INTERIM REPORT TO THE CEC ON AIR POLLUTION EFFECTS

RESEARCH USING OPEN-TOP CHAMBER STUDIES

AT ITE EDINBURGH, OCTOBER 1990

DR DAVID FOWLER

INTERIM REPORT TO THE CEC ON AIR POLLUTION EFFECTS RESEARCH USING OPEN-TOP CHAMBER STUDIES AT ITE EDINBURGH, OCTOBER 1990

INTRODUCTION

The work programme includes two distinct studies.

1. Effects of ozone and acidic mist on the physiology and frost hardiness of tree seedlings in open top chambers.
2. Open top-chamber properties.

For each of these studies, this interim report provides a description of the experimental work completed during the growing season of 1988-1989 and the work in progress during 1990. It includes the main results and examples of specific measurements and identifies the major developments and achievements. In the experimental study of effects of acidic mist and ozone on Norway spruce and Beech, the work forms a part of the forest decline studies in progress at a range of institutions throughout Europe. The second project includes descriptions of chamber properties and characteristics for agricultural crops and for trees. Within COST 612 the work on open-top chamber properties and their interactions with growth, development and pollution effect responses has a much wider application. The data base of chamber characteristics within this study is therefore available to all groups within this co-operative and contributions to the study of chamber effects will be encouraged during the analysis of data for the final report during 1991.

1. Effects of ozone and acidic mist on growth and physiology of Norway spruce and Beech and the frost hardiness of Norway spruce.

The treatments were designed to simulate two distinct aspects of the pollution climate of Europe.

a. High altitude forests exposed to acidic mist.

b. Central European mid altitude locations which experience between 20 and 50 episodes each year of Ozone at concentrations (an episode being an event during which Ozone concentration exceeds 70 ppbV, in practice such episodes in Europe show maxima between 70 and 150 ppbV).

For experimental reasons the treatments exclude other pollutants which would necessarily complicate the interpretation. Such additions (of SO_2 and NO_2 at the 5 to 10 ppb level) may be an important feature of future experiments.

Ozone and Ozone plus Acid Mist

In the experiments in 1988 and *1989*, Beech and Norway spruce seedlings which had been grown from seed in charcoal filtered air in a glasshouse *were subject to the following treatment:*

Charcoal filtered air (CF)	- 2 chambers - each with	50 Norway spruce + 50 Beech
Ambient (see table 1)	"	"
CF + episodes to 100 ppbV O_3	"	"
CF + " " 140 ppbV O_3	"	"
CF + " " 140 ppbV O_3 + acid mist	"	"

TABLE 2: ACID MIST CONCENTRATIONS 1988-1990

	Concentration (mM)			
1988				
	H	NO_3	SO_4^{2-}	NH_4^+
$H_2SO_4 + NH_4NO_3$	3.2	1.6	1.6	1.6
H_2SO_4 (pH 2.5)	3.2	0	1.6	0
(pH 3.0)	1.0	0	0.5	0
HNO_3	3.2	3.2	0	0
NH_4NO_3	0	1.6	0	1.6
NH_4SO_4	0	0	1.6	1.6
H_2O	0	0	0	0
1989				
$H_2SO_4 + NH_4NO_3$ (pH 2.7)	2	1	1	1
H_2 SO_4	2	0	1	0
$H_2SO_4 + NH_4NO_3$ (pH 5.0)	0.01	0.005	0.005	0.005
1990				
$H_2SO_4 + NH_4NO_3$ (pH 2.5)	3.0	1.5	1.5	1.5
$H_2SO_4 + NH_4NO_3$ (pH 5.0)	0.01	0.005	0.005	0.005

Episodes of O_3 were generated from pure oxygen and metered into the charcoal filtered outlet from the fan-filter unit whenever air temperatures in the chamber exceed 15°C <u>and</u> global short wave radiation exceeds 400 Wm^{-2}. Using these criteria the cumulative total during 1988 was 211 hours in the period June-September. The duration of individual episodes varied between 2 and 8 hours but averaged 6.3 hours for the 93 days. These exposures were designed to produce an episode regime similar to that at low or moderate altitude sites in Bavaria or the Black Forest. In this way they differ from high altitude sites (eg Schauinsland), where in episode conditions elevated O_3 concentrations may persist continuously for several days.

The acid mist treatment was included to simulate the moderate altitude site which experienced polluted cloud water twice each week as well as frequent O_3 episodes. The composition of the acid mist spray was H_2SO_4 + NH_4NO_3 at a pH of 2.5. The mixture had been shown in earlier work (autumn 1987) to induce damage to Red spruce.

<u>Acid Mist</u>

In a separate group of 12 open-top chambers the observations of extensive damage to Red spruce from the Autumn 1987 experiment was followed up by an experiment with Norway and Red spruce to show which ion or combination of ions caused the damage and to show the relative responses of Norway spruce and Red spruce to link the European studies to those of the NAPAP co-operative in North America. The treatments were all applied in charcoal filtered air in chambers with lids to exclude rain. The spray system provided droplets with a number mean radius of about 40 μm which were applied at a precipitation equivalent rate of 3 mm h^{-1}. Each application provided 2 mm of solution to the plants and was just enough to cause drip from the foliage.

RESULTS

The Beech and Norway spruce were subject to a range of physiological and growth analysis measurements during and following treatment.

1. Growth measurements

Plant height measurements throughout the treatment period showed no treatment differences. At harvest during December 1988 Norway spruce plants from all ozone treatments showed similar amounts of growth and with similar partitioning into foliage stems and roots. The large numbers of plants used allowed us to detect quite small treatment differences (< 10%) but no treatments effects were detected. Such results are similar to many published responses of conifers in the first year of ozone treatment. We therefore allocated a block of plants for the second year's experiment to show whether the second year produces larger treatment differences (> 10%), as has been shown by others. The Beech was subject to extensive aphid attack during the mid summer of 1988 which seriously confounded growth analysis and for this reason has not been tabulated.

Unlike the visible injury which had developed on Red spruce in response to acid mist at pH's in the range 2.5 to 3.5, the Norway spruce showed very few foliar lesions in any of the treatments tabled. In the Ozone 'episode' chambers the only treatments to show significant visible injury were the O_3 at 140 ppbV + acid mist. In these chambers by the end of the experiment a third of all plants showed > 20% needle necrosis (34 plants out of 100) both true replicate chambers showing the same response, Table 10, even though individual treatments of O_3 at 140 ppbV or acid mist H_2SO_4 + NH_4NO_3 at pH 2.5 produced no significant visible injury. The 1988 and 1989 experiments separated the major ions to identify the ion or ionic combination responsible for the damage result seen on both Red spruce and Norway spruce seedlings.

Norway spruce frost-hardiness response to acid mist

The method used to assess frost hardiness closely follows that developed for Red spruce and is based on electrolyte leakage (Murray et al., 1989). The method has been shown to quantify the needle mortality resulting from freezing treatment. The entire population of shoots taken from freezing tests at 6 temperatures evenly spaced over 10° above and below the killing temperature fall into two distinct populations, one with large electrolyte leakage rates, the needles from which quickly turn brown, and the other with small electrolyte leakage rates with needles which do not quickly turn brown.

Frost Hardiness

Frost hardiness of Norway spruce seedlings following experimental exposure to pollutants in open-top chambers (Table 2), was tested on 29 August, 19 September, 10 October and 7 November by excising sections of current-year shoots, exposing them to a range of controlled freezing temperatures, and evaluating damage by visual scoring and electrolyte leakage using methods developed at ITE (Murray et al., 1989). No significant effects of pollutant treatment were observed until frost hardening started in October. Significant effects of pollutant treatment on the degree of frost hardiness were then observed, with lethal damage to the most sensitive 20% of the shoot population being caused at higher temperatures than control trees. Figure 1 shows that the effect of polluted mist was related to the presence of sulphate and ammonium ions, not to acidity or nitrate. This response was similar to that shown for red spruce (*Picea rubens*) in the same experiment (Cape et al., 1989). No effect of exposure to episodes of ozone at 100 ppb was detected, and neither was there an effect of filtering

