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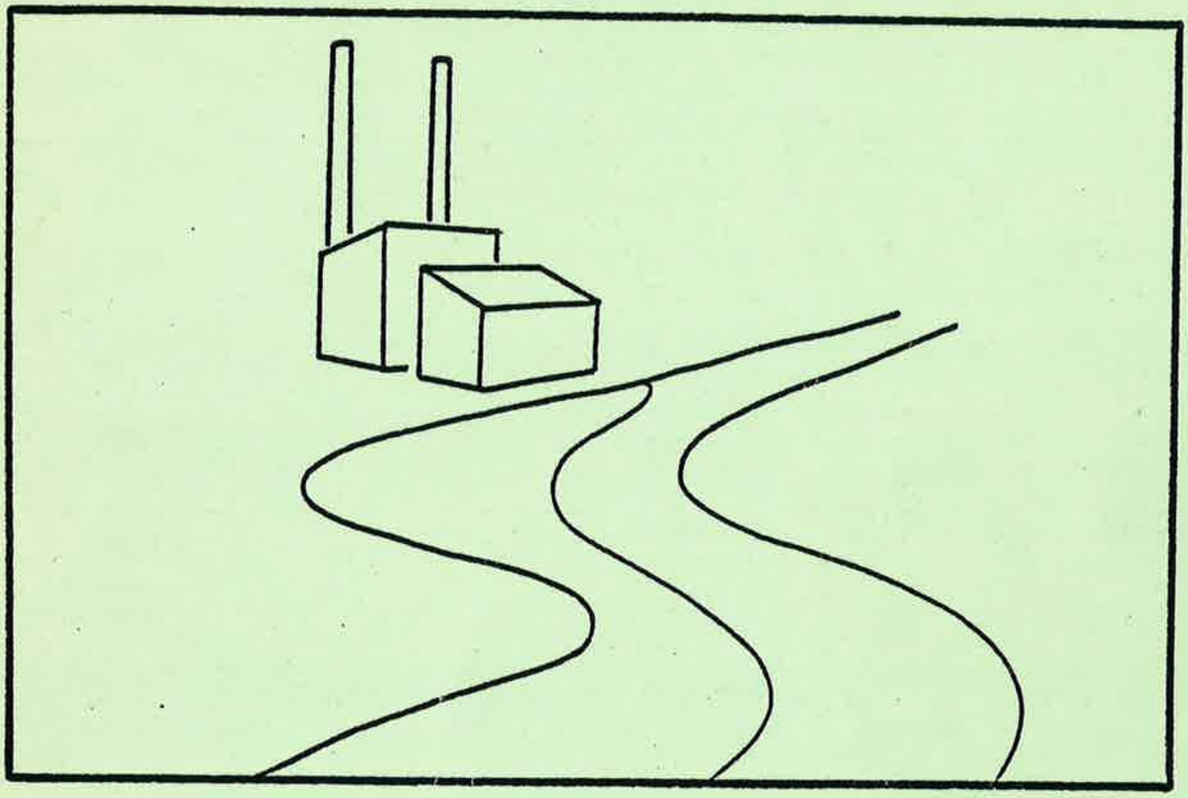

WASTE HEAT DISPOSAL FROM A 500MW POWER STATION TO THE WAIKATO RIVER

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ABSTRACT

A simulation study was made of mixing and river temperatures in the Waikato River below the Huntly (1000 MW) and proposed Clune Road (500 MW) power stations. Predicted changes in river temperature were greatest in autumn (April-May) when power demand was high, river flows low and ambient temperatures still high. During autumn predicted Huntly plume excess temperatures averaged 1.5-2.5 °C (max 3-3.5°C) for average generation (55% load factor) and 2.5-3.5°C (max 3.5-4°C) for high generation (70% load factor) in a low flow year. During autumn predicted Clune Road plume excess temperatures averaged 1-1.5°C (max 1.5-2.0°C) for average generation and 2-2.5°C (max 2.5-3°C) for high generation in a low flow year. In spring and early summer predicted Huntly plume and Waikato plume excess temperatures rarely exceeded 1.5°C and 0.5°C respectively, while in summer and winter they rarely exceeded 1.5-2°C and 1-1.5°C respectively. Predicted temperatures near the Clune Road power station nowhere exceeded those predicted near the Huntly power station, despite the fact that considerable residual waste heat from Huntly was predicted in the river at Clune Road. The combined effects of both stations was predicted to reduce the length of time river temperature was below 19 °C by 4-5 weeks in the Huntly plume, 1½-3 weeks in the Clune Road plume and ½-2 weeks in the estuary. Of the two control rules considered here the 'P8 Rule' allowed appreciably greater power generation in summer at the Huntly than the '26° Rule' but resulted in noticeably higher plume excees temperatures (up to 25%, 1°C). At Clune Road the combination of the 'P8 Rule' and the 'small' cooling tower resulted in higher plume excess temperatures than the combination of the '26° Rule' and 'large' cooling tower (up to 25%, 0.5°C) only during autumn with high generation and a low flow. Discharge of cooling water at Clune Road via a transverse multiport diffuser on the river bed was estimated to achieve rapid mixing with 75% of the river flow

within 25 metres. Cooling water is unlikely to impinge on the biologically sensitive littoral zone if the ends of the diffuser are 50 metres from the bank, and more detailed studies may demonstrate that at some sites this distance can be reduced to 20-30 metres. When the Clune Road station operates in closed-cycle mode, mixing of chemical effluents released into the cooling water outfall is unpredictable and to achieve rapid predictable mixing of chemical effluent during closed-cycle mode, a separate diffuser would be required. Closed-cycle operation was found to occur only rarely and storage of chemical effluent during closed-cycle mode may prove more desirable than a separate diffuser.

INTRODUCTION

This report presents findings of a computer simulation study of water temperatures in the Waikato River and the way in which this would be affected by cooling water discharges from the existing Huntly thermal power station (1000 MW) and the proposed Waikato coal-fired power station at Clune Road (500 MW) (see Figure 1 for locations). Hereafter the latter station is referred to either as the Clune Road or Waikato power station.

An earlier simulation study (Rutherford 1984) investigated: a 1000 MW Waikato station at two alternative sites (Rangiriri and Clune Road); three alternative restrictions on waste heat discharge at Waikato (the '26° Rule', '25° Rule' and '23° Rule'); high figures for the amount of power despatched (100% May-October, 75% November-April); and three fixed amounts of supplementary cooling at Waikato (0%, 50%, 75%). The frequency distributions of fully mixed river water temperature and plume temperatures were found to be noticeably affected by cooling water discharge in the case of open cycle and 50% supplementary cooling, with high temperatures, 23-27 °C, becoming more frequent. It was concluded that 10-20% of the biological drift community (notably larval smelt and galaxiids) were at risk from passage through the power station, unless intakes excluded them successfully and an additional 10-15% were threatened by entrainment into the waste heat plume. It was noted that the threat to upstream migrating juveniles (elvers and whitebait) would be minimised by a diffuser located of the order 50 metres from the nearest bank to minimise impingement of substantially undiluted cooling water on the littoral zone near the river edge.

The simulations reported here are refinements on Rutherford (1984) to investigate: a 500 MW station located at Clune Road; two alternative restrictions on waste heat discharge (the '26° Rule' and a new 'P8 Rule');

lower and more realistic figures for the amount of power generated; two alternative sizes of cooling tower at Clune Road; and two alternative methods of operation of the tower. Augmentations and minor revisions have also been made to the ambient river water temperature and river flow datasets used in the simulations.

The objectives of this study are:

a To compare the frequency distributions of daily average river water temperature with and without cooling water discharge on a month by month basis.

b To compare the lengths of time for which river temperatures are below 19 °C, thought to be the temperature at which trout migrate between the Lower Waikato River and upstream tributaries.

c To estimate the temperatures, heating and cooling rates experienced by drift organisms entrained into the cooling water plume.

d To estimate cooling tower use at Clune Road and power generation forgone at Huntly under different possible water right restrictions.

The results of this study are intended to facilitate making assessments of the impact of waste heat discharge on river biota but this report does not address biological issues in detail.

METHODS

Data

Ambient river water temperature was defined as the river temperature measured just upstream from the Huntly power station. Thus any net heating or cooling which occurs in the study reach, 50 km, in the absence of waste heat discharges was neglected. Data were collated from three sources:

1 Measurements made once daily (at 0800 hours) by the Huntly Borough Council at their water intake in Huntly (just upstream from the Huntly power station) covering the period 1973-1984, (hereafter referred to as the HBC dataset).

2 Daily average, daily maximum, daily minimum and 0800 temperatues estimated from continuous measurements made by Electricity Division, ED, at the Huntly power station covering 1983-1984 (hereafter referred to as the HPS dataset).

3 Daytime and diurnal measurements made prior to commissioning of the Huntly power station approximately monthly by the Auckland Regional Authority at Mercer (40 km downstream from Huntly) covering 1973-1983 (hereafter referred to as the ARA dataset).

The HPS and HBC datasets were used over 1983-84 to develop a model relating daily average temperature to 0800 measurements. This model was used on the HBC dataset to produce an eleven year time series of daily average ambient river temperature which provided the ambient temperature basis for the simulations. A rough comparison was made between daily average temperatures in the HBC and ARA datasets.

Daily average flows for the Rangiriri Bridge site were retrieved from the MWD TIDEDA system and used in these simulations. A 3 month gap in the flow record during summer 1983 was filled using data from the Huntly power station site and two similar gaps in 1979 and 1982 were filled using data from the Mercer site (see Figure 1 for locations). No attempt was made to correct the power station or Mercer data for tributary inflows which are small over this reach.

Simulations

Programmes were written in STATS (Anon, 1984) to enable simulations to be made, using the Vogel Computer, Wellington, of the daily average temperatures at various points in the river which would have occurred had both the Huntly and Clune Road stations been operating during the period 1973-1984. Several combinations were considered of power generation, river flow, ambient river temperature, Clune Road cooling-tower size and method of operation, and restriction on waste heat discharge. The simulations also took account of transverse mixing and excess heat decay in the river. Appendix 1 contains a description of the method used.

Power Despatch

Three alternative levels of power generation (hereafter termed 'despatch') were considered at both Huntly and Clune Road power stations:

a 55% load factor, the anticipated long-term average;

b 70% load factor, the anticipated annual average in a dry year;

c 100% load factor, a worst case situation which is possible in a dry year.

Note that one might expect high summer ambient water temperatures in a dry year.

Figures for the total number of hours in each month at a given despatch were taken from Gilbert-CMPS (1984). The number of hours were divided by 24 to give the total number of days in each month at a given despatch and the daily despatches distributed randomly throughout each month. This approach neglects diurnal variation of despatch. To illustrate, if the despatch for June (720 hours) comprised 360 hours at 0 MW and 360 hours at 500 MW, this would have been simulated as 15 days at 0 MW and 15 days at 500 MW. However, were despatch to be zero for 12 hours every night and 500 MW for 12 hours every day then this would have been better simulated as 30 days at 250 MW. Both Huntly and Clune Road are planned as base load stations for which small and irregular diurnal variations of despatch are expected. Despatches from Huntly during the period March-May 1984 on average showed only a weak diurnal variation. Thus the errors introduced into these simulations by the method of estimating the daily despatch are considered to be small. If anything they would have caused slightly higher frequencies of extreme (high and low) temperatures but were unlikely to have affected average temperatures. The ratio of waste heat produced to power generated was taken as 1.360 at the Huntly and 1.275 at the Clune Road power station (D. Willis, ED, pers. comm.).

Periods Simulated

The three alternative levels of despatch were simulated over different time periods and hence different values of ambient temperature and flow.

a	55% load factor	1973-1984 (viz the entire dataset)
b	70% load factor	1978 (viz the lowest flow year)
c	100% load factor	Jan-Mar 1978 (viz. the extreme low flow, high temperature period).

Clune Road Cooling Tower Size and Operation

Two sizes of tower for the Clune Road station were considered in this study: a 'large' tower, as suggested by Gilbert-CMPS (1984) and a 'small' tower, as suggested by D. Willis, (ED, pers. comm.). The maximum heat removal of each tower as a function of station despatch and ambient river temperature (measured above Huntly and an estimator of wet-bulb air temperature) is shown in Figure 2

(D. Willis, ED, pers. comm.). A linear regression model for each tower relating heat removal to despatch, ambient river temperature and the cross-product of despatch and ambient temperature was fitted to the data points shown in Figure 2. Each model explained over 95% of the variation in the data.

For these simulations a cooling-water flow of 15 $m^3.s^{-1}$ was assumed (the likely maximum value). This was assumed not to vary with despatch. Maximum cooling-water excess temperature corresponding to 500 MW despatch (638 MW waste heat) at Clune Road was then 10.2 °C. Slightly different results would be obtained using a different cooling water flow, but the same general conclusions would be reached. For example at a smaller cooling-water flow, the cooling towers would be less effective at removing waste heat (D. Willis, ED, pers. comm.).

The cooling towers could have been used just to ensure that the waste heat discharged by the Clune Road power station together with the residual waste heat from Huntly did not breach either the '26° Rule' or the 'P8 Rule' (discussed below). However, during spring, summer and autumn the cooling tower can be used in "helper-mode" at little additional cost (D. Willis, ED, pers. comm.). In "helper mode" the towers run continuously even though this may reduce waste heat output below the limit set by the control rule. In this study the cooling towers were assumed always to operate once ambient river temperature exceeded either 19°C or 17°C. Trout are thought to leave the lower Waikato once ambient temperature exceeds 19°C (D. Rowe, MAF, pers. comm.). Where the cooling tower looked likely to reduce outlet temperature below ambient river temperature (which was possible in summer when cooling efficiency was high) it was assumed that power to the fans was reduced until cooling water reached ambient temperature. Figure 3 shows in diagrammatic form the way in which the cooling tower was used and the control rule(s) applied.

Waste Heat Discharge Restrictions

The present water right for the Huntly power station restricts the quantity of waste heat which can be discharged as follows:

$$W = 12.6\,Q \qquad T<11.2\ °C$$
$$W = 22.2\,Q\,(1-T/25.9) \qquad 11.2>T>25.9 \qquad (1)$$
$$W = 0 \qquad 25.9<T$$

where W = permissible waste heat discharge, MW; Q = river flow at Huntly, $m^3.s^{-1}$; T = ambient river temperature (measured upstream from the Huntly power station), °C. Hereafter this is referred to as the '26° Rule'.

To date two possible water right restrictions have been suggested for the Clune Road power station in addition to the above: the so called '23° rule' and '25° Rule' (see Rutherford 1984 for details). These are not discussed here. A third formula, suggested by B. Wilkenson, ED, is

$$W = 12.6\,Q\,(1 - (T/25)^8) \qquad T<25\ °C$$
$$W = 0 \qquad 25<T \qquad (2)$$

Hereafter this is called the 'P8 Rule', (short for power of eight rule). The fully mixed river water temperature rises permitted by these two rules are illustrated in Figure 4.

The following nomenclature is used below to describe waste heat discharge restrictions and cooling tower use: '26° Rule' and 'P8 Rule' imply use of either equation (1) or (2) at Huntly while '26°/19° Rule', '26°/17° Rule' describe use of equation (1) at Clune Road with cooling tower use above an ambient river temperature of either 19°C or 17°C, and so on. 19°C is the temperature at which trout are thought to leave the lower Waikato for the cooler headwater streams (D. Rowe, MAF, pers. comm.). In these simulations at Clune Road the 'P8 Rule' was always used in combination with the 'small' tower and the '26° Rule' with the 'large' tower.

Mixing Below Huntly

The outfall at the Huntly power station was designed so that at full load cooling-water will mix rapidly with about 50% of the river flow. Cooling water flow rate varies depending on how many turbines are operating and hence how much power is being generated. Each 250 MW turbine requires about 8 $m^3.s^{-1}$ of cooling water. It is thought that as the cooling water flow varies, the initial mixing varies approximately linearly (R. Croad, Central Labs, MWD, pers. comm.); that is if a cooling water flow of 32 $m^3.s^{-1}$ mixes with 50% of the river flow, then a cooling water flow of 16 $m^3.s^{-1}$ will mix with 25% of the river flow, and so on. Near-field mixing has not been studied in detail since commissioning of the Huntly power station but some temperature measurements made during fisheries studies (J. Boubée, ED, pers. comm.; M. Simons, Waikato Valley Authority, pers. comm.) have shown that initial mixing was of the order 30% when cooling water flow was 16-24 $m^3.s^{-1}$ (50-75% design flow). Studies on transverse mixing of waste heat 5-30 km below Huntly are underway at present, but it is not yet possible to quantify precisely the effects of differing degrees of initial mixing on transverse temperature distributions at Clune Road. In this simulation study it was assumed that initial mixing of cooling water at Huntly was always with 50% of river flow regardless of the amount of power generated. This assumption may result in underestimating Huntly plume temperatures at low despatch but is not thought to affect estimates of Huntly plume temperatures at high despatch or temperatures at Clune Road.

Recent studies by the author (Water Quality Centre, unpub.) have shown that the residual waste heat from Huntly was almost, but not quite, completely mixed across the river at Clune Road. With Huntly operating at 50-70% full load, there was a transverse temperature difference of about 0.2 °C, with temperature on the left bank (west bank) some 20% above average and on the right bank (east bank) some 20% below the cross-section average. In this study average Huntly residual temperatures were estimated in the left and right halves of the river at Clune Road: respectively 10% above and 10% below the cross-section average.

Excess Heat Decay

Work is not yet complete on quantifying the waste heat decay (i.e. excess temperature decay) between Huntly and Clune Road (28 km), but preliminary results appear to substantiate the average figure of 40% decay (Rutherford 1984). Eventually it is hoped to estimate excess temperature decay rate coefficient below Huntly which will allow waste heat loss to be simulated as a function of excess temperature. It was assumed that between Clune Road and Tuakau Bridge, the beginning of the estuary (21 km), the same amount of mixing and waste heat decay occurred as between Huntly and Clune Road.

Figure 5 summarises the assumptions made about river mixing and waste heat decay.

Mixing at Clune Road

Cooling water discharge at the Waikato power station at Clune Road is likely to be via a sub-surface diffuser, located near mid-channel which is designed to achieve high initial dilution and to minimise plume impingement on the littoral zones. In the calculations described below the diffuser was assumed to have 30 ports located at 4 m centres (i.e. diffuser width = 116 m) each capable of discharging 0.5 $m^3.s^{-1}$ parallel with the river flow at a port velocity of 7 $m.s^{-1}$ (A.J. Brown, MWD, pers. comm.). Channel width was taken as 160 m, low flow 160 $m^3.s^{-1}$, mean velocity 0.5 $m.s^{-1}$, mean depth 2 m, and main channel depth 2.5 m.

Close to the diffuser, the discharge was assumed to behave like a series of simple jets. Using well-known formulae (Fischer et al. 1979, p. 328) estimates were made of the times taken for a jet to increase in diameter to 2.5 m (the channel depth), and for the maximum jet velocity to decrease to 0.5 $m.s^{-1}$ (river mean velocity). The former approximates the time for the jets to impinge on the surface hereafter referred to as zone 1: the latter the point where the jets merge with the ambient flow zone 2, See Figure 6. Within zone 1 temperature will be highly variable: there will be pockets of substantially undiluted cooling water and river water at ambient temperature. At the downstream end of zone 2 the plume should be well-mixed vertically and high transverse temperature gradients will occur only on the edges of the plume.

The standard formulae for estimating dilution (Fischer et al. 1979 p. 328) are for unconfined 3 dimensional jets. The formulae are probably accurate very close to the ports but increasingly become inaccurate as jets approach the channel bed, the water surface, and other jets; thereby reducing the amount of ambient river water available for entrainment and causing re-entrainment of hot water (Jirka and Harlemann 1973). A satisfactory theoretical solution to this problem is not available. Accordingly, a heuristic estimate of dilution in zones 1 and 2 was made by assuming that the river flow per unit width remained constant across the channel, and applying continuity. For example, it can be estimated that the total plume width at the downstream end of zone 1 is 78 m (see results section for details and note that the jets have not all coalesced at this point). For a river flow of 160 $m^3.s^{-1}$ and channel width of 160 m, 78 $m^3.s^{-1}$ would cross a 78 m wide plume, comprising 15 $m^3.s^{-1}$ of cooling water and 63 $m^3.s^{-1}$ of entrained river water. This gives an average initial dilution of 5.2 and initial mixing is with about 50% of the river flow. This is possibly an underestimate of initial dilution, since jet momentum could accelerate and entrain additional river water (Adams, 1972, cited in Jirka and Harlemann, 1973). At the downstream end of zone 2 this approach becomes more accurate, provided the plume width is known.

Average plume temperatures and excess temperatures were calculated at the downstream end of zone 1 assuming initial dilution with 50% of the river flow on a day by day basis using an 11 year record of river flows, ambient temperatures and assumed power despatches.

Average heating and cooling rates in zones 1 and 2 of the plume were calculated for a worst case situation of open cycle cooling, an initial excess temperature of 10.2 °C, and a low river flow of 160 $m^3.s^{-1}$. These estimates were made because organisms entrained into the plume are affected not only by the change of temperature but also by the rate of change.

RESULTS

Ambient Temperature

In the HPS and ARA data the 0800 hours measurements were indistinguishable from the daily minima. Thus, uncorrected, the HBC data would underestimate the daily average temperature. Figure 7 shows the difference between daily average and minimum temperature from the HPS data. There was high short-term variability (attributable principally to variation in incident solar radiation) superimposed on a clearly discernible seasonal pattern. Daily average river temperatures exceeded minimum temperatures by 0.2-0.4 °C in winter and by 0.3-1.0 °C in summer. A regression model was developed.

$$T_{av} - T_{min} = 1.01 - 0.10 \sin\left(\frac{2\pi t}{365}\right) + 0.16 \cos\left(\frac{2\pi t}{365}\right) - 0.0015\ Q \qquad (3)$$

($r^2 = 0.36$ $n = 429$)

where T_{av}, T_{min} = daily average and minimum HPS temperature, t = Julian day number and Q = daily mean flow.

The difference between 0800 hours HBC and minimum HPS temperatures during 1983-1984 had mean ± standard deviation of 0.05±0.79 (n = 673). There was weak seasonality in the difference: HBC data were higher than HPS data during winter and lower during summer. The most likely explanation for these differences is thermometer calibration errors and/or lateral non-homogeneity of river temperature.

Because the HBC data were to be used for simulation another regression model was developed:

$$T_{av} - T_{HBC} = 1.96 - 0.23 \sin\left(\frac{2\pi t}{365}\right) + 0.37 \cos\left(\frac{2\pi t}{365}\right) - 0.0039\ Q \qquad (4)$$

($r^2 = 0.23$ $n = 431$)

where T_{av} = daily average HPS temperature and T_{HBC} = 0800 hours HBC temperature. Note that there is higher scatter and a larger amplitude of seasonal variation in temperature difference in Figure 8 than in Figure 7 which arose from the differences between datasets discussed above. Individual daily average temperatures predicted using equation (4) had a 95% confidence interval of about ±1.0°C.

The predicted daily average Huntly temperatures appeared broadly similar to the ARA Mercer data, see Figure 9. In particular the high temperatures of 1975, 1978 and 1979 appeared in both datasets. There was a suggestion of a consistent low bias in predicted daily average temperature at Huntly throughout the summer of 1976-1977.

The frequency distribution of predicted daily average temperature (not shown here) was very similar to that given for 1974-1976 daytime measurements made by MWD (Davies-Colley, 1979).

The diurnal variation of river water temperature (maximum-minimum) was about 0.4-0.8 °C in winter and 0.6-2.0 °C in summer. This is not expected to change significantly when waste heat enters the river because the amount of waste heat discharged is small compared to solar radiation input. To illustrate, the diurnal variation of equilibrium temperature, estimated following Brady _et al_. (1972), is large: ranging from about 7 °C in winter to about 17 °C in summer. By comparison waste heat discharges will cause fully mixed temperature rises of 1-2 °C. Thus the daily average temperatures predicted in this study can be used to estimate daily minima and maxima based on the currently observed diurnal variation of river temperature.

Table 1 summarises annual average temperatures and flows. The statistic temperature/flow was used to help identify low-flow/high-temperature periods: critical conditions for waste heat discharge. 1978 can be identified as the est flow year and January-March 1978 the critical low flow/high temperature iod. Note, however, that April may be the critical month for waste heat c arge because ambient temperatures remain fairly high, flow is often low and atch from the thermal power stations is higher than in January-March. Flows mmarised in Figure 10.

	Annual mean			January-March		
	Flow	Temp	Temp/Flow x 100	Flow	Temp	Temp/Flow x 100
1973	300±80	16.6±3.7	6.1±2.4	240±35	20.9±0.7	8.9±1.4
1974	350±130	16.5±4.2	5.7±3.0	240±50	22.0±1.5	9.3±1.7
1975	400±140	15.2±4.5	4.6±2.7	275±70	21.2±1.5	8.1±1.5
1976	430±150	14.9±3.2	4.0±1.9	360±105	18.3±0.6	5.4±1.3
1977	364±140	16.0±3.9	5.4±3.0	230±30	20.9±.0	9.1±1.2
1978	290±110	16.6±4.2	6.5±2.9	240±40	21.7±1.3	9.4±1.4
1979	400±120	16.1±4.2	4.6±2.6	280±83	21.9±1.9	8.4±2.3
1980	410±90	15.2±3.5	3.9±1.3	390±105	19.5±1.3	5.2±1.0
1981	390±100	15.9±4.0	4.5±2.0	310±40	21.1±0.8	6.8±0.9
1982	300±50	15.0±4.3	5.1±1.8	290±30	20.8±1.7	7.3±1.1
1983	320±80	14.8±3.5	5.0±2.1	240±30	19.0±0.6	8.2±1.0
1984	-a	16.4±3.3	-a	290±40	19.9±0.8	7.1±1.1

Notes (a) Flow data are not yet available for whole year

(b) Mean ± std. dev.

