IMPLICATIONS OF INCREASING TROPOSPHERIC BACKGROUND OZONE CONCENTRATIONS FOR VEGETATION IN THE U.K.

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A review for DEFRA under contract EPG 1/3/173: Development and Application of Methods for Modelling and Mapping Ozone Deposition and Flux in Europe

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1. Arrochar Alps and Loch Lomond from Beinn Breac, 2. Glen Feshie, Cairngorms, Scotland both from the Scottish Mountain Photo Gallery (http://www.gla.ac.uk/medicalgenetics/gallery.htm), 3. bluebells and woodland by Loch Tay, Perthshire, Scotland (M Coyle) and 4. ripe wheat at Sutton Bonnington, Nottingham, England (M Coyle).

May 2002

CONTENTS

Executive Summary

1. Analysis of UK monitoring data conducted for the NEGTAP report demonstrates that peak ozone concentrations have declined over the past decade, while mean concentrations have increased, as predicted by global ozone models.

2. This report assesses the implications of these trends for changes in ozone exposure profiles over the period to 2100, focussing on exposure indices of relevance for assessment of effects on vegetation.

3. A method was developed to simulate diurnal and seasonal exposure patterns in 2030, 2060 and 2100 at eight current rural monitoring sites, which were selected to be representative of the UK.

4. The effects of changes in mean ozone concentration on the frequency distribution of concentrations are particularly marked around the value of 40 ppb which has been identified as critical for effects on vegetation. The percentage of daylight hours above 40 ppb is predicted to change from 7-21% (depending on site) in 1996-2000 to 11-40% in 2030 and 38-92% in 2100. This leads to exceedance of the critical level for effects on crops and semi-natural vegetation at all but one site in 2030 and for forests at all but one site in 2060.

5. The large increases in ozone exposure predicted for 2060 and 2100 have significant implications for effects on vegetation but need to be considered in the context of other significant changes in climate and atmospheric composition. Therefore, analysis in this report focuses on the more immediate issue of the significance of changes predicted over the period 2000-2030.

6. Recent developments in relating external ozone concentration to the ozone flux into the leaf, which is thought to be more closely related to adverse effects on vegetation, suggest that biologically significant fluxes for sensitive vegetation may occur with external concentrations in the range 20-30ppb. Thus, the predicted increases in background concentrations in the UK, which are typically in the range 20-40ppb, may significantly increase flux and effects for such species by 2030.

7. Few experimental studies have investigated effects on vegetation at mean concentrations in the range 20-50ppb without including some peak exposures. Thus, there is little direct evidence of the effects of predicted changes in background concentrations. However, a small number of studies do demonstrate the potential adverse effects of concentrations in the range 40-50ppb.

8. The predicted increases in background concentrations are greatest in winter and early spring and least in mid-summer, when peaks from local or regional precursor emissions are most important. The changing seasonal pattern of exposure will significantly alter current assessments of the risks of ozone impacts, with species that grow actively over winter and early spring being at increased risk of damage.

9. This review has identified large gaps in current knowledge which make it almost impossible to predict the impacts of changes in background ozone concentrations on vegetation. However, the review clearly indicates that these impacts could be substantial and it is clear that further research is urgently needed to improve the scientific basis of any future assessment.

10. The priorities for further research include new experimental studies, both in the field and in controlled experimental chambers, and the use of flux modelling. This research needs to be focussed on species and communities which, because of their location and seasonal development patterns, are likely to be particularly affected by increases in background ozone concentrations, and especially upland plant communities.

11. A key policy conclusion from this review is that the AOT40 concept, which is used in current risk assessment for ozone in Europe, cannot capture the effects of changing ozone exposure caused by increased background concentrations. It therefore needs to be replaced either by a flux-based approach or an exposure index which includes the contribution of concentrations in the range 20-40ppb.

1. Introduction

The recent report to DEFRA of the National Expert Group on Transboundary Air Pollution has identified a number of important changes in the pollution climate of the UK (NEGTAP, 2001). Among these is a clear signal that peak ozone concentrations declined by about 30% over the past decade, probably reflecting reduced regional precursor emissions. However, there is also evidence of an increase in annual mean concentrations, of about 0.1ppb yr^{-1}.

This increase in annual mean concentrations may reflect the impact of global increases on background concentrations, driven by global increases in precursor emissions. Predictions from the global three-dimensional Langragian chemistry model, STOICHEM, run with emission scenarios developed by the Intergovernmental Panel on Climate Change, predicted steady increases in background ozone concentrations both over the northern hemisphere (Stevenson et al., 2000) and for central England (NEGTAP, 2001). For central England, the STOICHEM estimate of an increase of 5ppb over the 40 year period from 1990 is broadly consistent with the trend of 0.1ppb yr^{-1} the 1990s identified by NEGTAP (2001).

To date, there has been no detailed analysis of the implications for vegetation in the U.K. of these changes in ozone exposure patterns, although the role of background ozone has been discussed in general terms in the context of global change (e.g. Ashmore & Bell, 1991). It is already established that ozone has significant adverse impacts on vegetation in southern and central England, but it is possible that these impacts could change substantially by 2030 given the trends referred to above. This brief review aims to provide a more rigorous assessment. In the first section, seasonal and diurnal ozone exposures are simulated for different parts of rural Britain. The implications of these exposures for vegetation are assessed in the second section, while a brief final section evaluates the implications for ozone risk assessment and for future research priorities.

2. Predicted Changes in Background Concentrations

2.1. Introduction

Ozone measurements from the national air-quality monitoring network show that peak ozone levels are declining while average concentrations are increasing, as predicted by ozone models (NEGTAP 2001). The implications of these changes in the ozone climate, for UK vegetation are largely unknown. The following analysis uses the network measurements and model predictions to assess the likely changes in the frequency distribution of hourly ozone concentrations and the seasonal exposure of vegetation to concentrations in excess of 40 ppb. This is a necessary prerequisite to design experimental approaches to investigate the probable consequences of the future ozone climate.

2.2. Methodology and Results

Global models predict an increase in average surface ozone concentrations, mainly in the Northern hemisphere, and the magnitude of the increase varies throughout the year (Figure 1). Surface ozone concentrations in the UK consist of the background concentration with episodic peak values and variations due to meteorology superimposed. In this short study the effects of increasing the background ozone concentration have been simulated. Eight UK sites (Table 1) were selected to be representative of different ozone climates and vegetation. The background seasonal cycle for each site was extracted from the hourly ozone measurements by smoothing the daily average afternoon concentrations. The five most recent years available, 1996 to 2000, were selected (all sites have >75% data capture for every year except Wicken Fen where regular measurements did not start until late in 1997). The average of the 7 day running mean of the 1000 – 1800 h averages was taken to be representative of the background cycle. This background cycle was then enhanced using the monthly difference between 1990 and the future years from the STOCHEM model, plotted in Figure 1. Although the model prediction is for 1990, the emission scenario used is typical of current values and so the 1990 ozone concentrations can be considered as representative of the period 1996-2000. Figure 2 shows the measured data and enhanced seasonal cycles at each site.

Hourly average time series for the years 2030, 2060 and 2100 were constructed by:

1. Making an hourly average background time series by allocating a days 1996-2000 average 7-day running mean value to all 24 hours in that day.
2. Scaling the 2030, 2060 & 2100 series by the relative difference between the 1996-2000 background cycle and hourly averages of 1996-2000 data.

Figure 2 illustrates this method. The structure of the diurnal cycle and the amount of nocturnal ozone depletion is maintained and the daily index ((max – min)/average) remains the same for each data set although the daily range (max – min) increases with time. The increase in the daily range is greatest during the summer months when the diurnal cycle tends to be more pronounced, as shown in Figure 4. The influence of site altitude can also be seen in Figure 4 as the range increases as altitude decreases (the plots are ordered from highest altitude site to lowest). Figures 5a to h show the monthly mean diurnal cycles during 1996-2000, 2030, 2060 and 2100 for each site.

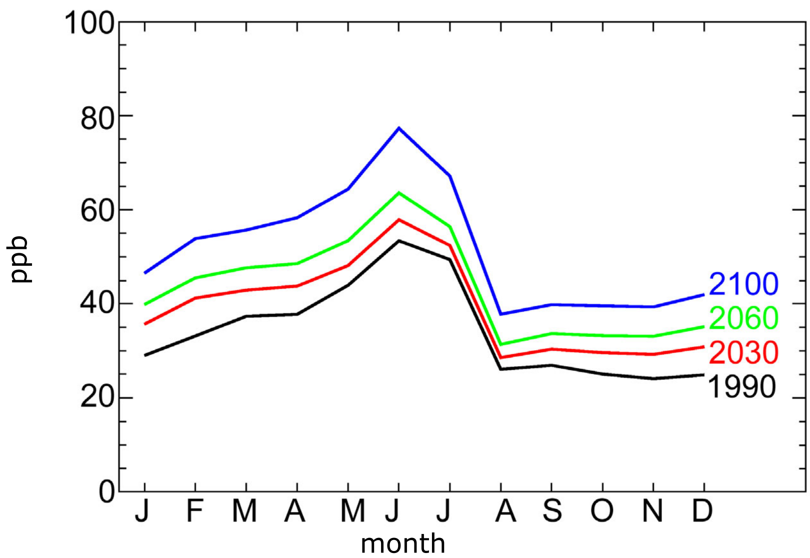

Figure 1. Monthly surface ozone concentrations (ppb) predicted by the STOCHEM model with the IPCC SRES A2 emission scenario, for a grid square covering central England (Stevenson, Johnson *et al*. 2000).

Table 1. Rural ozone monitoring sites

Full Name	Site Ref.	OS East, km	OS North, km	Altitude, m	Start	Description
Strath Vaich	SV	234.7	875	270	03/18/87	Remote hilly moorland, used for sheep-grazing.
Dunslair Heights	DH	328	643	600	06/13/92	On open hilltop, surrounded by forestry plantation.
Eskdalemuir	ES	323.5	602.8	269	04/23/86	Situated on open moorland adjacent (500 m) to Met Office Laboratory, surrounded by forestry plantations.
High Muffles	HM	477.6	493.9	267	07/16/87	Hilly moorland and forestry plantation.
Aston Hill	AH	329.8	290.1	370	06/26/86	On the summit of a hill with clear views of surrounding arable farmland.
Wicken Fen	WN	556.4	269.2	5	08/12/97	On edge of Wicken Fen, surrounding land flat (barely above sea level) and predominantly agriculture.
Somerton	SS	348.6	126.8	55	01/26/96	Located at Somerton Radio Station at the summit of a hill. In open pasture with minor roads 2 km south of Somerton.
Yarner Wood	YW	278.6	78.9	119	06/26/87	Undulating moorland with semi-natural broadleaved woodland.

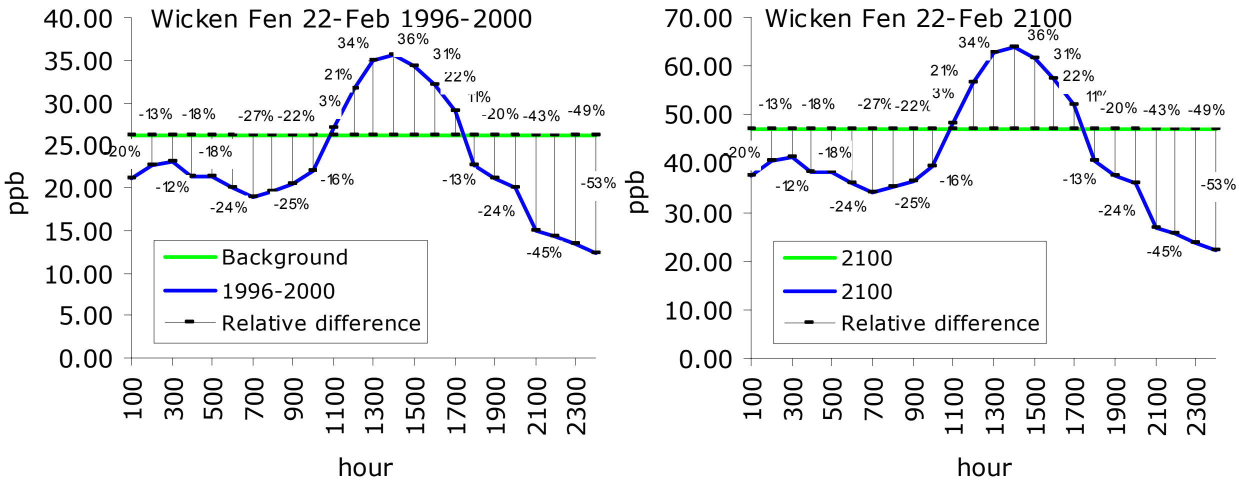

Figure 2. Illustration of the method used to construct hourly average annual data.

Figure 3.a.

Aston Hill

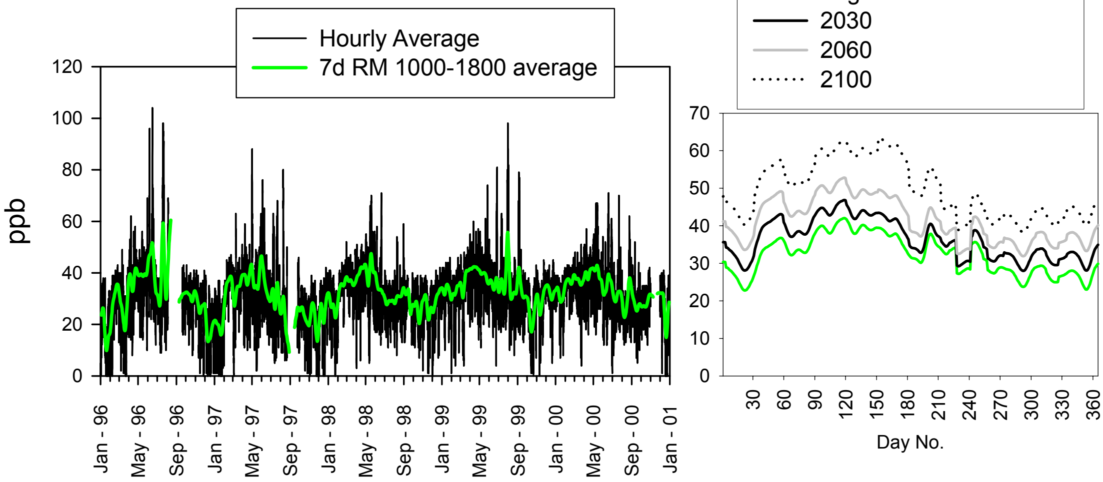

Figure 3.b.

Dunslair Heights

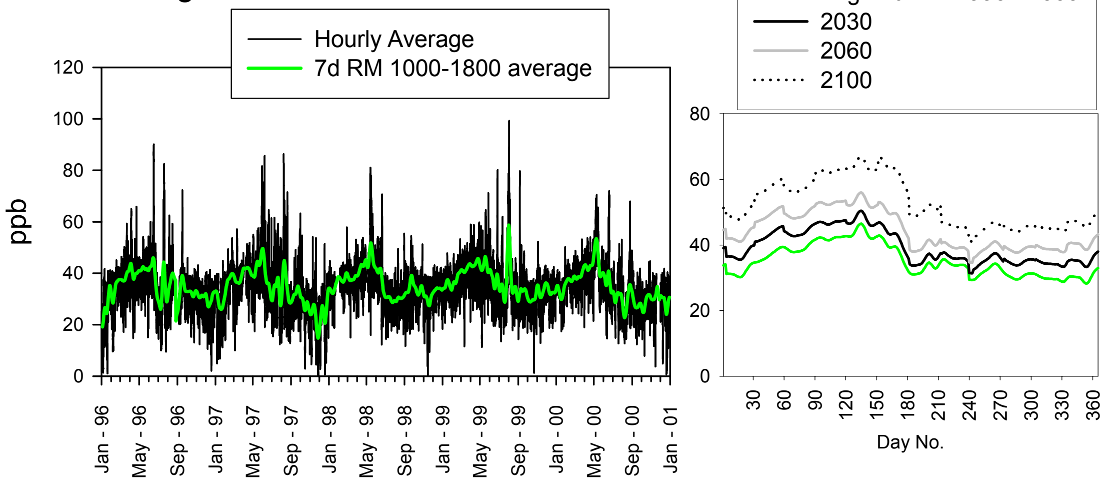

Figure 3.c.