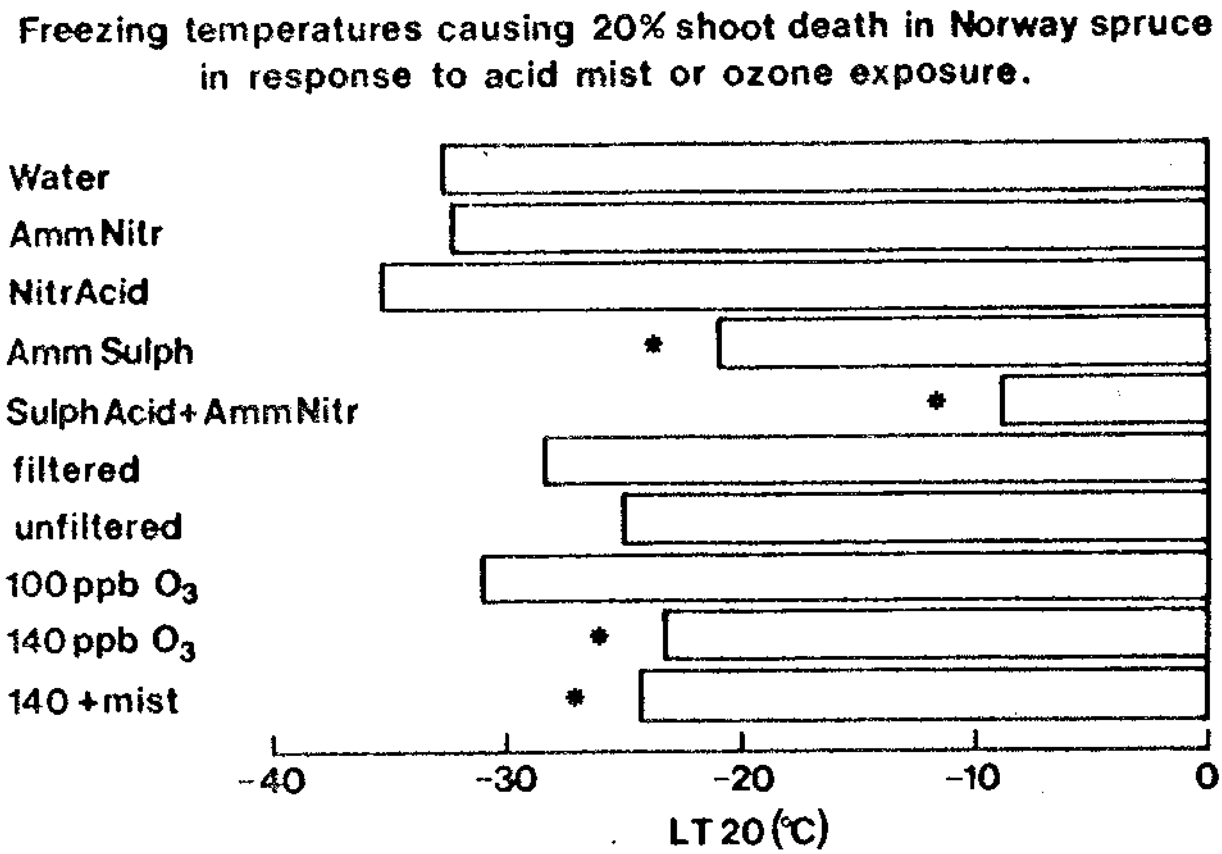


Figure 1. Freezing temperatures causing 20% shoot death in Norway spruce in response to acid mist or ozone exposure.

ambient air. However, episodes of 140 ppb ozone produced a small but significant increase in frost sensitivity. The effect of the combined treatment with 140 ppb Ozone and mist was similar to that for Ozone alone, demonstrating that effects of ozone and polluted mist on frost hardening were not additive, and may indeed have been less than for polluted mist alone. We conclude that exposure to polluted mist and, to a lesser extent, ozone at concentrations typical of high elevation forests can induce greater sensitivity to frost in Norway spruce seedlings in autumn, and that the effects of mist are associated with ammonium and sulphate ions.

Frost Hardiness 1989

Frost hardiness of Norway spruce seedlings was tested on 7 November 1989. Results from the experiments involving treatments with acid mist (see Table 2) are given in Table 3, expressed as the LT_{50}, or temperatures required to cause lethal damage to 50% of shoots. Treatment effects on lethal temperatures were smaller overall than in 1988, perhaps reflecting better soil conditions. However, the polluted mist treatment containing H^+, NH_4^+, NO_3^- and SO_4^{2-} at pH 2.5, applied as 8mm precipitation equivalent per week, gave an LT_{20} about 2 deg C higher than the control treatment at pH 5 (Figure 1). There was no significant effect with the lower treatment rate (2mm/week), showing that observed effects are caused by dose and/or frequency of exposure to mist, rather than to pH or concentration alone.

Sub-treatments within chambers, where extra sulphuric acid was added to the soil, made seedlings slightly less sensitive to frost, suggesting that adverse effects of polluted mist on frost hardiness were caused by direct action of pollutant mist on foliage rather than by root uptake.

Results from the ozone treatment, as in 1988, showed no significant effects of treatment with episodes of 100 ppb ozone, largely because of big differences between replicate chambers. These results illustrate the requirement for true treatment replication at the chamber level if meaningful experiments are to be conducted. Frost hardiness of current year and previous year (1988) needles were tested, including 1989 needles which had been exposed in both 1988 and 1989. There was no detectable effect of two years' ozone exposure on frost hardiness of older needles, but older needles were found (in all treatments) to be 8-9 deg C more sensitive to frost than current-year needles (Table 4).

TABLE 3: Calculated LT_{50}s for Norway spruce shoots following experimental treatments in 1989

Treatment	Sub-treatment	LT_{50}
'Control' 8mm/week H_2SO_4+NH_4NO_3 pH5	Normal	-26.7
	extra H_2SO_4 to soil	-28.6
	all	-27.7
Sulphuric acid 2mm/week pH 2.5	Normal	-27.8
	Extra H_2SO_4 to soil	-26.8
	all	-27.3
Mixture 2mm/week H_2SO_4+NH_4NO_3 pH 2.5	Normal	-28.5
	Extra H_2SO_4 to soil	-28.4
	all	-28.4
Mixture 8mm/week H_2SO_4+NH_4NO_3	Normal	-24.7
	Extra H_2SO_4 to soil	-27.0
	all	-25.8
all	Normal	-26.9
	Extra H_2SO_4 to soil	-27.7

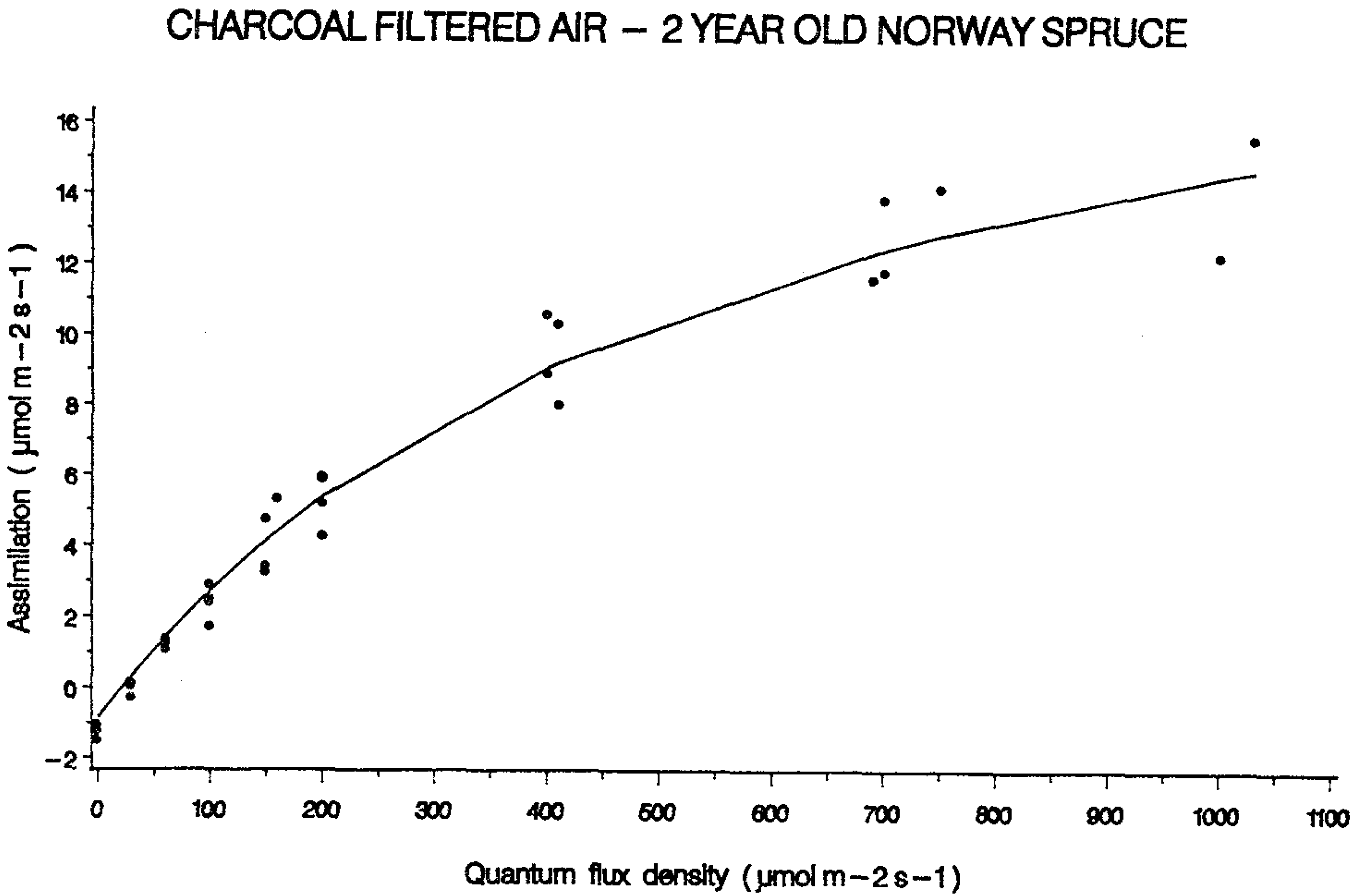
TABLE 4: Frost hardiness of Norway spruce following ozone and acid mist treatment.