Table 1 Summary of daily average flows and temperatures, Waikato River at Huntly 1973-1984.

Power Forgone at Huntly

In the simulations, whenever the waste heat discharge at Huntly exceeded the allowable limit set by either the '26° Rule' (equation (1)) or the 'P8 Rule' (equation (2)) then some generation was forgone. Table 2 summarises the average power forgone. Water right restrictions were greatest during summer (December-April) as can be seen from Figure 11.

Huntly Plume Temperatures

Figures 12 compare the frequency distributions of calculated Huntly plume and ambient temperatures. As discussed above, plume temperatures were calculated assuming complete mixing of waste heat with 50% of river flow. Figure 13 shows the frequency distribution of plume excess temperature (difference from ambient, measured just upstream from the Huntly Power Station).

In winter, spring and early summer (May-January), the two control rules, '26° Rule' and 'P8 Rule', gave predicted temperature distributions which were almost indistinguishable from each other for the 55% LF average year and 70% LF low flow year simulations. The reason is that there were relatively few restrictions placed on power generation by either rule at these times. In late summer and early autumn (February-April) for the 55% LF and 70% LF and for all three summer months (January-March) for the 100% LF simulations, higher plume temperatures occurred for the 'P8 Rule' simulations than for the '26° Rule' simulations. The differences were barely discernible for the simulation of 55% LF but were quite marked (1-1.5 °C) for the 70% LF and 100% LF low flow simulations, notably in April.

Plume temperature increments (Figure 13) were lowest in spring and early summer (October-January) rarely exceeding 1.5 °C. They were highest in autumn (April-May) when for the 55% LF simulation they were most commonly 1-2.5 °C

Period	Load Factor	26° Rule G.W.hr	26° Rule MW	26° Rule %	P8 Rule G.W.hr	P8 Rule MW	P8 Rule %
1973-1984	55%	54.7	15.2	2.8%	19.8	5.5	1.0%
1978	70%	256.6	71.3	10.2%	61.5	17.1	2.4%
Jan-Mar 1978	100%	2010.4	558.7	55.9%	672.2	186.8	18.7%

Note % forgone = MW forgone/MW installed/load factor

Table 2 Average power forgone at Huntly in order to comply with restrictions on waste heat discharge.

(maximum 3.5-4 °C) and for the 70% LF low flow simulation they were most commonly 2-3.5 °C (maximum 3.5-4 °C). For 100% LF at low flows in January-March, increments averaged 1-2 °C but there were substantial restrictions imposed on power generation by the control rules. For the 70% low flow simulations, plume excess temperatures were higher for the 'P8 Rule' than the '26° Rule'.

The period during which plume temperatures were below 19 °C decreased from 36½ weeks (ambient) to 32½ weeks at 55% LF in an average year and from 30½ weeks (ambient) to 26 weeks at 70% LF in a low flow year.

Huntly Residual Temperatures

Figures 14 show the frequency distributions of calculated temperatures in the left half of the river at Clune Road resulting from residual waste heat from Huntly. The temperature differences in the Huntly plume described above were attenuated by transverse mixing (50% at Huntly and 90% at Clune Road) and heat decay (40% loss between Huntly and Clune Road) (see Figure 5).

The two control rules at Huntly, '26° Rule' and 'P8 Rule', resulted in almost indistinguishable frequency distributions in all cases except April for the 70% LF and March for the 100% LF simulations, when the 'P8 Rule' resulted in temperatures higher by at most 0.5 °C.

Figures 16 contain Huntly residual excess temperature distributions at Clune Road. From July-February Huntly residual excess temperatures did not exceed 1°C for either the 55% LF simulation or the 70% LF low flow case. In April-June, residual excess temperatures occasionally exceeded 1°C for the 55% LF case, and were commonly 0.5-1.5°C for the 70% LF low flow case. The 'P8 Rule' at Huntly gave slightly higher residual excess temperatures than the '26° Rule'.

The period during which residual temperatures were below 19 °C decreased from 37½ weeks (ambient) to 36 weeks in the 55% LF simulation and from 30½ weeks (ambient) to 28½ weeks for the 70% LF low flow simulation.

Waikato Plume Mixing

The standard formulae (Fischer et al. 1979) predict that a simple jet with a discharge of 0.5 $m^3.s^{-1}$ and a port velocity of 7 $m.s^{-1}$ discharging into stagnant water attains a diameter[1] of 2.6 m (channel depth) within 10 m (5 seconds) and the maximum velocity drops to 0.5 $m.s^{-1}$ (mean river velocity) within 25 m (25 seconds). These results may be taken as a first approximation to the case of multiple jets discharging only slightly buoyant effluent into a swift shallow river.

Thus for the proposed diffuser discharging 15 $m^3.s^{-1}$ of cooling water, zone 1 (see Figure 6), in which the 30 individual jets impinge on the surface, is likely to extend some 10 m (5 seconds) below the outfall. Two estimates are possible of dilution at the downstream end of zone 1. The standard formulae (Fischer et al. 1979 p 328) suggest a jet diameter of 2.6 m and hence a total width for 30 jets of 78 m. Assuming that at low flow the discharge per unit width remains constant at 1 $m^3.s^{-1}.m^{-1}$, the plume will entrain 63 $m^3.s^{-1}$ of river water into the 15 $m^3.s^{-1}$ of cooling water at this point. This gives a dilution of 5.2, means that initial mixing is with about 50% of the low flow, and for open cycle operation gives an average plume excess temperature of +2.0 °C. This is a likely lower bound to dilution since jet momentum is likely to entrain more than 63 $m^3.s^{-1}$ into the plume. The standard formulae for jet entrainment (Fischer et al. 1979 p 328) suggest a dilution of 9.4 (i.e.

[1]where concentraton equals $^1/_e$ (0.3) maximum centreline concentration

entrainment of 126 $m^3.s^{-1}$, twice the earlier estimate) and an average plume excess temperature of +1.1 °C. This is a likely upper bound to dilution because entrainment is likely to be reduced at the downstream end of zone 1 by the proximity of jets to each other, the bed, and the water surface (Jirka and Harlemann, 1973). Temperature in zone 1 is likely to vary, being highest near the centreline of each jet at about 1.4 times the average (Fischer et al. 1979). The average heating rate of water entrained into zone 1 is about 20 $°C.min^{-1}$ and the average cooling rate is about 100 $°C.min^{-1}$. Table 3 summarises plume dilutions and open cycle temperatures.

After impinging on the surface, the jets are likely to persist for about another 15 m (20 seconds) during which time they coalesce and the plume spreads to at least 123 m wide (average jet angle 8°: Fischer et al. 1979). The area from 10-25 m below the diffuser is denoted zone 2 (see Figure 6). The jet entrainment formula cannot be used with confidence to estimate dilution in zone 2. Assuming that discharge per unit width remains constant then, in addition to the 63 $m^3.s^{-1}$ entrained into zone 1, another 45 $m^3.s^{-1}$ of river water is entrained into zone 2 giving a final dilution of 8.2 and reducing the average temperature to +1.2 °C (overall cooling rate 21 $°C.min^{-1}$) and maximum temperature to +1.7 °C. Considerable mixing between jets is likely in zone 2 and the plume is likely to become vertically homogeneous. Transverse temperature gradients will be small at the centre of the plume but large near the outside edges. Entrained water increases in average temperature to +1.2 °C at a rate of 3 $°C.min^{-1}$. This entrainment is likely to contain a substantial proportion of surface water.

At distances greater than 25 m from the outfall, transverse spreading approximates a one-dimensional Fickian process. This is denoted zone 3 (see

Figure 6). Complete mixing (dilution 10.7, temperature +0.96 °C) is assured 9 hours (16 km) below the outfall (Rutherford, 1984) and may occur somewhat sooner.

These calculations are sensitive to variation of cooling water flow rate and port velocity but the results presented here should provide an indication of likely plume conditions. It would be desirable to conduct model tests to check these calculations.

Zone	Time sec	Distance m	Dilution av	Excess av °C	Temperature max °C	Heating °C.min^{-1}	Cooling °C.min^{-1}
	0	0	0	10.2	10.2	-	-
1							
	5	10	5.2-9.4	2.0-1.1	1.5-2.8	20	100
2							
	25	25	8.2-9.4	1.2-1.1	1.5-1.7	3	20

River flow = 160 $m^3.s^{-1}$, river width = 160 m, mean velocity = 0.5 $m.s^{-1}$
Cooling water flow = 15 $m^3.s^{-1}$, number of ports = 30, port velocity = 7 $m.s^{-1}$, port spacing = 4 m
Waste heat = 637.5 MW, Cooling water temperature = 10.2 °C

Table 3 Estimated plume dilutions and open cycle excess temperature

Plume Temperatures at Clune Road

Average plume temperatures at Clune Road were calculated on a day by day basis assuming that the plume mixed rapidly with 50% of the river flow. Note that at low flow, 160 $m^3.s^{-1}$, this implies a dilution of 5.3, the lower bound estimate at the downstream end of zone 1 (see Table 3). Once the method of cooling water discharge has been finalised and the initial dilution at different flows determined (either by model studies or field tests) simulations could be repeated with variable amounts of initial plume mixing. The results reported here provide an initial estimate. Excess temperatures from Waikato were added to the residual excess temperature from Huntly in the right half of the channel at Clune Road, taken as 90% of the fully-mixed Huntly residual excess temperature (refer to Figure 5). Figures 15 compare the distributions of calculated Waikato (Clune Road) plume temperatures (in the right half of the channel) and Huntly residual temperatures (in the left half of the channel) with ambient temperatures (measured above Huntly). Figures 16 show the distributions of Waikato (Clune Road) plume excess temperatures. In Figures 15 and 16 cooling tower use was mandatory for ambient river temperatures above 19°C.

Although details are omitted here, a comparison showed that the two alternative combinations: '26° Rule'/'large' tower and 'P8 Rule'/'small' tower, gave calculated plume temperature and excess temperature distributions which were almost indistinguishable from each other; except in March and April for the 70% LF and 100% LF low flow simulations, when the 'P8/19° Rule'/'small' tower combination gave slightly higher temperatures (about 0.5 °C) than the '26°/19° Rule'/'large' tower combination.

Waikato plume excess temperatures were seldom greater than 0.5 °C during December-January in all simulations, and in July-November averaged 0.5-1 °C for the 55% LF case and 1-1.5 °C for the 70% LF low flow case. Highest Waikato plume excess temperatures occurred in autumn: average values of 1-1.5 °C with occasional values up to 2.5 °C in April-May for the 55% LF simulation and average values of 1.5-2.5 °C with occasional values up to 3°C in May-June for the 70% LF low flow simulation.

The increase in Waikato plume temperature over the residual Huntly temperature was negligible in December-February because the cooling towers were in use; from July-November and February-April it was about 0.5 °C; and from May-June it was 0.5-1.0 °C for the 55% of LF case and 0.5-1.5 °C for the 70% LF low flow case.

The highest excess temperatures at Waikato (2.5-3.0 °C) occurred in May (and not April as they did at Huntly), because the cooling tower was used occasionally during April when ambient temperatures were above 19°C but was rarely used in May.

The period during which Waikato plume temperatures were below 19 °C decreased from 30½ weeks (ambient) to 27½ weeks at 70% LF during the low flow year 1978 but only changed from 36½ weeks (ambient) to 34 weeks at 55% LF for 1973-1984.

Simulations of Waikato plume temperatures were also made assuming cooling tower operation was mandatory above an ambient river temperature (measured above Huntly) of 17 °C (cf 19 °C). Resulting distributions of temperature increment are shown in Figures 17 and 18 respectively. Greater use of the cooling towers reduced temperatures in March-May as expected; by a barely discernible amount for the 55% LF case but by 0.25-0.5 °C for the 70% LF case, notably with the 'P8 Rule'. The time during which the Waikato plume temperature were below 19 °C increased to 29 weeks for both the '26/17° Rule'/'large' tower and 'P8/17° Rule' 'small' tower combinations in the 70% LF low flow case, compared to 30½ weeks (ambient) and 27½ weeks for both the '26°/19° Rule'/'large' tower and 'P8/19° Rule'/'small' tower combinations.

These simulations are sensitive to variations of cooling water flow rate, here assumed to be 15 m^3s^{-1}. If a lower flow rate is found to be cost effective then the cooling towers would be less effective in removing heat in helper mode (D. Willis, ED, pers. comm.). It would be desirable to repeat some of these simulations once cooling water flows and outfall design have been finalised.

Waikato Outlet Temperatures

Figure 19 shows the calculated excess temperature at the outlet, prior to any dilution with river water. Note that a cooling water flow rate of 15 $m^3.s^{-1}$ was assumed and if a lower flow is used then outlet temperatures will be higher. The outlet temperature is the maximum excess temperature which a few organisms might experience for a relatively short time if entrained into the plume. Slightly higher summer outlet temperatures occurred for the combination of the 'small' cooling tower and the 'P8 Rule' than for the combination of the 'large' tower and the '26° Rule' and with cooling tower use above 19°C than above 17°C.

Estuary Temperatures

Figures 20 show the frequency distributions of calculated temperatures at the Tuakau Bridge (see Figure 1), the upstream end of the estuary. Complete mixing of Huntly residual waste heat but incomplete mixing of Waikato residual waste was assumed (see Figure 5) and average temperatures in the right half of the river (the warmer half) were calculated.

The two control rules gave temperature frequency distributions almost indistinguishable from each other. For the 55% LF simulation, the predicted distributions were very little different from ambient: at most, power station operation increased temperatures by about 0.25 °C. For the 70% LF simulation in a low flow year winter temperatures were 0.5-1.0 °C higher than ambient: the highest temperatures occurred in April and May. Summer temperatures were little different from ambient in any of the simulations.

The period during which temperatures were below 19 °C in the estuary decreased by less than 1 week for the 55% LF simulation and by just over 1 week for the 70% LF simulation in the low flow year.

Cooling Tower Use

Table 4 summarises cooling tower use under three categories:

1 despatch equalled available capacity (open cycle - helper mode);

2 despatch was lower than available capacity (open cycle - helper mode);

3 closed cycle cooling.

Figures given are the percentage use made of the total cooling capacity and are lower than the percentage of time the cooling towers were used because, on occasions, power to the fans was reduced to prevent outlet temperature dropping below ambient.

In all categories there was a very slight increase in cooling tower use moving from the '26°/19° Rule'/'large' tower to the 'P8/19° Rule'/'small' tower combination and from the '26°/17° Rule'/'large' tower to the 'P8/17° Rule'/ 'small' tower combination. Lowering the temperature at which cooling tower use commenced increased cooling tower use, by 2-9%. In these simulations little closed-cycle operation occurred because of the efficiency of the cooling towers in helper mode and the relatively small waste heat produced by the 500 MW station. Note, however, that were a smaller cooling water flow rate used than the 15 $m^3.s^{-1}$ assumed here, cooling tower efficiency could drop necessitating greater tower use. Simulations could be repeated to quantify the possible increase in tower use.

Control Rule	55% LF 1973-1984			70% LF 1978			100% LF Jan-Mar 1978		
Category	1	2	3	1	2	3	1	2	3
26/19	10	18	0	20	20	0	100	0	0
P8/19	10	20	0.4	19	23	1.1	100		13
26/17	12	27	0	22	29	0	100	0	0
P8/17	12	29	0.4	22	30	1.1	100	0	13

Notes 1 Despatch = available capacity

2 Despatch < available capacity

3 Closed cycle

Table 4 Cooling Tower Use (% of total cooling capacity)

Impingement on the Littoral Zone

Several gaugings of flow in the vicinity of Clune Road indicate that for relatively straight and uniform sections of the channel the flow per unit width is very low within about 10 m and 15 m of grassed and willow-lined river banks respectively. These zones of low flow and low velocity are important biologically, both as habitat for resident plants and animals and as migration routes for upstream moving juvenile fish (notably eels, whitebait and freshwater shrimps). It is highly desirable to locate the outfall so that substantially undiluted cooling water does not impinge on these littoral zones.

At the downstream end of zone 2 each plume would be about 7 m wide. For average plume excess temperatures of +1.2 °C, the excess temperature 3.5 m from the centreline would be 0.65 °C. It might be wise to allow at least 5 m between the edge of the littoral zone and the centreline of the first diffuser port. Thus the ends of the diffuser should be at least 15-20 m from the bank.

The forgoing analysis neglects the effect of transverse currents which could possibly carry the plume into the littoral zone. Such transverse currents are commonly encountered at bends in the river. For example on the outside of a sharp bend at Taupiri it was found that dye patches released 25 and 35 m from the bank impinged on the bank within 50 m. The bulk of a dye release 50 m from the bank remained clear of the bank for at least 500 m downstream although a small patched drifted into the bank. Dye released 75 m from the bank approached no closer than 40 m to the bank at 500 m downstream, (Gillman and Partners, pers. comm.). On a slight bend at Fairfield Bridge, aerial photographs showed that two dye patches released about 50 m from left and right banks did not impinge on the bank within 750 m. One patch released 25 m from shore on the outside of the bend impinged within 500 m and another released 20 m offshore on the inside of the bend impinged immediately, (Water Quality Centre, unpublished). This suggests that the outfall should be located 25-50 m offshore depending on the curvature of the channel.

There is considerable sand movement in the vicinity of Clune Road. Sandbanks appear and disappear on time scales of months and deep channels meander within the well defined banks, particularly at the wider cross-sections. Meandering could cause a deep channel to develop close to one or other bank and were this to happen immediately downstream from the diffuser, undesirable high temperatures could occur close to the bank. The worst case conditions would arise if, in addition, a substantial sandbank developed between the bank and the diffuser. This would reduce the flow of ambient river water available for entrainment along the edge of the plume. Temperatures comparable with those in zone 1 could then occur close to the bank, that is +1.5-2.8 °C. Probably the only method to prevent this occurring is to choose a site for the outfall where sandbanks are unlikely to form, that is at a cross-section which is historically stable, narrow and deep.

The tracer experiments described above tell us nothing about the effects of buoyancy or jet momentum on transverse currents below a cooling water outfall. Buoyancy effects are likely to be small: densimetric Froude numbers are 50-100 indicating that momentum will dominate buoyancy. The momentum of the jets will cause localised lowering of water levels in zone 1, estimated to be of the order of 2 cm. This may promote recirculation, possibly into the littoral zone, which would spread the plume transversely more rapidly than has been estimated above. It is possible that transverse currents may arise comparable with those found near sharp bends. More detailed investigation of recirculation is required once a site and an outfall design have been selected.

In conclusion, cooling water is unlikely to impinge on the biologically sensitive littoral zone if the diffusers are located no closer than 50 m to the bank. Model studies may demonstrate that reductions to 20-30 m may be possible for carefully designed outfalls at sites where sand-dunes are unlikely to form.

Discharge of Chemical Effluents

In addition to cooling water, the power station must dispose of boiler blow-down, boiler cleaning effluent, coal stock-pile runoff, ash supernatant and collected leachate (if wet disposal is used): collectively termed "chemical effluents". Some or all of these may be discharged to the river. Chemical effluent flow totals about 0.13 $m^3.s^{-1}$, except during heavy rain when coal stock-pile runoff may reach 1 $m^3.s^{-1}$.

When the power station operates in the open-cycle or supplementary cooling mode this effluent can be mixed with the cooling water, but provision must be made to dispose of such effluent separately when the station operates in closed-cycle mode. Options considered here included disposal via:

A cooling water outfall at full design flow (15 $m^3.s^{-1}$)

B cooling water outfall at much reduced flow (0.13 $m^3.s^{-1}$)

C single jetted outfall

D multiple jetted outfall with 10 ports, at 12.9 m centres and port velocity 5 $m.s^{-1}$

E multiple jetted outfall with 30 ports, at 4 m centres and port velocity 5 $m.s^{-1}$.

If only chemical effluent is discharged via the cooling water outfall (option B) it is likely to emerge slowly from whatever ports are free from sand, the highest flows probably occurring at ports nearest the header tank. The worst case was considered here of all the effluent mixing passively below a single port. The actual performance of Option B is, however, highly unpredictable. Mixing close to the jetted outfalls was analysed using standard jet dilution formulae (Fischer et al. 1979). Where jet momentum vanished, passive mixing was analysed using the Fickian models outlined in Rutherford (1981). Initial jet mixing was accounted for in the Fickian calculations by commencing the latter at a hypothetical virtual origin (someway upstream from the real diffuser location) such that the dilution calculated by the jet dilution and Fickian formulae were equal where the jet vanished.

"Chemical effluent" may also be heated (e.g. boiler blowdown has a maximum ΔT = 10.2 °C, winter $\Delta T \sim 10$ °C, summer $\Delta T \sim 5$ °C) and so the likelihood of buoyant plume development in the river after discharge was considered using standard formulae (Fischer et al. 1979).

Results are summarised in Table 5.

Buoyant plume behaviour was predicted for Options B and E for excess temperatures in the vicinity of +10 °C. This would reduce dilutions substantially from those in Table 5. For Options A, C and D, however, jet momentum caused enough entrainment to prevent buoyant plume behaviour.

A jetted single port (Option C) resulted in higher dilution than a single unjetted release (Option B) only within 30 metres of the outfall and further downstream dilutions were comparable. Options A and E gave comparable dilutions at 30 m but note the caveat about buoyant plume behaviour with Option E. Option D gave lower dilutions than Option E close to the outfall but dilutions were comparable at 50 m and option D avoided possible buoyant plume behaviour.

Results presented in Table 4 indicate that closed-cycle cooling is likely to be required only rarely. Option B would, therefore, be a rare event and if adequate ponding was provided a separate outfall (Options C, D and E) might not be necessary.

Option	Ports	Port velocity $m.s^{-1}$	Flow $m^3.s^{-1}$	Dilution at specified distances below outfall 2 m	4 m	10 m	30 m	50 m	100 m	200 m	500 m
A	30	7	15	-	-	600	950				
B	1†	0	0.13	1	(2.5)*	(5)*	(30-50)	(60-80)	(120)	(200)	(300)
C	1	5	0.13	3	6	16	(40-60)	(60-80)	(120)	(200)	(300)
D	10	5	0.13	10	20	(50-60)	(300)	(600)	(1000)		
E	30	5	0.13	17*	(30-50)*	(150)*	(900)				

( ) Denotes passive mixing
* Denotes buoyant plume likely: dilutions upper bound estimates
† It is uncertain whether 1 or more ports will discharge effluent

Table 5 Mixing of chemical effluents

SUMMARY AND CONCLUSIONS

A simulation study was conducted of mixing and river temperatures below the proposed Waikato (500 MW) power station at Clune Road and the existing Huntly (1000 MW) power station. The study accounted for: cooling tower use at Clune Road; variations of power generation, river flow and ambient temperature; transverse mixing and evaporative cooling of waste heat and initial mixing at each power station. Two alternative operating control rule and cooling tower combinations were investigated: the 'P8 Rule'/'small' tower and the '26°/19° Rule'/'large' tower.

Waste heat discharge caused the greatest change in predicted river temperature during autumn (April-May).

In autumn, predicted Huntly plume excess temperatures averaged 1-2.5 °C (max 3.5-4 °C) for average generation (55% LF) and averaged 2-3.5 °C (max 3.5-4 °C) for high generation (70% LF) in a low flow year.

In spring and early summer (October-January), predicted Huntly plume temperatures rarely exceeded 1.5 °C, and during summer (February-March) and winter (June-September) they averaged 1-2 °C (with occasional values up to 3 °C).

In autumn, predicted Waikato plume excess temperatures averaged 1-1.5 °C (max 2.5 °C) for average generation (55% LF) and 1.5-2.5 °C (max 3.0 °C) for high generation in a low flow year. In spring and early summer, predicted Waikato plume temperatures rarely exceeded 0.5 °C, while in summer and winter they averaged 0.5-1.5 °C.

Note that predicted Waikato plume temperatures at no time exceeded predicted Huntly plume temperatures, despite the fact that at Clune Road there was appreciable residual waste heat from Huntly.

Of the two control rules considered here, the 'P8 Rule' allowed appreciably greater power generation in summer at Huntly but resulted in noticeably higher plume temperatures (by up to 25%, 1 °C). At the Waikato power station, the combination of the 'small' tower and the 'P8 Rule' resulted in appreciably higher plume temperatures (by about 0.5 °C, 25%) only during autumn in a low flow/high generation year than the combination of the 'large' tower and the '26° Rule'.