Eskdalemuir

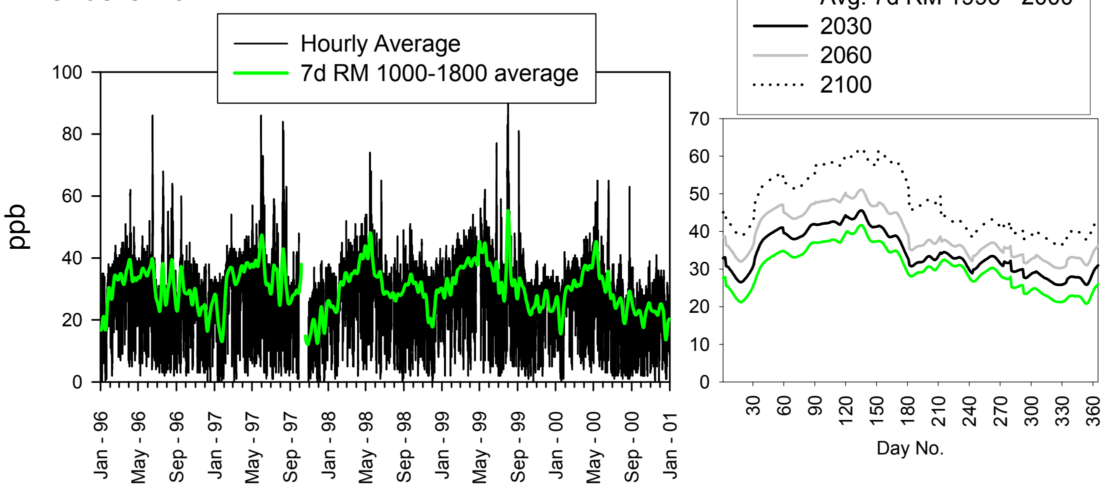

Figure 3.d.

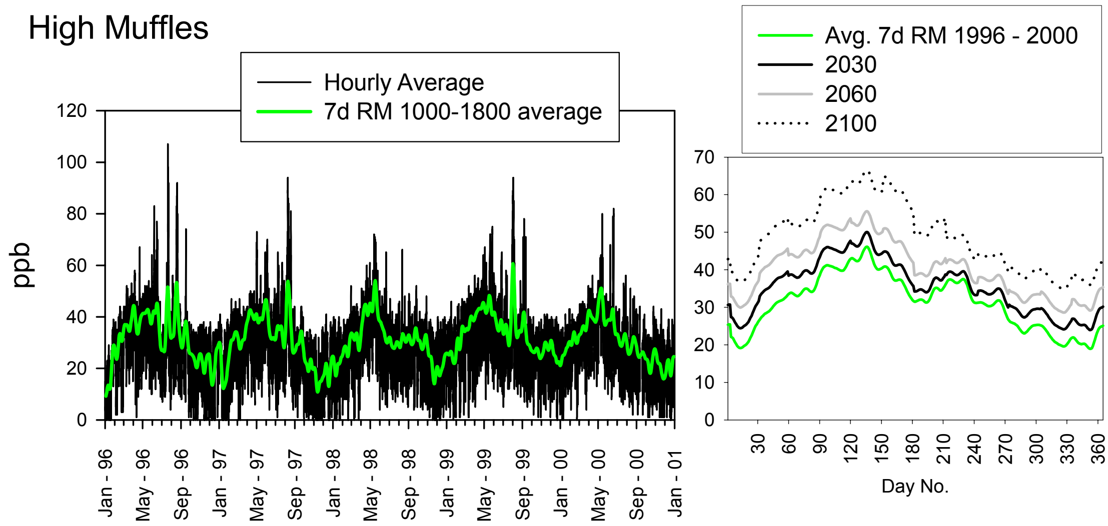

Figure 3.e.

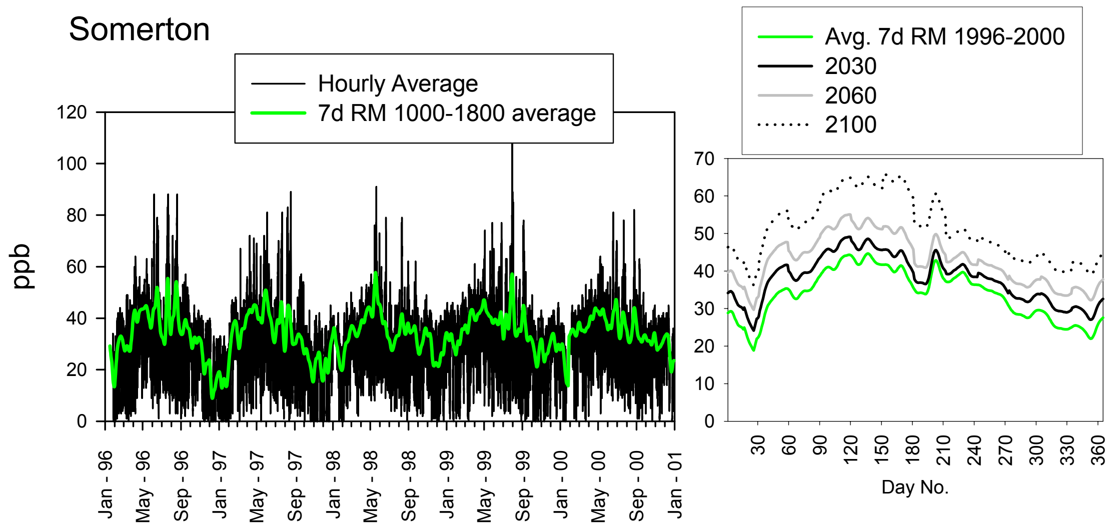

Figure 3.f.

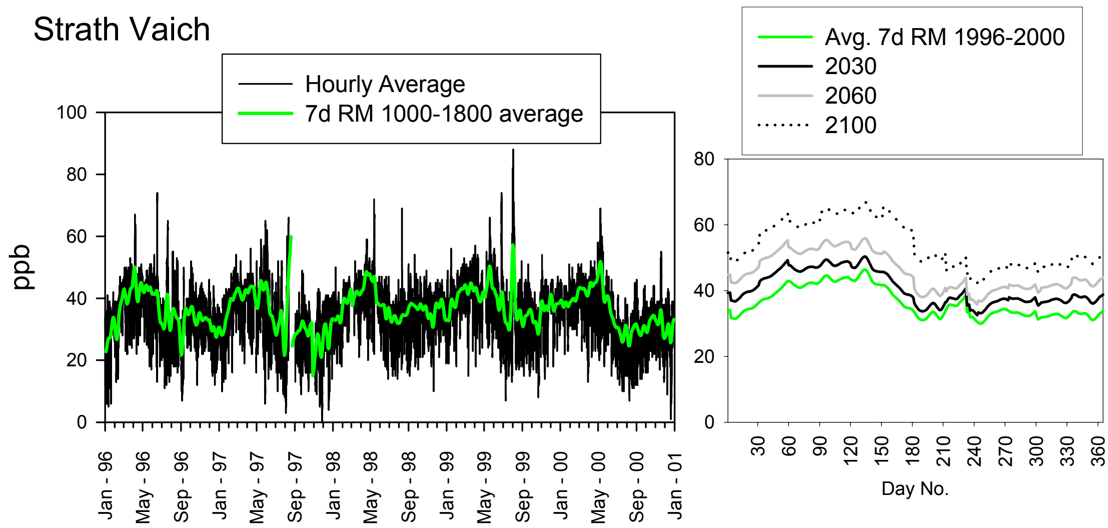

Figure 3.g.

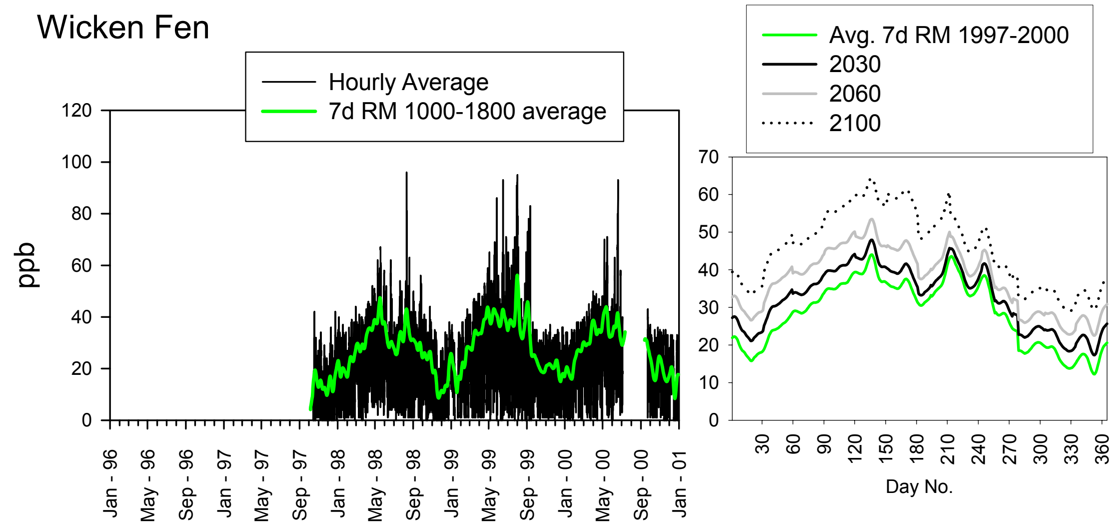

Figure 3.h.

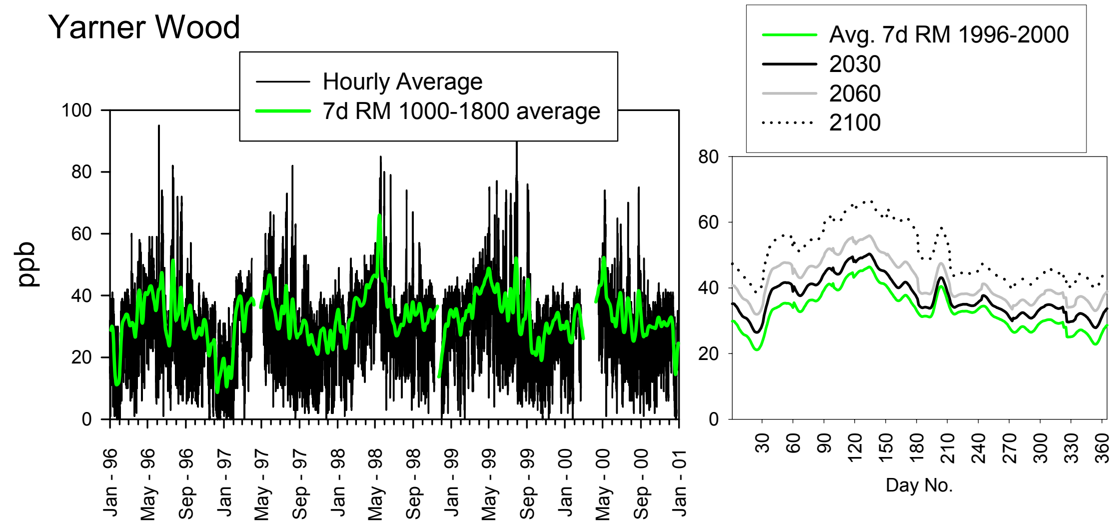

Figure 3. Hourly averages and 7 day running mean (7d RM) 1000-1800 h averages from 1996 to 2000. 1996-2000 average 7d RM and this cycle enhanced by the STOCHEM predictions shown in Figure 1 for 2030, 2060 and 2100.

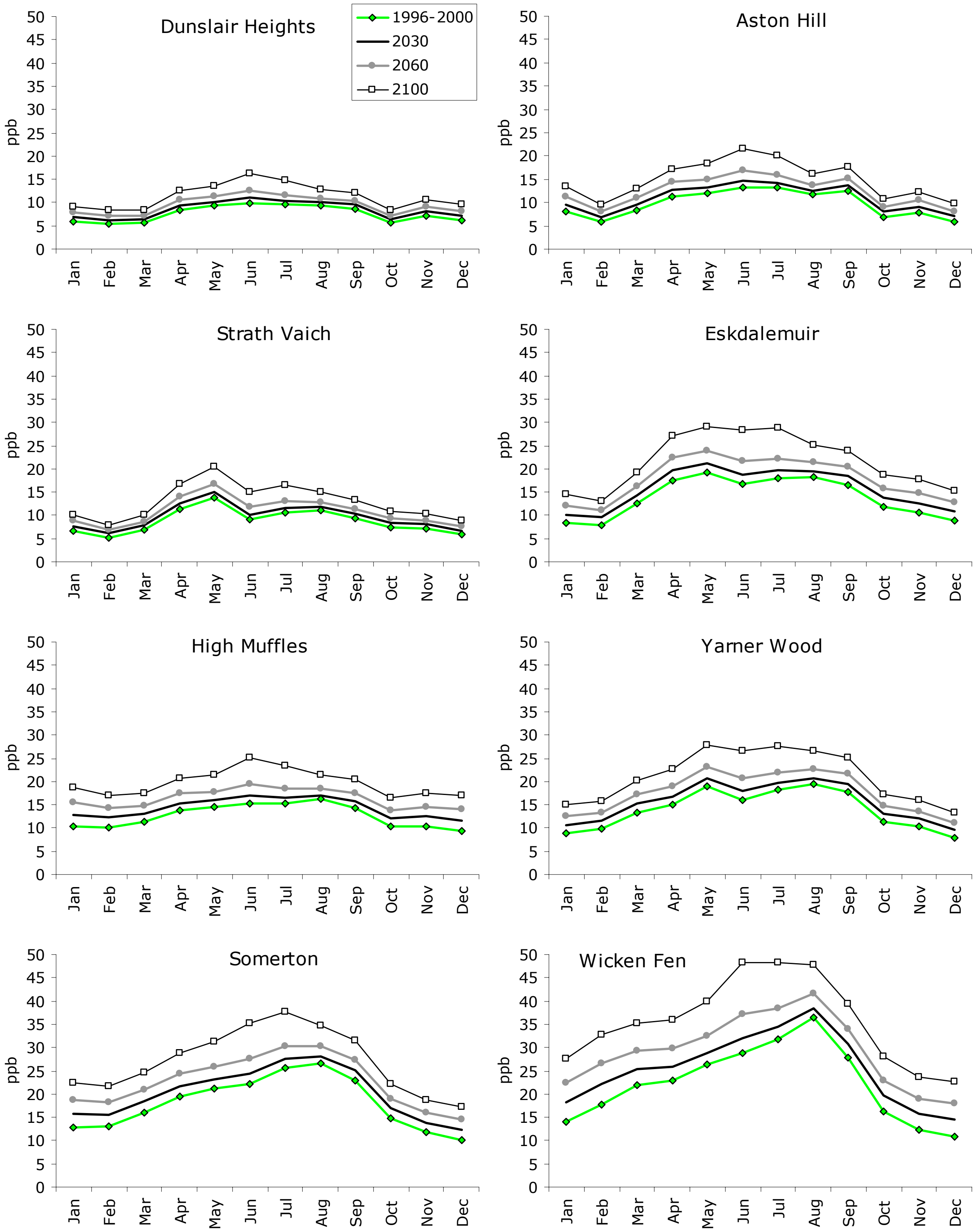

Figure 4. Monthly average daily range (max-min) in ozone concentration at each site for the 1996-2000 average, 2030, 2060 and 2100 data sets.