	Lethal temperature °C for LT_{100} needle death (LT_{100})
Charcoal filtered air	-34
Ambient	-33
CF + 100 ppbV O_3 (207h)	-34
CF + 140 ppbV O_3 (207h)	-28 *
CF + 140 ppbV O_3 (207h) + acid mist (pH 2.5)	-29 *

Gas Exchange

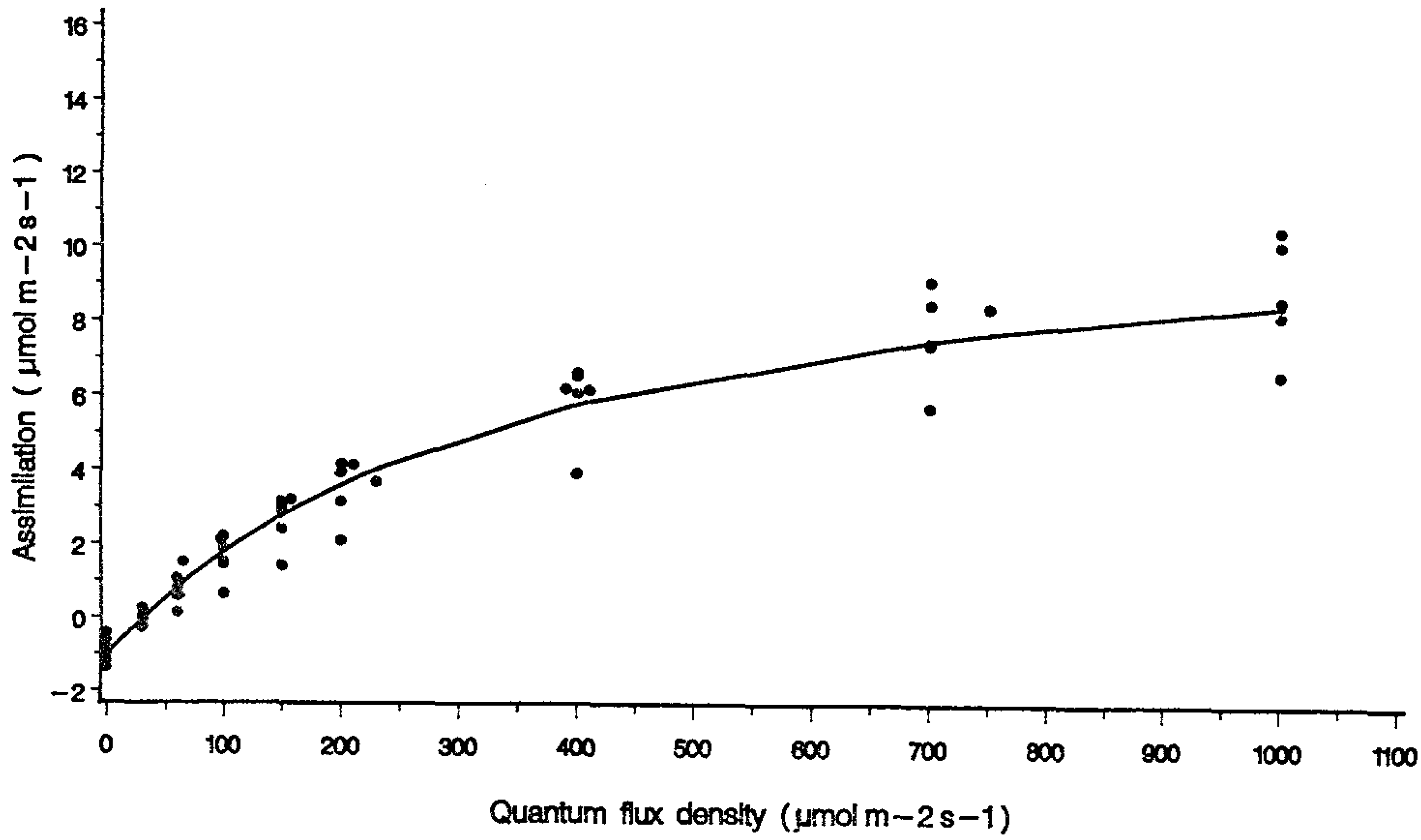
The treatments with acid mist and ozone have been shown to change the frost hardiness of Norway spruce. The major processes of photosynthesis and evapotranspiration have been shown by other research groups to be influenced by ozone. In this study plants from all three treatments (acid mist, ozone and acid mist plus ozone) have been examined using gas exchange techniques to determine the light response curve for photosynthesis. A full light response curve for assimilation was determined using a laboratory based open gas exchange system consisting of a hench top IRGA (ADC 225 Mk III) and a Michell Series 3000 cooled mirror dewpoint hygrometer. Illumination was supplied by two metal halide (Wotan power star lamps HQI 250 W), and the photon flux density was varied using neutral density filters.

The assimilation-photon flux density relationships (A/Q curves) for each of the treatments are presented as figures 2, 3 and 4. The data for each have