Waste heat discharge resulted in predicted decreases of the period for which river temperatures were below 19 °C by: 3 weeks and 1½ weeks in the Waikato plume and 1-2 weeks and ½-1 weeks in the estuary; for high generation (70%) in a low flow year and average generation (55%) respectively. These figures assumed use of the cooling towers at the Waikato power station in 'helper mode' once ambient river temperature exceeded 19 °C. Use of the towers above an ambient temperature of 17 °C reduced the above figures by about 50%. The predicted reductions resulting from waste heat discharge at Huntly were: 5 weeks and 4 weeks in the Huntly plume; and 2½ weeks and 1½ weeks just above the Waikato power station, for high generation in a low flow year and average generation respectively.

Cooling-tower use averaged 30-40% for average generation and 40-45% for high generation in a low flow year: almost all of which was in "helper mode". Closed cycle operation was necessary only 13% of the time when the Waikato and Huntly station generated at full capacity during a low flow summer period.

Discharge of cooling water at the Waikato station from a 116 metre long transverse multi-port diffuser was estimated to achieve rapid mixing with 50% of the river flow within about 5 seconds (10 metres) and mixing with 75% of the river flow within about 25 seconds (25 metres).

Cooling water is not likely to impinge on the biologically sensitive littoral zone along the banks if the diffuser is located no closer than 50 metres to either bank, and more detailed studies may demonstrate that at some sites reductions to 20-30 metres are possible for a carefully designed diffuser.

Discharge of chemical effluents, such as boiler blow-down, cleaning chemical, and coal stock-pile runoff, is feasible via the cooling water outfall except when the station operates in closed-cycle. At such times satisfactory mixing could be achieved by providing a separate smaller multi-port diffuser. Jet momentum would need to be high to avoid buoyant plume behaviour either by keeping the number of ports to about 10 and/or jet velocity above 5 $m.s^{-1}$. Alternatively, since closed-cycle mode was predicted to occur only rarely, ponding could be provided for chemical effluents thereby avoiding the necessity of a separate diffuser.

ACKNOWLEDGEMENTS

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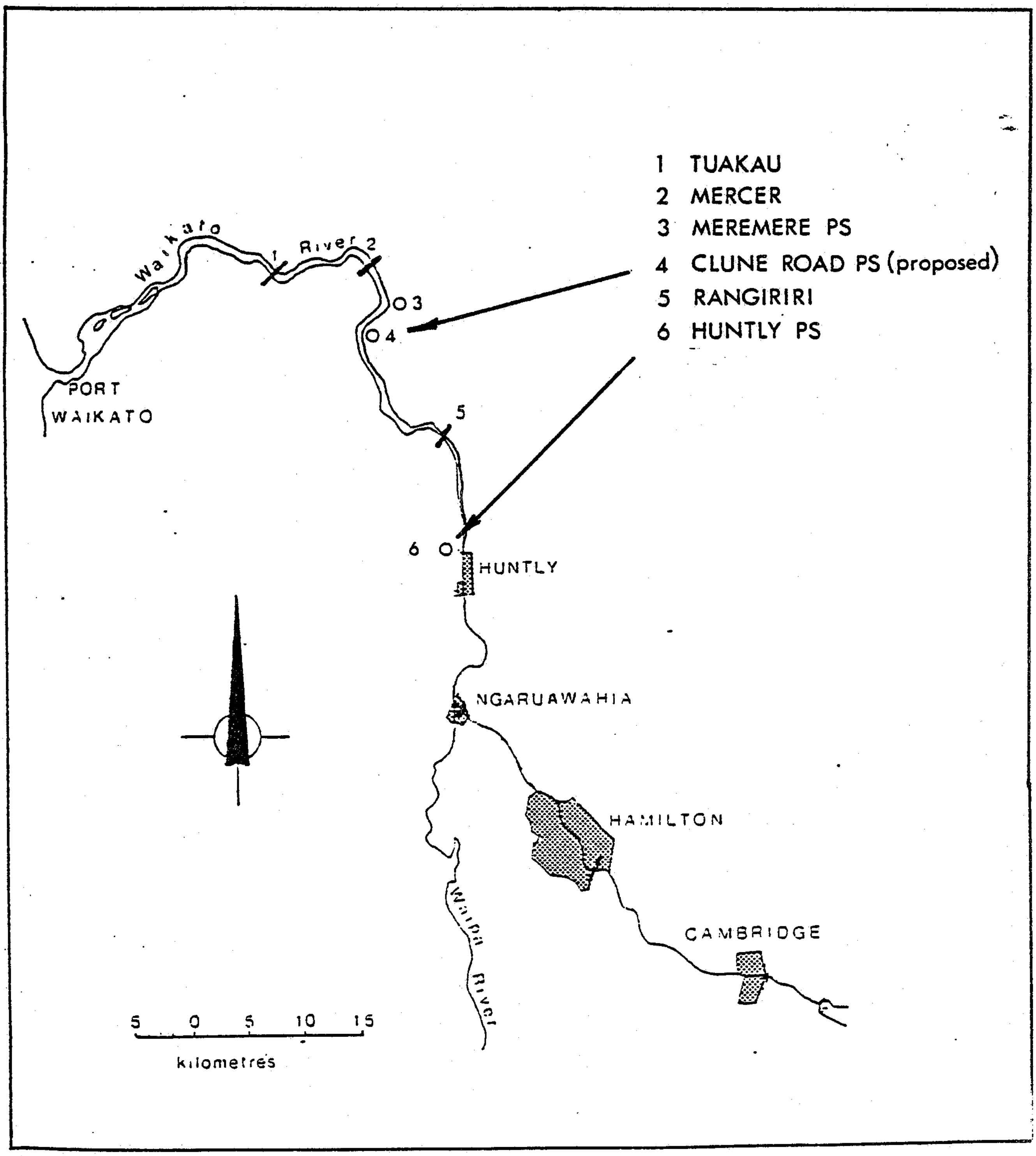


Figure 1: Location Map.

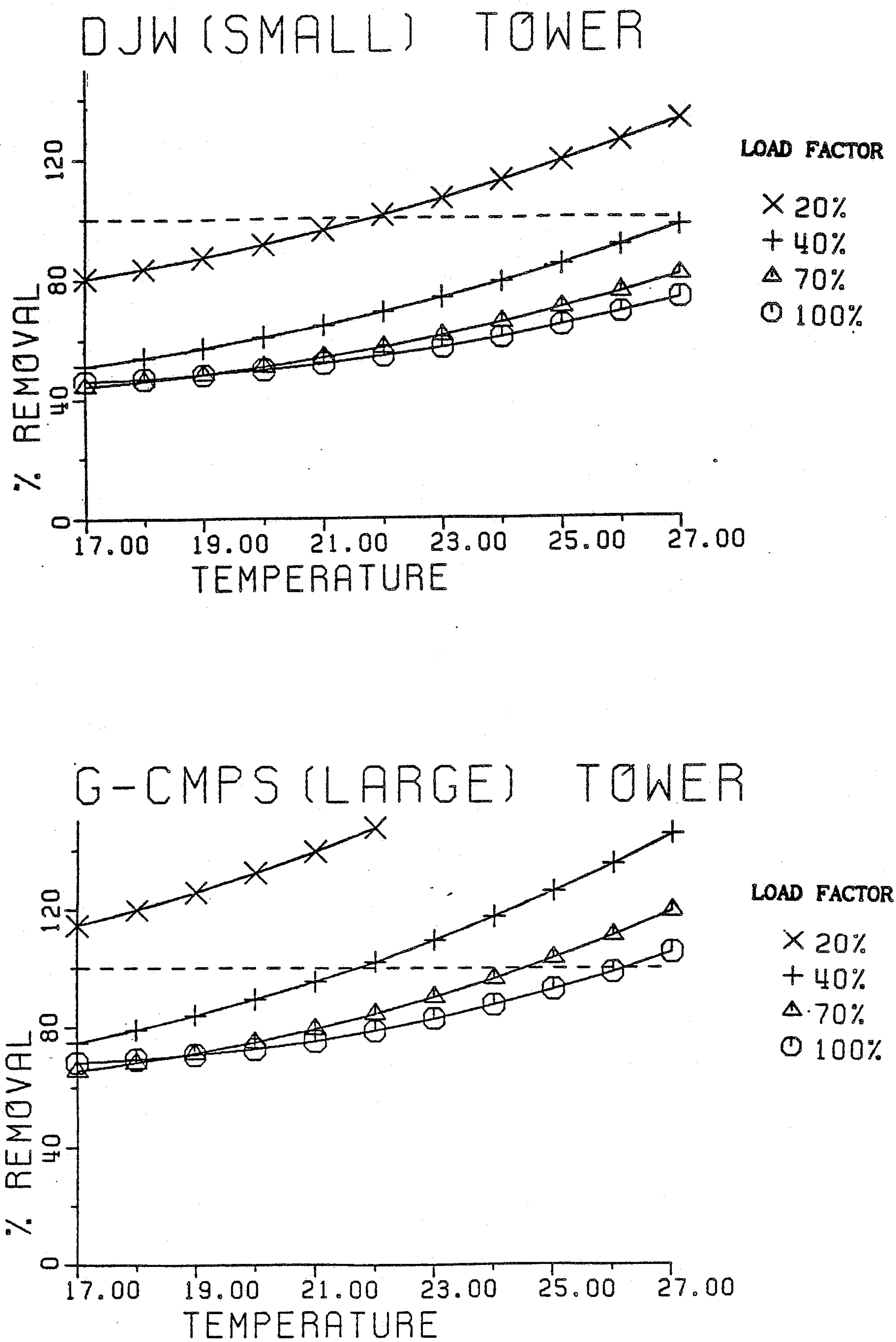
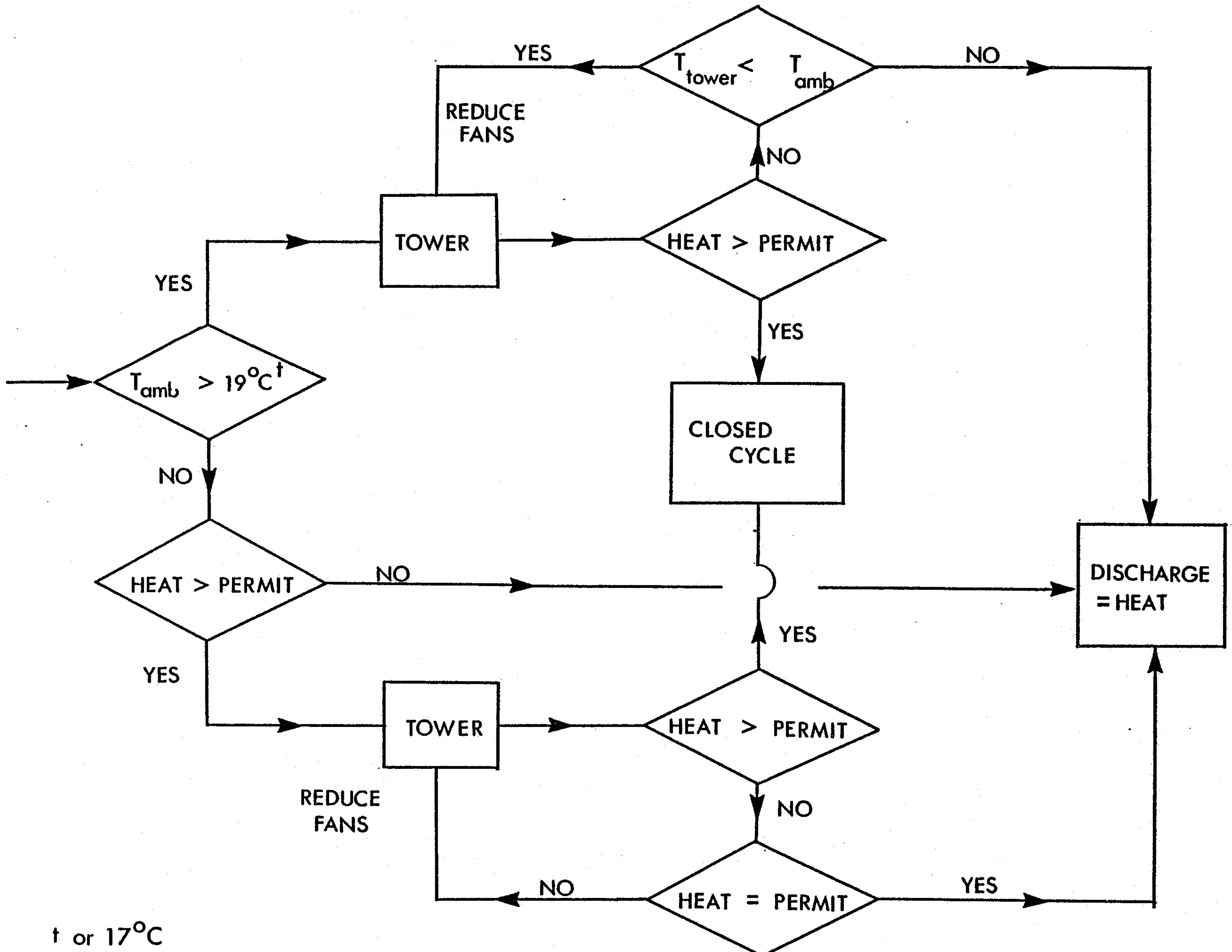


Figure 2: Cooling Tower Performance as a function of ambient river temperature and load factor.



t or 17°C

T_{amb} = ambient river temp, °C (measured upstream from the Huntly Power Station.)

T_{tower} = tower outlet temp, °C

HEAT = waste heat, MW

PERMIT = allowable waste heat discharge, MW

Figure 3: Cooling Tower Operation at Waikato.

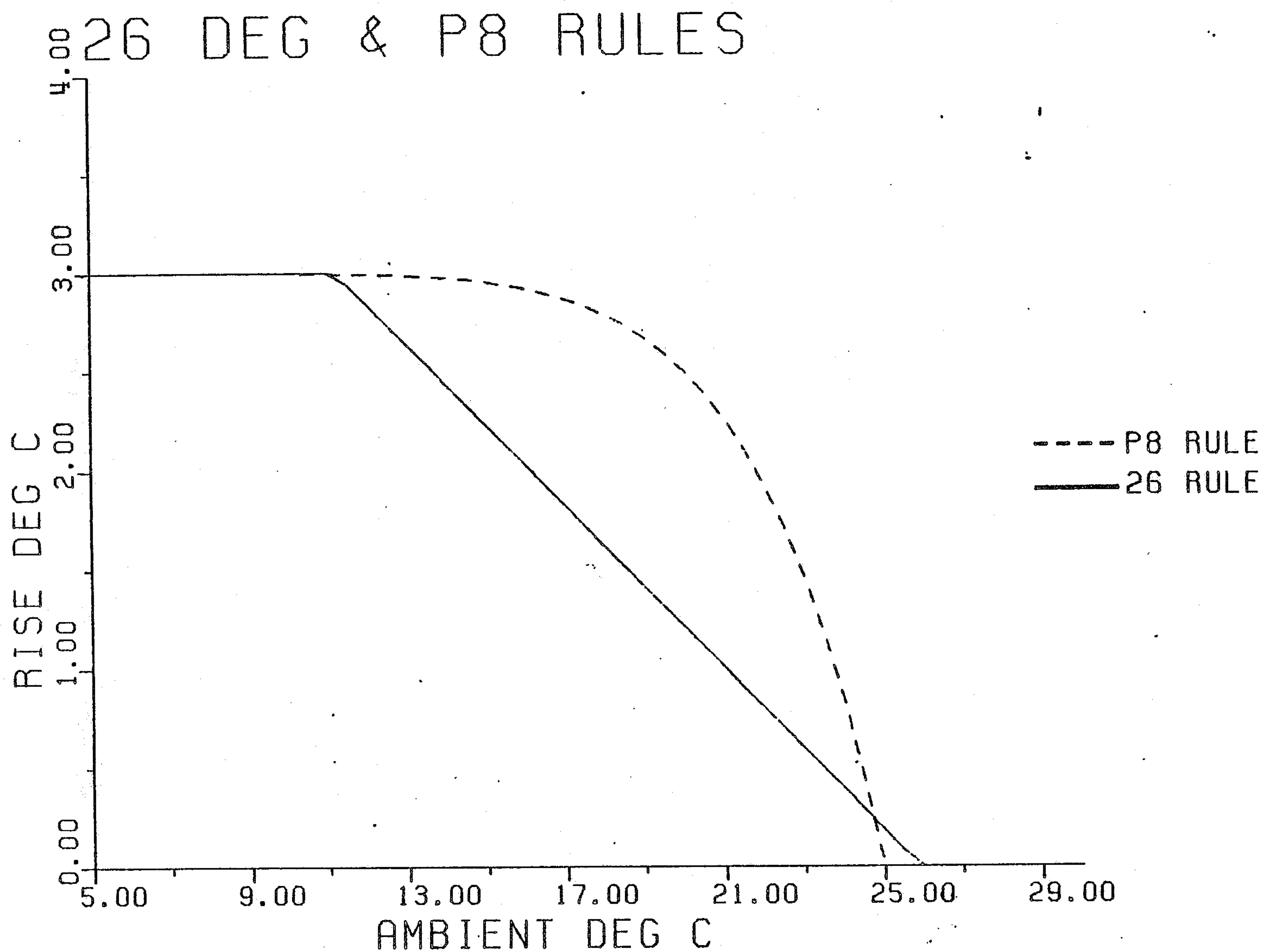
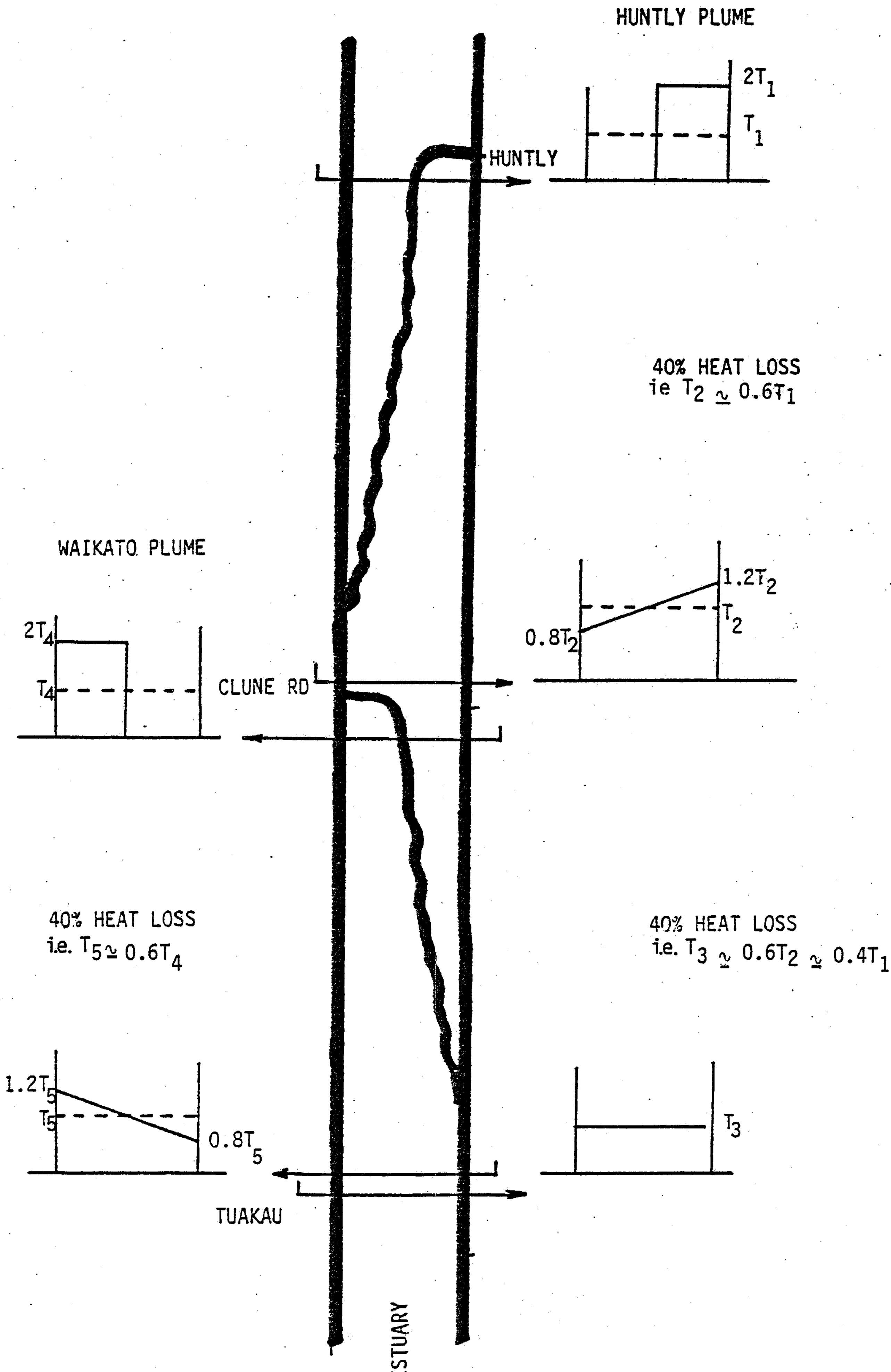


Figure 4: Allowable Fully-mixed River Temperature Rise: 26° and P8 Rules.



NOTES: (a) Huntly and Waikato plumes shown separately
(b) Ti=fully mixed temperature i=1,2..5

Figure 5: Diagram of Transverse Mixing and Heat Decay.

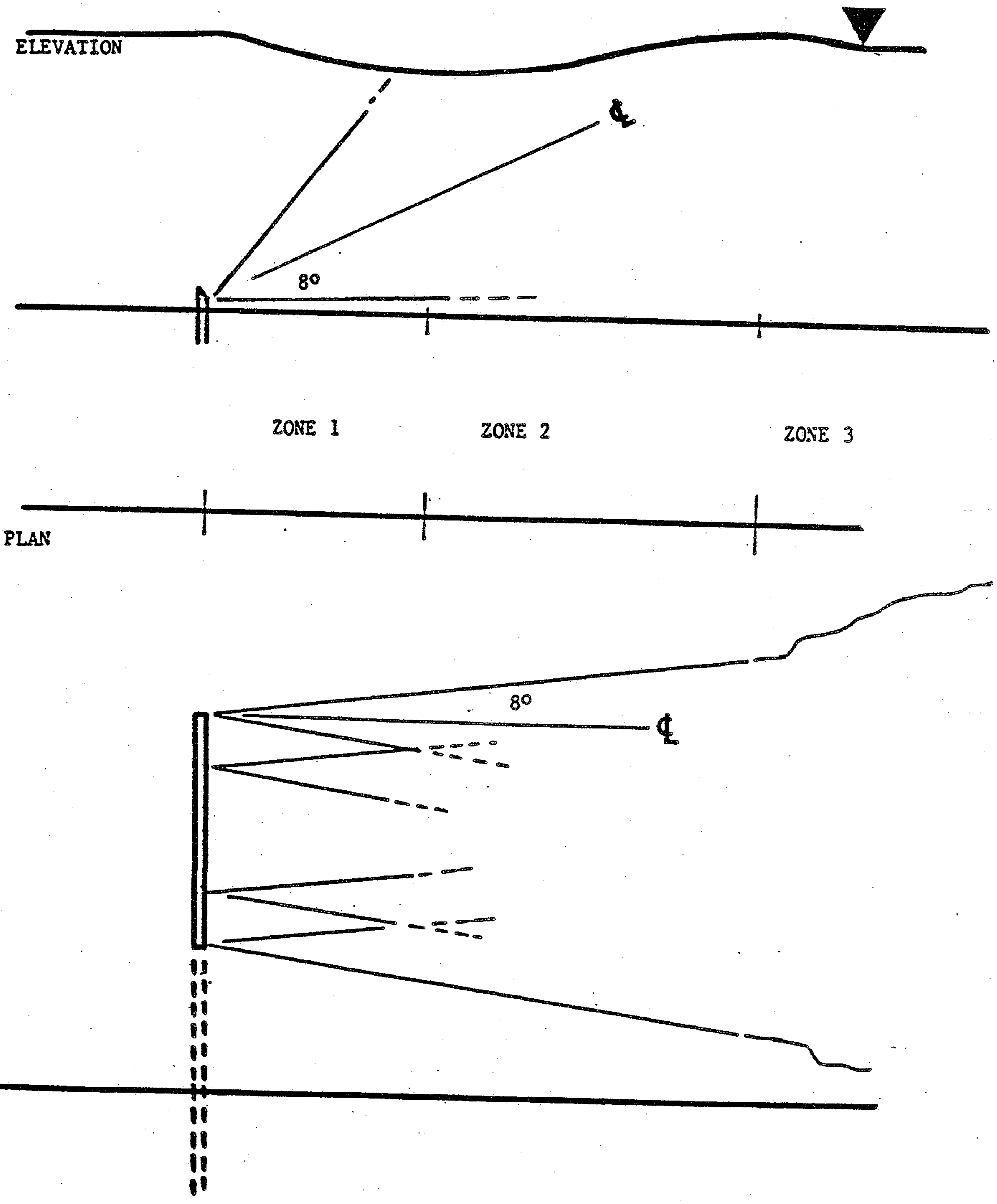


Figure 6 : Mixing Below a Diffuser.