Figure 5.a. Aston Hill (x-axis = hour, y-axis = ppb)

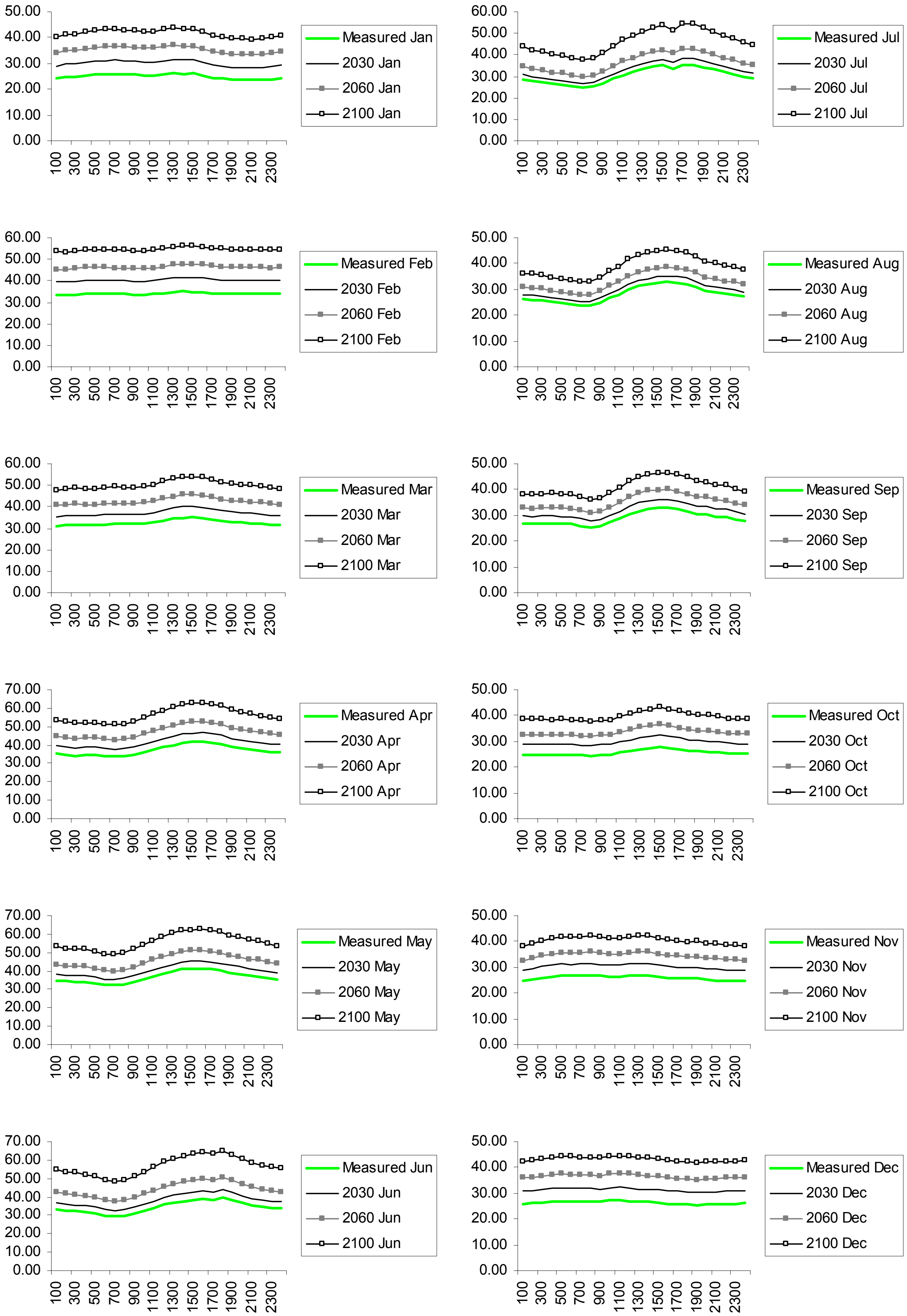

Figure 5.b. Dunslair Heights (x-axis = hour, y-axis = ppb)

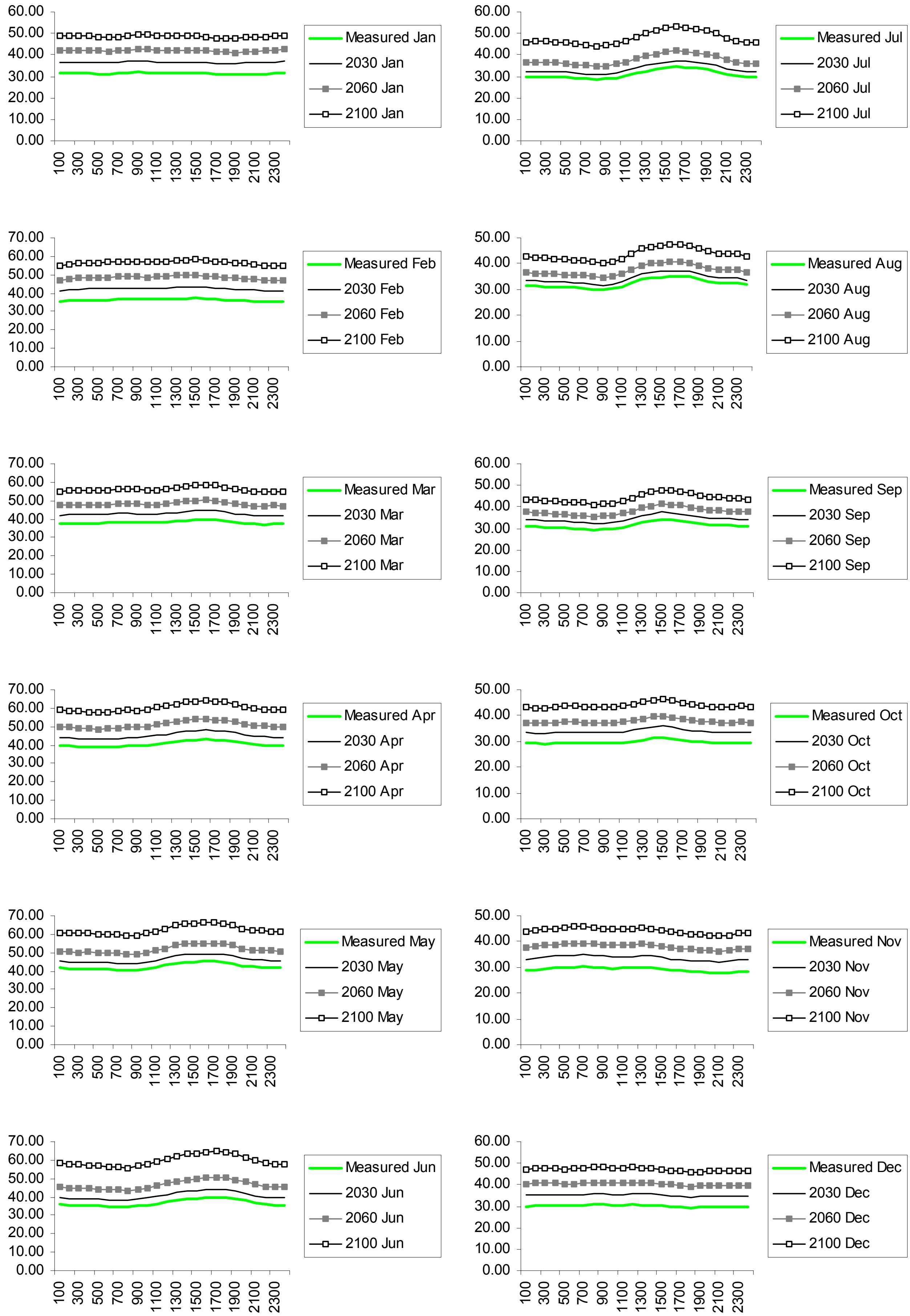

Figure 5.c. Eskdalemuir (x-axis = hour, y-axis = ppb)

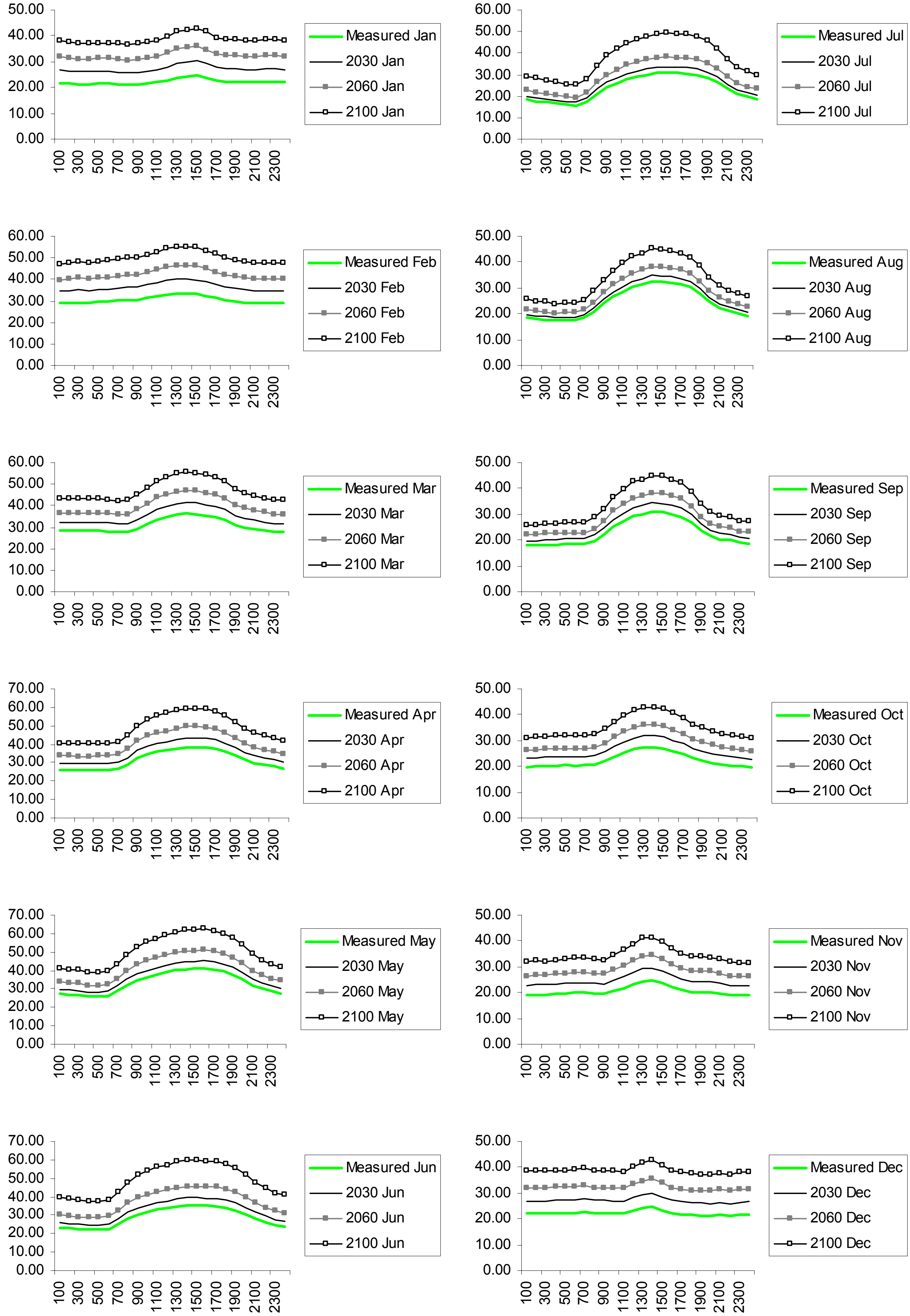

Figure 5.d. High Muffles (x-axis = hour, y-axis = ppb)

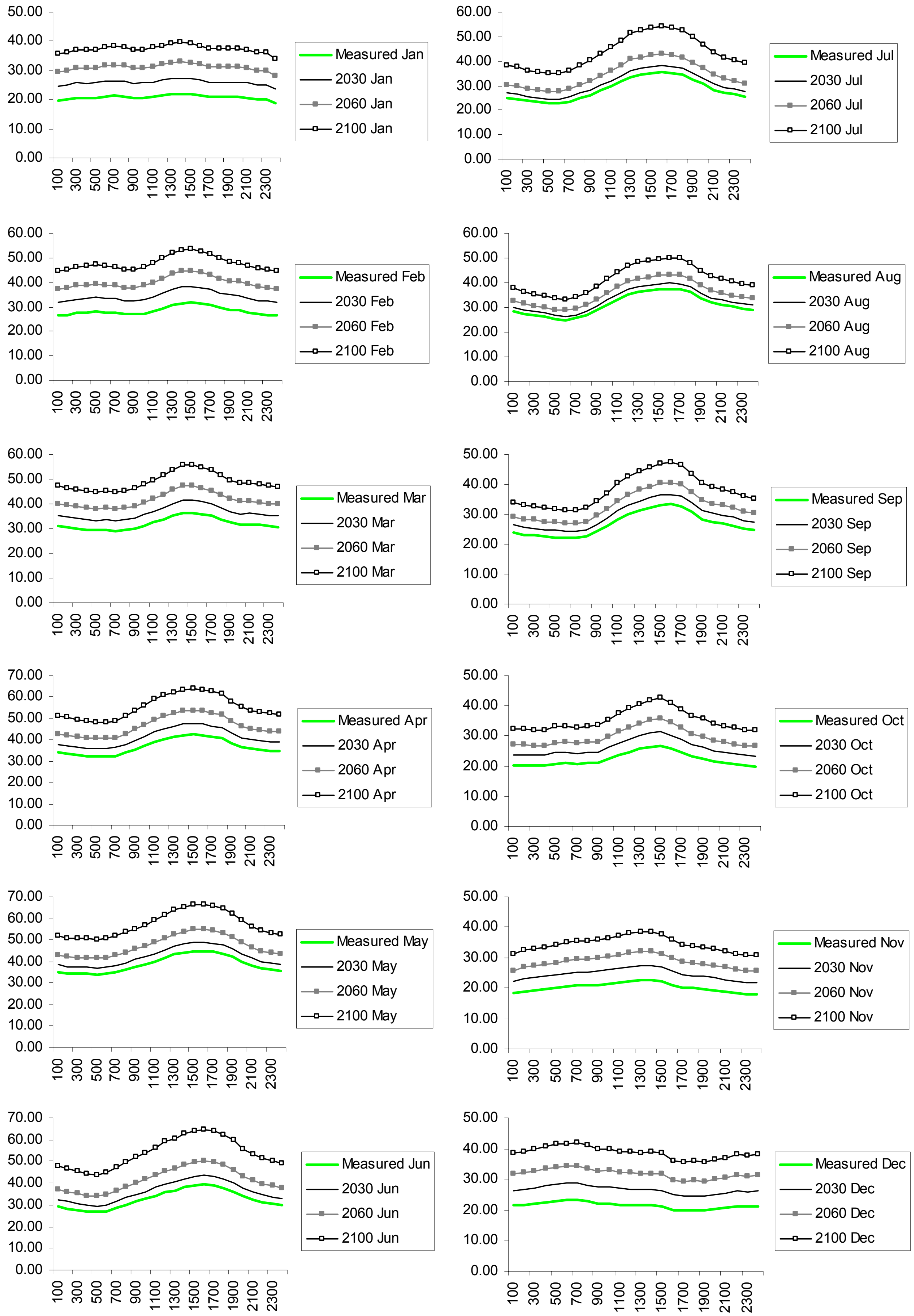

Figure 5.e. Somerton (x-axis = hour, y-axis = ppb)

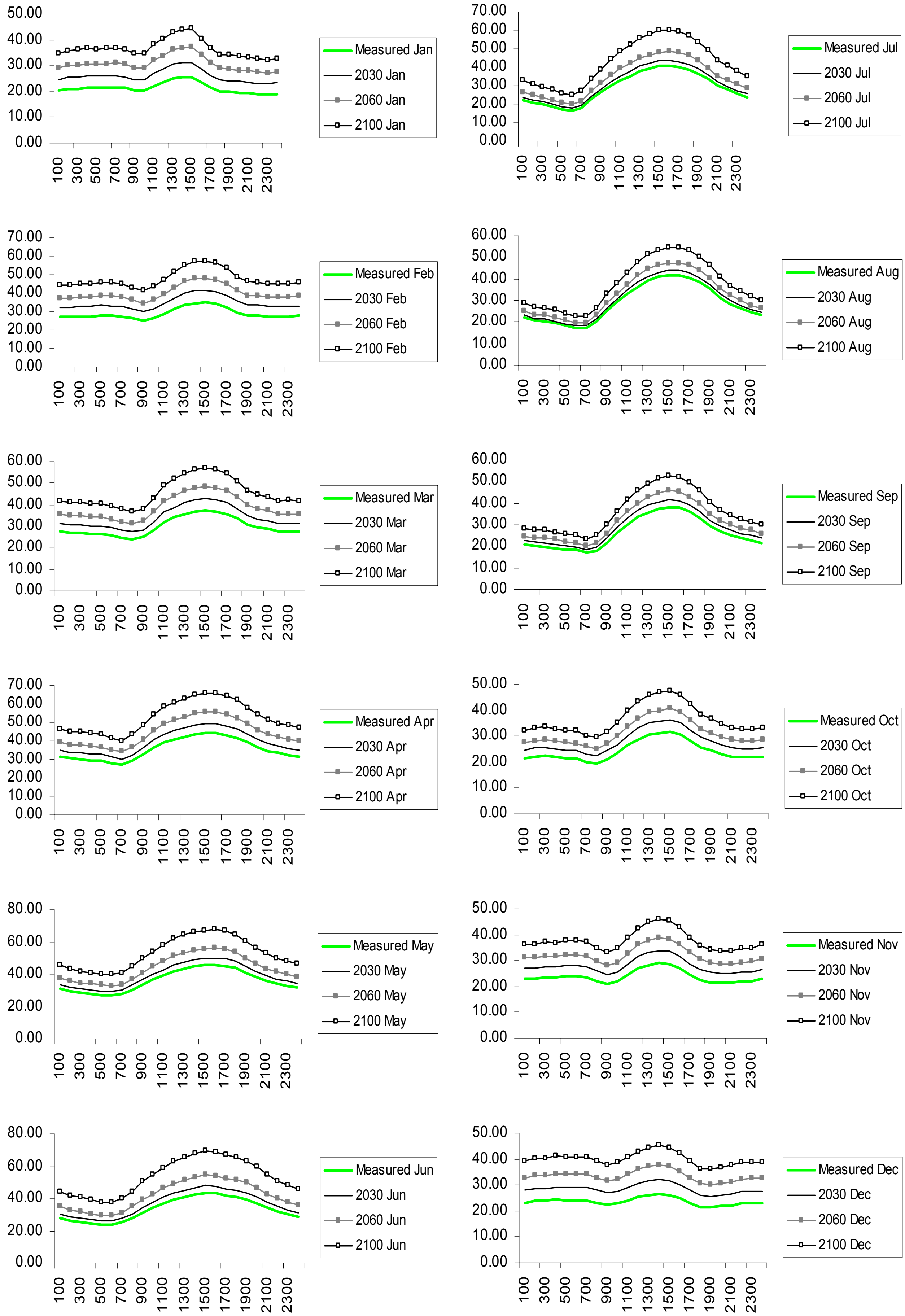

Figure 5.f. Strath Vaich (x-axis = hour, y-axis = ppb)