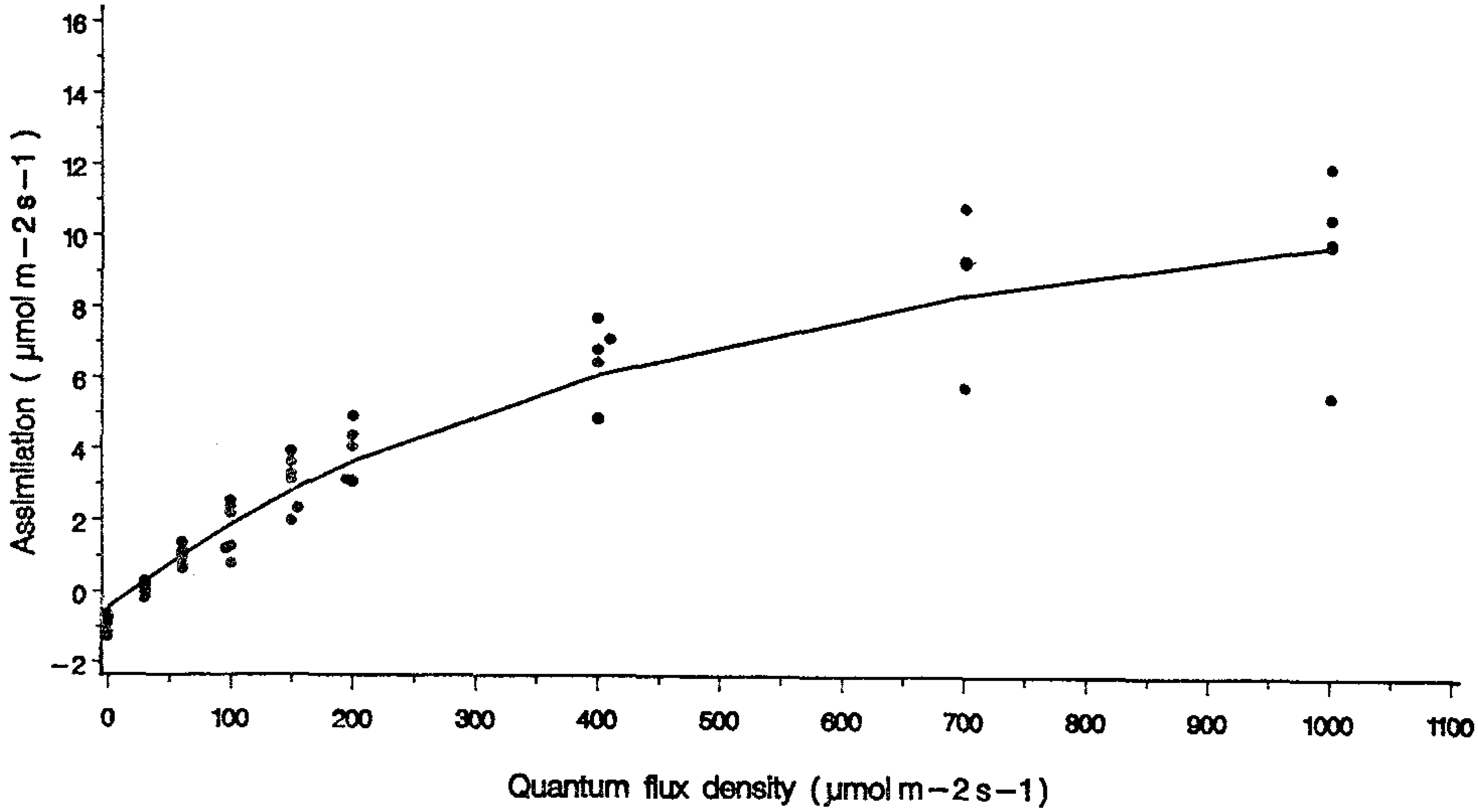


CHARCOAL FILTERED AIR – 2 YEAR OLD NORWAY SPRUCE
Assimilation (µmol m–2 s–1)
16
14
12
10
8
6
4
2
0
–2
0
100
200
300
400
500
600
700
800
900
1000
1100
Quantum flux density (µmol m–2 s–1)

OZONE (140 ppb) TREATED 2 YEAR OLD NORWAY SPRUCE



OZONE (140 ppb) AND ACID MIST (pH 2.5) TREATED
2 YEAR OLD NORWAY SPRUCE



been analysed using the model of Jarvis et al., (1985) to fit a non-rectangular hyperbola to the assimilation (A) and photon flux density (Q) data.

The estimated parameters from the model show:-

1. That the light saturated rates of photosynthesis (A_{max}) are larger in the control treatment than either the ozone which is reduced by 58% or acid mist plus ozone treatments which is reduced by 66%.

2. Stomatal conductances in the ozone treatment were reduced by almost 50% relative to the control treatment, but a smaller 'stomatal closure' response was noted for the ozone + acid mist treatment.

3. Dark respiration rates in filtered air and for the ozone treatment were similar but rates of dark respiration in the ozone + acid mist treatment were smaller than the control.

The analysis of variance for the gas exchange data and the values for parameters derived from these data are presented in tables 5 and 6.

TABLE 5: Combined curve analyses of variance (Ross 1981) for curves fitted using the theoretical model of Jarvis _et al_., (1985).

Curve Comparisons	Degrees of Freedom	Sum of squares	Mean sum of squares	F Ratio
Filtered vs treated	4	151.77	37.943	42.87***
Between treated	4	1.84	0.460	0.52
Separate curves	128	113.29	0.890	
TOTAL	139	2178.20	15.670	

TABLE 6: Estimated parameter values from the theoretical model (Jarvis _et al_., 1985)

Treatment		gm	Rd	A_{max}
Combined data	0.0319 se 0.0040	0.05331 0.00450	0.593 0.261	15.40 1.08
Filtered (Charcoal)	0.0422 se 0.0047	0.07750 0.00660	0.866 0.311	22.40*** 1.62
Ozone (140 ppb)	0.0360 se 0.0049	0.0394 0.0028	0.994 0.260	13.13 0.98
Ozone (140 ppb) and acid mist (pH 2.5)	0.0273 se 0.0047	0.0533 0.0068	0.446 0.326	14.87 1.42

Visible Injury

The acid mist and ozone treated Norway spruce were scored each week for visible injury, as in earlier work on Red spruce, the acid mist treatments had been shown to provide visible injury at activities in the range pH 2.7 to pH 4.5.

The first two months showed no injury in any treatment but during the third month of treatment (August) small amounts of foliar injury were detected in the treatments containing SO_4^{2-} at the largest concentrations. By late October (after 5 months of treatment application) significant differences were observed in the mixed ion treatments (H^+, SO_4^{2-}, NH_4^+, NO_3^- referred to in table 7 as BREW) but no damage was evident in nitric acid treatments. The sulphuric acid treatment at pH 2.5 died from visible injury after 3 weeks treatment, and the part of Table 7 with H_2SO_4 is a new set of trees and acidity reduced from pH 2.7 to 3.0. The treatment with O_3 and acid mist with all ions present also developed significant needle injury. The injury detected in this work is very similar to that observed in earlier work on Red spruce. There is a smaller visible injury response to acid mist than Red spruce by about a factor of 2, (the combined treatment for Red spruce in otherwise similar conditions provided 20% needle damage after 6 months of treatment). Such findings are closely analogous to the frost hardiness response which is also smaller in Norway spruce than Red spruce.

TABLE 7 Assessment dates 1988 % damage per treatment

	7/6	14/6	19/8	7/9	22/9	29/9	17/10	2/11	24/11
Brew	0	0	0.02	0.07	0.35	1.40	5.00*	6.2*	8.9*
HNO_3	0	0	0	0	0	0	0.01	0.04	0.04
NH_4SO_4	0	0	0	0.02	0.06	0.20	0.30	0.30	0.40
NH_4NO_3	0	0	0	0	0	0	0	0	0
H_2SO_4	0	0.05	0.01	0.01	0.01	0.08	0.10	0.50	1.00
H_2O	0	0	0	0	0	0	0	0.05	0.05
O_3 Brew	0	0	0	0	0	1.2	3.5*	8.2*	13.3*

Visible injury to Norway spruce throughout the treatment period in 1989.
(Brew = H^+, SO_4^{2-}, NO_3^-, NH_4^+).

Chamber Properties

The air pollution effects research on short vegetation within Europe and North America during the last decade has been largely devoted to studies of the effects of ambient concentrations of the major pollutants. In this work the effects have been much more variable than in earlier work with large concentrations of pollutants in which large vegetative responses were common. Not only have the results been more variable in magnitude, they have also shown positive and negative responses, as in the work at small SO_2 and NO_2 concentrations by Fowler et al., (1986). At these small concentrations the interaction of the chamber environment with the pollutant effect becomes very important. The work at ITE during the last two years has concentrated on providing a description of the physical environment within the chambers, and showing how the small differences in temperature and the larger changes in the radiation environment affect growth, development and pollutant response. In this report we briefly describe the physical measurements made and an analysis of the major effects of changes in the energy budget within chambers on crop growth.

Measurements

The measurement of temperatures within the open-top chambers in use at the ITE laboratories include air temperature - inside and outside the chamber and in the manifold air, soil temperature, in pots containing young trees, leaf temperature and wall temperature (on North and South facing walls).

These measurements were made using a combination of radiation shielded thermocouples and small thermocouples attached to plant leaves or to chamber components. Data from all sensors were recorded using Campbell 21x loggers.

Humidity

Measurements have been made using psychrometers inside and outside the open-top chambers.

Solar Radiation

Tube and Kipp solarmetres have been used inside OTCs to show both the spatial variability and the average loss of short wavelength radiation within the chambers.

Net radiation

Net radiometres have been used to show both the variability in net radiation within the chamber and the differences between inside and outside.

To illustrate the results of these measurements a series of example figures are presented which demonstrate the main features.

Temperature

The average air temperatures inside open-top chambers are invariably larger than ambient. The magnitude of the differences lies generally in the range 0.2 to 2°C depending mainly on location and the flow rate of air through the chambers, the increase in temperature consists of two components, one due to the action of the blower or pump which is constant and one which depends on incident solar radiation. Both components are offset by incursion of ambient air through the open-top chamber of the chamber and therefore introduce an effect which is proportional to the external windspeed.

