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FORECASTS OF SCREEN TEMPERATURE USING THE 10-LEVEL MODEL

by

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ABSTRACT

A description is given of a method of deriving screen temperatures from 10-level model forecasts. Results from testing the model in both cloudy and cloudless situations are given. It is found that most of the major errors in the predicted temperatures are associated with inadequate rectangle forecasts.

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1. Introduction

Numerical weather prediction models often use the surface temperature to compute the fluxes of sensible and latent heat for use in boundary layer schemes. However little appears to be known about the quality of these temperatures. This note is concerned with a simple model which can be used in conjunction with the 10-level model to predict surface and screen temperatures. The model could form the basis of a scheme for parameterising the surface exchanges in a numerical forecast model.

The method adopted is based on the surface heat balance equation

$$S_N + R_N - H - LE - G = 0 \qquad (1.1)$$

with $R_N = R_D - R_u$

S_N - net shortwave radiation at the ground

R_N - net longwave radiation at the ground

R_D, R_u - downward and upward longwave radiation at the ground

H, LE - surface flux of sensible and latent heat with E the evaporation rate

G - ground heat flux.

The exact form of the ground heat flux term determines whether (1.1) is used as a diagnostic or prognostic equation for the surface temperature.

In the following sections we will describe the way in which each of the terms in (1.1) is formulated. Also we present a pragmatic approach to the specification of a 10 m temperature from that at 950 mb which is the only low level temperature available from the 10-level model. The way in which a screen temperature is derived will be described and the forecasting potential of these will be discussed.

Comparisons are made between the proposed method of deriving screen temperatures and that used by Wickham (1978) for the worded forecast.

2. The net shortwave radiation

Hunt (1976) found that the solar radiation scheme used in the 10-level model is quite adequate in both cloudy and cloudless conditions. Therefore it is with some confidence that we use this scheme, which for completeness is outlined below.

If α is the albedo of the earths surface (taken to be 0.25), F the transmission functions, Ψ the solar zenith angle and S the solar constant, then

$$S_N = (1 - \alpha) \, SF \sin \Psi \tag{2.1}$$

The effect of cloud on F is included by assuming that

$$F = F_c(\Psi) \, g \text{ (cloud distribution)} \tag{2.2}$$

where F_c is the transmission function for clear skies and g is a function which depends upon the cloud distribution. Lumb (1964) suggested that

$$F_c = 0.6 + 0.2 \sin \Psi \tag{2.3}$$

and his observations of the effect of cloud on the transmission function led Gadd and Keers (1970) to use

$$g = (1 - 0.4 \, C_L)(1 - 0.7 \, C_M)(1 - 0.4 \, C_H) \tag{2.4}$$

where C_L, C_M and C_H are the fractional cloud cover of low, medium and high cloud.

3. The net longwave radiation

In the 10-level model the net longwave radiation is given by a constant value which is modified by the amount of cloud. Hunt (1976) investigated this treatment of longwave radiation and found it inadequate. He suggested that a Brunt type expression should be used and this is the approach adopted here.

The upward longwave radiation from the ground is given by

$$R_u = \varepsilon_0 \sigma T_0^4 \tag{3.1}$$

where T_0 is the surface temperature, σ is Stefans constant and ε_0 is the emissivity of the ground which is taken to be 0.9. In order to calculate R_D we use a Brunt type formula; this was investigated by Monteith (1961) who showed that for clear skies over the British Isles

$$R_D = (a + b\sqrt{e}) \, \sigma T_S^4$$

Here T_S and e are the temperature and vapour pressure at screen level and a and b are constants which Monteith found to be 0.53 and 0.065 respectively. In place of T_S we use a 10 m temperature (denoted by T_1) so

$$R_D = \varepsilon_1 \sigma T_1^4 \tag{3.2}$$

where ε_1 is the effective emissivity given by

$$\varepsilon_1 = a + b\sqrt{e_1} = a + b\sqrt{1.61\,p_1 q_1}$$

Here q_1 and p_1 are the mixing ratio and pressure at 10 m. From (3.1) and (3.2) we have

$$R_N = \varepsilon_1 \sigma T_1^4 - \varepsilon_0 \sigma T_0^4 \tag{3.3}$$

The effect of cloud on R_N is taken into account in the same way as in the 10-level model; therefore R_N becomes