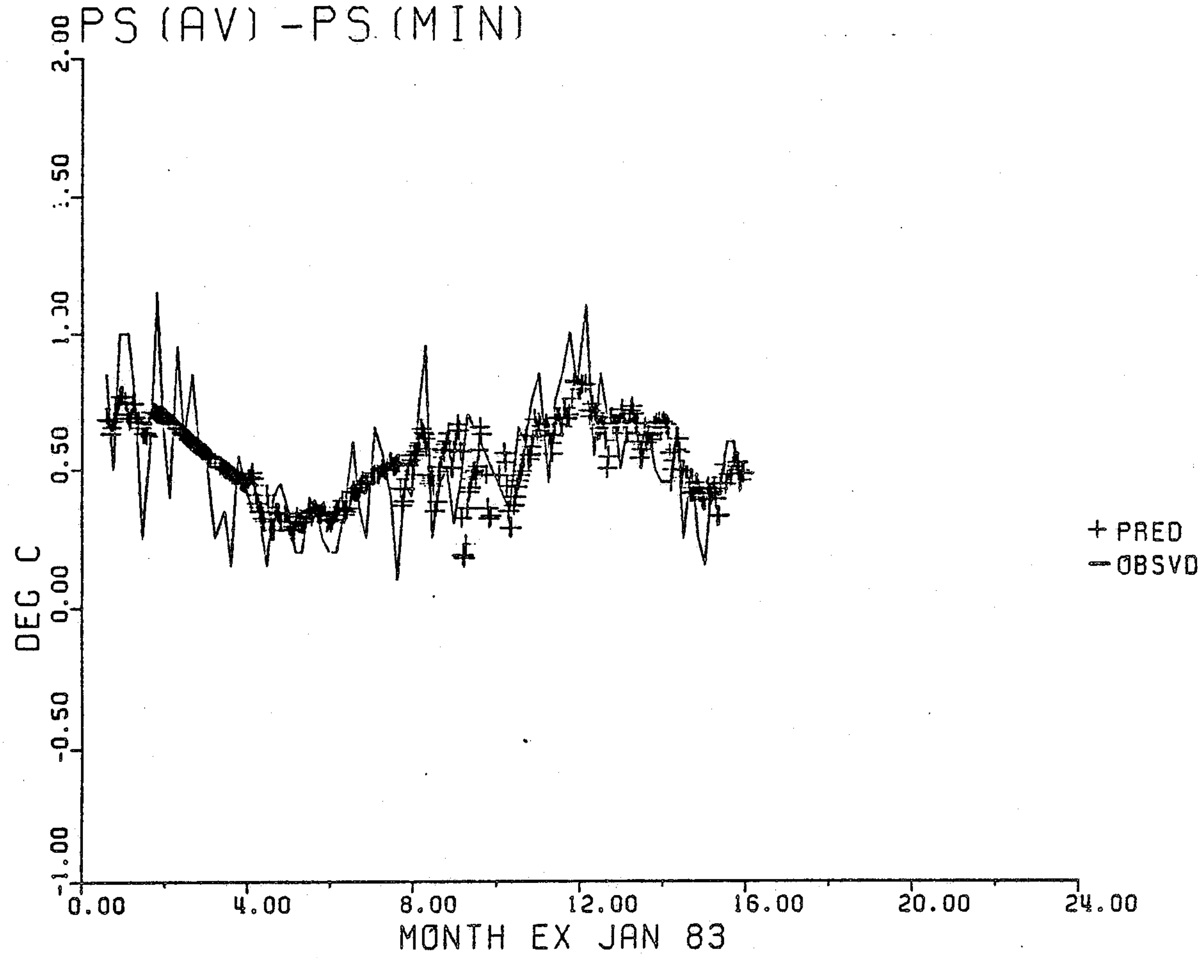


Figure 7: Average(HPS) - Minimum(HPS) Temperature 1983-1984.

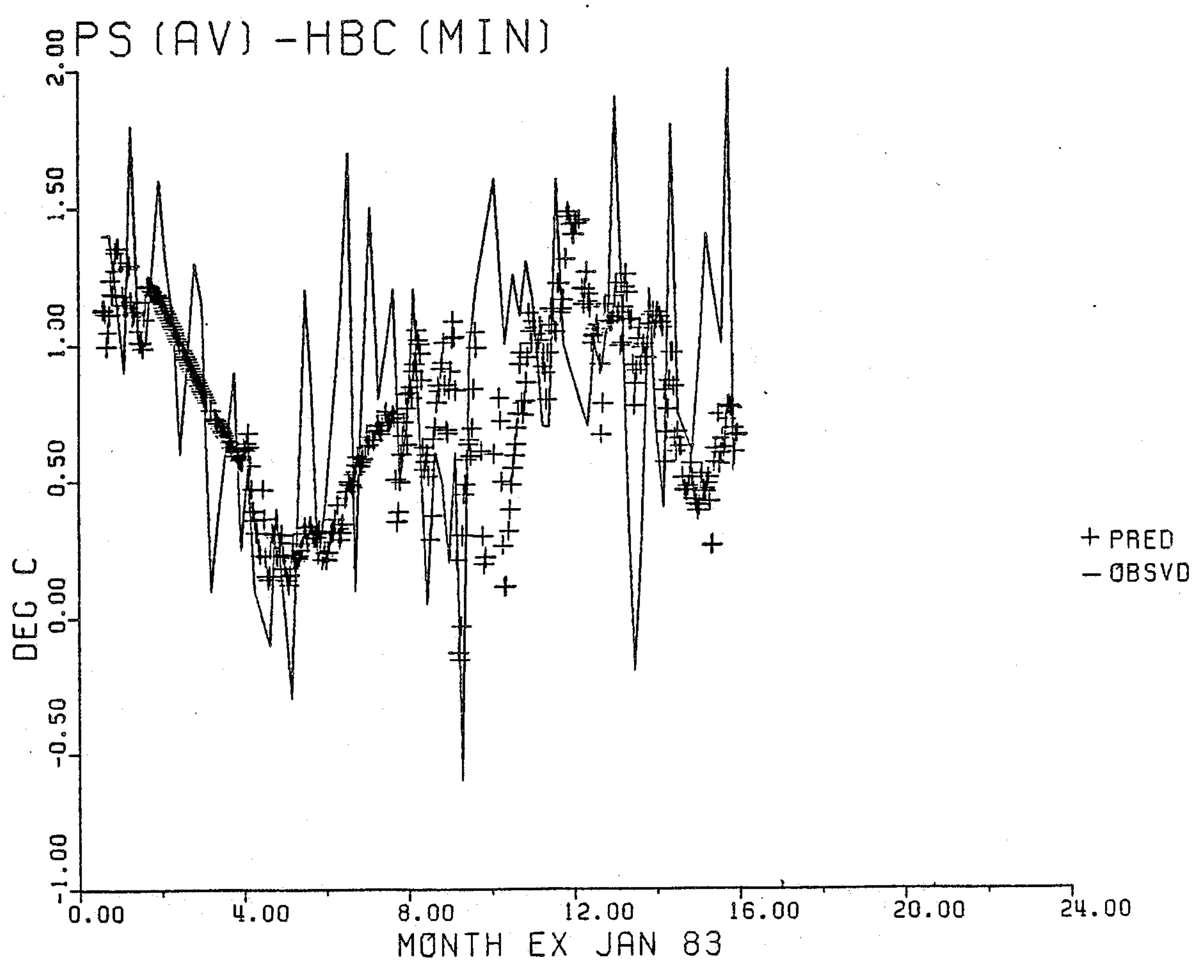


Figure 8: Average(HPS) - Minimum(HBC) Temperature 1983-1984.

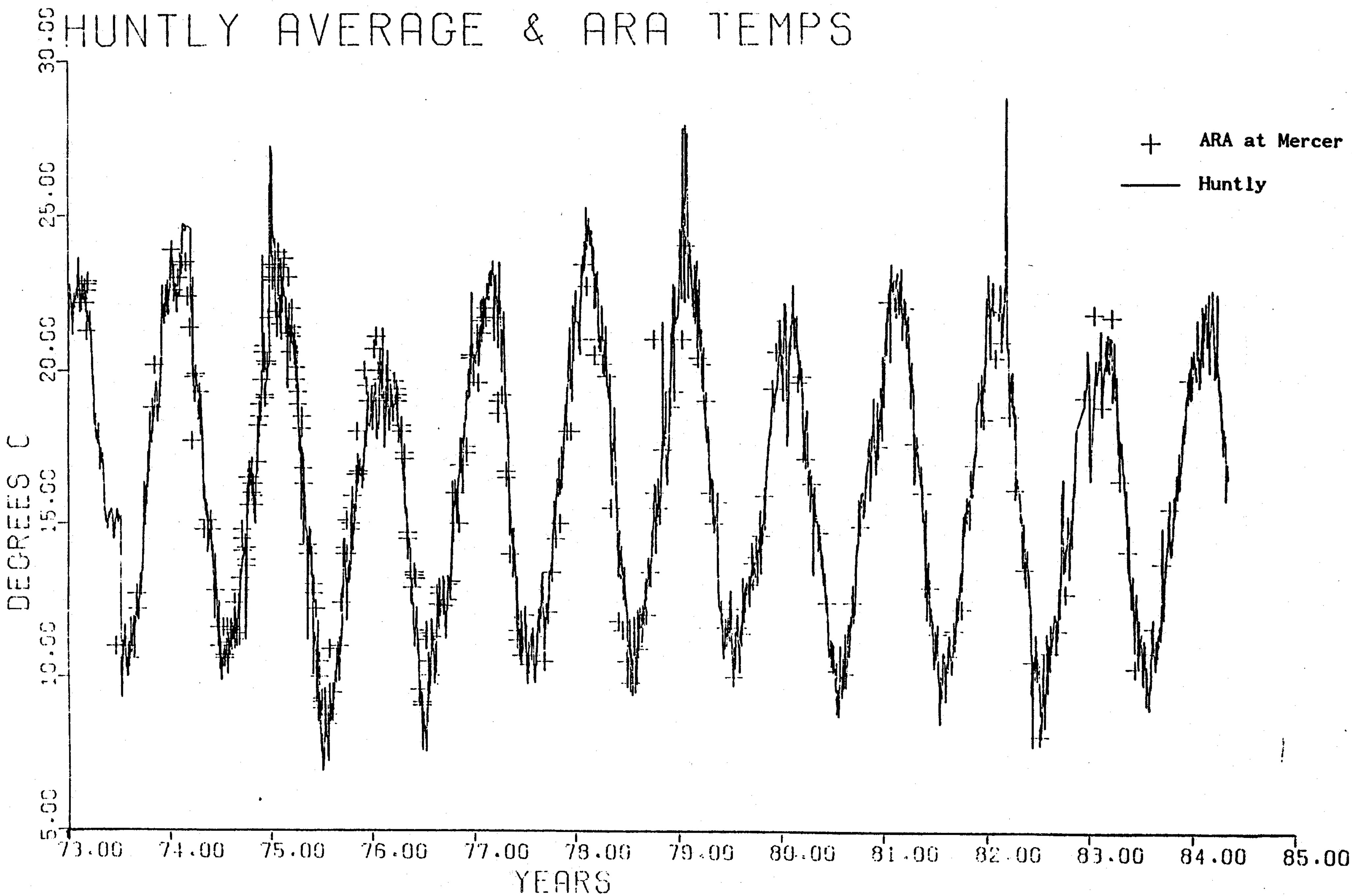


Figure 9: Daily Mean Temperature 1973-1984.

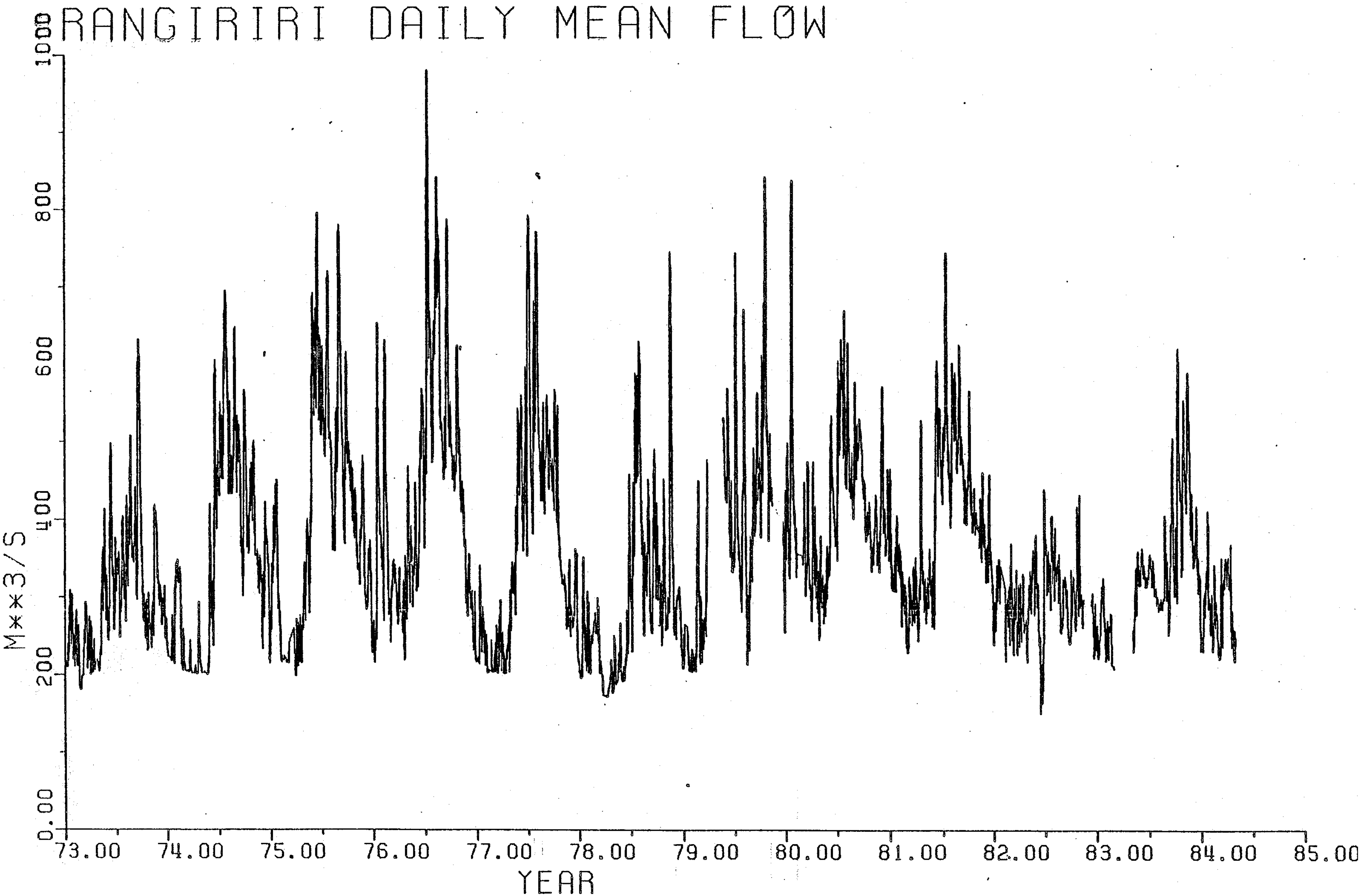


Figure 10: Daily Mean Flow at Rangiriri 1973-1984.

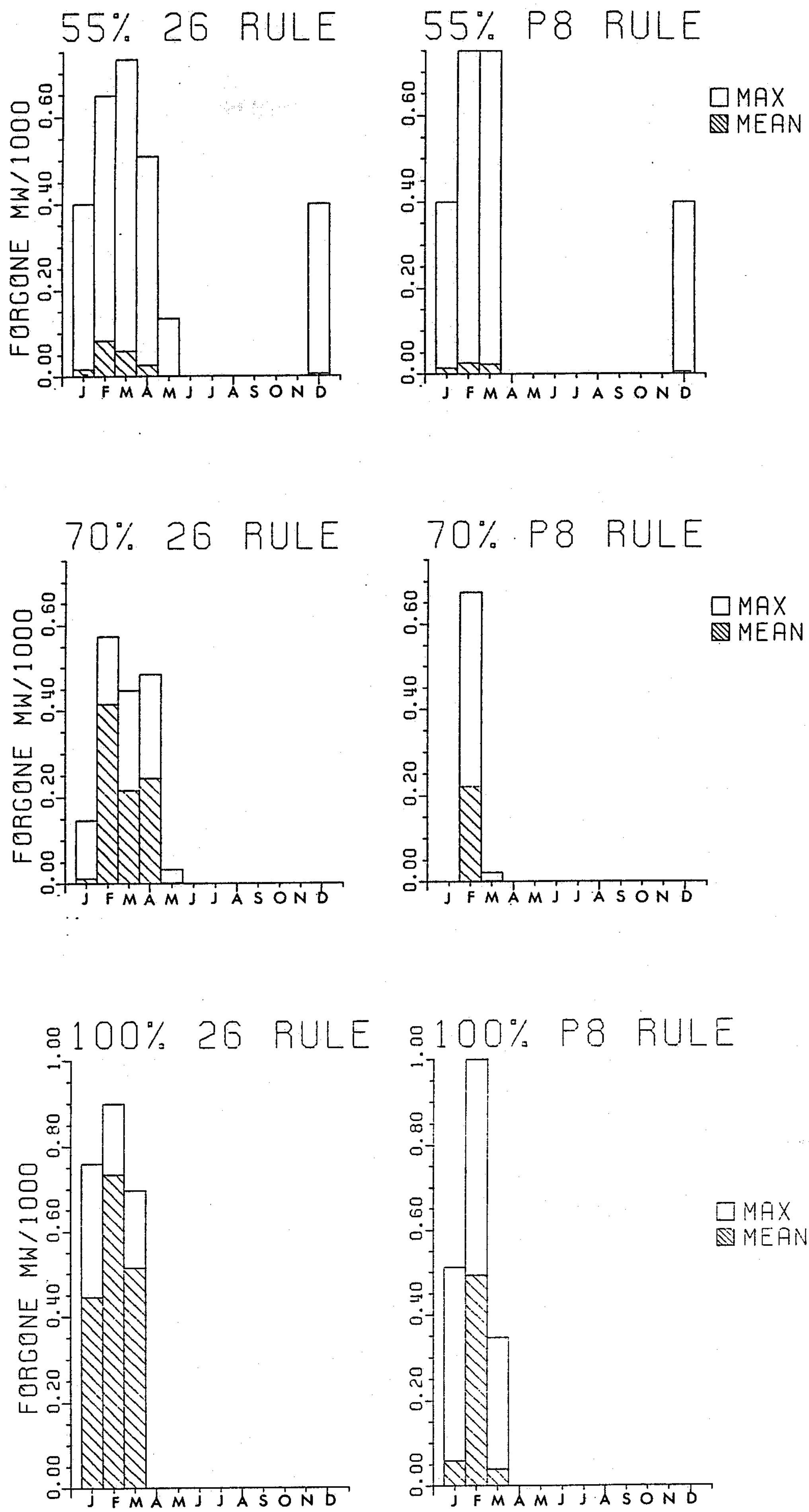
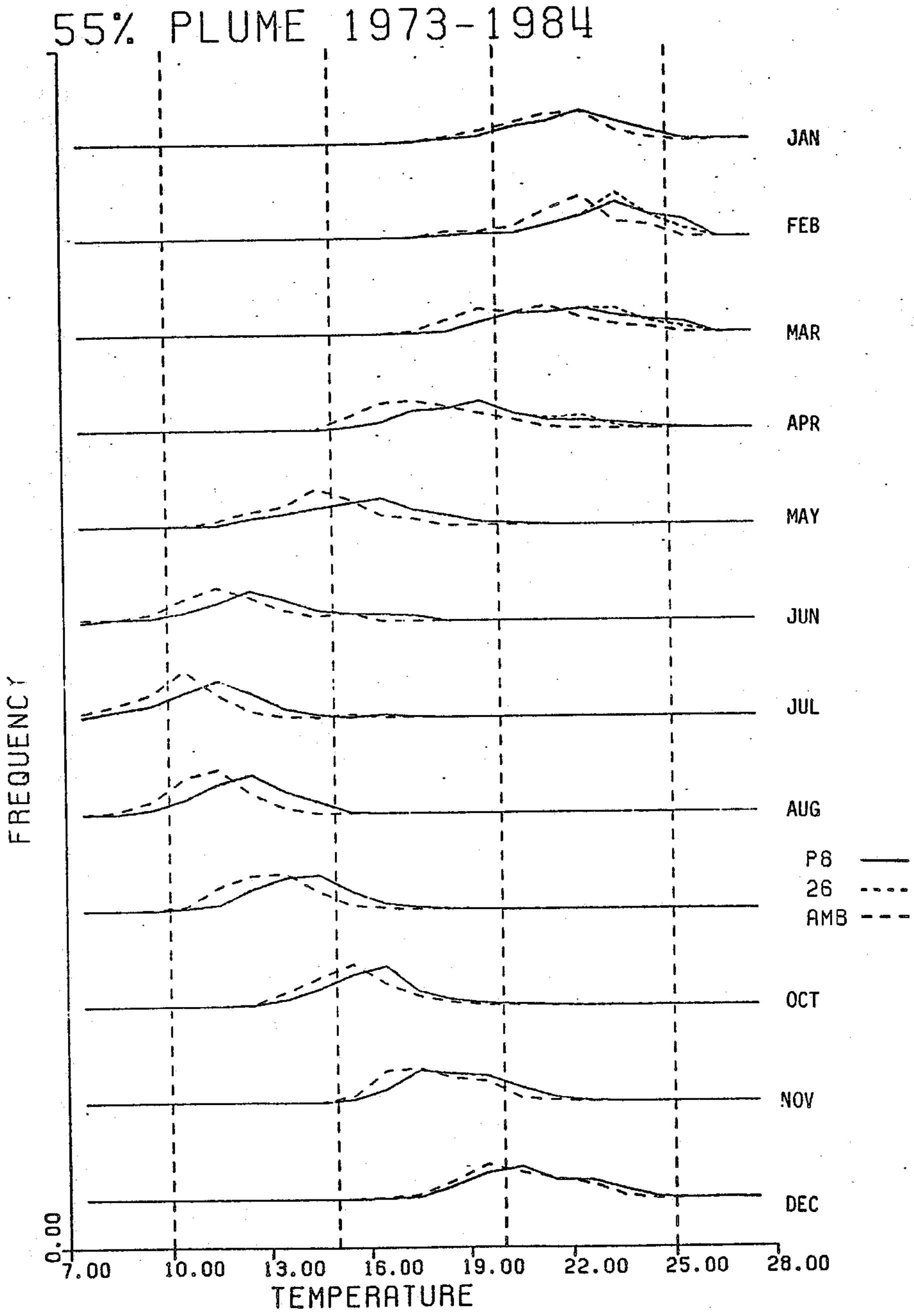