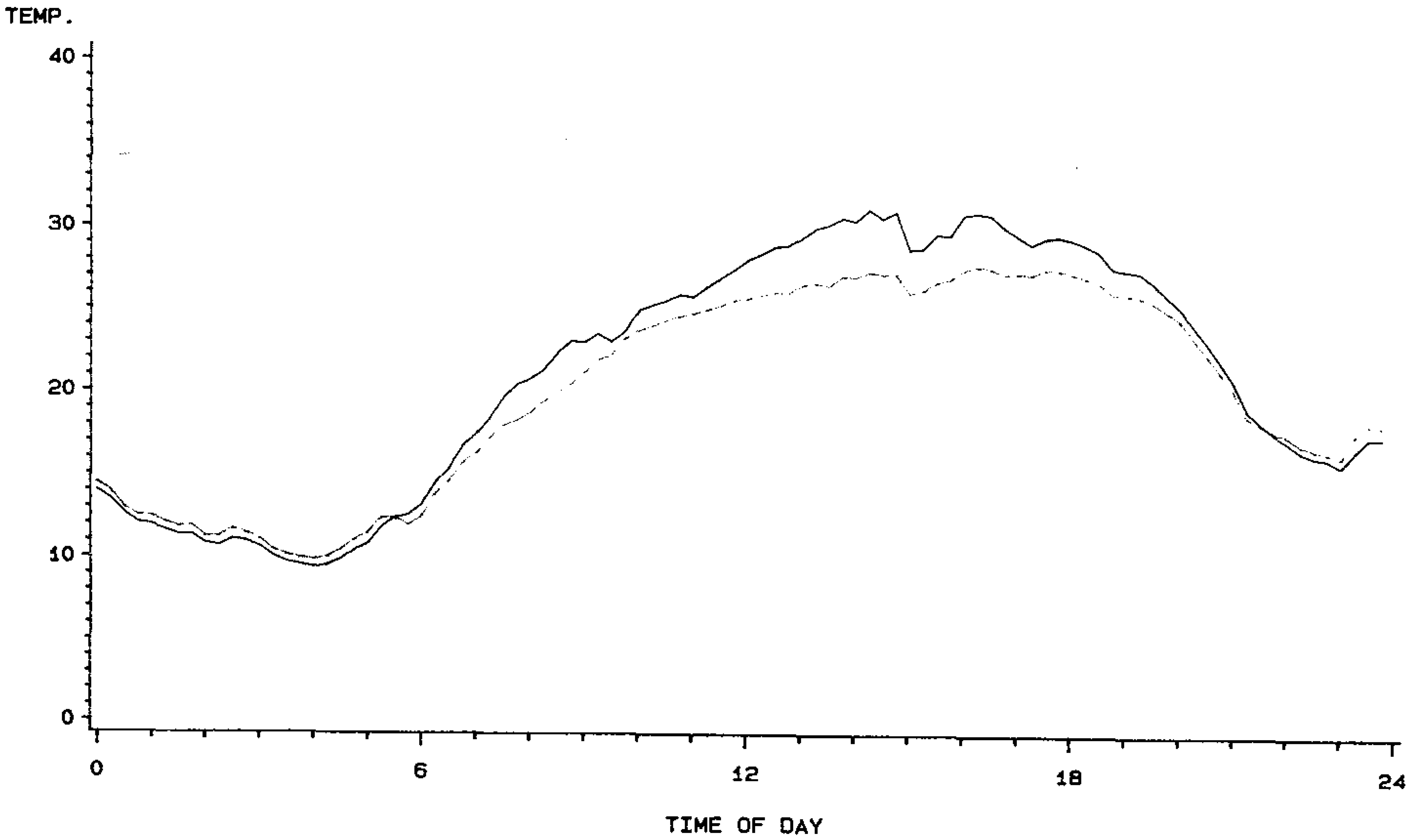
The manifold temperatures measured in our studies include the component which is due to the pump (0.25°C) so that for Figure 5 the increase in air temperature inside the chamber during one of the hottest days of 1989 is shown to exceed manifold temperature (ie ambient + 0.24°C) by up to 4°C.

The walls of the chamber which are glass intercept radiation and as a consequence wall temperatures on the sunlit side are in some cases 10°C larger than on the walls of the octagonal chamber which lie parallel to direct solar beam (Figure 6).

Solar radiation

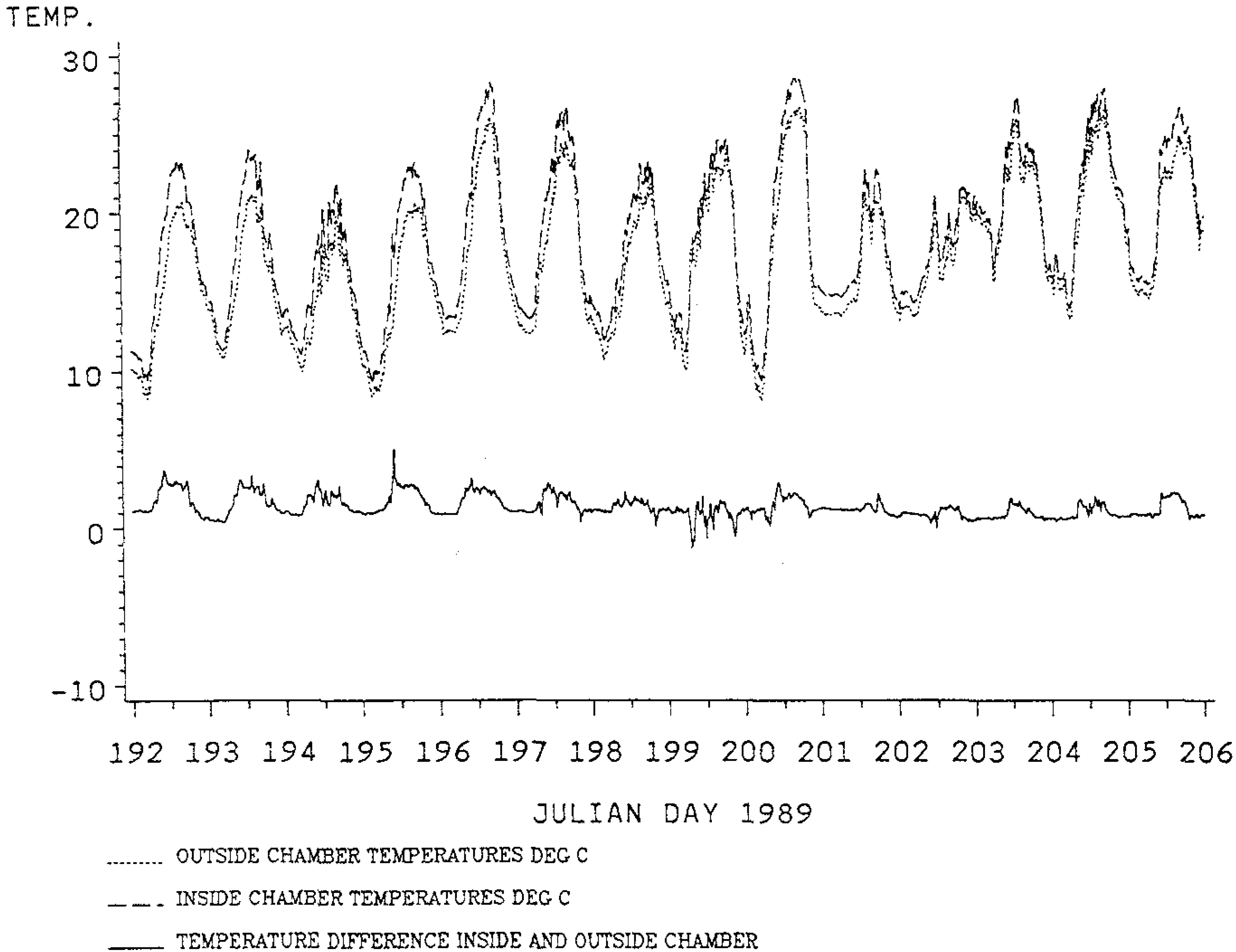
The attenuation of short wave radiation by the chamber walls and manifold is well illustrated by the data in Figure 7. The spikes for the internal

MANIFOLD & AIR TEMPERATURE INSIDE OTC (185 1989)