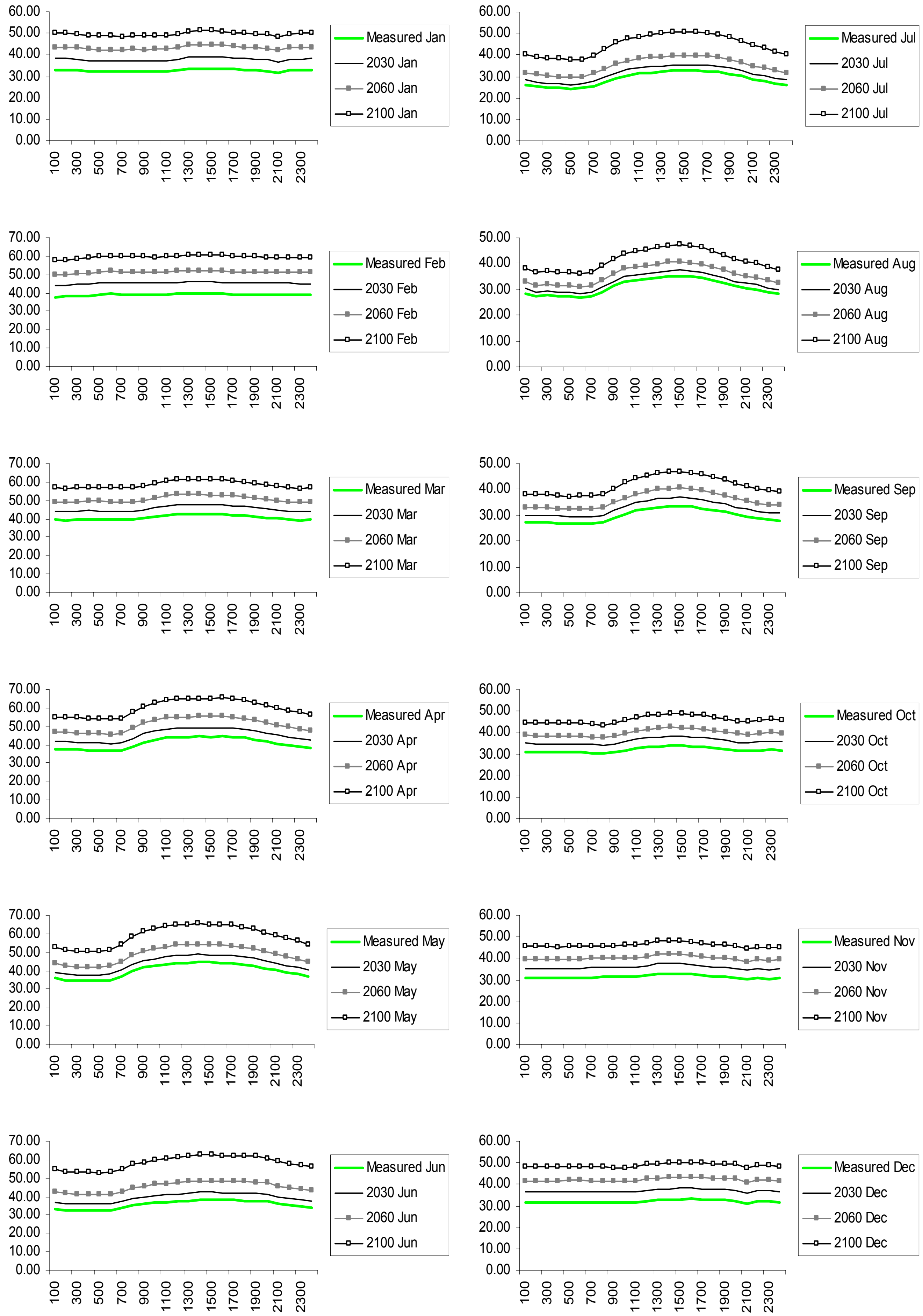

Figure 5.g. Wicken Fen (x-axis = hour, y-axis = ppb)

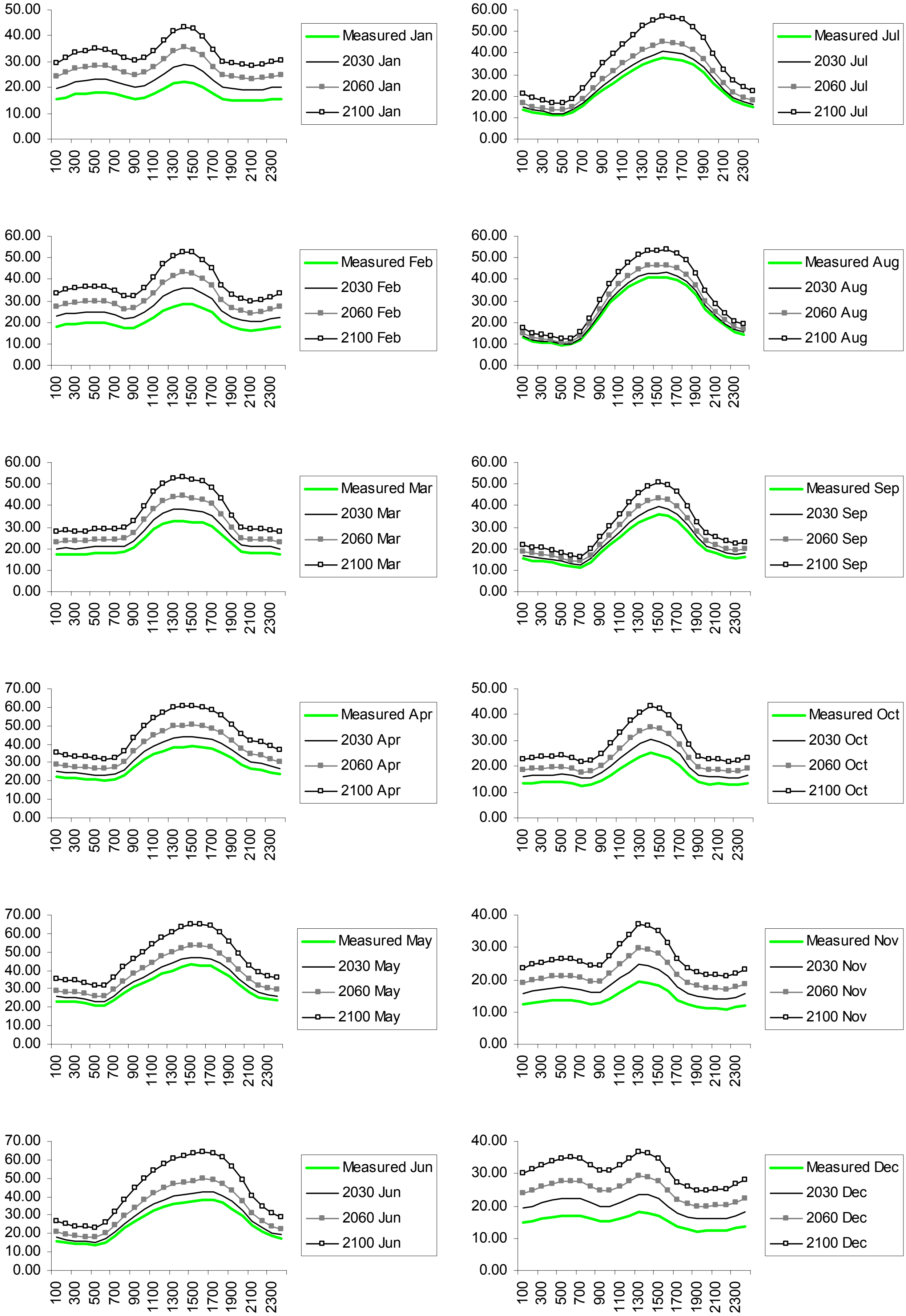

Figure 5.h. Yarner Wood (x-axis = hour, y-axis = ppb)

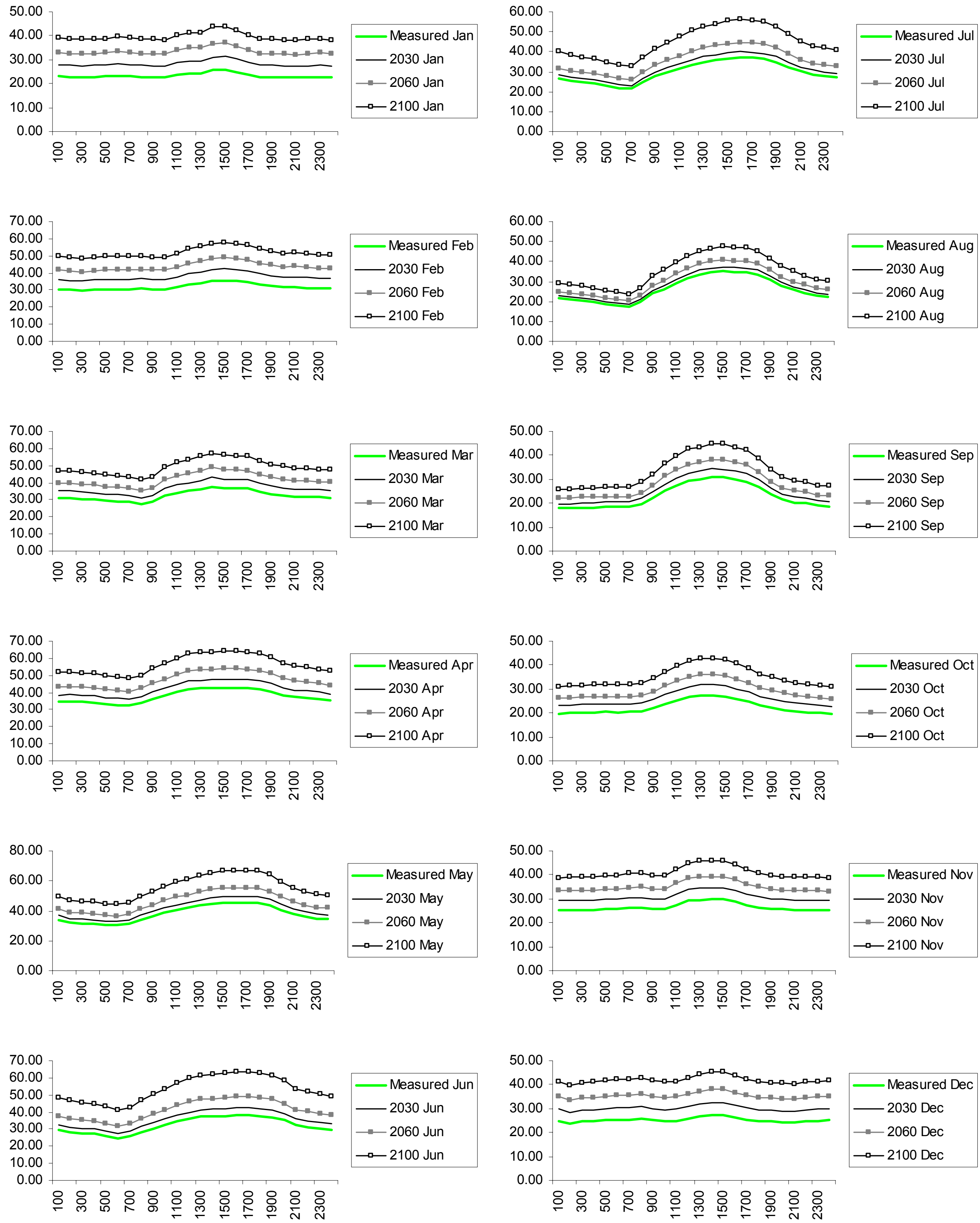

Figure 5. Monthly average diurnal cycles in ozone from 1990-1996 measured hourly averages (Measured) and constructed hourly averages for 2030, 2060 and 2100.

Table 2 below summarises the hourly averages for each period during (a) 24 hours and (b) daylight hours only (solar radiation > 50 Wm^{-2}). The skew characterizes the degree of asymmetry of a frequency distribution around its mean. Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values. Negative skewness indicates a distribution with an asymmetric tail extending toward more negative values (Microsoft 2000). Kurtosis characterizes the relative peakedness or flatness of a distribution compared with the normal distribution. Positive kurtosis indicates a relatively peaked distribution. Negative kurtosis indicates a relatively flat distribution (Microsoft 2000).

The averages, maxima, minima, medians and standard deviations all increase with time as expected. The skew and kurtosis values indicate changes in the frequency distribution of hourly ozone, in general it becomes more symmetrical and spread-out with time and this effect is most pronounced at the low level sites which tend to experience more nocturnal ozone depletion. Figure 6 shows plots of the frequency distribution at each site and Figure 7 shows plots of the cumulative frequency distributions during daylight hours only.

Table 2a. Hourly average data summary

Stat	**1996-2000**	**2030**	**2060**	**2100**
Aston Hill				
Average	30.38	34.42	39.11	46.99
Max	54.80	58.70	66.98	86.13
Min	10.25	12.47	14.76	17.76
Median	29.80	33.93	38.77	46.37
StDev	6.41	6.91	7.84	9.77
Skew	0.29	0.21	0.18	0.26
Kurtosis	-0.07	-0.22	-0.32	-0.21
Dunslair Heights				
Average	34.08	38.21	43.01	51.10
Max	55.61	61.25	69.95	89.24
Min	18.41	21.69	25.07	29.51
Median	33.14	37.48	42.29	50.02
StDev	5.70	6.16	7.00	8.70
Skew	0.40	0.26	0.21	0.34
Kurtosis	-0.32	-0.45	-0.52	-0.37
Eskdalemuir				
Average	26.08	29.83	34.17	41.40
Max	52.00	56.92	63.86	80.88
Min	6.75	7.36	8.34	9.91
Median	25.60	29.65	34.10	41.31
StDev	7.11	7.84	8.94	10.98
Skew	0.22	0.08	0.03	0.09
Kurtosis	-0.40	-0.44	-0.45	-0.36
High Muffles				
Average	28.28	32.18	36.70	44.28
Max	57.80	62.74	69.71	83.48
Min	3.50	4.44	5.41	6.59
Median	27.80	31.77	36.30	43.80
StDev	8.06	8.37	9.25	11.27
Skew	0.21	0.15	0.12	0.16
Kurtosis	-0.23	-0.20	-0.25	-0.23

Stat	**1996-2000**	**2030**	**2060**	**2100**
Somerton				
Average	28.33	31.97	36.18	43.21
Max	61.00	64.83	70.97	86.46
Min	0.00	0.00	0.00	0.00
Median	27.60	31.46	35.79	42.70
StDev	8.67	9.31	10.43	12.73
Skew	0.30	0.17	0.12	0.19
Kurtosis	0.04	-0.05	-0.11	-0.02
Strath Vaich				
Average	34.43	38.47	43.16	51.04
Max	53.25	57.77	64.15	76.76
Min	16.20	17.54	19.70	25.06
Median	34.00	38.30	43.11	50.65
StDev	5.83	6.61	7.55	9.02
Skew	0.14	0.00	-0.04	0.01
Kurtosis	-0.27	-0.38	-0.47	-0.52
Wicken Fen				
Average	21.70	25.10	29.01	35.50
Max	69.00	76.53	88.14	113.89
Min	0.33	0.00	0.00	0.00
Median	20.00	23.93	27.79	34.10
StDev	10.51	11.36	12.78	15.60
Skew	0.68	0.51	0.41	0.40
Kurtosis	0.32	0.08	-0.09	-0.03
Yarner Wood				
Average	29.41	33.26	37.71	45.15
Max	56.67	61.58	68.53	82.24
Min	10.60	13.10	14.60	16.79
Median	28.80	32.92	37.47	44.80
StDev	7.52	8.15	9.19	11.25
Skew	0.33	0.21	0.16	0.19
Kurtosis	-0.17	-0.29	-0.35	-0.30

Table 2b. Daylight hours data summary

Stat	1996-2000	2030	2060	2100
Aston Hill				
Average	31.73	35.60	40.33	48.76
Max	54.80	58.70	66.98	86.13
Min	10.25	12.47	14.76	17.76
Median	31.20	35.13	39.93	48.09
StDev	6.61	7.17	8.17	10.26
Skew	0.26	0.17	0.13	0.21
Kurtosis	-0.22	-0.31	-0.36	-0.25
Dunslair Heights				
Average	35.23	39.15	43.97	52.67
Max	55.61	61.25	69.95	89.24
Min	19.52	22.87	25.63	31.20
Median	34.65	38.56	43.41	52.05
StDev	5.96	6.52	7.44	9.25
Skew	0.29	0.18	0.14	0.24
Kurtosis	-0.49	-0.57	-0.62	-0.49
Eskdalemuir				
Average	29.14	32.89	37.47	45.69
Max	52.00	56.92	63.86	80.88
Min	6.75	7.36	8.34	10.78
Median	29.20	32.94	37.56	45.56
StDev	7.25	7.95	9.05	11.20
Skew	-0.08	-0.16	-0.18	-0.12
Kurtosis	-0.44	-0.38	-0.37	-0.34
High Muffles				
Average	31.32	35.13	39.80	48.15
Max	57.80	62.74	69.71	83.48
Min	8.40	10.48	12.62	15.43
Median	31.00	34.68	39.27	47.40
StDev	8.11	8.45	9.35	11.48
Skew	0.10	0.09	0.09	0.11
Kurtosis	-0.45	-0.45	-0.49	-0.48