Figure 11: Power Forgone at Huntly

Note: MAX denotes worst day
MEAN denotes average day

Periods covered: 55%, 1973-1984: 70% 1978: 100% 1978/J-M



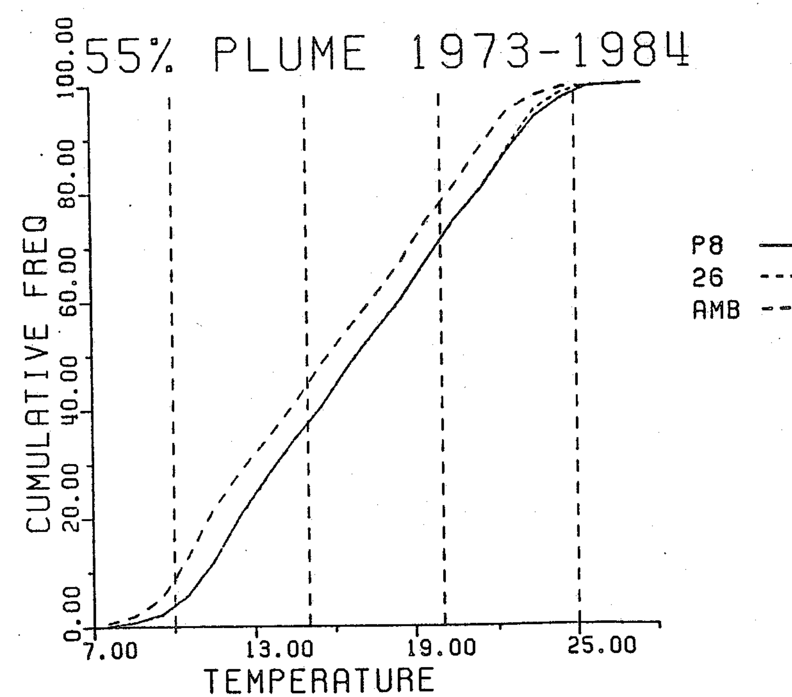
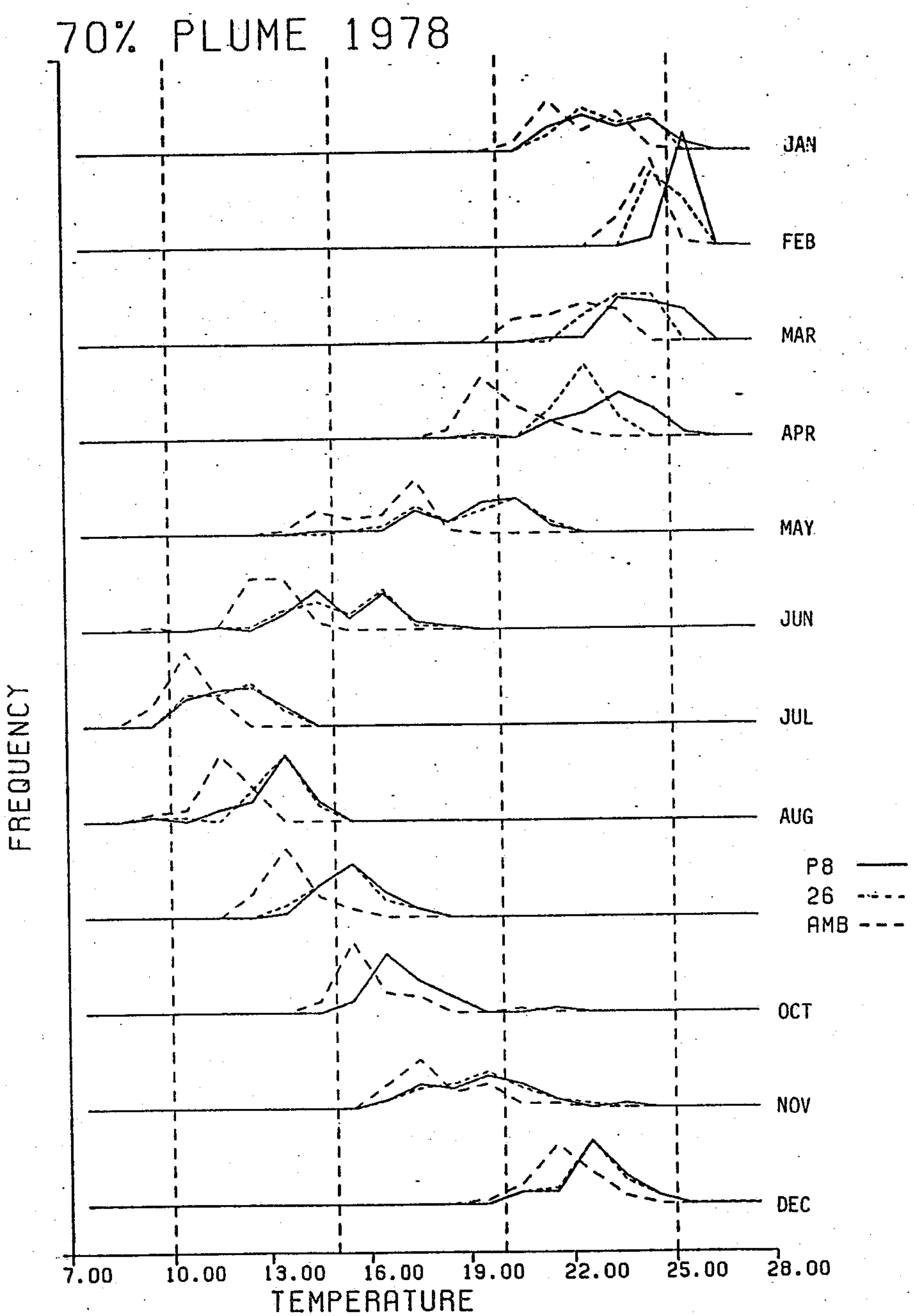


Figure 12a: Huntly plume temperatures



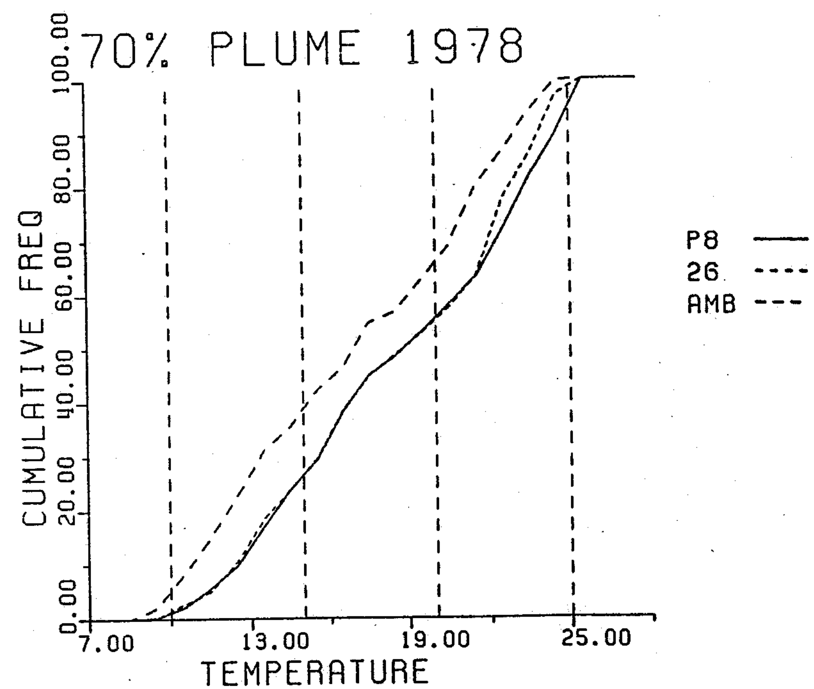
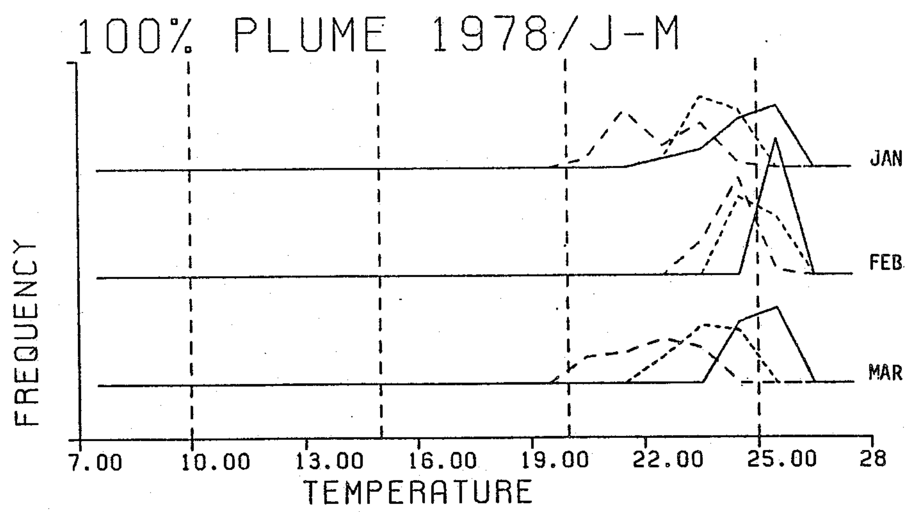


Figure 12b: Huntly plume temperatures



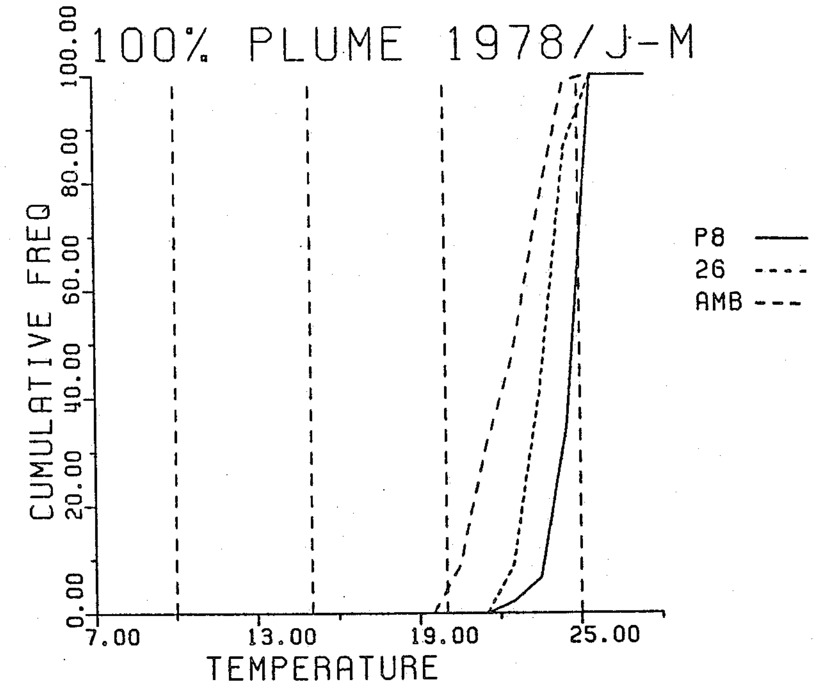


Figure 12c: Huntly plume temperatures

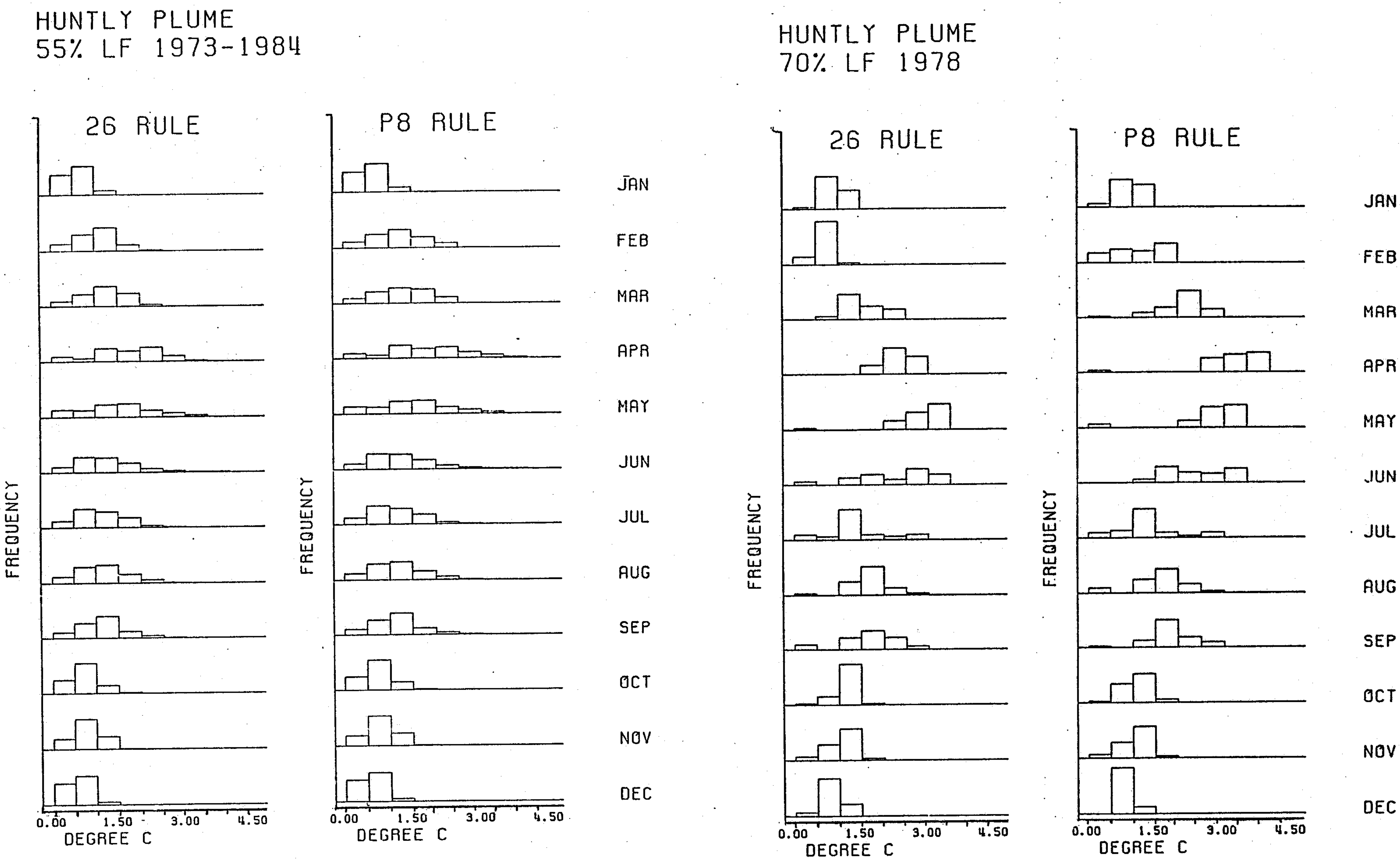
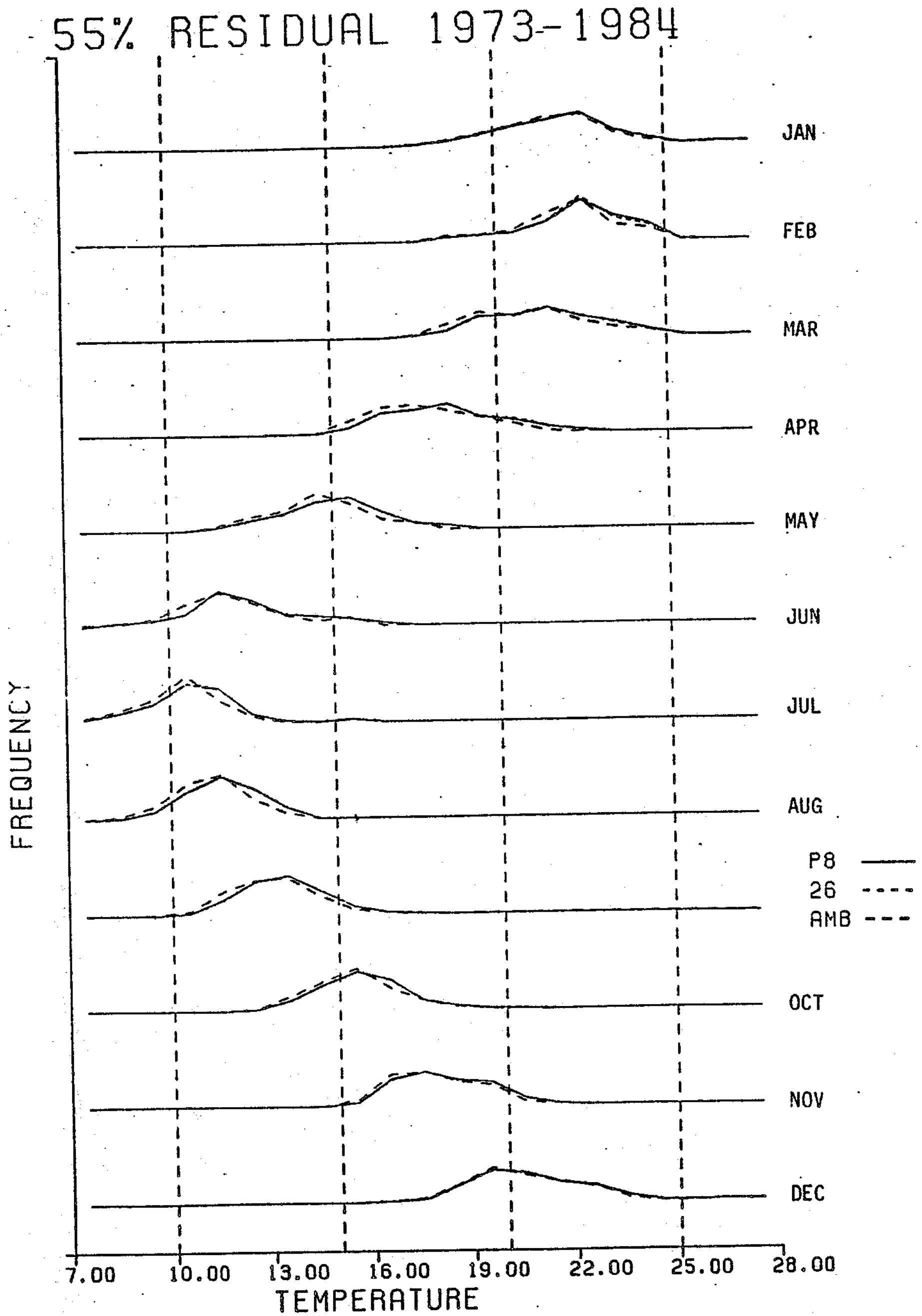


Figure 13: Huntly plume excess temperatures



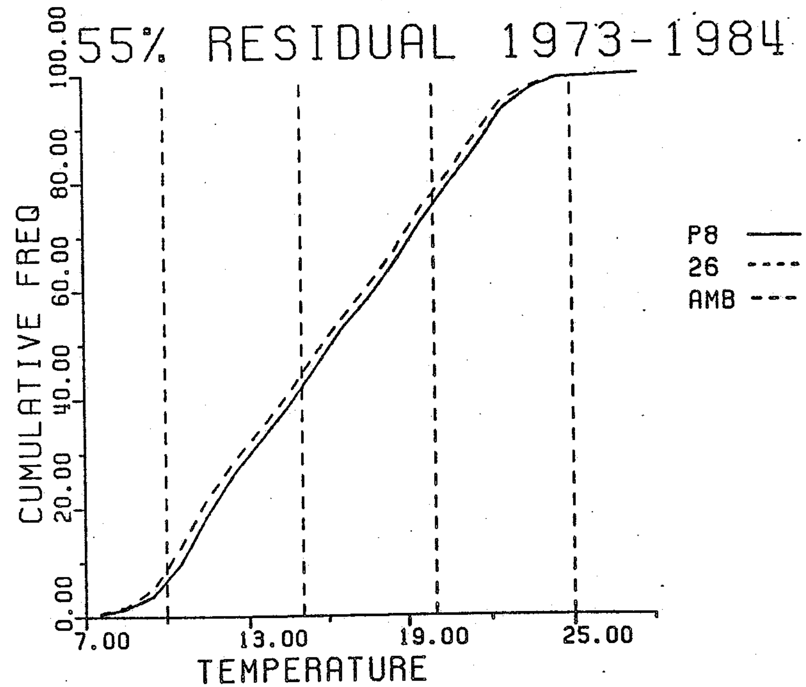
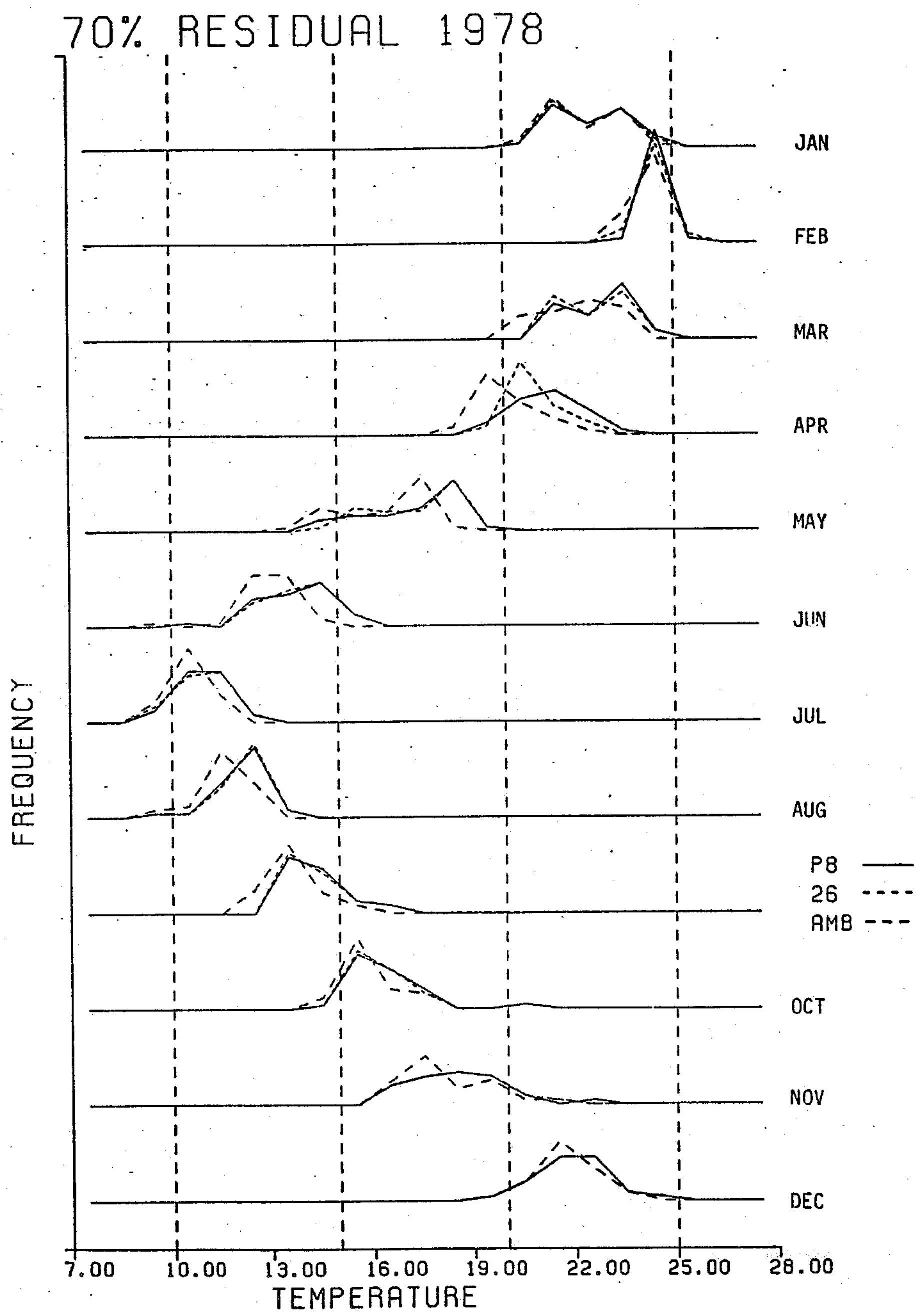