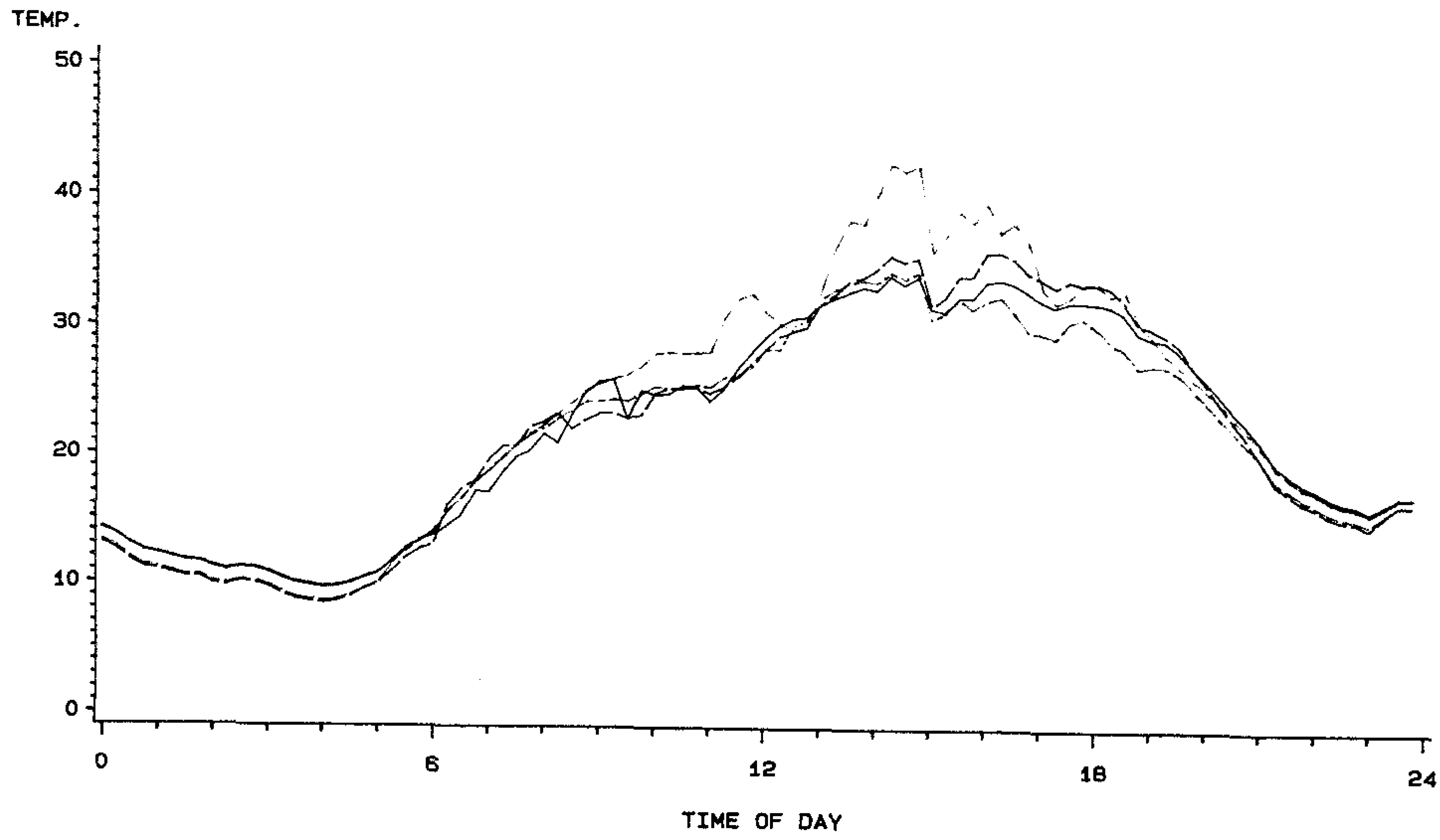


BLUE=MANIFOLD TEMPERATURE DEG C
RED=CHAMBER TEMPERATURE DEG C

INSIDE AND OUTSIDE CHAMBER TEMPERATURE DIFFERENCE

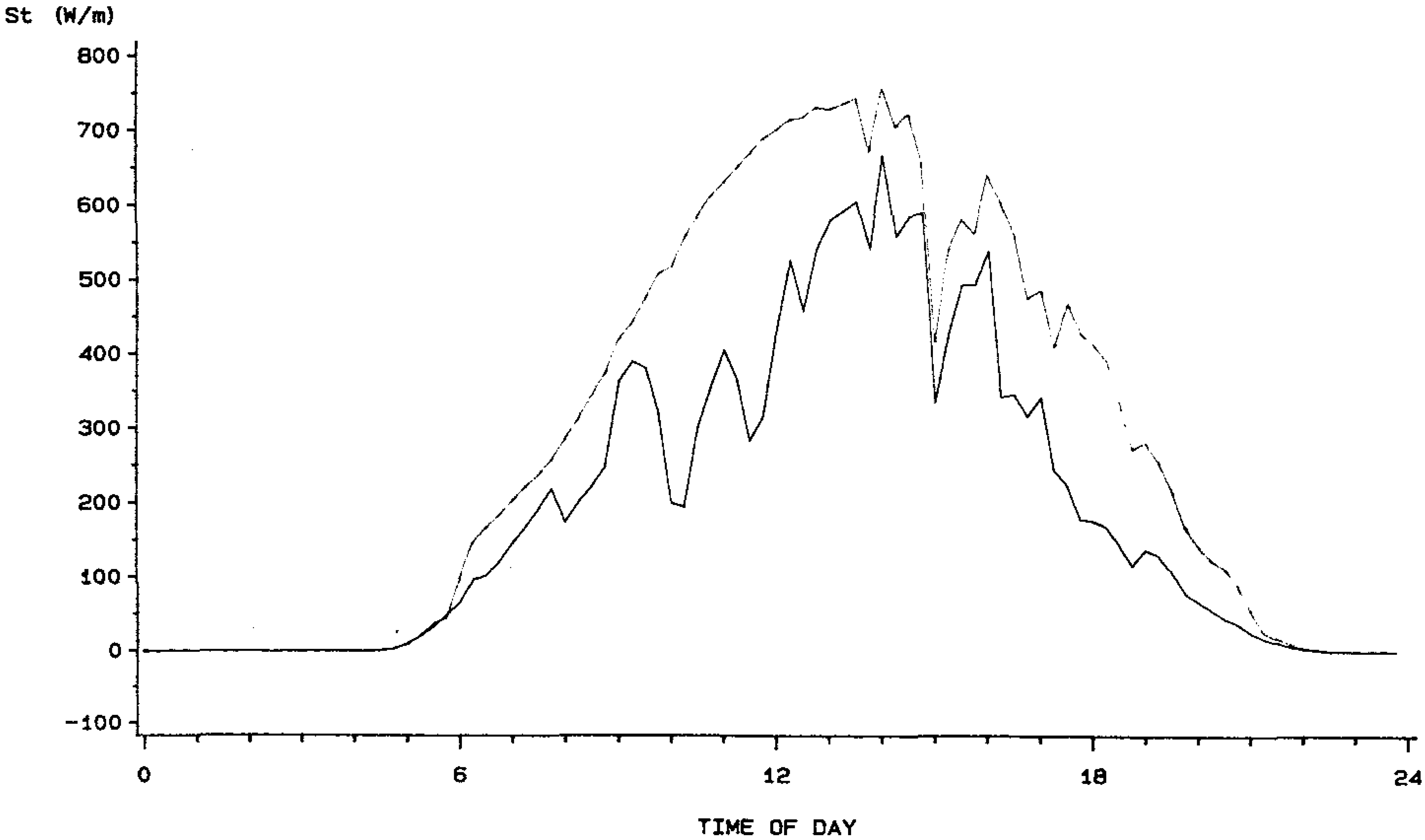


CHAMBER WALL TEMPERATURE INSIDE OTC (185 1989)



BLUE= SUNNY WALL TEMPERATURE DEG C
RED= DULL TEMPERATURE DEG C
---- =1.5m - - - =0.5m

SOLAR RADIATION INSIDE & OUTSIDE OTC (DAY185 1989)



BLUE=SOLAR RADIATION (W/m) OUTSIDE OTC
RED=SOLAR RADIATION (W/m) INSIDE OTC

radiation measurement result from shadows of components of the chamber crossing the radiometer (a Kipp solarimeter in this case). For average values tube solarimeters have been used and these show a 15% attenuation in the shortwave radiation when the chamber walls are clean. The value increases to a maximum of 25% when walls are dirty, at the end of a 3-month winter period during which the chambers were not in use.