Stat	1996-2000	2030	2060	2100
Somerton				
Average	31.69	35.36	39.81	47.71
Max	61.00	64.83	70.97	86.46
Min	2.00	2.49	3.00	3.62
Median	31.60	35.55	40.21	47.81
StDev	9.39	10.03	11.21	13.74
Skew	0.01	-0.11	-0.14	-0.06
Kurtosis	-0.43	-0.40	-0.38	-0.33
Strath Vaich				
Average	35.65	39.48	44.23	52.85
Max	53.25	57.77	64.15	76.76
Min	16.20	17.54	19.70	25.06
Median	35.20	39.17	44.11	52.60
StDev	6.20	7.00	7.97	9.58
Skew	0.05	-0.02	-0.05	-0.07
Kurtosis	-0.38	-0.50	-0.60	-0.67
Wicken Fen				
Average	27.07	30.75	35.19	43.04
Max	69.00	76.53	88.14	113.89
Min	0.00	0.00	0.00	0.00
Median	27.00	30.82	35.43	43.20
StDev	10.98	11.63	12.92	15.76
Skew	0.32	0.19	0.10	0.11
Kurtosis	-0.11	-0.11	-0.13	-0.03
Yarner Wood				
Average	31.63	35.41	39.99	48.12
Max	56.67	61.58	68.53	82.24
Min	11.40	13.33	14.60	16.79
Median	31.50	35.33	39.96	47.75
StDev	8.00	8.66	9.75	11.97
Skew	0.11	0.02	-0.02	0.01
Kurtosis	-0.35	-0.36	-0.38	-0.35

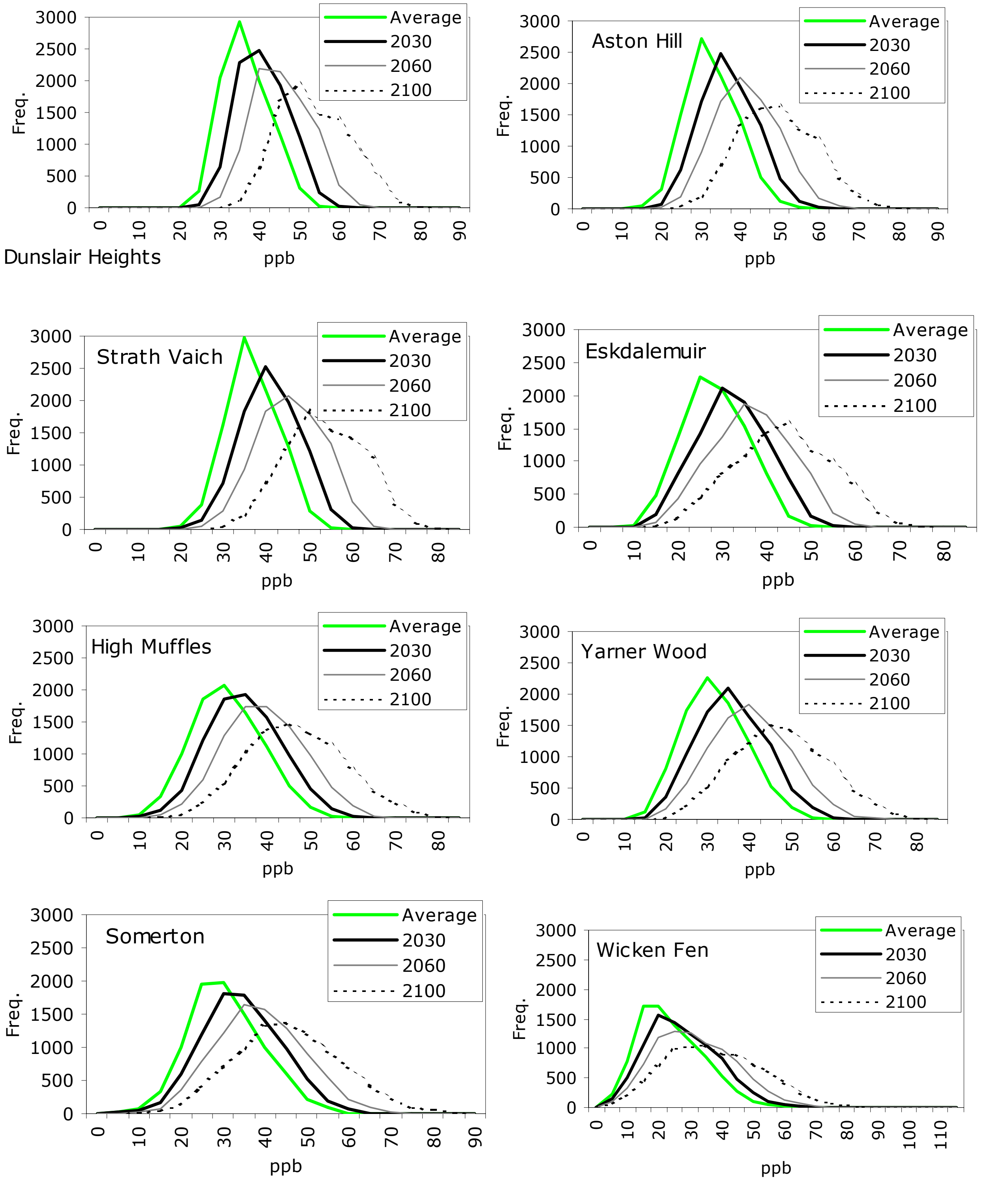

Figure 6. Frequency distributions of hourly averages for each site ordered from highest altitude to lowest.

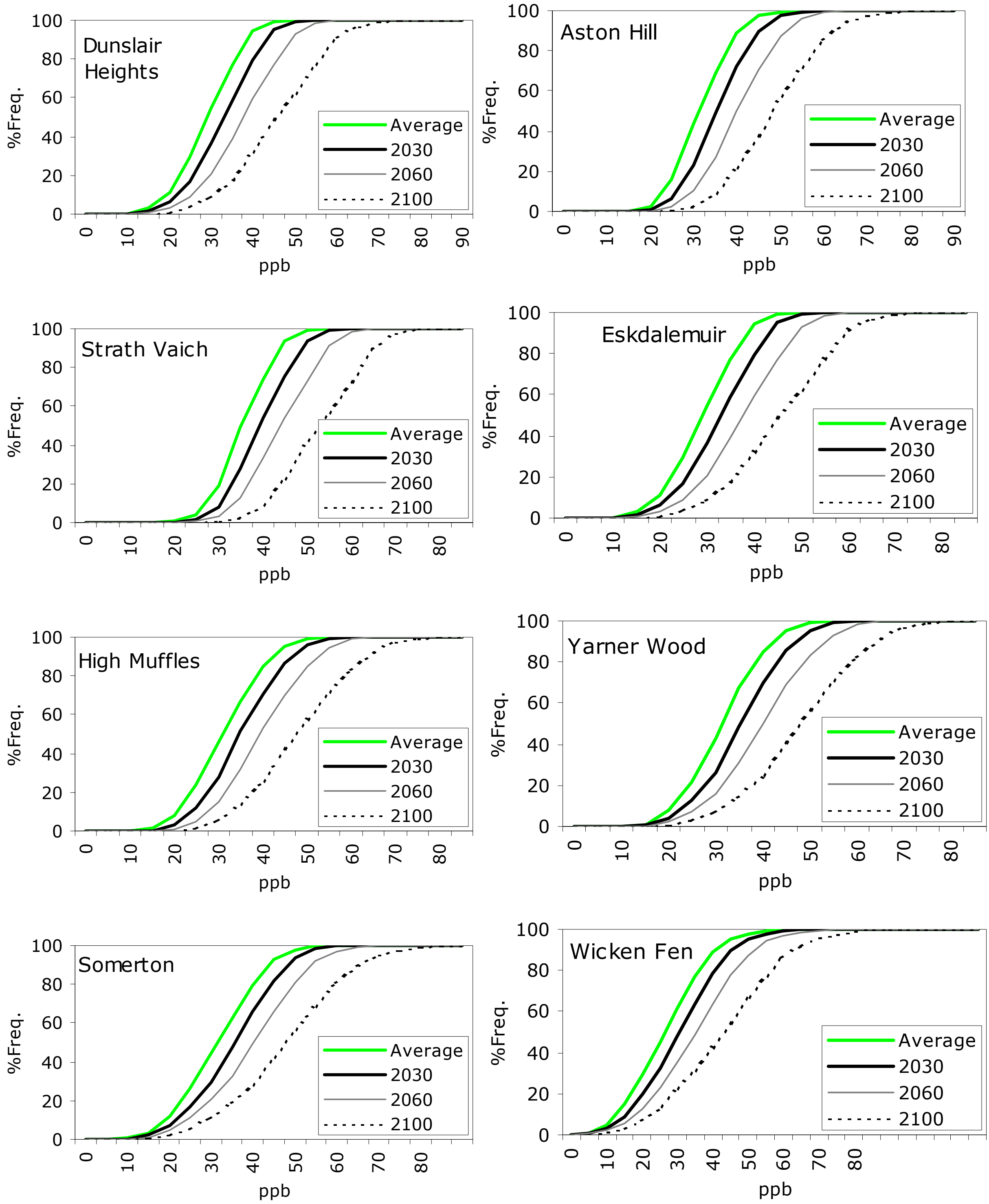

Figure 7. Cumulative %frequency distributions of daylight hour averages for each site ordered from highest altitude to lowest.

The following plots show the AOT40s for each site. In general all the sites have increasing AOT40s with exposure starting earlier and continuing longer each year, until there are exceedances of 40 ppb almost every day of the year in 2100. All sites except Eskdalemuir exceed the Forests AOT40 by 2060, Eskdalemuir exceeds in 2100. Similarly for crops and semi-natural vegetation all sites exceed the AOT40 in 2030 except Eskdalemuir which exceeds in 2060.