Figure 14a: Huntly residual temperatures at Clune Road site



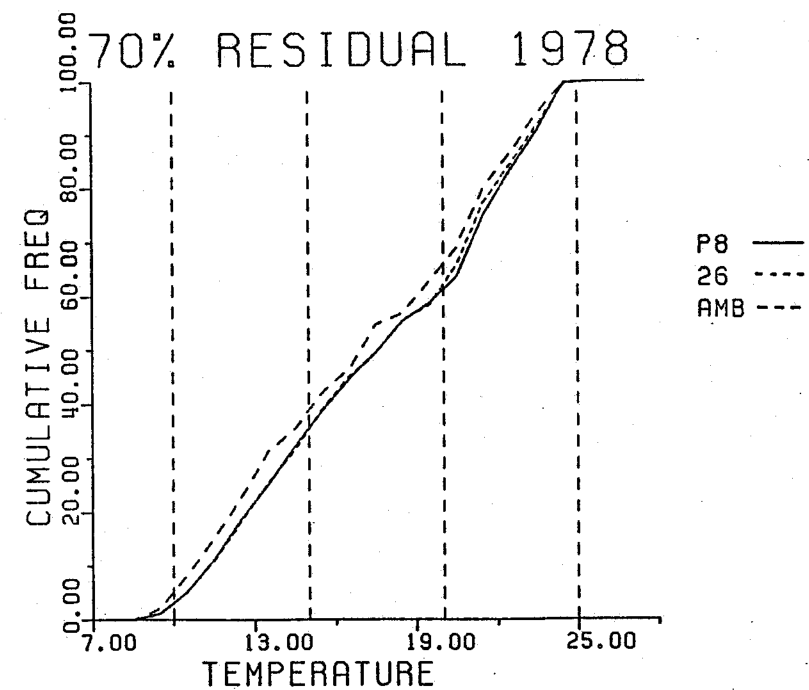


Figure 14b: Huntly residual temperatures at Clune Road site

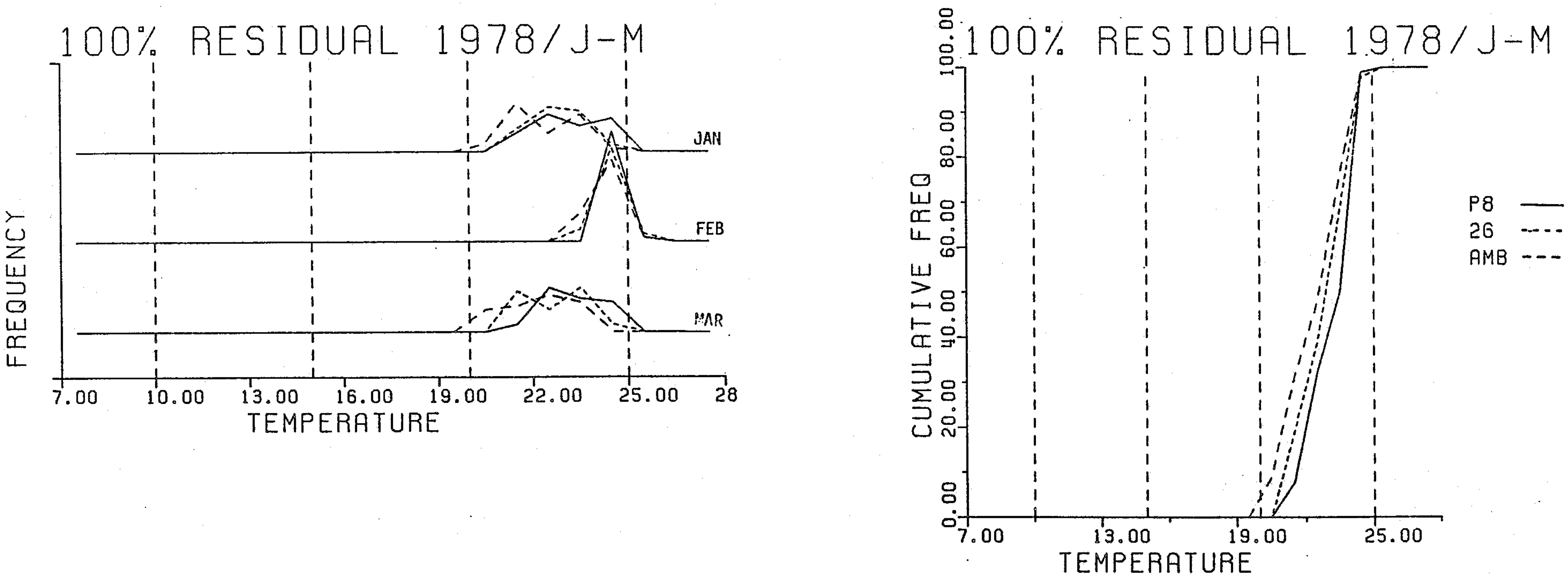
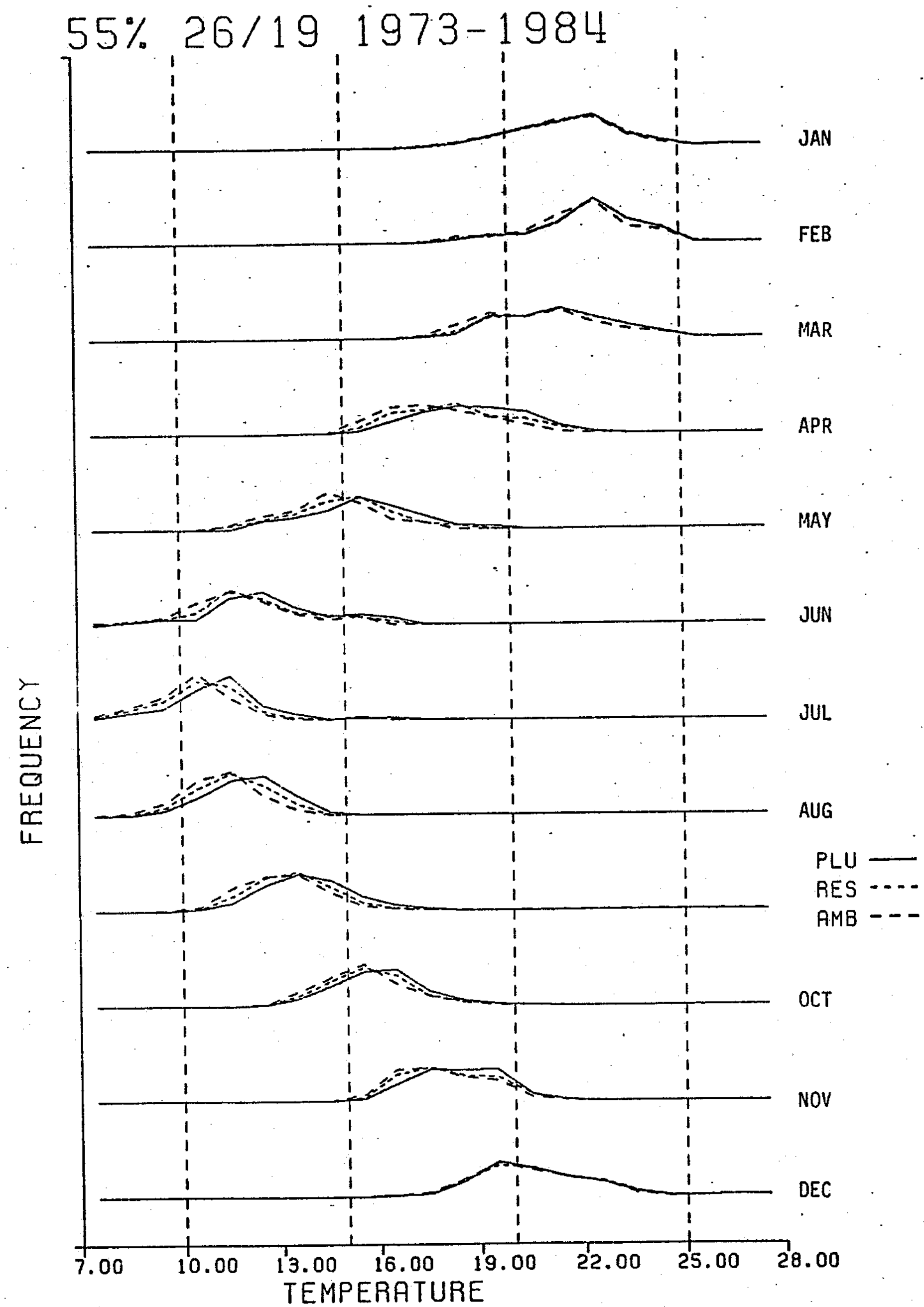


Figure 14c: Huntly residual temperatures at Clune Road site



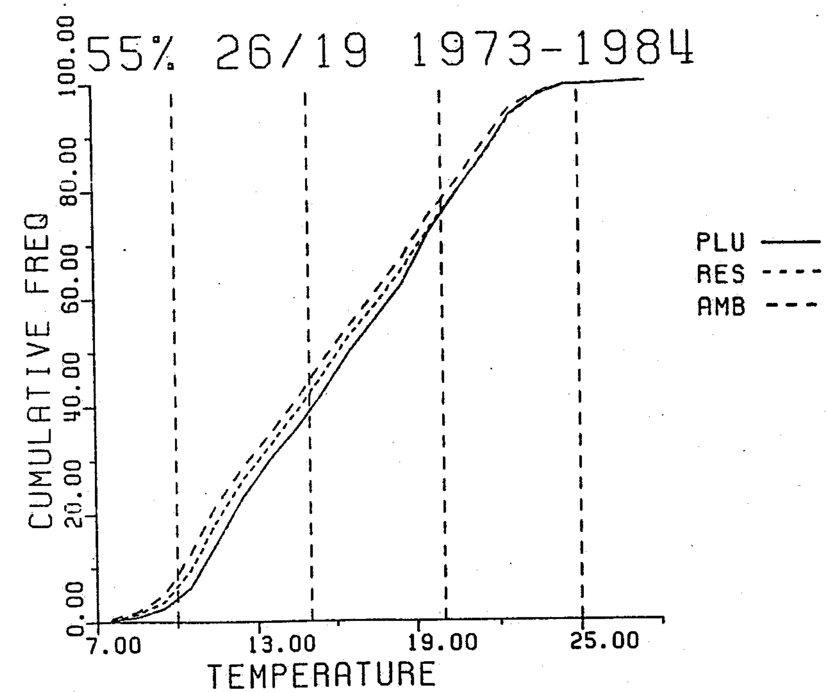
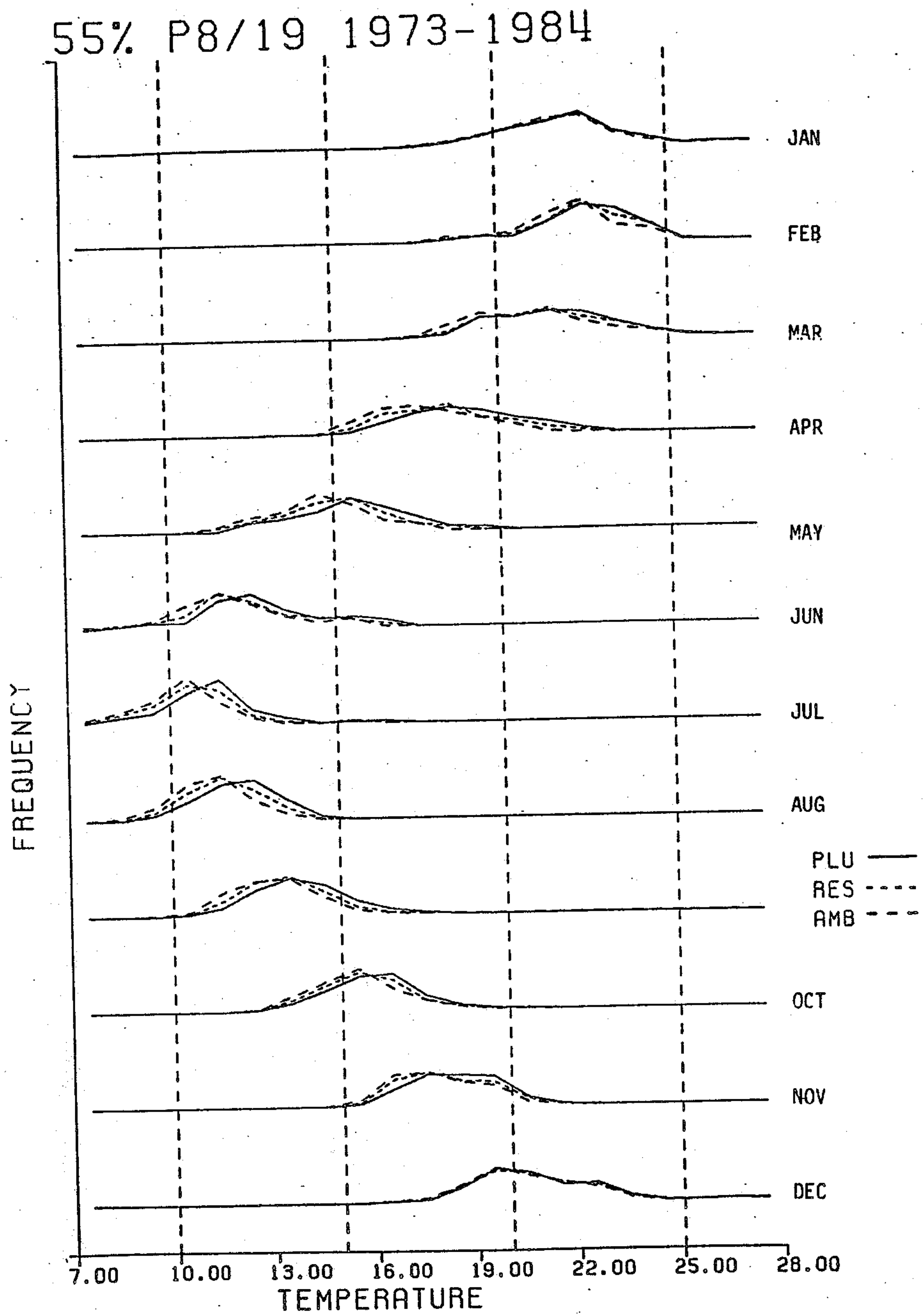


Figure 15a: Waikato plume temperatures



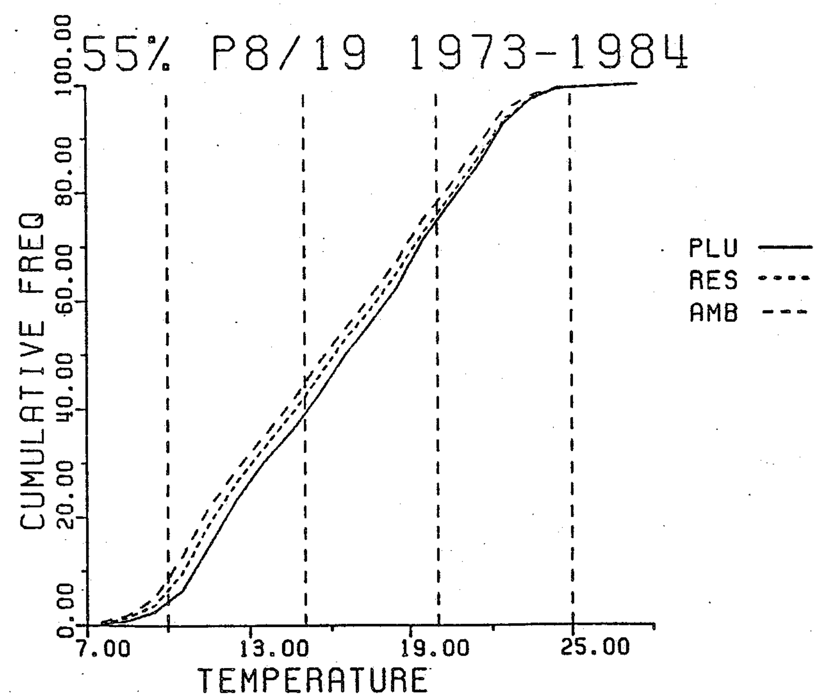
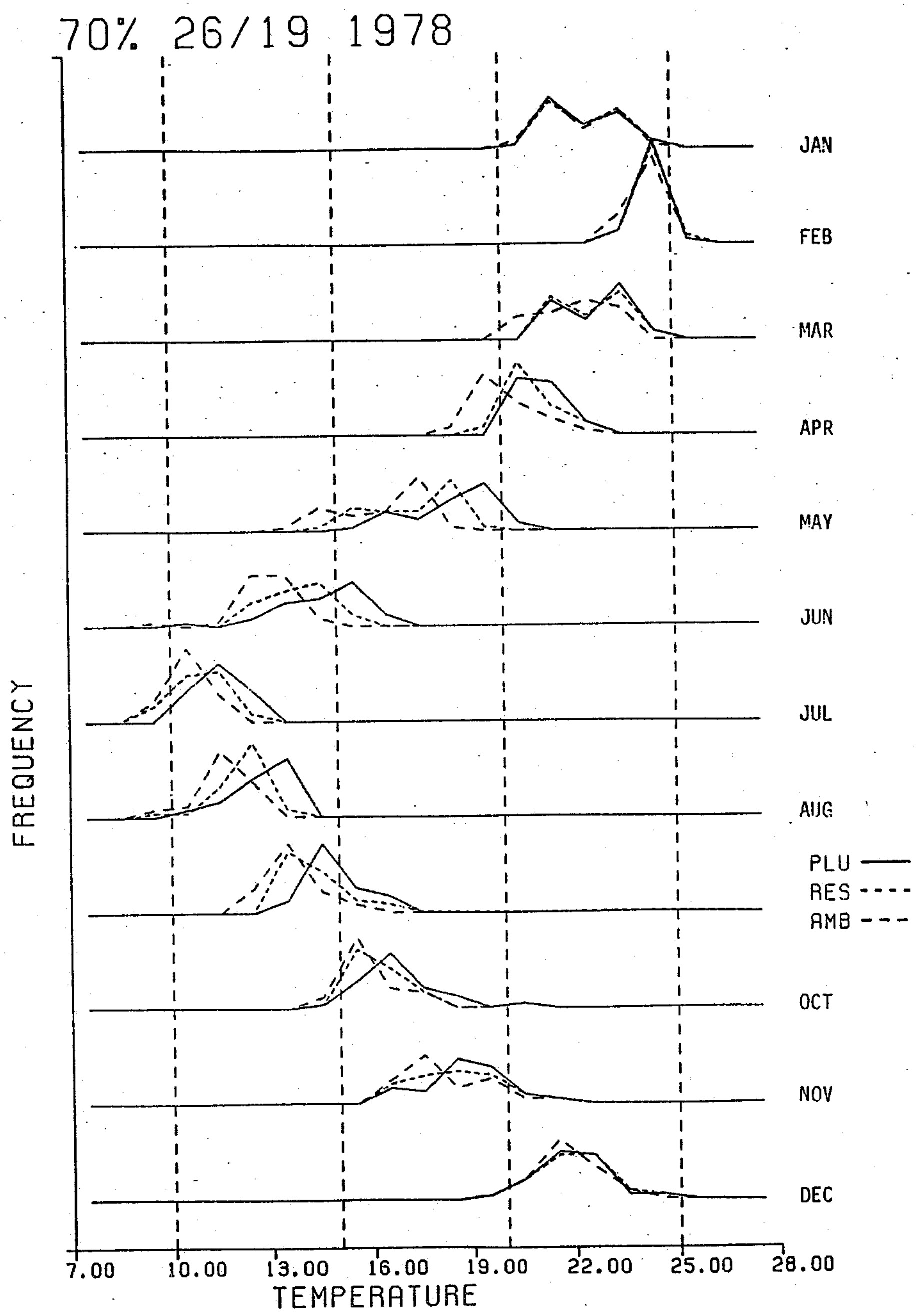