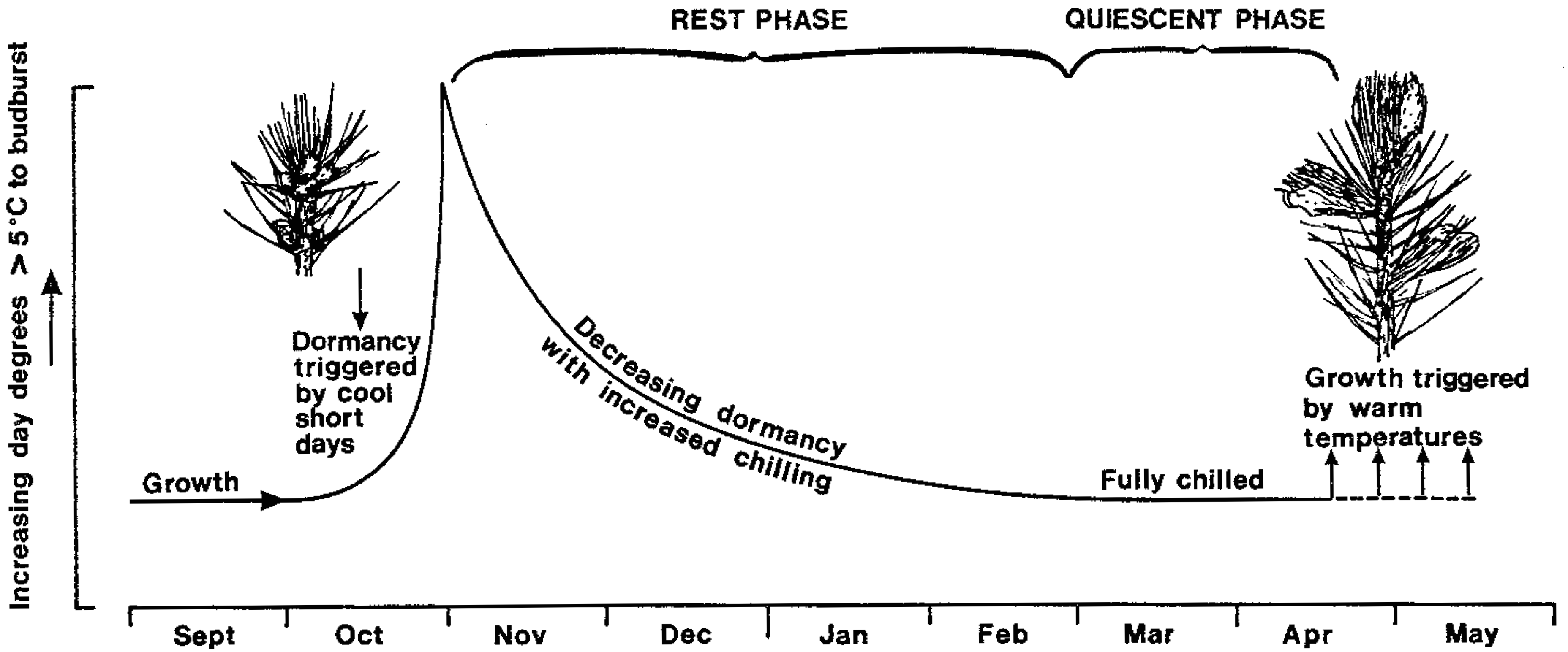
Temperature effects

Temperature is one of the most important components of the plant environment. Warming of as little as 1°C has been shown to increase plant productivity by about 10% (Grace, 1988 and Juntilla, 1986), for many species, however some annual crops may be negatively affected. (Monteith, 1981). He explained this phenomenon by stating the rate at which the crop develops from sowing, through phenological stages to flowering, is often determined by temperature. Therefore during warm years, the crop duration is reduced and consequently the total photosynthesis and dry matter production is also reduced. However, warm years also tend to be dry, so it would be unwise to base too much confidence on the field data in the absence of more detailed investigation.

Temperature also affects plants at the cellular level via carbon uptake and partitioning. The main affect commonly seen is an increase in the shoot/root ratio (Rajan et al., 1971, Pearcy, 1976). Temperature may have an immediate affect on enzymatic systems which control the rate and partitioning of photosynthetic products, the effects of temperature on individual enzymatic systems are often unknown. The overall affect of temperature on product partitioning of carbon leads at higher temperatures to more sucrose and at lower temperatures, where growth is reduced, more starch.

At another level plant phenology is closely coupled to temperature . The stages of bud phenology and how temperature controls them is described in Figure 8. During autumn (September to November in Britain) the growing plant apices receive cooler temperatures and shortening daylengths which trigger the onset of bud dormancy. Dormancy can be split into two phases: 'rest' and 'quiescence'. The initial phase (rest), physiologically maintained by the plant itself, as a very high thermal time (day degrees) to budburst requirement. This is progressively decreased by exposure to chilling temperatures during the winter months, until further exposure, no longer reduces the thermal time for buds to begin growing in a warm environment. The buds at this stage are said to be fully chilled and have entered the quiescent phase of dormancy. The quiescent phase is maintained while environmental conditions; such as cool temperatures, remain unfavourable for growth. During the spring temperatures rise and as soon as the buds have received sufficient warm temperatures they will flush and resume growth (Nienstaedt, 1967, Fuchiganil et al., 1982; Doorenbos, 1953).

All buds have a thermal heat requirement which differs between cultivars of the same species and between different species (Couvillar and Hendershott, 1974). The accumulation of degree days and its effect on developmental processes such as budburst will vary with increasing daily temperatures. The level of winter chilling and thereby the rate at which the resting phase of dormancy is progressively decreased during the winter months will also vary. Budset although sensitive to daily temperatures, is controlled


REST PHASE
QUIESCENT PHASE
Increasing day degrees > 5°C to budburst
Growth
Dormancy triggered by cool short days
Decreasing dormancy with increased chilling
Fully chilled
Growth triggered by warm temperatures
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May

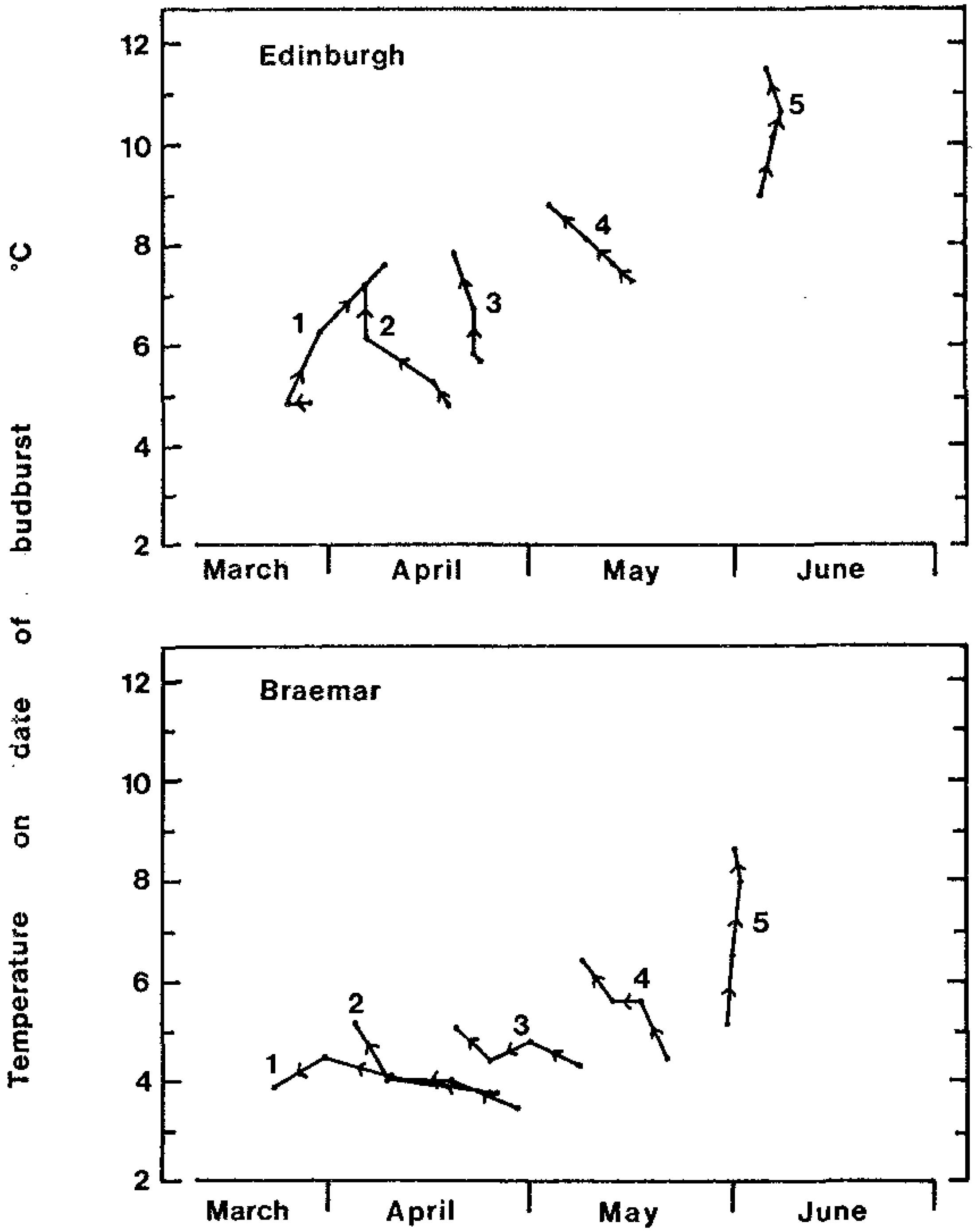
more closely by daylength. Therefore any alteration of the enrichment within an open-top chamber will have a greater influence on spring than autumn phenology.

Increases in temperature within an OTC could if large enough, have dramatic consequences by reducing the number of chill days over the winter and thereby increase the requirement for warm days to budburst for many plant species.