Figure 8.a. Strath Vaich

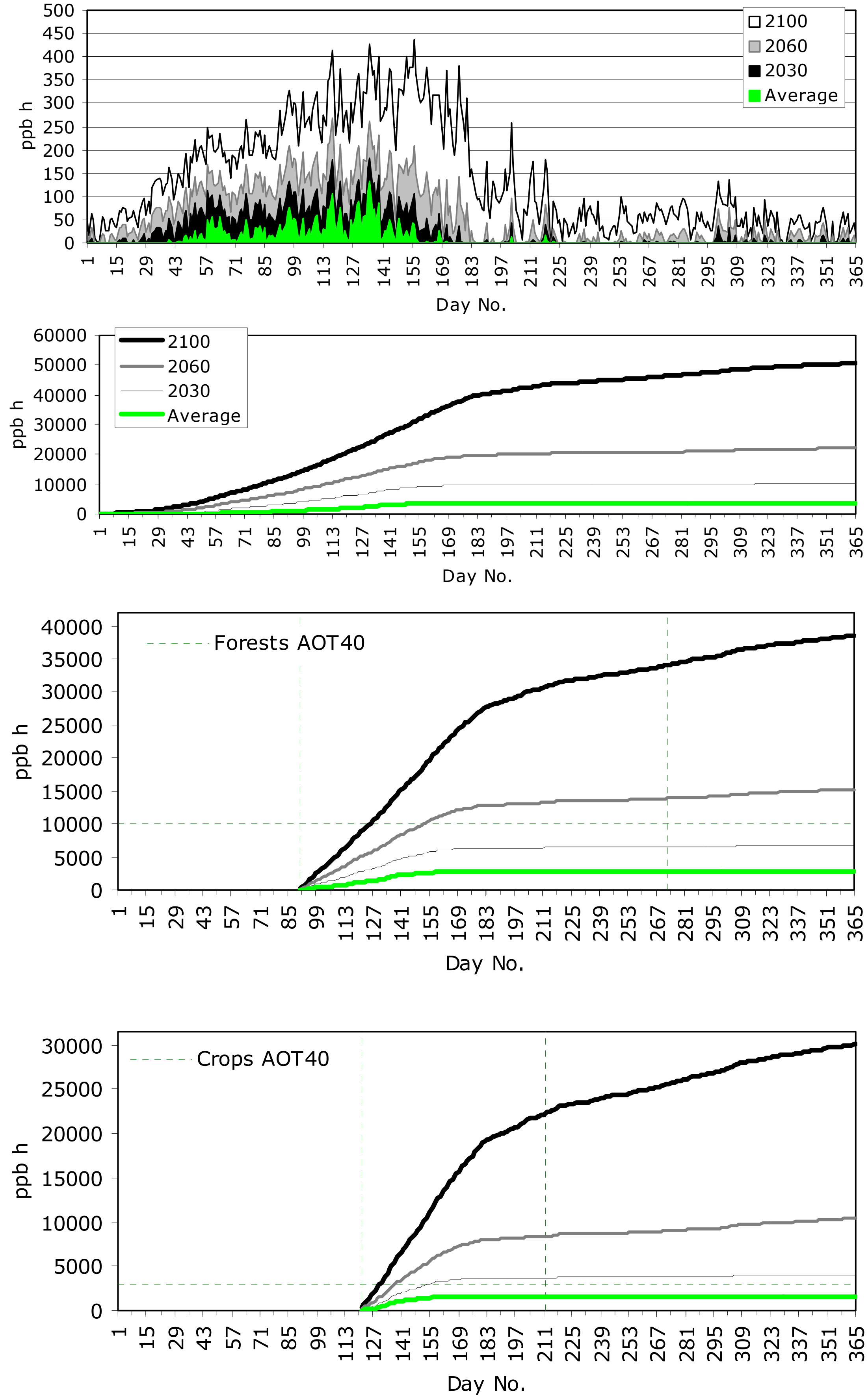

Figure 8.b. Dunslair Heights

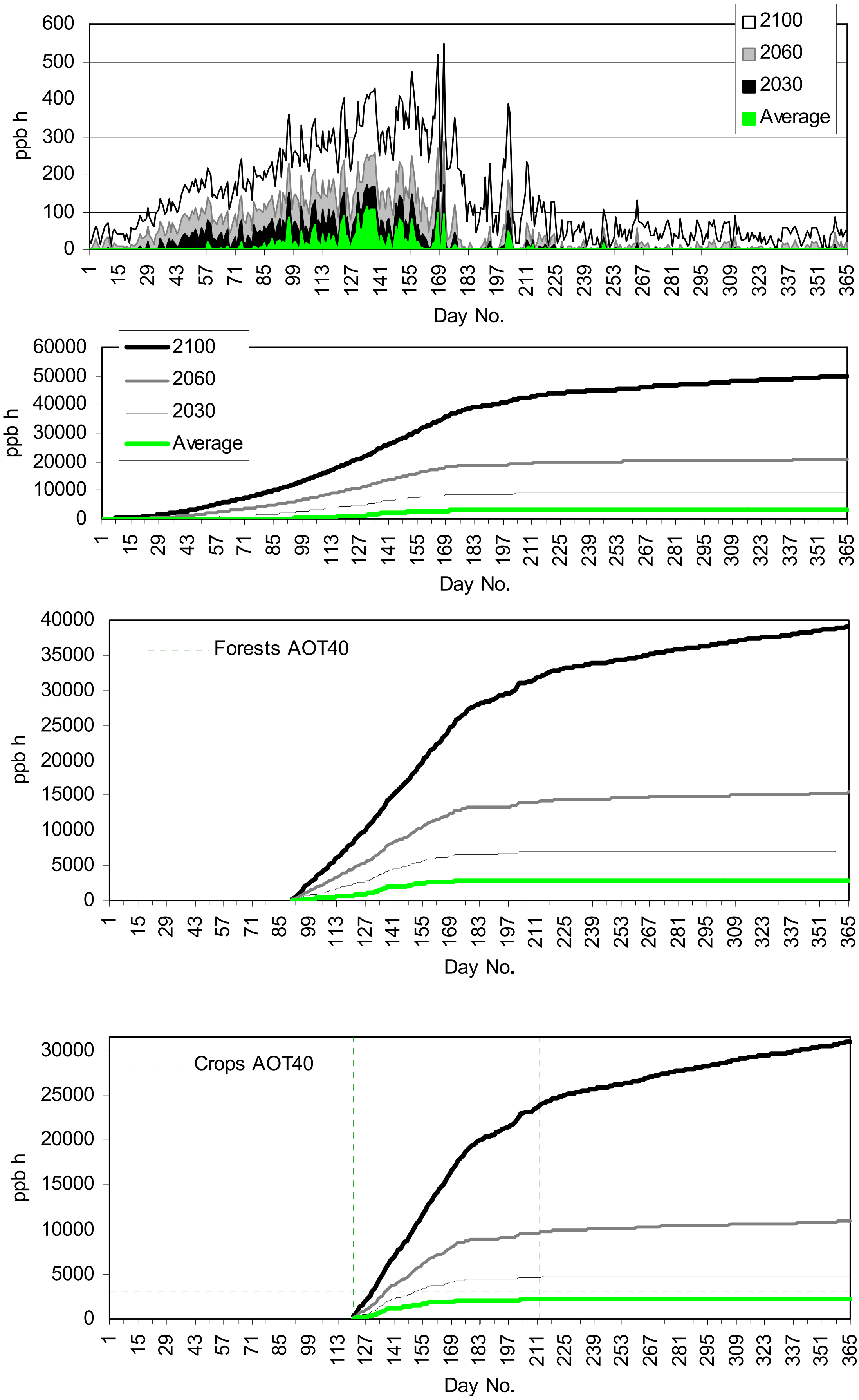

Figure 8.c. Eskdalemuir

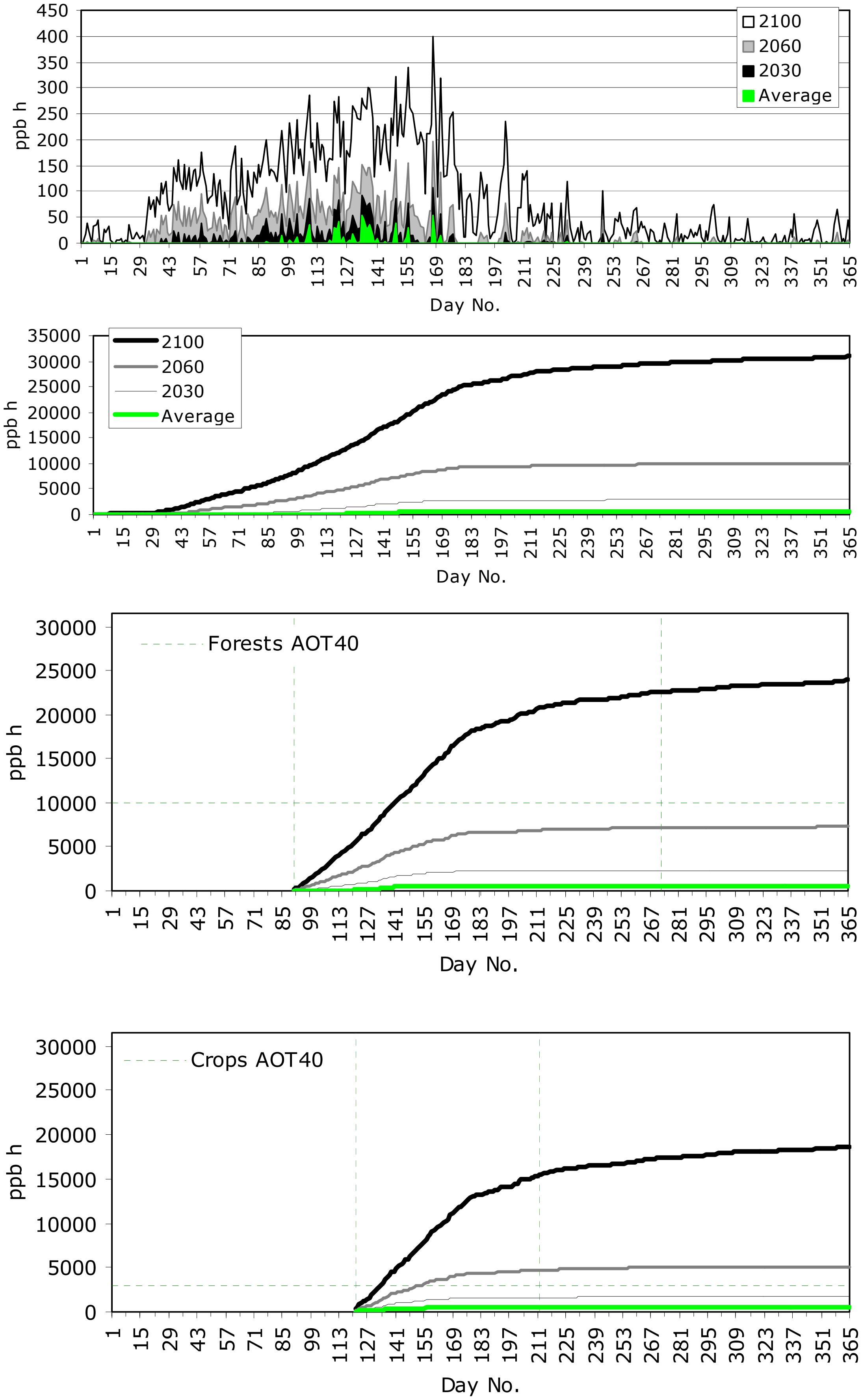

Figure 8.d. High Muffles

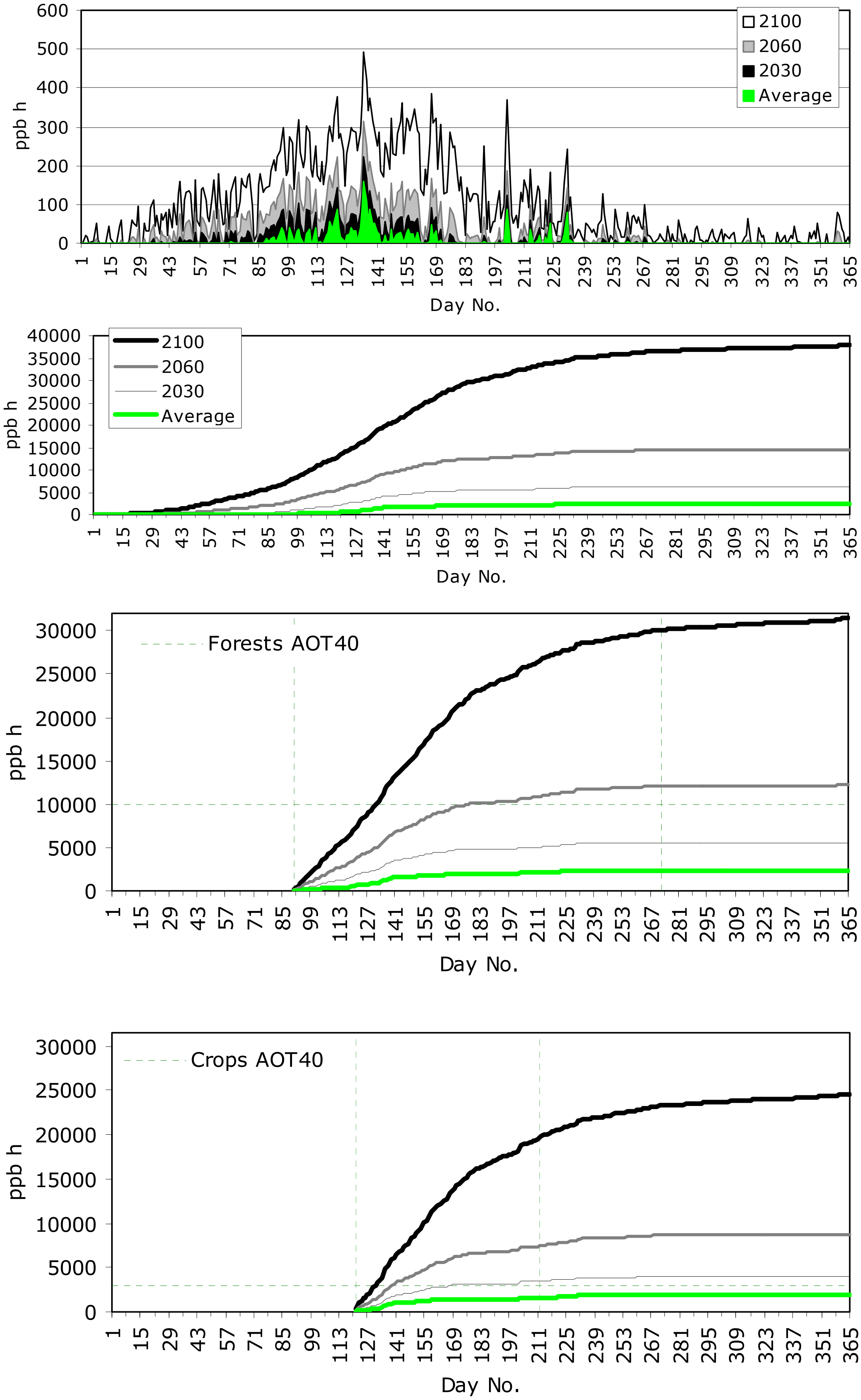

Figure 8.e. AstonHill

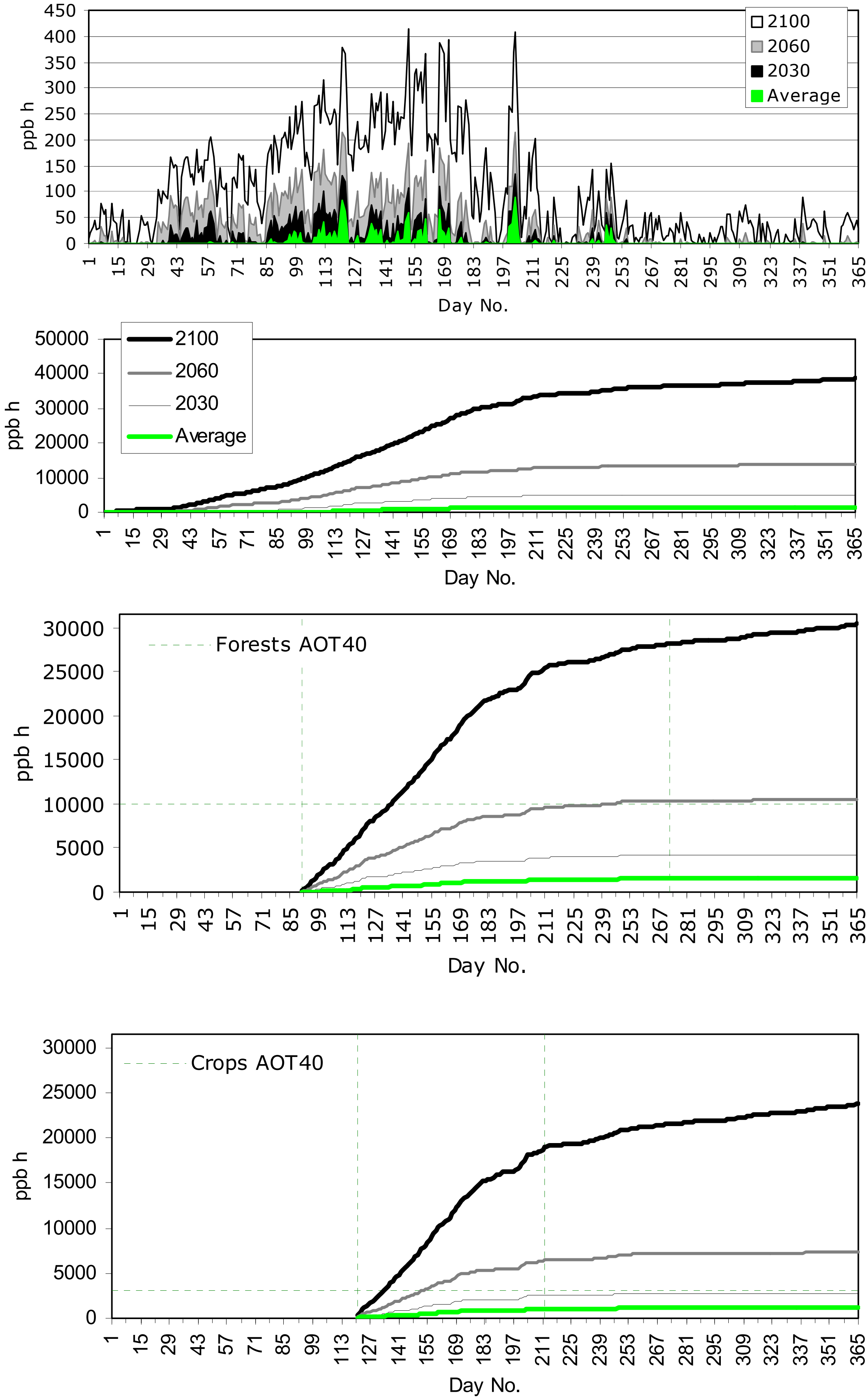

Figure 8.f. Wicken Fen

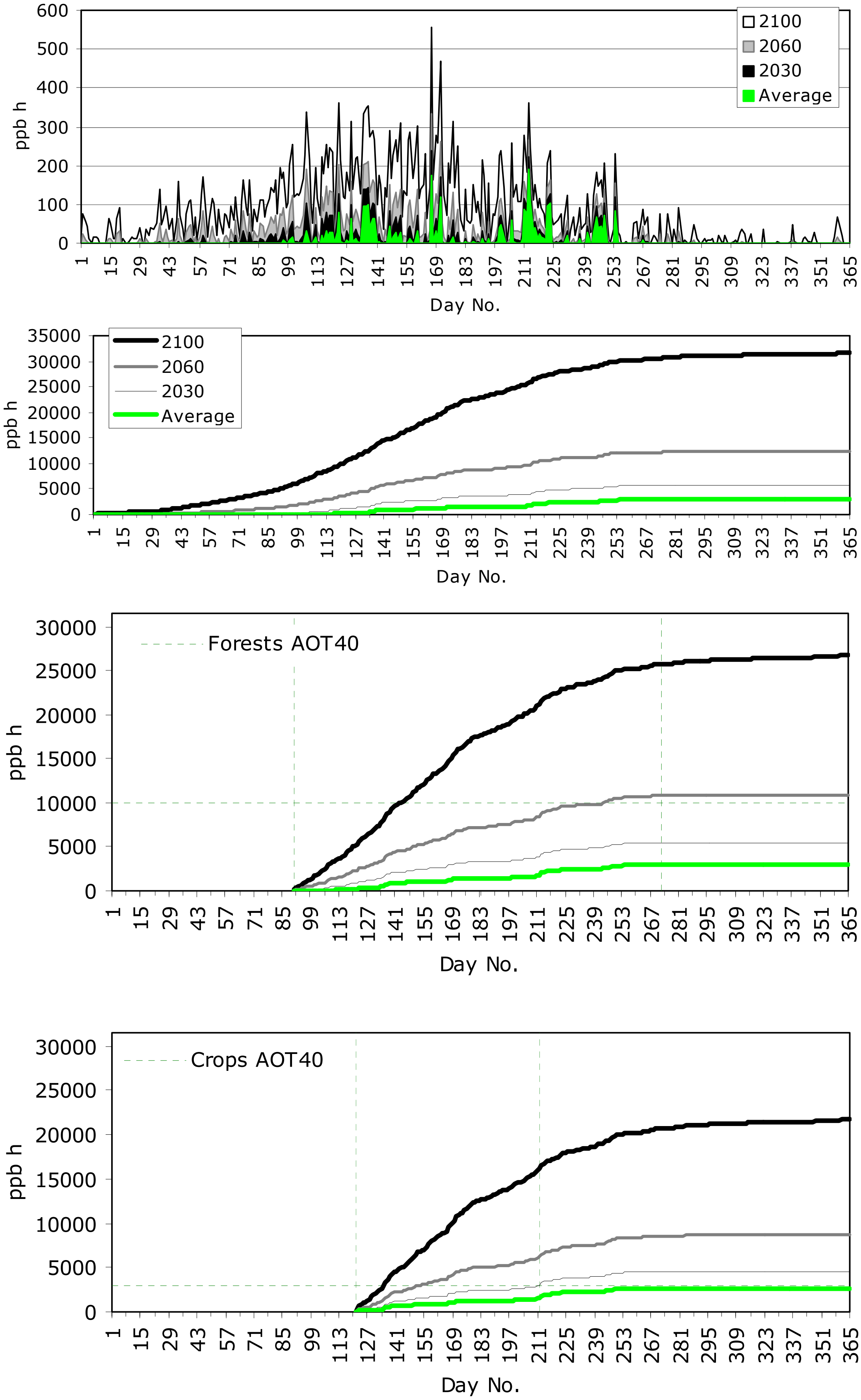

Figure 8.g. Somerton

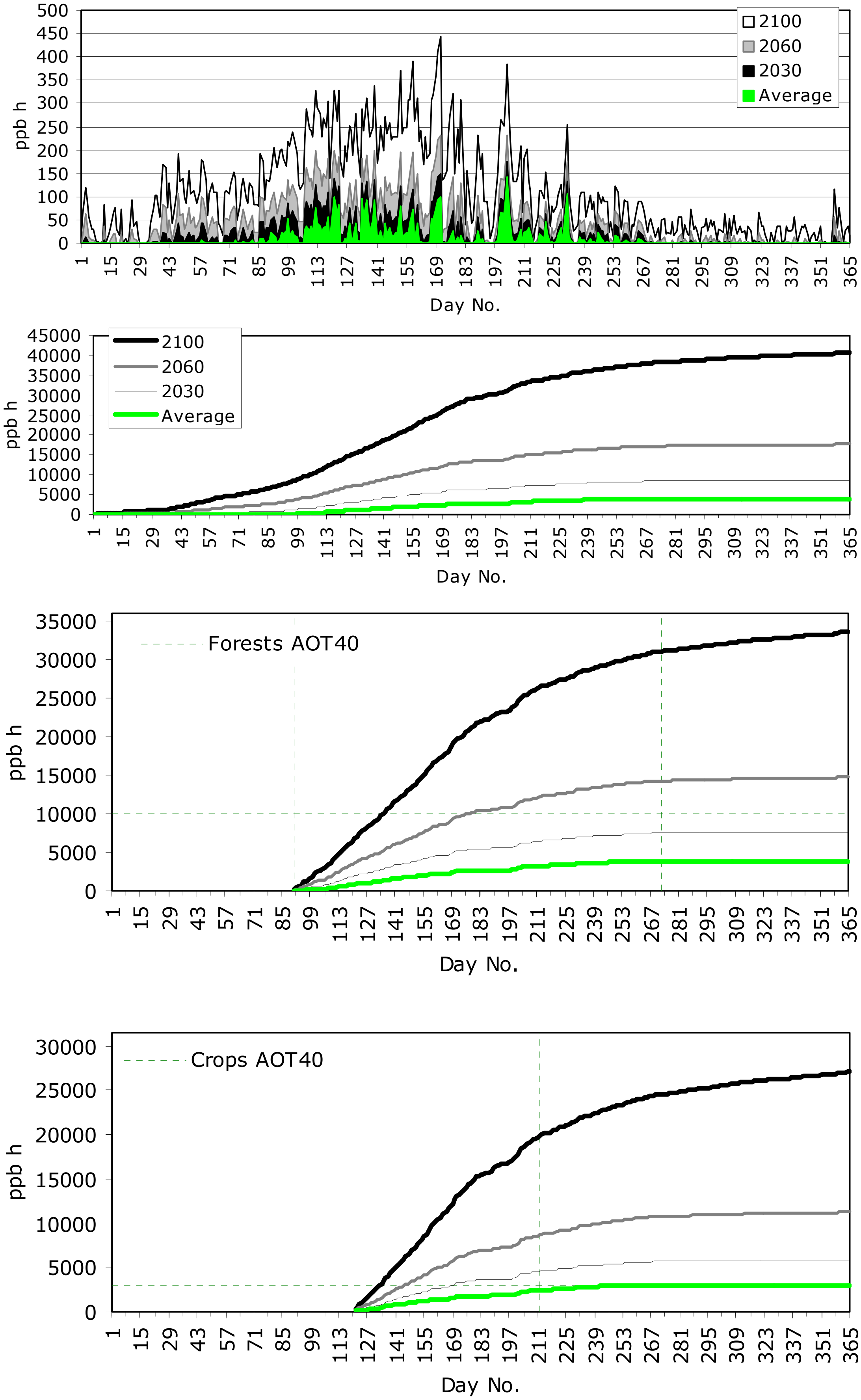

Figure 8.h. Yarner Wood

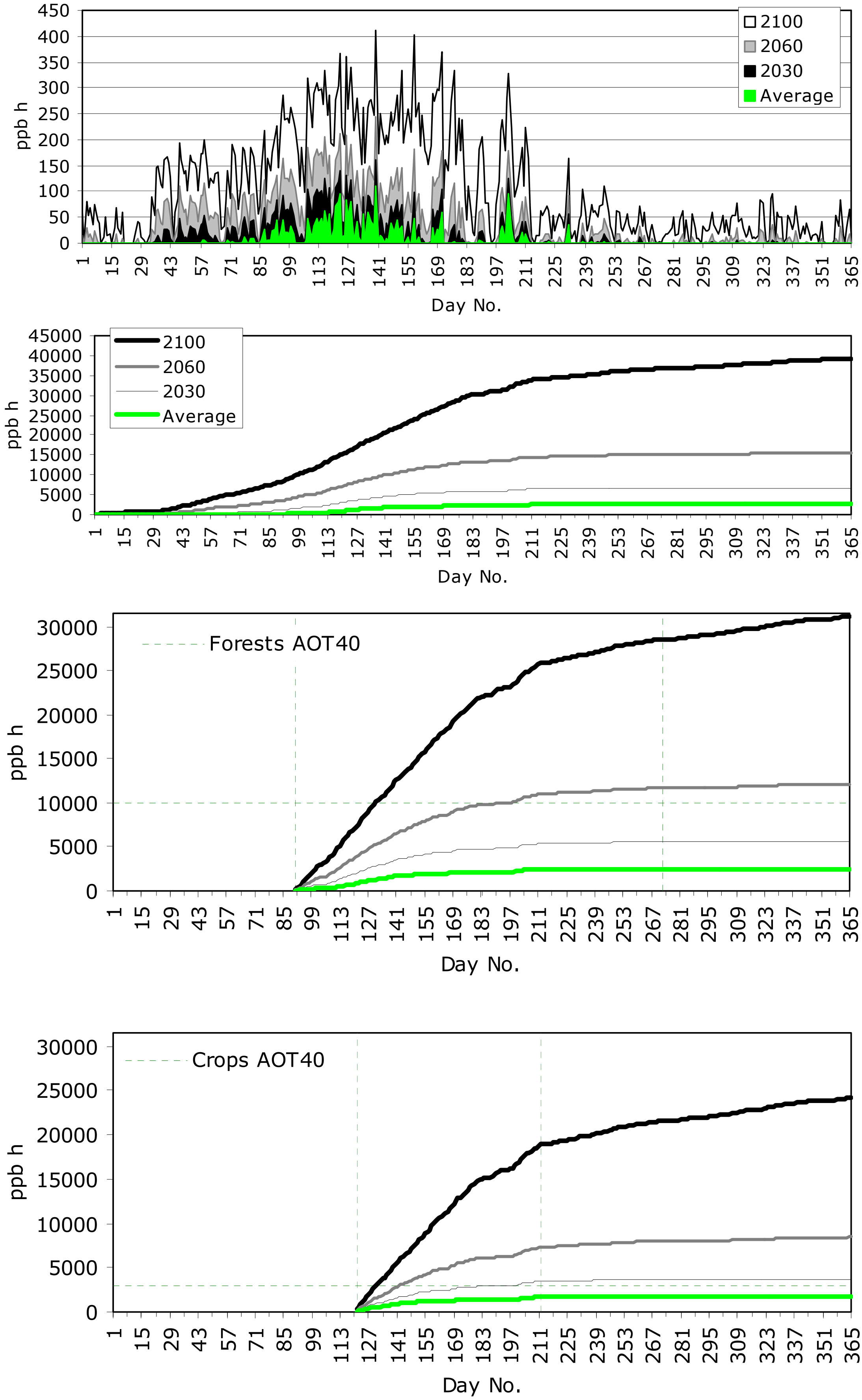

Figure 8. Daily AOT40, annual daily accumulated AOT40, April-September accumulated AOT40 and May-July accumulated AOT40, all during daylight hours. The sites are ordered from N to S.

3. Effects on Vegetation

3.1 Increases in AOT40

Current assessments of the risk of ozone impacts to vegetation in Europe are based on the AOT40 concept (Fuhrer et al., 1997). The projections for 2060 and 2100 in the previous section show clearly that large increases in AOT40 values would be expected throughout the UK due to the increased global background concentration of ozone. Although the effect of reduced peak concentrations may moderate these increases to a small extent, the main driver for this large increase in AOT40 exposures is the fact that daylight mean concentrations at all sites except Wicken Fen and Eskalemuir are predicted to be at, or above, 40 ppb by 2060. Hence, it can be expected that there will be a contribution to the cumulative AOT40 value on the majority of days throughout the year.

These large increases in AOT40 should have significant effects on crop yield and forest growth, although the exposure-response relationships for AOT40 are based on chamber studies and may not be extrapolated to field conditions. However, by the second half of the next century, a number of other significant changes to the UK environment may have occurred which will influence the extent to which the predicted impacts of increased AOT40 would actually occur. The implications of changes in global background ozone concentrations for impacts on vegetation in the wider context of global change were considered by Ashmore & Bell (1991), who identified a number of important interactions. In summary, these include:-

(i) Increased atmospheric CO_2 concentrations. It is clearly established that the impacts of ozone are reduced under elevated CO_2 concentrations;

(ii) Altered ecosystem and crop distributions under a changing climate. Different cropping patterns will emerge in response to climate change which will completely change current risk assessments for ozone effects on agricultural production. Likewise, although in a more complex pattern, the species composition of semi-natural communities will change in response to climate change;

(iii) Increased summer droughts. Decreased water availability in the event of hotter drier summers is likely to lead to reduced ozone flux into vegetation and hence reduced impacts of ozone. However, there is evidence that ozone exposure can exacerbate the impact of water stress, for example because of reduced carbon allocation to the roots or interference with the control of water loss from the leaves;

(iv) Increased prevalence of insect pests and fungal diseases. It is known that ozone can influence the performance and prevalence of insect pests and plant pathogens, some of which are likely to be favoured in a warmer UK climate.

These are all issues about which more information is needed to assess the significance of ozone in the context of future changes in the UK climate. However, these are long-term concerns which are better addressed after the implications of the projected increases in global background ozone concentrations are first understood in isolation.

In contrast, the projected changes in AOT40 between the current measurements and those simulated for 2030 are much smaller and there should be fewer other large-scale changes in climate and atmospheric composition to consider. Therefore, it is simpler to consider the impact of the changes in ozone concentrations over this period in isolation from other environmental changes. Nevertheless, the issue arises as to whether the AOT40 concept is the most appropriate method of assessing the impact of the predicted changes in background concentration.

3.2. Flux-based assessment

It is currently accepted that flux of ozone into the leaf is more closely related to plant response than to external concentrations or exposure indices. For example, Pleijel *et al.* (2000) demonstrated that data on the yield of wheat in open-top chamber dose-response studies in southern Sweden over several years could be better related to modelled ozone flux than to AOT40. In particular, use of AOT40 showed very different relationships to yield in different years due to climatic variability; these differences between years were largely eliminated by the use of flux. For this reason, we consider the changes in ozone concentration frequency distribution predicted in Section 2 in the context of flux, as well as in terms of concentration.

In order to consider the modelled changes in background concentrations of ozone in the context of flux, it is first necessary to consider the relationship between ozone concentration and flux. Figure 9 shows the modelled relationship between ozone concentration and cumulative ozone uptake over an hour for wheat (Pleijel, pers. comm.), derived from a stomatal model based on that of Emberson *et al.* (2000). The hourly ozone flux is based on data for wheat grown in open-top chambers, and represents the flux above a critical threshold (4 nmol m^{-2} s^{-1}).