Figure 15b: Waikato plume temperatures



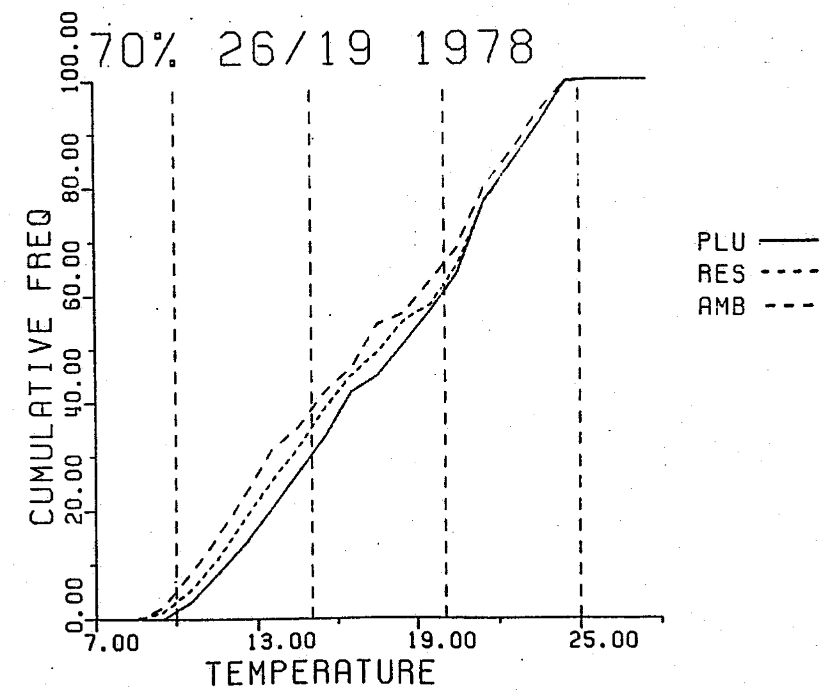


Figure 15c: Waikato plume temperatures

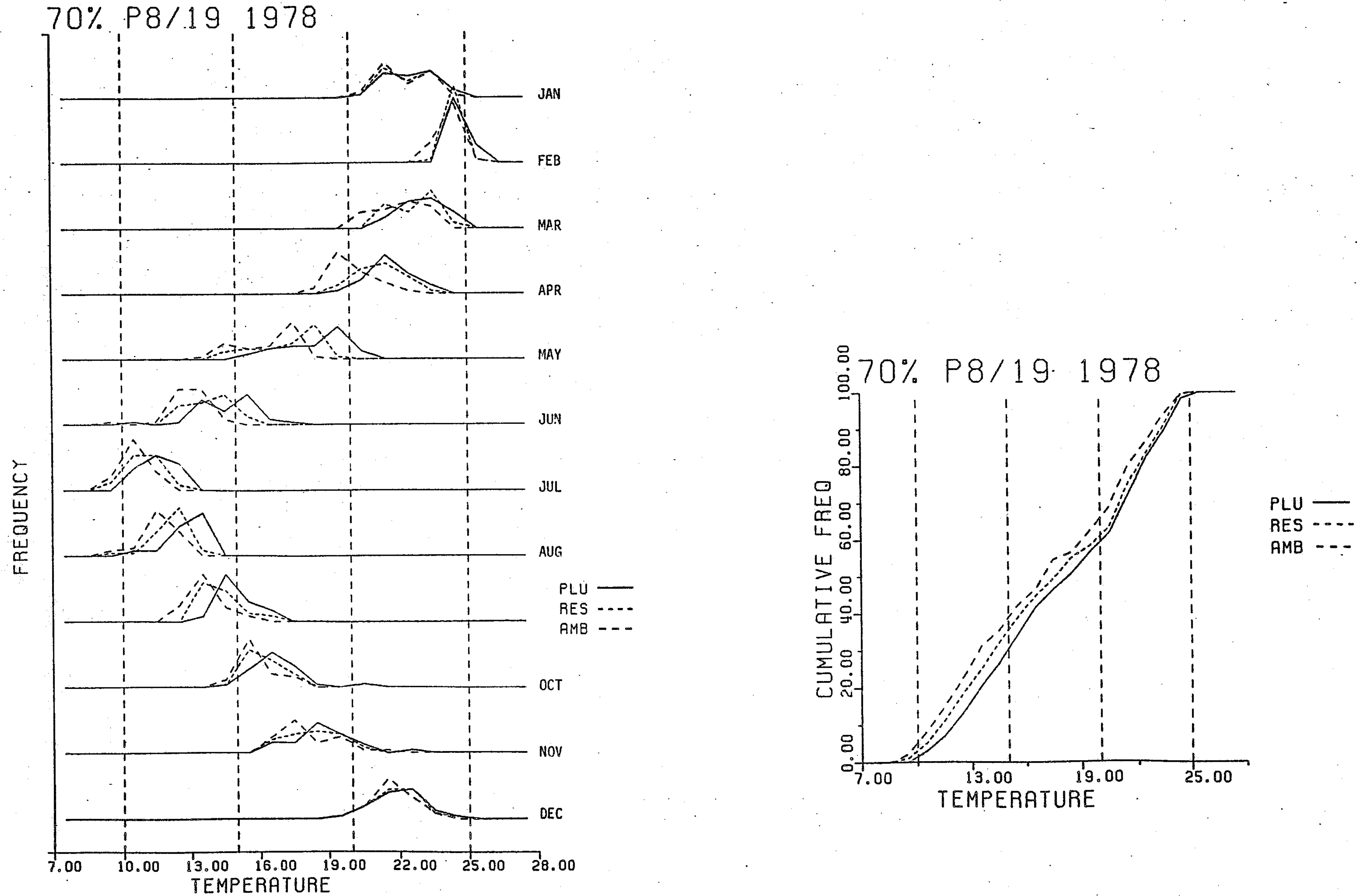


Figure 15d: Waikato plume temperatures

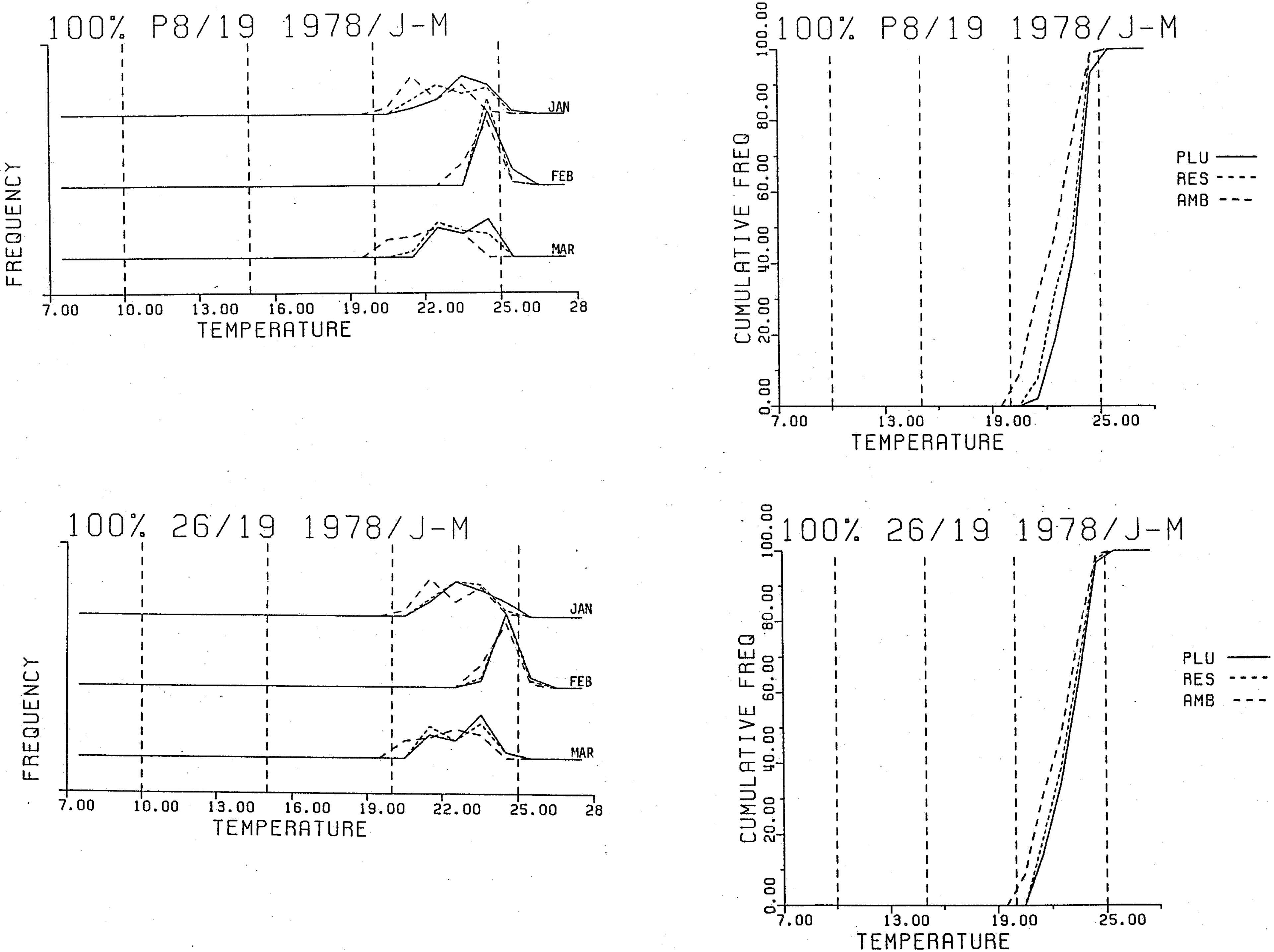


Figure 15e: Waikato plume temperatures

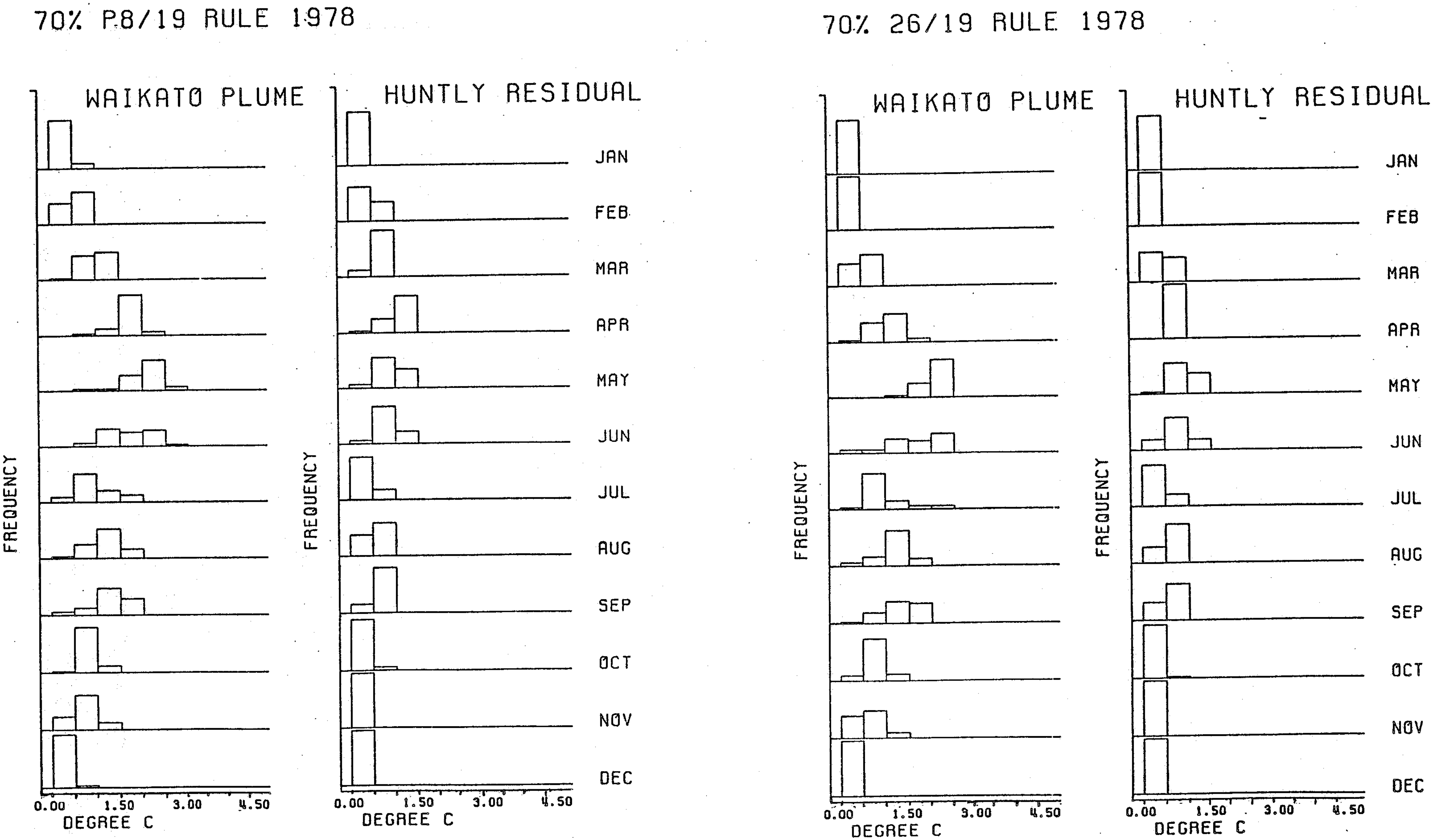


Figure 16a: Waikato plume excess temperatures

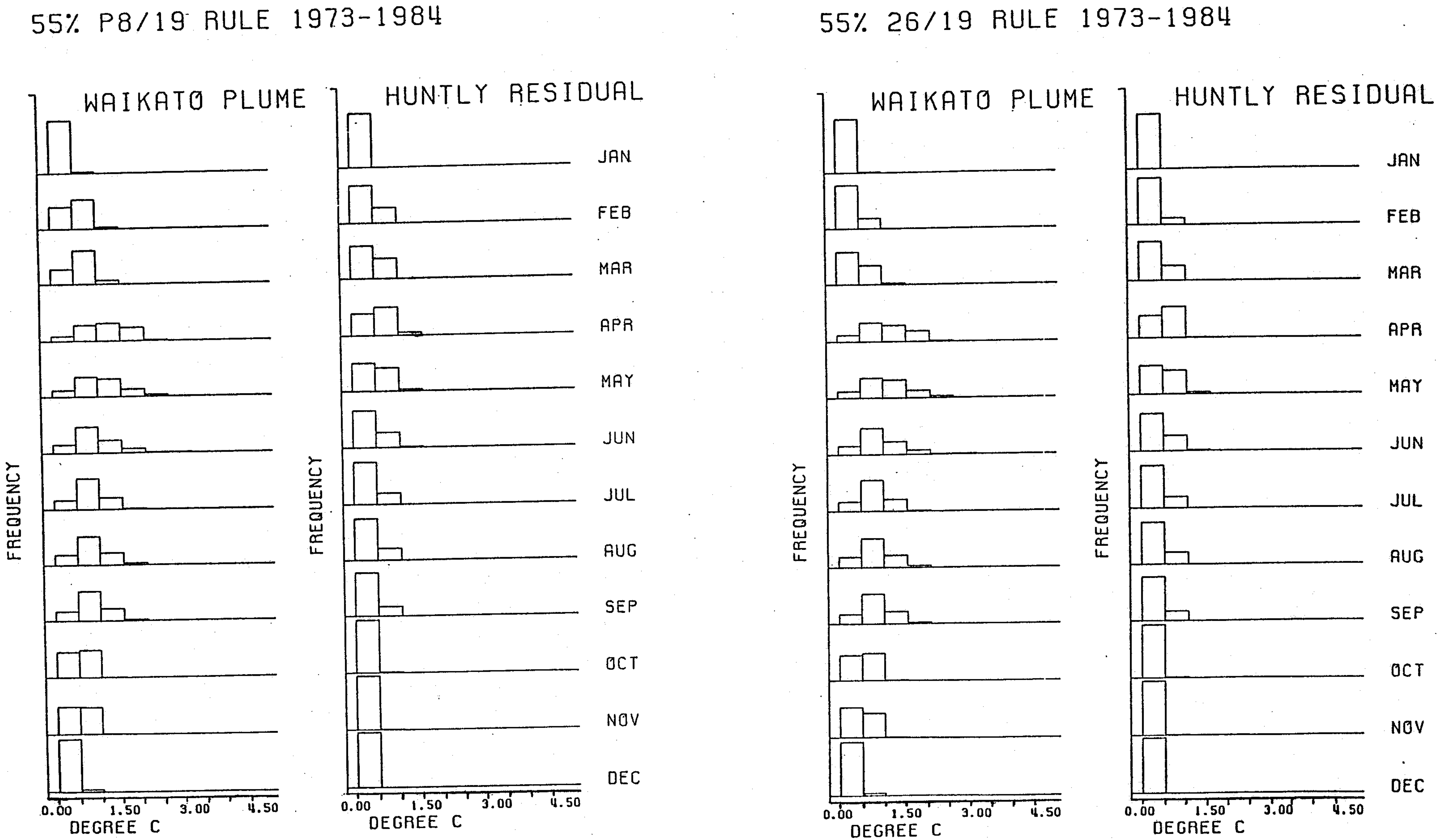
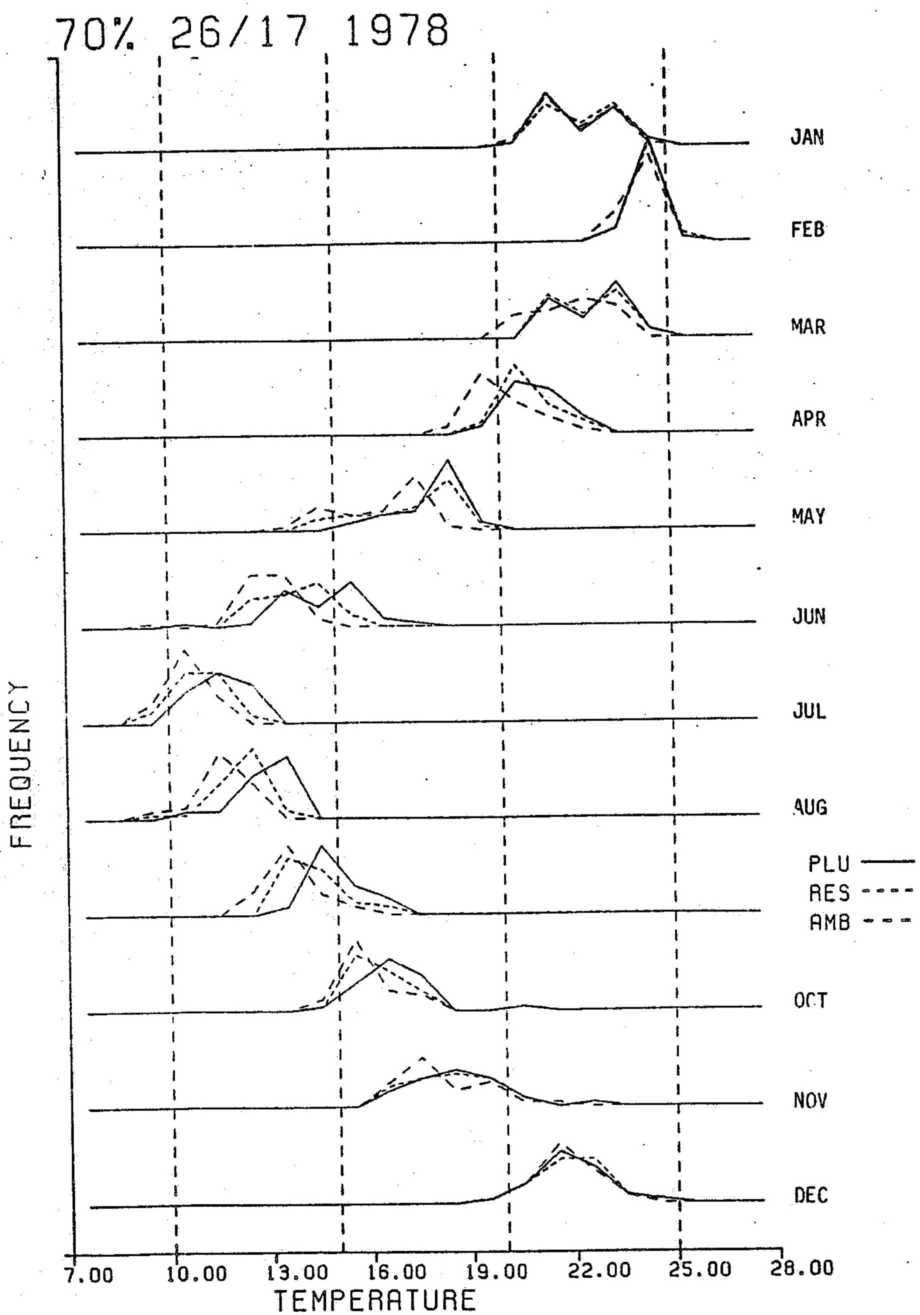


Figure 16b: Waikato plume excess temperatures



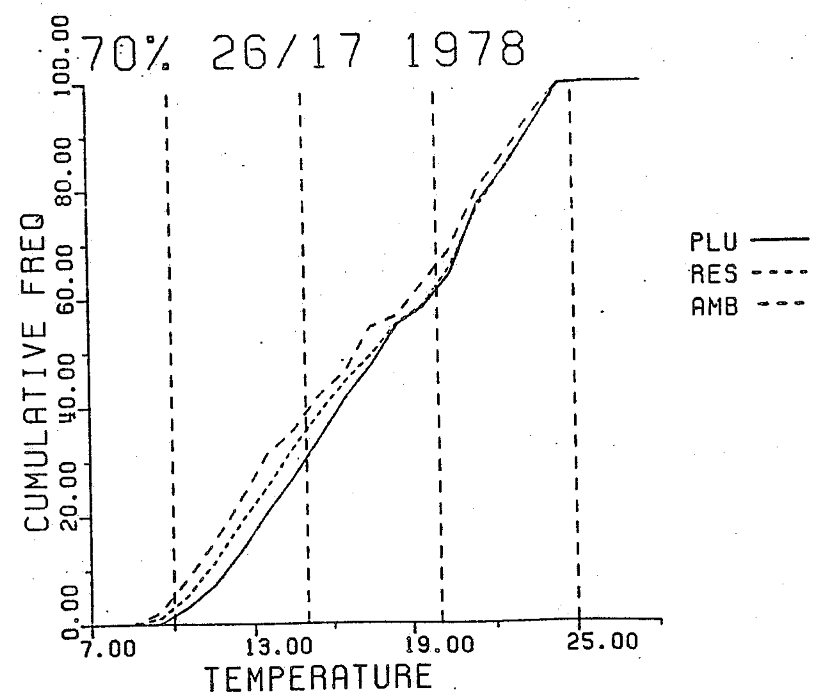
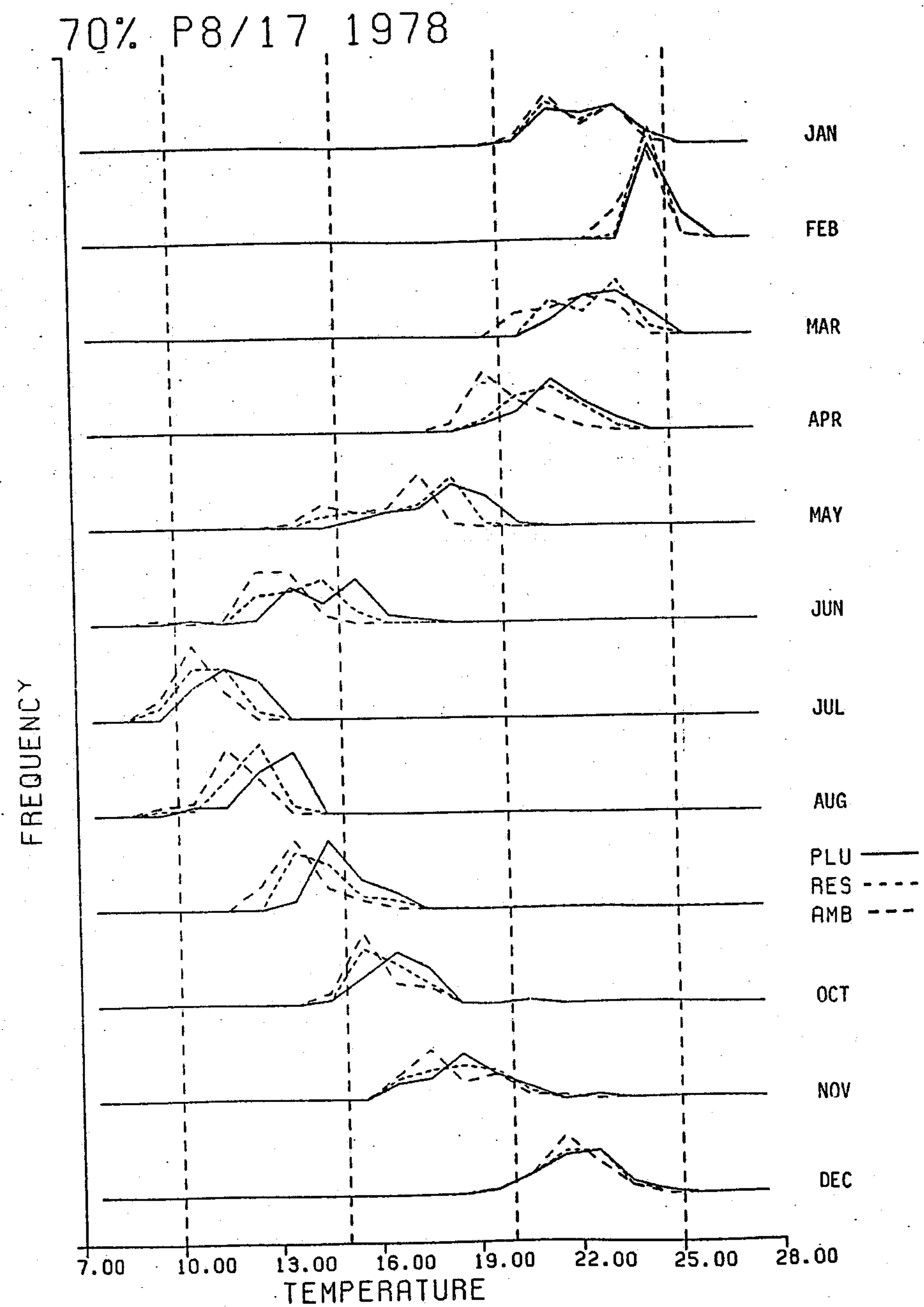


Figure 17a: Waikato plume temperatures



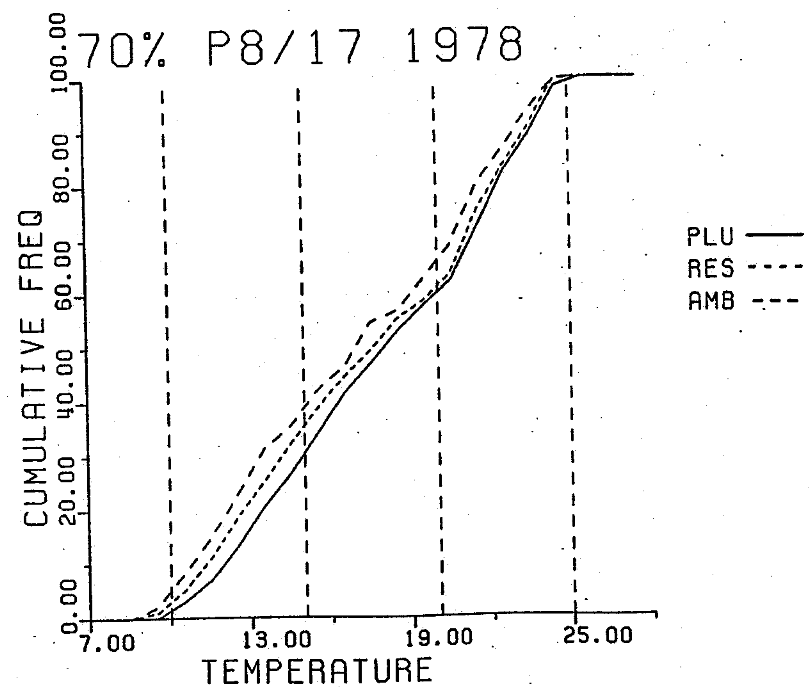


Figure 17b: Waikato plume temperatures

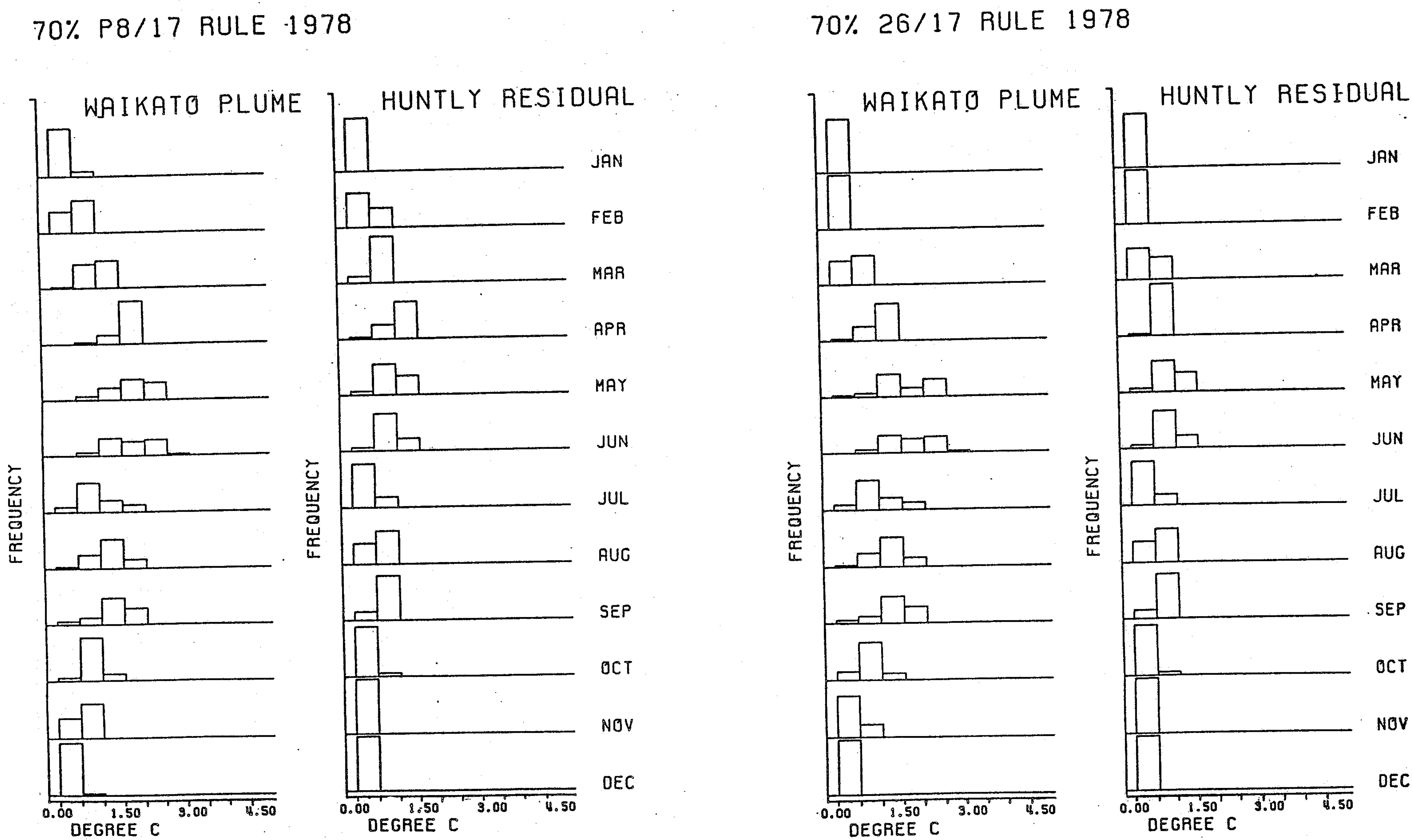
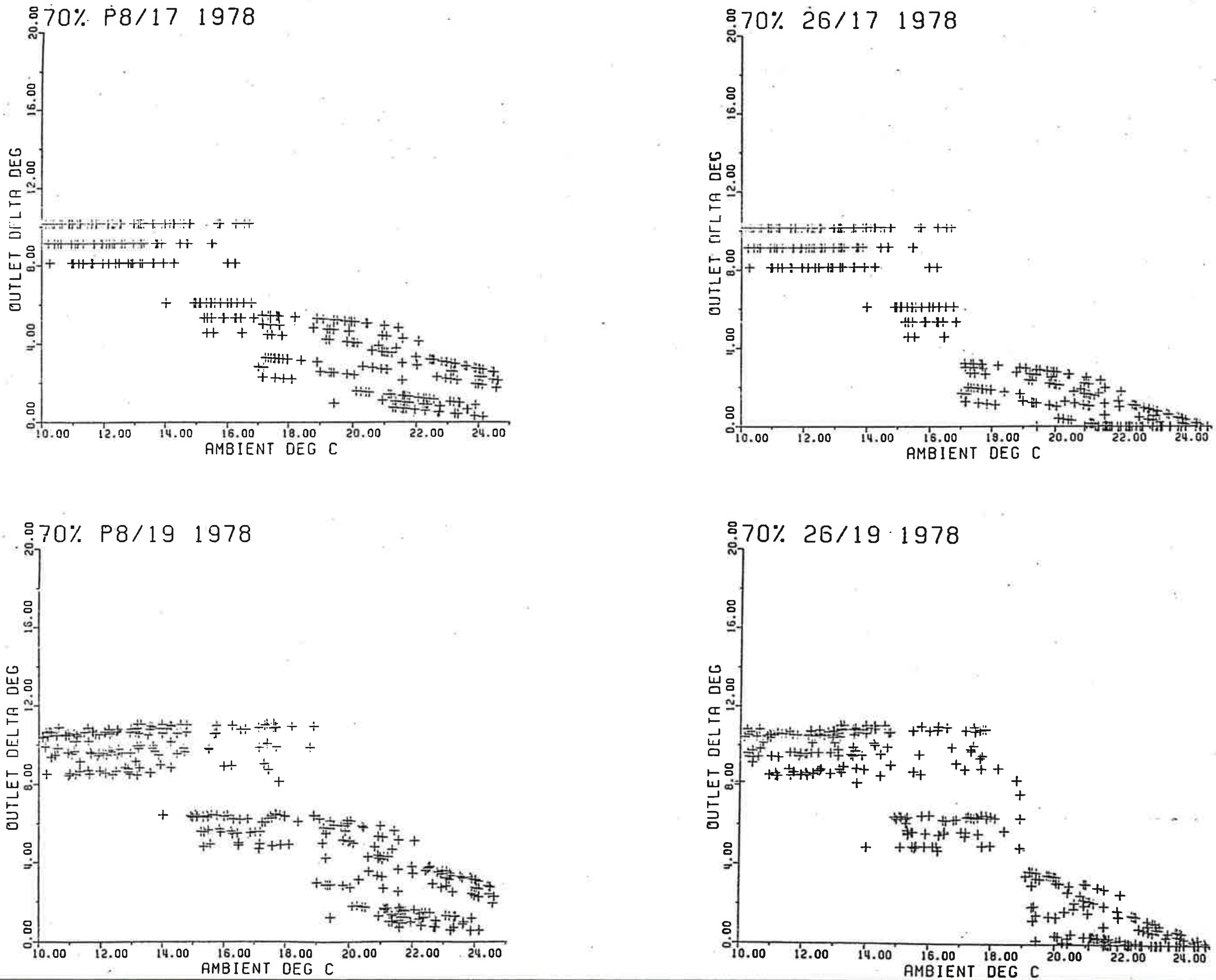
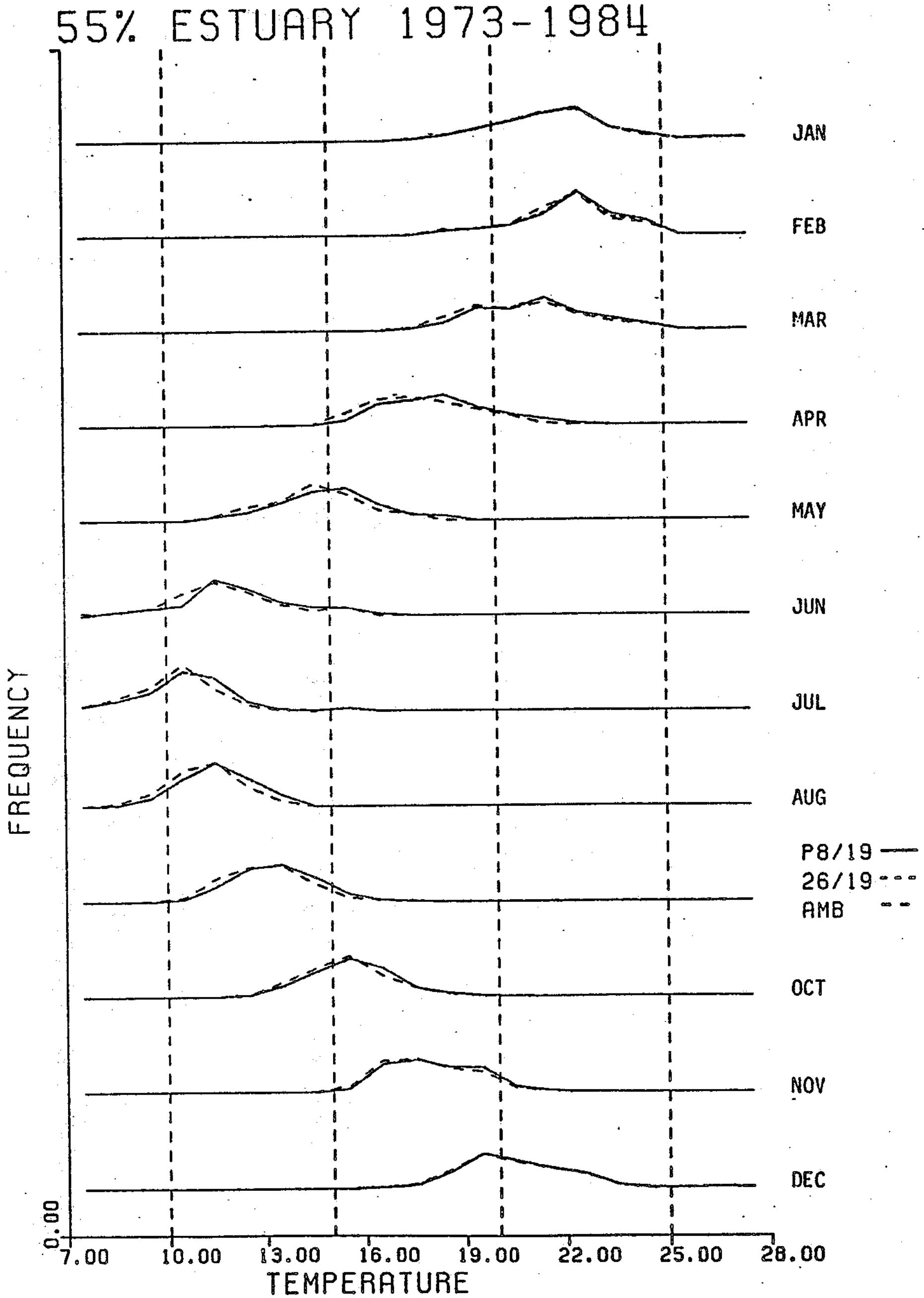