Murray, Cannell and Smith (1989) parameterize models for 15 woody perennial species based on an empirical thermal time-chilling model developed by Cannell and Smith (1983). The models were used with met data collected at two sites in Scotland, a mild lowland site and a harcher upland site, to predict the effect of increasing temperatures on timing of budburst and the temperature on the date of budburst, their results are shown in Figure 9.

Figure 9: Predicted changes in the date and temperature on the day of budburst as a consequence increased temperatures for 5 groups of woody perennials at Edinburgh and Braemar. Each point denotes a 1°C warming in the direction of the arrows.

A one-degree rise in the mean daily temperature as found in many open-top chambers would have very little effect on the timing of budburst except at harsher sites. However, temperature rises above 2°C will delay budburst for some species by as much as 2 weeks and, will also advance budburst by an equivalent amount for other species.

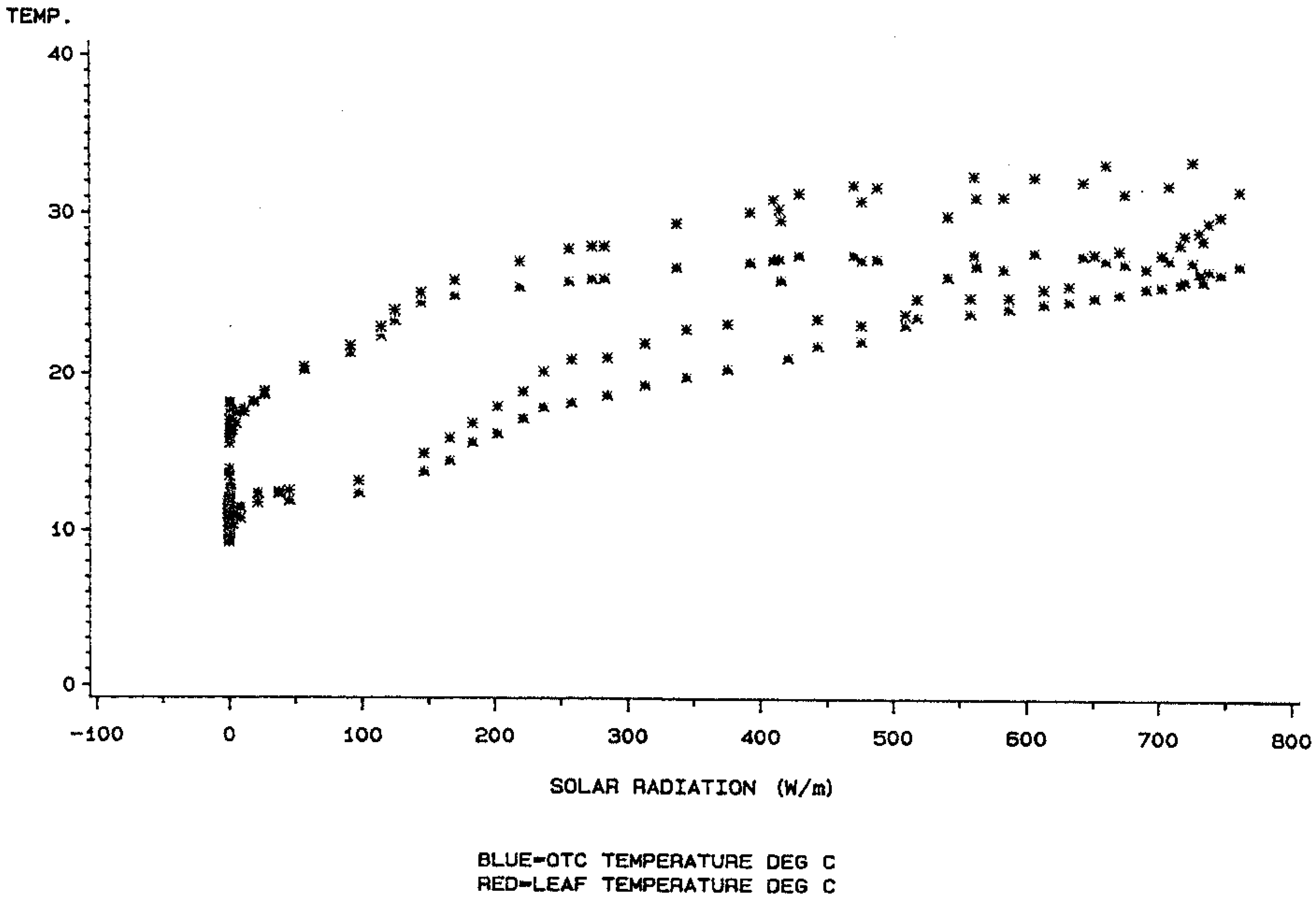

Temperature on date of budburst °C
Edinburgh
Braemar
12
10
8
6
4
2
1
2
3
4
5
March
April
May
June

Leaf temperature

For studies of growth and development the leaf (and meristem) temperature are of greater interest than air temperature. The measurement of leaf and air temperatures during the same day shown for manifold and air temperature (Figure 10), shows that even in the well stirred air inside these chambers, leaf temperatures (on Beech leaves) may exceed air temperatures by up to 6°C. The effects of the chamber of leaf development are therefore an important mechanism by which the growth of plants are affected by open-top chambers. These measurements are consistent with those of earlier studies in which smaller OTCs were used to study barley growth and yield responses to air pollutants. In these studies the growth in the chambers at higher temperatures led to earlier crop senescence by two weeks. The effect was entirely consistent with an effect mediated by thermal time above a base temperature of 4°C. The plant temperatures inside the chambers averaged 0.5°C above those outside and this for the cereal crop in these experiments would have acceleratred development by approximately 2 weeks.

A development of this analysis is in progress at the institute using two versions of a crop growth model (Thornley, 1989). The model for grass and for forest growth is being used to investigate the long term effects of temperature differences in the range 0.5 to 5.0 °C on growth development and yield. The initial results of the model show a 20% decrease in dry matter yield of grass in response to a 5°C increase in air temperature. Such results are consistent with the effects observed in open-top chambers relative to outdoor - ambient plots from the cereal experiments at Glasgow.

SOLAR RADIATION VS LEAF & OTC TEMP. (DAY185 1989)



It has not been possible so far to extend the work using the tree growth model, but this will be one of the tasks during analysis for the final report.

REFERENCES

CANNELL, M.G.R. & SMITH, R.I. 1983. Thermal time, chilldays and prediction of budburst in *Picea sitchensis*. J. Appl. Ecol., 20: 951-963.

CAPE, J.N., FOWLER, D., EAMUS, D., MURRAY, M.G., SHEPPARD, L.J. & LEITH, I.D. 1989. Effects of acid mist and ozone on frost hardiness of Norway spruce seedlings. In: Air Poll. Res. Rep. 26, pp 331-335. Eds. H.D. Payer, T. Pfirrmann and P. Mathy.

COUVILLON, G.A. & HENDERSHOTT, C.H. 1974. A characterization of the 'after-rest' period of flower buds of two peach cultivars of different chilling requirements. J. am. Soc. Hort. Sci., 99: 23-26.

DOORENBOS, J. 1953. Review of the literature on dormancy in buds of woody plants. Meded. Landbouwhogesch - Wageningen Vol. 53: 1-24.

FUCHIGAMI, L.H., TIMMIS, R. & GUSTA, L.V. 1982. A degree growth stage (°GS) model and cold acclimation in temperate woody plants. In: Plant cold hardiness and freezing stress Vol. 2. Ed. P.H. Li & A. Sakai. Academic Press. pp92-116.

GRACE, J. 1988. Temperature as a determinant of plant productivity. In: Plants and temperature. Ed. S.P. Long and F.I. Woodward. pp 91-107. Society for Experimental Biology.

JUNTILLA, O. 1986. Effects of temperature on shoot growth in northern provenances of *Pinus sylvestris* L. Tree Physiology 1, 185-192.

MURRAY, M.B., CANNELL, M.G.R. & SMITH, R.I. 1989. Date of budburst of fifteen tree species in Britain following climatic warming. Journal of Applied Ecology, 26, 693-700.

MONTEITH, J.L. 1981. Climatic variation and the growth of crops. U.R. Met. Soc. 107, 749-774.

NIENSTAEDT, H. 1967. Chilling requirements in seven *Picea* species. Silvae Genetica; 16: 65-68.

PEARCY, P.W. 1976. Temperature effects on growth and CO_2 exchange rates in control and desert races of *Atriplex lentiformis*. Oecologia 26, 245-255.

RAJAN, A.K., BETHERIDGE, B. & BLACKMAN, G.E. 1971. Interrelationships between the nature of light source, ambient air temperature and the vegetative growth of different species within growth cabinets. Ann. Bot. 35, 923-943.