Three features are apparent in Figure 9. Firstly, under certain conditions (e.g. at nighttime) there is no flux above the threshold over a range of ozone concentrations (0-80ppb). Secondly, there is an upper boundary to the relationship which represents those hours in which the actual stomatal conductance was close to the maximum value for wheat. Thirdly, at high concentrations of ozone, especially in warmer high-ozone summers such as 1994, many of the points are well below this maximum flux line, indicating substantial stomatal limitation of ozone uptake.

Two features of this relationship are very important in the context of assessing the implications of increased background ozone concentrations:-

(a) there is a significant contribution from ozone concentrations under 40 ppb (indeed down to 20 ppb) under the model assumptions and parameterisation;

(b) the highest contributions to flux did not necessarily result from periods with the highest ozone concentration.

This latter point has already been identified as a significant issue by Emberson *et al.* (2000); their pan-European modelling of flux to beech and wheat demonstrated that on days with midday concentrations above 60 ppb, the reduced stomatal conductance caused by the higher values of vapour pressure deficit meant that modelled fluxes were relatively low.

In assessing the impact of the modelled changes in ozone concentrations in Section 2 of this report, it is clearly crucial where the intercept on the x axis lies. This intercept, $[O_3]c$, represents the minimum concentration at which a flux above the threshold can occur if conditions are favourable. This value is basically dependent on three parameters:-

(i) the maximum stomatal conductance of the species (in this case wheat). Species with a high stomatal conductance will have a greater flux at a given concentration, and hence $[O_3]c$ will be lower for these species and background concentrations correspondingly more significant;

(ii) the threshold flux for cumulative ozone uptake, which would also be expected to be species specific. It is reasonable to assume that this threshold flux represents the capacity of the plant to detoxify incoming ozone. $[O_3]c$ will be greater in species with a higher detoxification capacity, for which background concentrations will be correspondingly less significant;

(iii) the aerodynamic resistance to transfer of ozone from the measurement height to the leaf surface. In this case of experimental data from chamber studies, such as those in Figure 3.1, these values are low, but this resistance is important in interpreting the effects of ozone concentrations at the standard measurement height of 2-3 m, such as those modelled in Section 2. Land uses with a high aerodynamic resistance, such as grasslands, will tend to have a higher value of [O3]c, especially outside the time of day when the atmosphere is well-mixed. This will tend to make changes in background concentration less significant than over land uses with a lower aerodynamic resistance, such as forests.

It is important to note that whereas terms (i) and (iii) are readily measured or modelled, values of (ii) cannot be directly assessed, and current estimates depend on empirical relationships between modelled CUO_3 and yield loss. Although biochemical models of scavenging of ozone by anti-oxidant systems in the apoplast are being developed, and offer the potential for estimation of a detoxification capacity in flux terms, there are significant gaps in our understanding of the relative significance of the different anti-oxidant systems which need to be addressed before this is possible.

The relationship in Figure 9 indicates that for species with a high conductance and a relatively low threshold flux, contributions to flux may occur at concentrations above 20 ppb. However, this particular example is based on analysis of data from open-top chamber experiments in which ozone concentrations are measured close to the top of the crop canopy. A more realistic assessment of the implications of the predicted ozone concentrations at network measurement height would be based on a full deposition model and consider the effect of additional resistances, in particular the aerodynamic resistance above the canopy. This more detailed modelling, which is beyond the scope of this exercise, is likely to increase [O3]c towards 30 ppb in this particular example.

3.3. Concentration-based assessments

It is important to note that the literature contains a wide range of experiments in which seasonal mean exposures (e.g. 7h mean or 12h mean concentrations) or AOT40 values are reported and related to observed effects on vegetation. However, very few of these studies report the distribution of concentrations around this mean or the contribution of different concentrations to the cumulative AOT40 value.

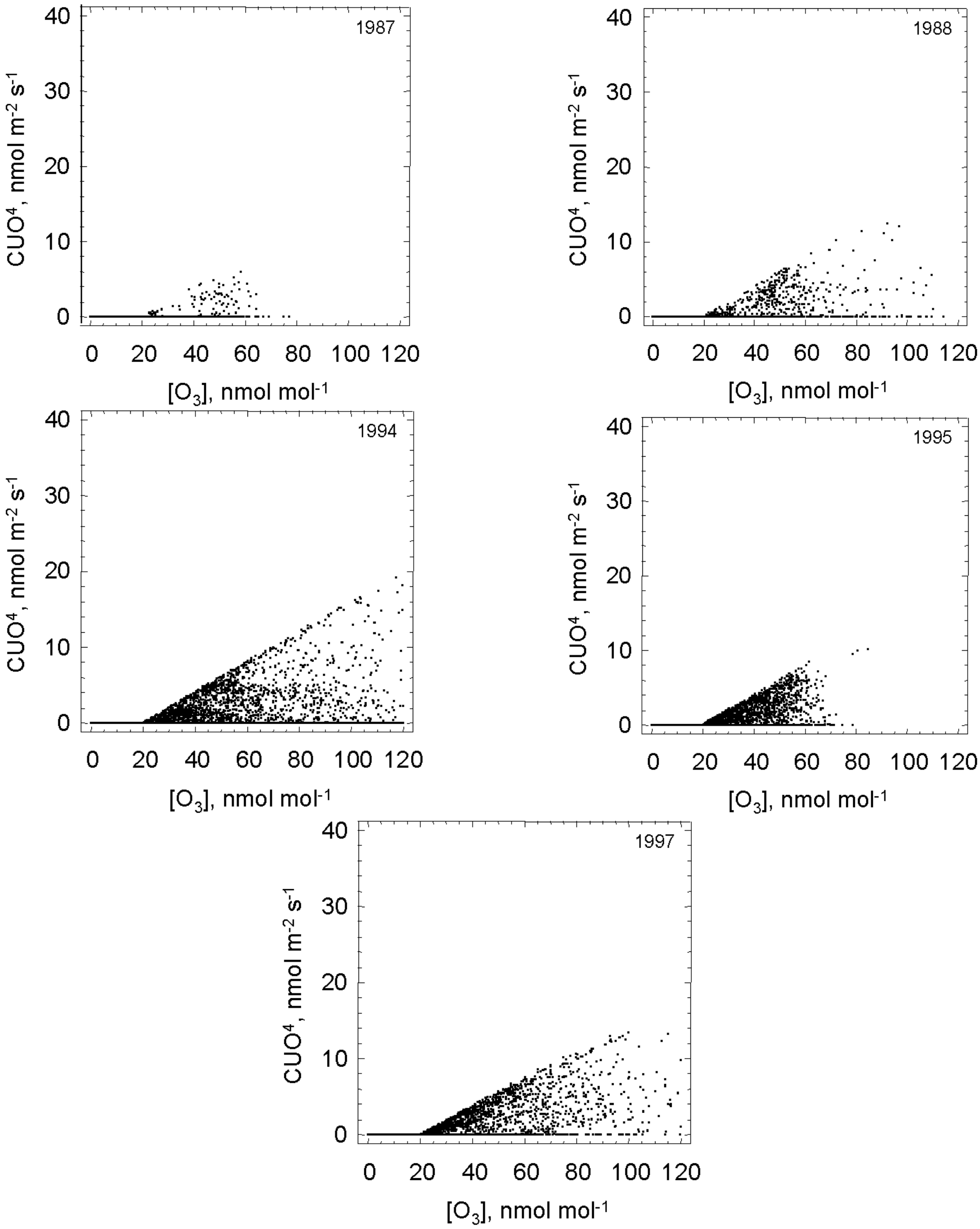

Figure 9. Relationship between hourly mean ozone concentrations in open-top chambers and ozone flux, estimated using a conductance model, for wheat grown in different seasons in Southern Sweden. Source: Pleijel, *pers.comm.*

In most field or open-top chamber studies, it is likely that episodic peak concentrations will have contributed to the impacts on vegetation observed in these experiments. Indeed, those studies which have attempted to assess the contribution of peak exposures to effects of long-term exposure have concluded in general that exposures with episodic peaks have a greater impact that those with the same mean concentrations but fewer peaks (e.g. Hogsett *et al.*, 1985). However, most of these studies have been conducted under controlled laboratory conditions; under field conditions, the peak exposures are often associated with lower flux and thus may be less significant (Emberson *et al.*, 2000).