Figure 18: Waikato plume excess temperatures



Note: Cooling water flow = 15 m^3s^{-1}

Figure 19: Waikato outlet temperatures



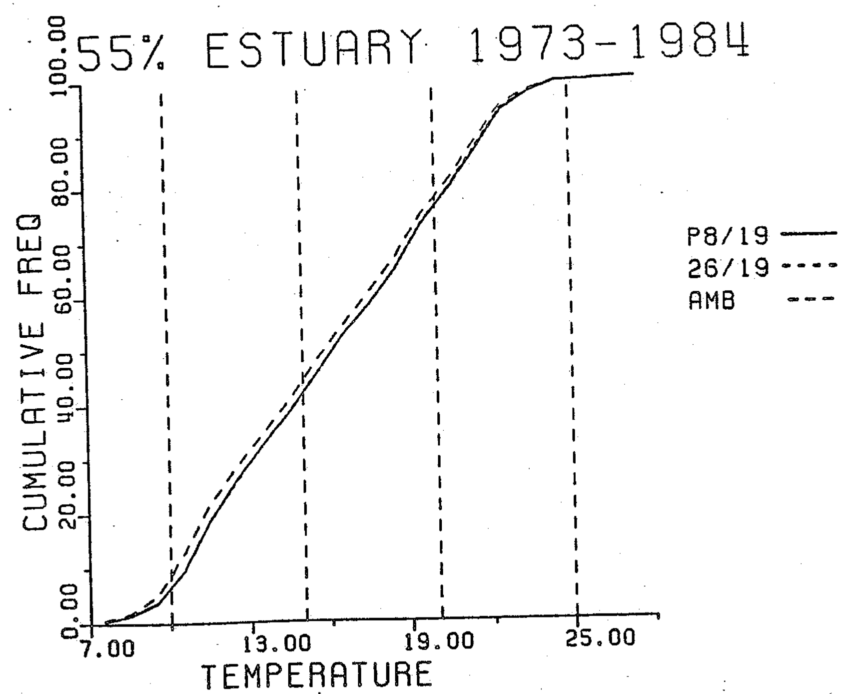
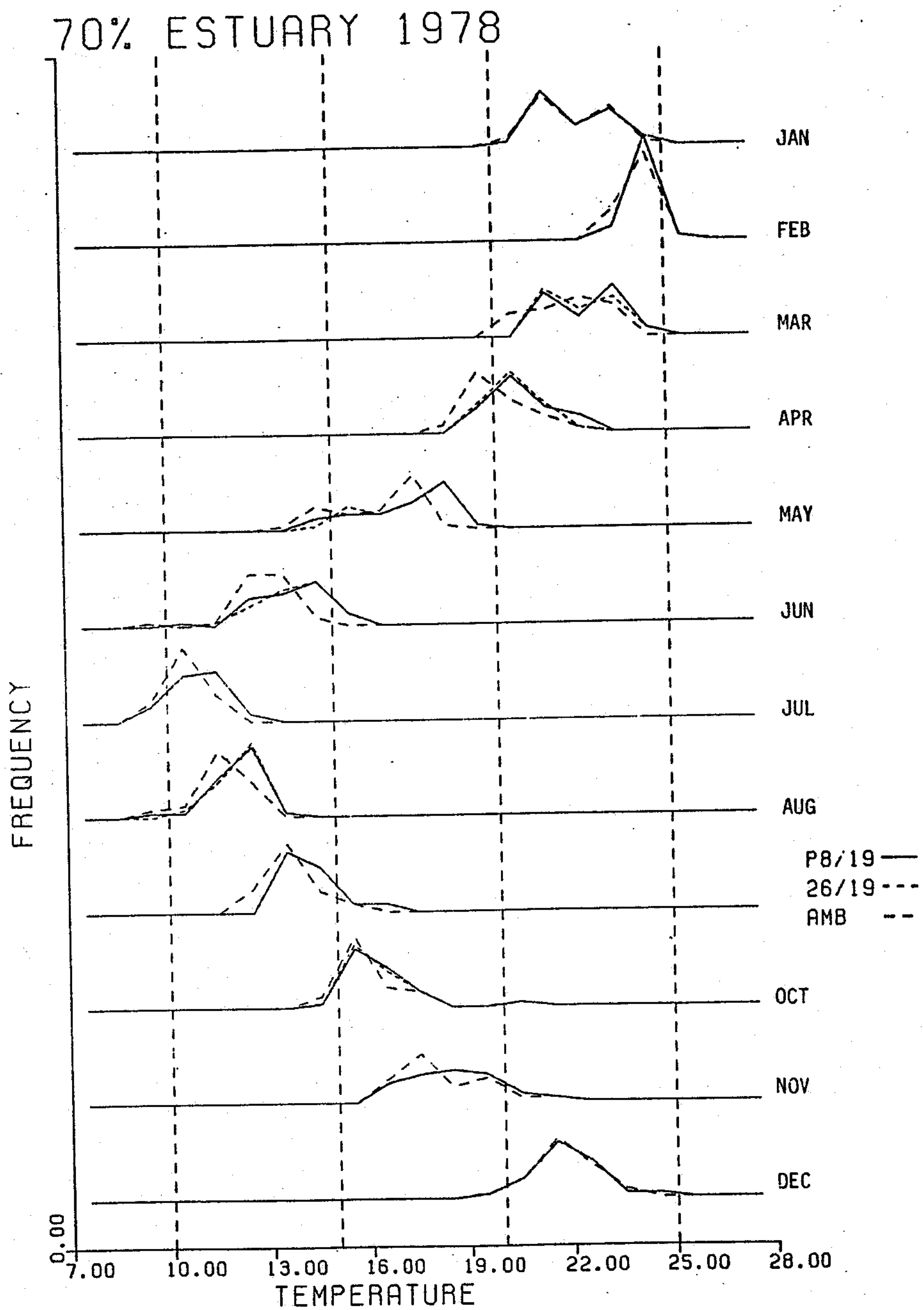


Figure 20a: Estuary temperatures



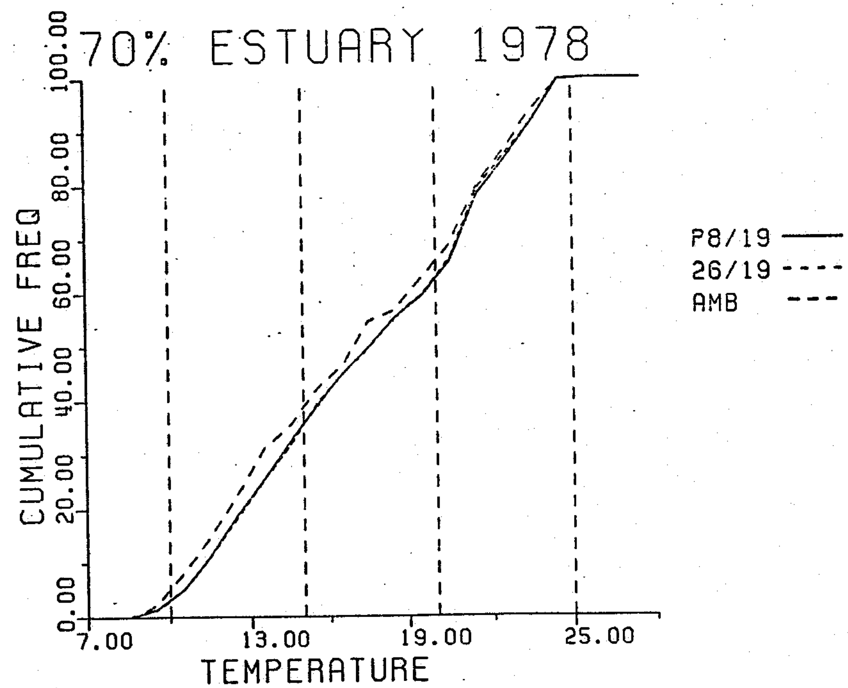
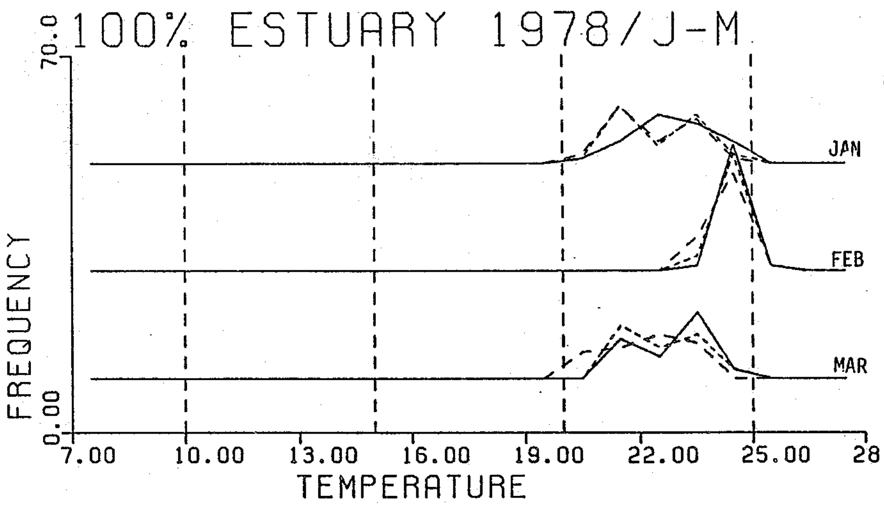


Figure 20b: Estuary temperatures



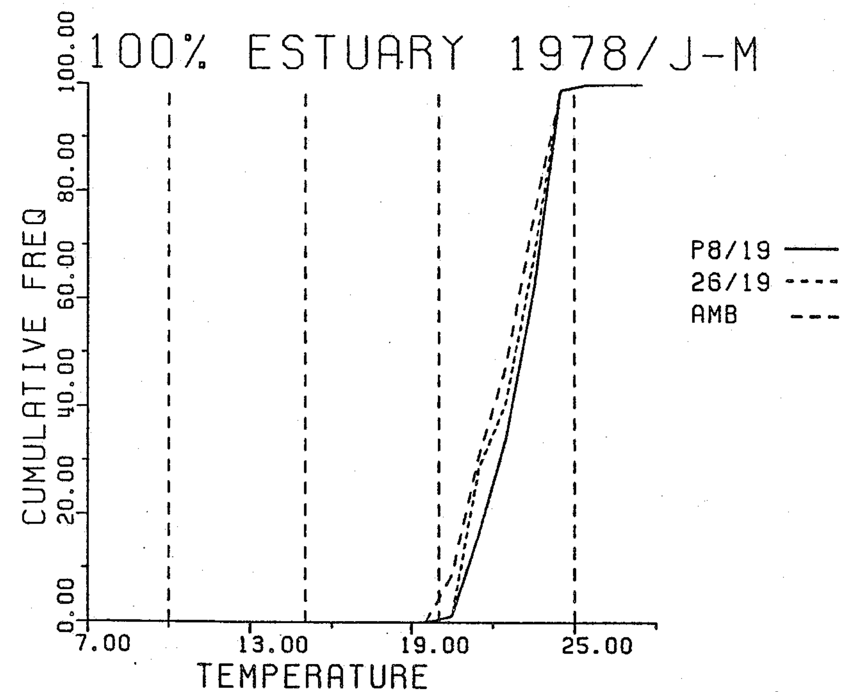
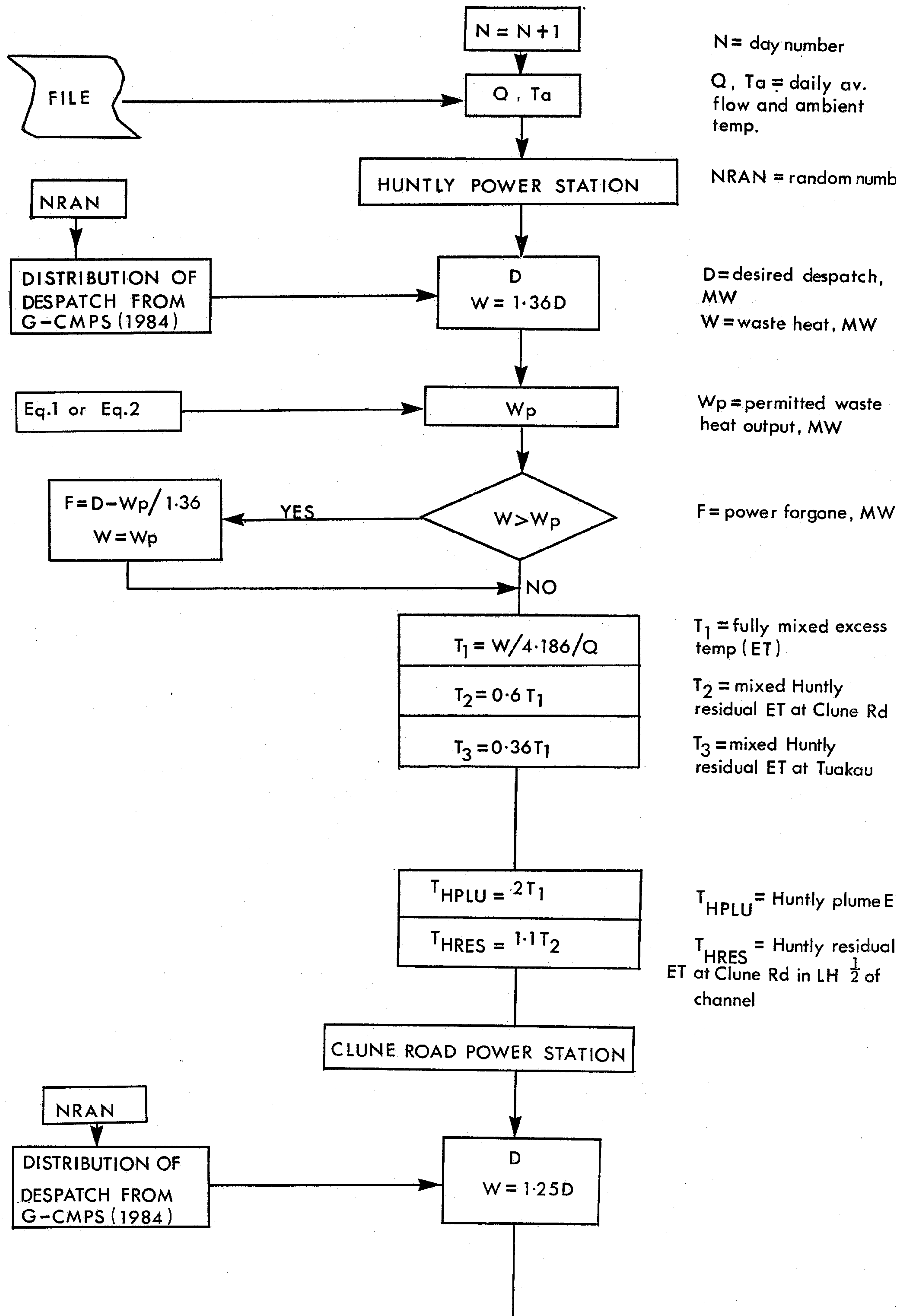
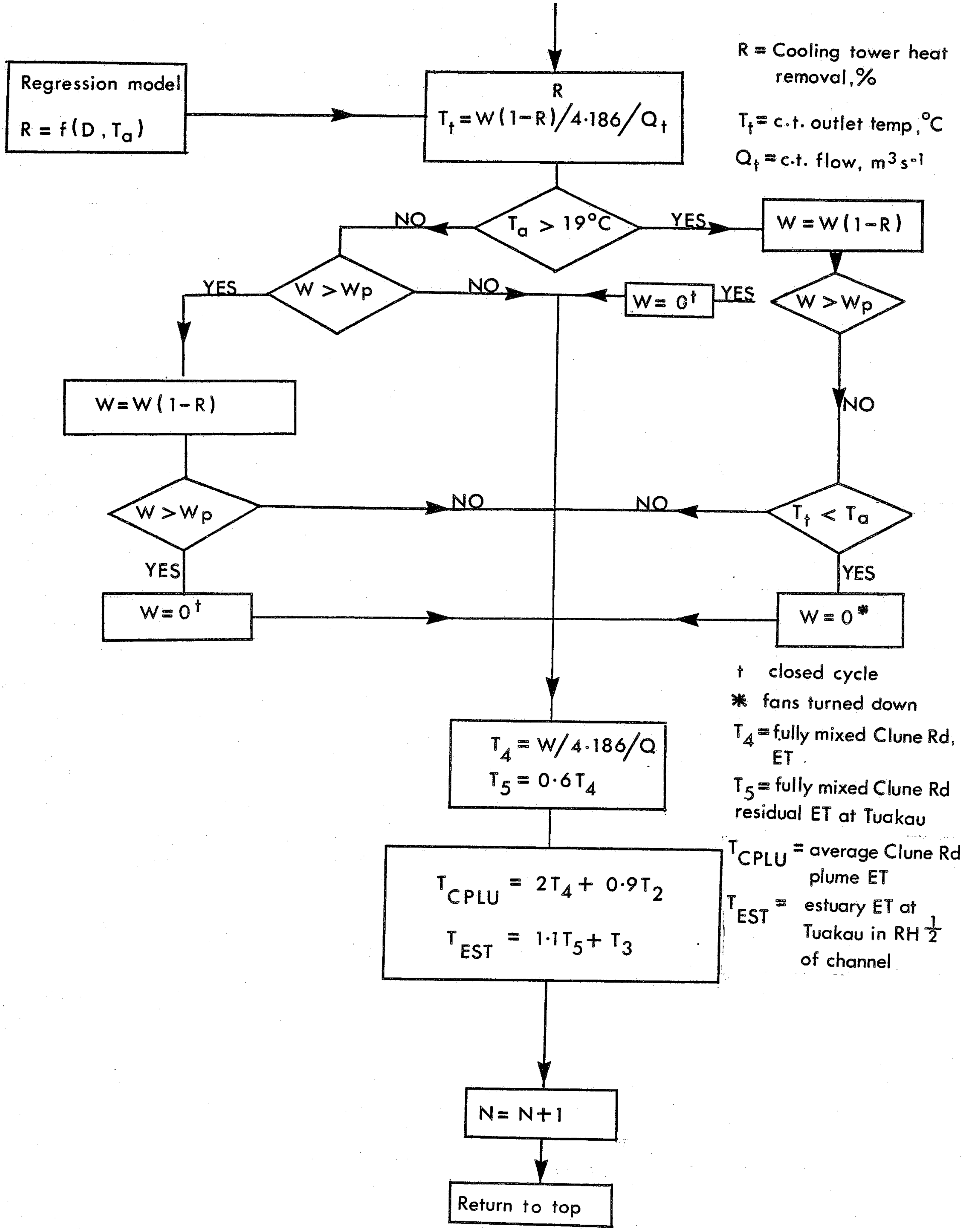


Figure 20c: Estuary temperatures

Appendix 1 Flow chart of simulation programme





Regression model
R = f(D, Ta)
R
Tt = W(1−R)/4·186/Qt
R = Cooling tower heat removal, %
Tt = c.t. outlet temp, °C
Qt = c.t. flow, m3 s-1
Ta > 19°C
NO
YES
W = W(1−R)
W > Wp
YES
NO
W = 0†
YES
W > Wp
NO
W = W(1−R)
W > Wp
NO
NO
Tt < Ta
YES
YES
W = 0†
W = 0*
† closed cycle
* fans turned down
T4 = W/4·186/Q
T5 = 0·6T4
T4 = fully mixed Clune Rd, ET
T5 = fully mixed Clune Rd residual ET at Tuakau
TCPLU = 2T4 + 0·9T2
TEST = 1·1T5 + T3
TCPLU = average Clune Rd plume ET
TEST = estuary ET at Tuakau in RH ½ of channel
N = N+1
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