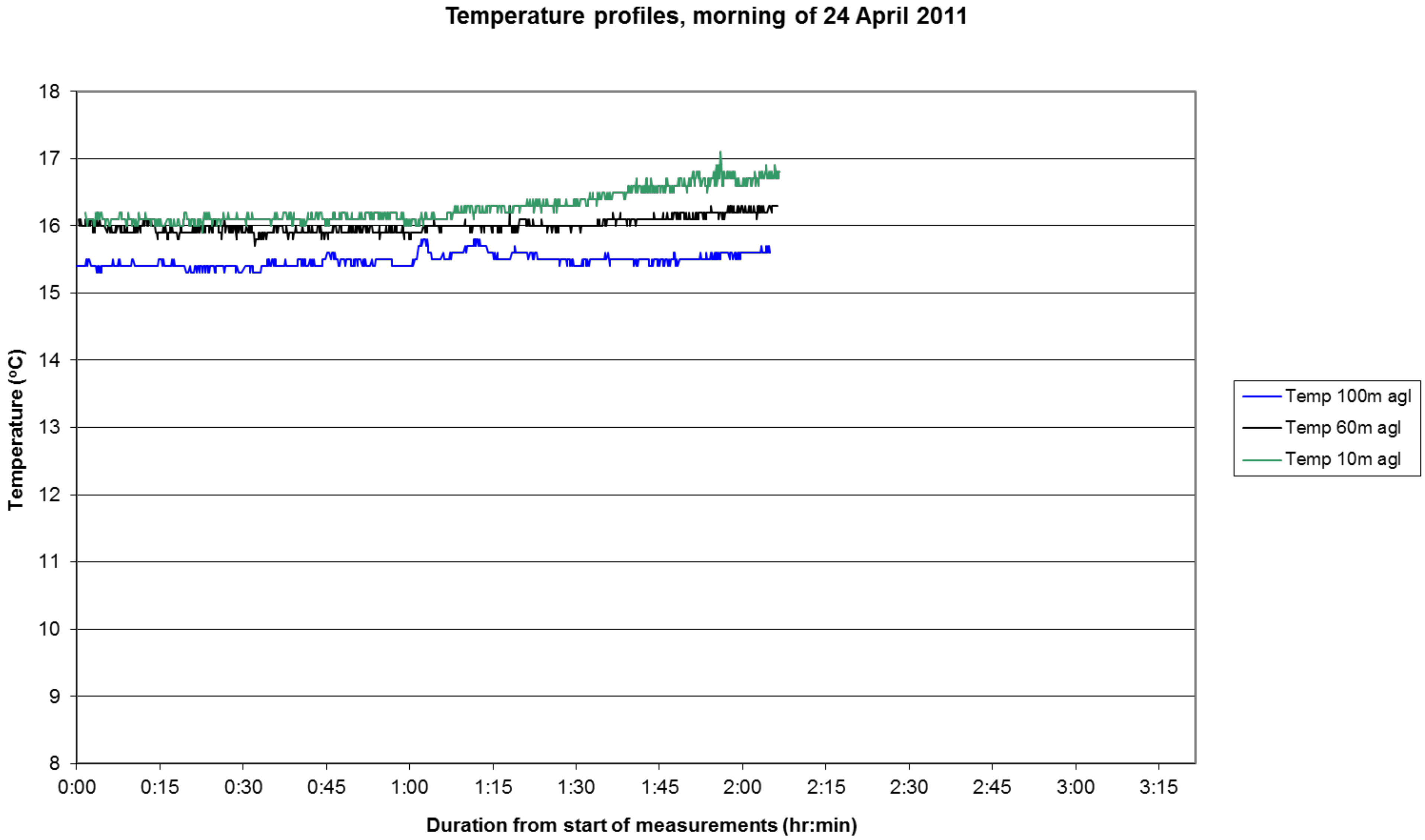

Temperature profiles, morning of 22 April 2011, showing inversion breakup
Temperature (ºC)
18
17
16
15
14
13
12
11
10
9
8
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurement (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl

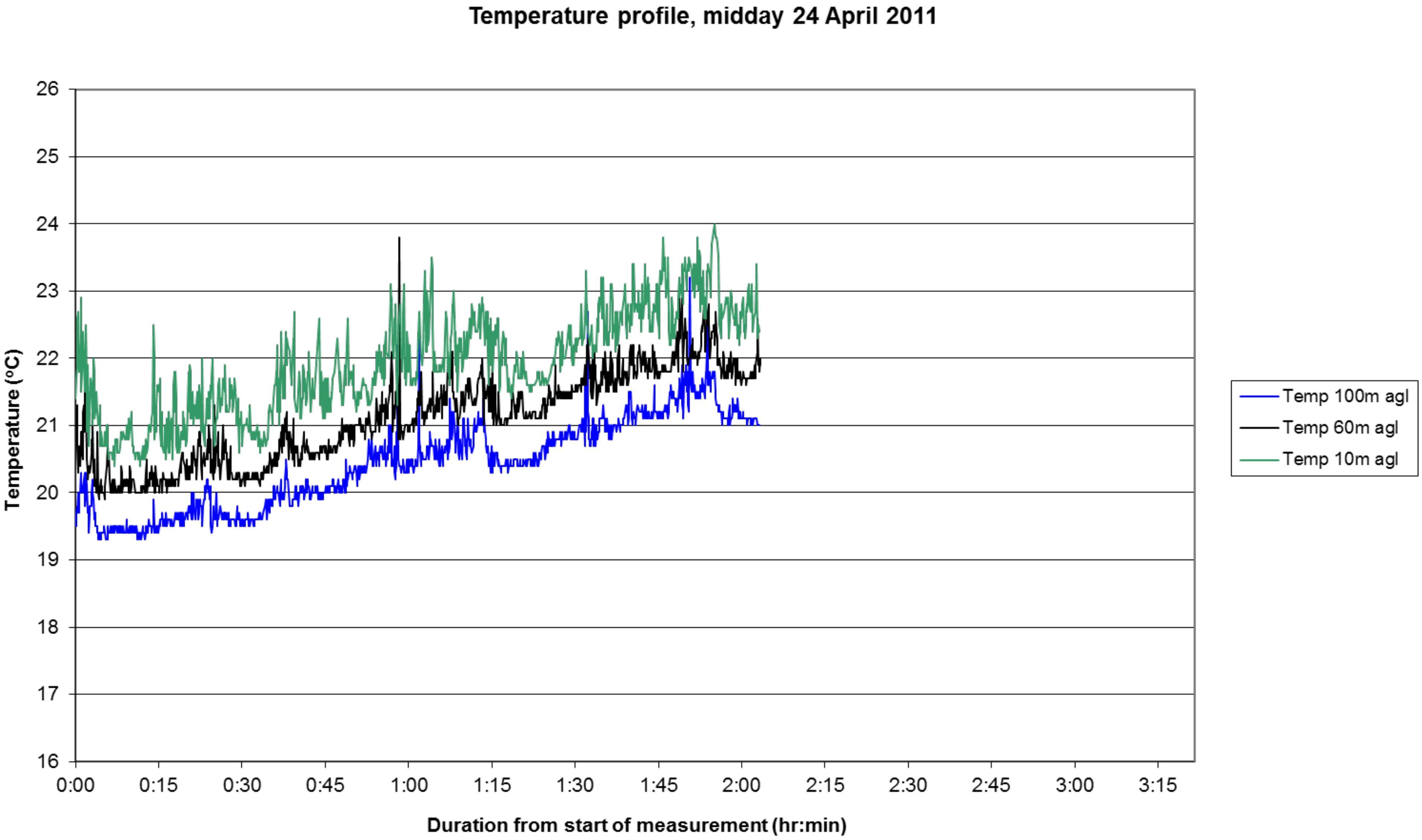

Temperature profiles, midday 22 April 2011
Temperature (°C)
27
26
25
24
23
22
21
20
19
18
17
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurement (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl

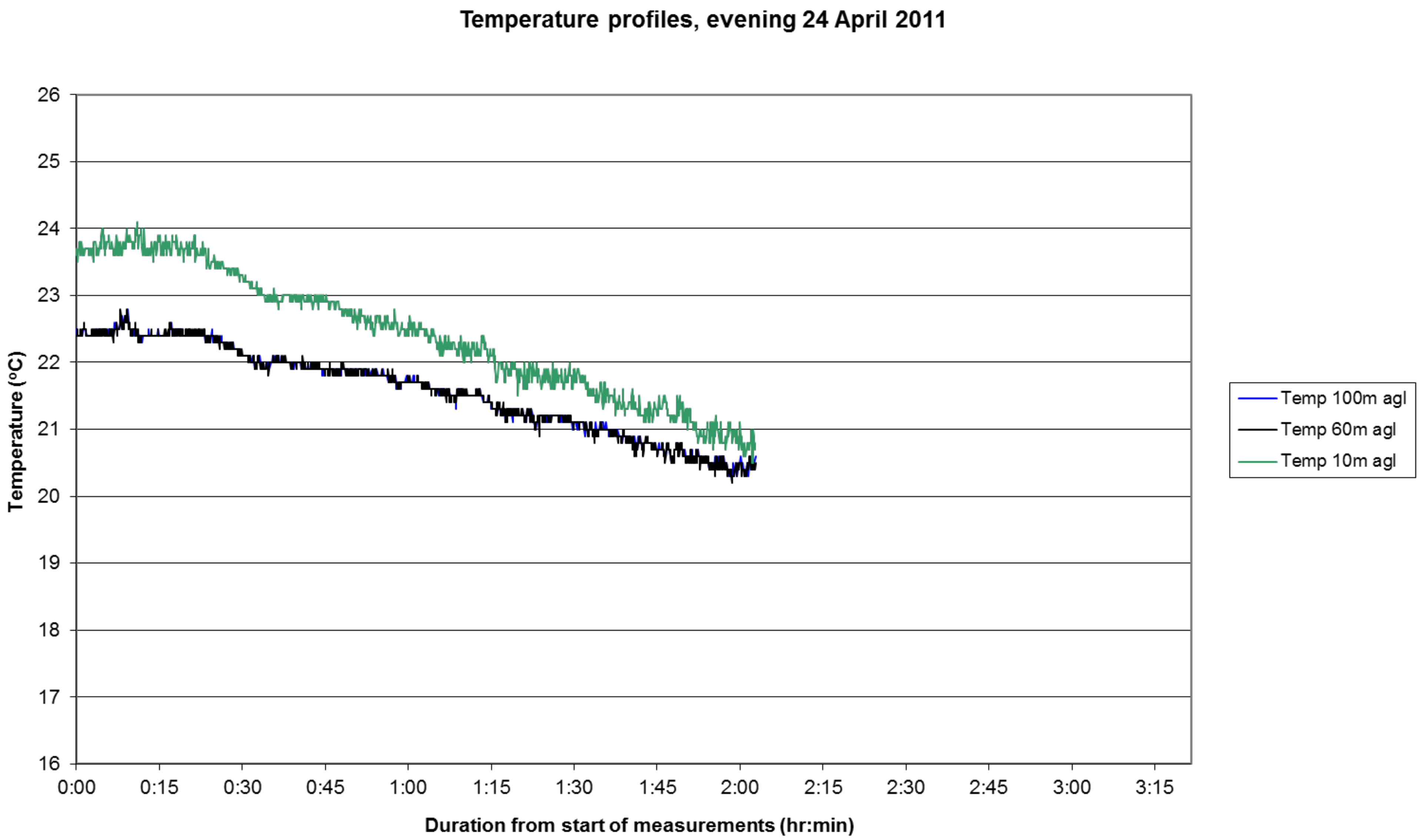

Temperature profiles, morning of 23 April 2011
Temperature (ºC)
16
15
14
13
12
11
10
9
8
7
6
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurement (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl


Temperature profiles, midday 23 April 2011
Temperature (ºC)
26
25
24
23
22
21
20
19
18
17
16
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl


Temperature profile, evening of 23 April 2011
Temperature (°C)
22
21
20
19
18
17
16
15
14
13
12
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl


Temperature profiles, morning of 24 April 2011
Temperature (ºC)
18
17
16
15
14
13
12
11
10
9
8
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl


Temperature profile, midday 24 April 2011
Temperature (ºC)
26
25
24
23
22
21
20
19
18
17
16
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurement (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl


Temperature profiles, evening 24 April 2011
Temperature (ºC)
26
25
24
23
22
21
20
19
18
17
16
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
3:15
Duration from start of measurements (hr:min)
Temp 100m agl
Temp 60m agl
Temp 10m agl

Appendix B Electronic copy of Access MQ raw data (read only)

See www.epa.nsw.gov.au/noise/140011invstrength.htm