For example, a recent compilation of data from the literature on crop yield responses by Mills *et al.* (2000) demonstrated linear relationships between yield loss of sensitive crop species and the 7h mean concentration in open-top chamber experiments in both Europe and North America. The yield-response relationships fitted to these data are linear and allow the 7h mean value corresponding to a given yield loss to be estimated. In the case of potato, the 7h mean concentration corresponding to a 10% yield loss would be 39 ppb, while for wheat, a more sensitive crop, the corresponding value is 32 ppb. These values are within the range of predicted mean concentrations in the middle of the day at several of the modelled sites. However, leaving aside the issue of seasonality which is considered in more detail below, such a direct comparison is not valid because the frequency distribution of ozone in the experimental treatments used to generate these relationships is different from the modelled changes in ozone frequency distribution in Section 2 – briefly the experimental treatments are distinguished by the size and frequency of peak concentrations, while the modelled changes from present to 2030 are distinguished mainly by the background concentration. Exactly the same arguments apply to the interpretation of yield-response relationships for AOT40.

A different approach to estimating critical limits for effects on vegetation has recently been proposed by German workers (Grunehage *et al.*, 2001). This pools data from all available experiments, but expresses ozone exposure as the mean daily concentration, rather than the cumulative concentration above 40 ppb, as for AOT40. The estimates of maximum permissible ozone concentrations (MPOC) are summarised in Table 3 for different averaging times.

Table 3: Summary of estimated maximum permissible ozone concentrations, expressed as daily mean concentrations, for different effects, receptors and averaging times. Adapted from Grunehage *et al.* (2001).

Averaging time	**MPOC (ppb) ensuring extensive protection**		**MPOC (ppb) above which lasting adverse effects**	
	Herbaceous species	**Forests**	**Herbaceous species**	**Forests**
1 week	55	86	97	148
1 month	33	63	57	108
3 months	22	50	39	86
6 months	-	43	-	74

It is important to note that these values of estimated MPOC represent values at the top of the canopy, not at the measurement height above the canopy, and hence cannot be directly compared with the modelled values in Section 2. Nevertheless, the estimates for herbaceous species (wild plants and crops) imply that the modelled increase in background ozone concentrations may contribute significantly to widespread exceedance of the threshold daily mean MPOC. However, it is important to emphasise that the estimates derive from experimental studies in which there may be substantive contributions to the daily mean concentration and hence to the MPOC from peak concentrations in the middle of the day, and hence are subject to the same provisos as the experimental studies discussed above.

In contrast, very few studies have been conducted specifically to examine the effects of ozone at concentrations at or below 40 ppb. However, there is some direct evidence, either from exposure-response studies covering a range of concentrations or from studies using concentrations in the range 40-60ppb of significant effects in this concentration range. In this report, we do not attempt to summarise all these studies in a comprehensive fashion; one reason for this is that, almost without exception, these studies were conducted in closed chamber systems to prevent ingress of ozone in ambient air and to ensure greater control of the target concentration. It is not possible that the effects observed at a particular target concentration under these artificial conditions will be found at the same concentration under field conditions.

For forest species, there are particular technical difficulties in assessing the impact of low concentrations of ozone. Nevertheless, a recent study of poplar (*Populus nigra* and *Populus euramericana*), one of the most ozone-sensitive species, showed significant effects of exposure for six weeks to ozone concentrations of about 40 ppb (AOT40 of 1 ppm.h). There was an increase in leaf abscission and an increase in water loss due to changes in leaf conductance; there was also evidence of changes to the properties of leaf cuticles (Schreuder *et al.*, 2001). This finding is consistent with much earlier studies in controlled environment chambers which demonstrated that exposure to 40 ppb for 12 h day^{-1} for five months caused extensive leaf loss from sensitive *Populus* cultivars (Mooi, 1980).

There is a well-established genetic variation in sensitivity to ozone. However, very few studies have determined the implications for such variation for thresholds for ozone effects. In one the few studies to attempt such an analysis, Taylor (1994) used the results of fumigation studies of the sensitive North American pine species, loblolly pine (*Pinus taeda*) to estimate the threshold concentration for adverse effects on the most sensitive genotpes in the population. The value estimated was 26 ppb, as a 12h mean concentration over a growing season. This compares with a threshold value of about 45 ppb estimated for the mean of the population.

For semi-natural vegetation, few studies have used concentrations as low as 50 ppb. Batty and Ashmore (2001) investigated the short-term responses of a range of sensitive UK lowland species to fumigation with a concentration of 55 ppb in closed chambers. At this concentration for three weeks, significant effects were found on the growth or photosynthetic rate of three species:- *Epilobium hirsutum*, *Digitalis purpurea*, *Eupatorium cannabinum* and *Typha latifolia*. In a series of growth chamber studies, Mortensen (1996) found that season-long exposure to ozone concentrations in the range 43-52 ppb caused significant growth reductions in a small proportion of the studies species, including *Plantago lanceolata*, *Phleum alpinum*, and *Trifolium pratense*.

The criteria used in most of the experimental studies relate to the impacts on plant growth or carbon assimilation. However, there is evidence that ozone concentrations close to the global background can cause changes in leaf chemistry or leaf surfaces which may influence the response of insect pests or plant pathogens. For example, Bell *et al.* (1993) reported that fumigation of *Chenopodium album* to 41 ppb ozone for 8h day^{-1} for 4 days caused a 40% increase in the growth rate of the aphid species, *Aphis fabae*.

Some information on the response of sensitive crops to low concentrations of ozone has been obtained from studies of visible injury, which provide the opportunity for comparison of the effects of short-term exposure periods with differing concentrations. For example, Tonneijck & van Dijk (1993) showed that exposure of a sensitive bean (*Phaseolus vulgaris*) cultivar to 30 ppb ozone for several weeks was sufficient to produce traces of injury, while 45 ppb was sufficient to injure many of the leaves. Tonneijck (1993) used results from the Dutch biomonitoring network to show that the onset of ozone injury in the sensitive tobacco cultivar Bel-W3 was more closely related to the cumulative weekly dose above 20 ppb than to the use of higher thresholds. Such a result is consistent with the value of [O3]c derived for a sensitive crop species from Figure 9.

3.4. Seasonality of ozone exposure

An important feature of the predictions in Section 2 is that the increases in background ozone concentration will be greatest in winter and early spring and least in mid-summer, when peak ozone concentrations from photochemical production are most significant. The result is (cf. Figure 5) that the highest daily mean concentration are predicted to occur in the period February-May at many sites by 2030. In contrast, currently the AOT40 index is applied for the fixed periods of May-July for crops and April-September for forests, and so may not encompass many of the key periods of increased vegetation exposure.

Very few studies have examined the effects of early-season ozone exposure on the subsequent growth and development of vegetation. However, under the recent DEFRA ozone umbrella contract, Mansfield *et al.* (2001) exposed young beech trees to ozone episodes early and late in the growing season. There was clear evidence that trees exposed earlier in the growing season showed a greater reduction in carbon assimilation in response to ozone. A further experiment in which the date of bud-burst was manipulated clearly demonstrated that this was due to an increased sensitivity of young leaves in the weeks after budburst rather than to the dates of exposure per se.

Although this experiment involves episodic exposures to relatively high concentrations, the demonstration that ozone can have greater effects in the early season implies that thresholds for adverse effects may be lower soon after budburst than later in the season when buds have hardened, i.e. that background ozone concentrations could be more significant in this period than current critical limits, based on season-long exposure, imply. However, it is difficult to generalise from this one experiment.

For crop species such as wheat, results reported in literature demonstrate clearly that it is exposure later in the growing season, around the period of grain filling, which is most critical. This suggests that it is changes in summer ozone exposures which are likely to be most critical. However, there are early-season or over-wintering crops for which increases in ozone concentrations in winter and early spring are more significant, for instance oilseed rape is known to be moderately sensitive to ozone (Mills *et al.*, 2000), and effects on both yield and oil content were reported in an open-top chamber experiment in northern England by Ollernshaw *et al*. (1999).

There is very limited information available on the sensitivity of semi-natural vegetation at different stages in the growth cycle. However, annual species occupy a range of seasonal niches and there are likely to be early-season species for which the increased background ozone concentration is most significant. In assessing the effects of increased early spring exposure to ozone, it is important to remember that changes in climate, in particular the warmer winters which have been experienced in recent years and which are consistent with predictions of climate change models, may lead to earlier emergence of many wild species and earlier budburst in some tree species.

3.5. Geographical Distribution of Ozone

Current maps of AOT40 distributions across the UK for both crops and forests show a strong gradient of decreasing values from the south and east of the country to the north and west, with a small effect of increased values at higher elevations (NEGTAP, 2001). The changes predicted by 2030 in Section 2 suggest that this clear trend is likely to be lost over the coming decades, primarily because of the large number of additional hours which will exceed 40 ppb under the influence of increased global background concentrations.

This change has considerable implications for the validity of existing risk assessments based on AOT40. However, most research on ozone impacts has focussed on arable crops and on herbaceous species of lowland pastures and of wetlands. For example, Batty *et al.* (2001) attempted to assess the possible sensitivity of the range of grassland communities found throughout the U.K., based on the divisions with the National Vegetation Classification. This included a classification of the sensitivity to ozone of the dominant species in each community, based on reports in the literature. However, while such a classification was possible for calcareous and mesotrophic grasslands, it was not possible for the acidic and montane grasslands, which dominate the regions where the increases in background ozone concentrations are most significant, because of the lack of previous studies.

There are also important interactions between the seasonality of the response to ozone and the geographical distribution of impacts to vegetation. In general, vegetation growth is less likely at northern and upland sites in the critical early spring period when ozone concentrations are increased, and hence the impact is likely to less significant in these areas. There is little convincing evidence in the literature that background ozone levels affect the winter hardiness of vegetation, which is likely to be a more critical issue in these areas.

A key difference between the eight sites for which predictions were made in Section 2 is between sites at which there is a strong diurnal profile in ozone concentration and those more remote and high elevation sites at which there is much lower nocturnal depletion of ozone. The higher daily mean concentrations at sites such as Strath Vaich reflect to a considerable extent the lack of nocturnal depletion of ozone. It has been assumed previously (e.g. in applying the AOT40 concept) that ozone concentrations are only significant in daylight hours. However, this assumption has been challenged, for example by Musselman & Minnick (2000), who rely both on the fact that many species have a significant stomatal conductance at night and that a limited number of experimental studies have shown significant effects of night-time exposure to ozone. This may be an important issue in assessing the significance for impacts on vegetation of the increase in nocturnal concentrations at times of the year with a relatively short daylength, depending on whether nocturnal conductance allows flux to exceed thresholds for damage.

4. Implications for Policy and Research

The previous two sections of this brief report have clearly demonstrated that significant changes in the impacts of ozone on vegetation may occur across the next three decades under the influence of increased global background concentrations. However, while it is possible to speculate about the scale of these changes, and to identify key issues which may influence the impacts of this changed ozone climate, very little experimental evidence exists which directly addresses this specific issue. It is clearly essential that future research priorities for effects research within DEFRA recognise the importance of obtaining a more informed basis for this assessment.

4.1 Policy Implications

Currently, national and European assessments of the potential risk of impacts of ozone impacts on vegetation are based on the application of the AOT40 index. Although this index has had considerable value in terms of identifying areas where adverse effects on vegetation are possible, the dangers of using it to quantify and compare the relative impacts of ozone in different locations have long been recognised (Fuhrer *et al.*, 1997). Furthermore, concern has been expressed about the difficulty of applying the index in areas of northern Europe when many hours are close to 40 ppb, and hence there is considerable uncertainty in AOT40 assessments introduced by small uncertainties in ozone concentrations (e.g. Tuovinen, 2000).

These difficulties are clearly exacerbated in the case of applying the AOT40 concept to assessing the impact of changes in background ozone concentrations. A major effect of the predictions for 2030 is that the frequency distribution of concentrations is likely to shift significantly within the range 20-50ppb, and the significance of these shifts depends critically on the concentration threshold used. When the AOT40 concept was first developed, it was recognised that equally good fits to many experimental datasets with a wide range of ozone exposures could be obtained by using AOT30 (i.e. a threshold of 30 ppb) rather than 40 ppb. However, the implications of the modelled changes in ozone frequency distribution in 2030 would be quite different if 30 ppb rather than 40 ppb were used as the basis of the AOT calculation. The application of the AOT40 index with a fixed time-window (May-July for herbaceous species and April-September for trees) is clearly also inadequate to address the modelled annual cycle of changes in ozone frequency distributions.

Furthermore, the flux modelling discussed in section 3.2 implies that for sensitive species the threshold concentration above which biologically significant fluxes can occur is in the range 20-30 ppb. While a limited number of hours of exposure above 20 ppb may have a minimal biological significance, a major shift in the frequency distribution of concentrations within the range 20-40 ppb, while having no effect on the value of AOT40 could be significant in terms of the impacts of ozone.

A very significant implication of this finding is that the AOT40 concept is inadequate for assessment of the impacts of increased global background ozone concentrations. It is therefore important that it is replaced as the key tool for ozone risk assessment in Europe. Clearly, a flux based approach would most effectively capture the real impacts of ozone concentrations close to the background on sensitive vegetation, but the relative complexity of this approach may be an important barrier to its application in pan-European risk assessment. An alternative approach would be the use of a modified AOT index, either by using a fixed lower threshold such as 30ppb (AOT30) or a variable threshold depending on species sensitivity. This lower threshold would more effectively capture the influence of rising background concentrations in the range 20-40ppb.

4.2. Research Priorities

It is important to emphasise that the assessment in Section 3 is based on a combination of first principles, mechanistic understanding and a very limited experimental database. It can therefore realistically only serve as an indication of the POSSIBLE ways in which changing global background concentrations may influence vegetation. While our analysis suggests that the changes predicted for 2030 could be significant for parts of the UK and certain types of vegetation, there is almost no firm basis for realistic predictions or identification of key geographical areas or vegetation communities of concern. It is clear, therefore, that further research is needed.

We propose the following as key areas of investigation:-

(i) Experimental studies

There is little direct evidence in the literature of the effects of changes in background concentrations in the range 20-50 ppb. We propose two types of study:-

- studies in controlled environment conditions with particularly sensitive species to determine if concentrations in this range are biologically significant and what mechanisms are involved;
- field studies, using open-top chambers or field fumigation techniques, initially with sensitive crop species such as wheat, for which exposure-response relationships are well-established to establish whether changes in ozone exposure predicted from increased background ozone concentrations would have comparable effects from changes in exposure resulting from varying peak concentration and frequency.

(ii) Flux modelling

Current flux models suggest that concentrations below 40 ppb could lead to significant fluxes above a critical threshold for effects. They thus represent an important tool in evaluating the significance of increased global background ozone concentrations. We propose three types of study:-

- further studies with existing models to assess in more detail the implications of predicted changes in ozone exposure over the UK in 2030 for ozone flux, taking into account the interactions with climate;
- studies to define the critical flux threshold for a wider range of species, using appropriate experimental studies, including both types of study proposed under (i);
- comparisons of flux models with field measurements of flux over different vegetated surfaces to better understand processes controlling flux and to improve the parameterisation of existing flux models.

(iii) Responses of upland vegetation

Improved information on the sensitivity to ozone of important upland plant species is needed. We propose two types of study:-

- short-term studies in controlled environment conditions to assess the ozone sensitivity of individual species;
- longer-term field studies with species mixtures to assess the response of species composition to changes in background ozone concentrations; such studies might be focussed on particular conservation issues, e.g. in the management of ESAs or in key communities under the Habitats Directive.

(iv) Seasonality of response

There is very little basis currently for evaluating the significance of increased ozone exposure in the early spring. We propose two types of study:-

- short-term studies to establish the ozone sensitivity of species likely to be physiologically active in the critical period of February-April, using appropriate climatic conditions;
- longer-term field studies of probable sensitive species using open-top chambers or field fumigation, in which ozone exposures are increased specifically in the early spring period.

These studies should be designed to incorporate the possible effects of ozone on winter hardness and on stomatal control over the winter/spring period

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