$$R_N = (\varepsilon_1 \sigma T_1^4 - \varepsilon_0 \sigma T_0^4)(1 - f(C_L, C_M, C_H)) \tag{3.4}$$

where $f(C_L, C_M, C_H) = 0.6\,C_L + 0.3\,C_M + 0.1\,C_H$

4. Fluxes of sensible and latent heat

The fluxes of sensible and latent heat are given by the usual bulk aerodynamic formulae

$$H = \rho C_p C_H V_1 (T_0 - T_1) \tag{4.1}$$

$$LE = \rho L C_W V_1 (q_0 - q_1) \tag{4.2}$$

where V_1 is the wind speed at 10 m and T_0, q_0, T_1 and q_1 are the temperature and humidity mixing ratio at the surface and 10 m. The drag coefficients C_H and C_W are derived from the Monin-Obukhov similarity theory of turbulence in the way described by Carpenter (1977), so

$$C_H = C_H(R_{ib}, Z_1/Z_0)$$

$$C_W = C_W(R_{ib}, Z_1/Z_0)$$

where R_{ib} is the bulk Richardson number. If we ignore the effect of humidity on R_{ib} we have

$$R_{ib} = \frac{g Z_1}{T_1 V_1^2}(T_1 - T_0) \tag{4.3}$$

where Z_1 = 10 m and the roughness length Z_0 is assumed to be 10 cm.

In order to compute LE from (4.2) it is necessary to know q_0. In the 10-level model the surface relative humidity is fixed according to climatic type. However in reality the surface relative humidity will depend upon soil type, vegetation, rainfall history and time of day; therefore we follow Carpenter (1977) in reformulating the evaporation rate in terms of a surface resistance Γ , so that

$$E = \frac{\rho\left(q_s(T_0) - q_0\right)}{\Gamma} \tag{4.4}$$

Eliminating q_0 between (4.4) and (4.2) gives

$$E = \frac{\rho C_w V_1}{1 + \Gamma C_w V_1}\left(q_s(T_0) - q_1\right) \tag{4.5}$$

Hence, if Γ is known, E can be calculated. The value of Γ depends upon the ground conditions (soil, moisture, vegetation etc) and it also has a marked diurnal variation which is taken into account in the way suggested by Carpenter. If Γ_s is a typical daytime value for Γ , then

$\Gamma = 0$ if $E < 0$

$\Gamma = \Gamma_s$ if $E > 0$ during the day

$\Gamma = 3\Gamma_s$ if $E > 0$ during the night

We use $\Gamma_s = 50\ m^{-1}$ which is between typical values for grass ($30\ sm^{-1}$) and pine forests ($100\ sm^{-1}$).

5. The ground heat flux

In the 10-level model the ground heat flux is taken to be a given proportion of the net radiation; the proportion depending upon whether it is day or night. The advantage of this approach is that (1.1) becomes a diagnostic equation for T_0 . However, rather than use this empirical approach, it is more satisfactory to derive the ground heat flux from the heat diffusion equation. The surface heat balance equation is then a predictive equation for T_0 .

Carpenter (1977) has developed a two level model based on the heat diffusion equation in an ideal medium which has prognostic equations for both T_0 and a deep soil temperature. For our needs it is probably sufficient to keep the deep soil temperature constant (at T_g say). Therefore following Blackadar (1976) we have

$$G = \frac{\rho_s C_s d}{C_1}\left\{\frac{\partial T_0}{\partial t} + \frac{C_2\left(T_0 - T_g\right)}{\tau}\right\} \tag{5.1}$$

where ρ_s and C_s are the soil density and soil specific heat, and $d = \sqrt{\tau a}$ with a the thermal diffusivity. Since we are mainly concerned with the diurnal temperature wave τ has a value of 1 day. The soil parameters depend upon the type of soil and its water content, but initially we have used constant values of

$$\rho_s C_s = 1.55 \times 10^6 \ J\, m^{-3}\, kg^{-1}$$
$$a = 0.4 \times 10^{-6} \ m^2 s^{-1}$$

Blackadar recommended the use of (5.1) and found that the best results were found by using $C_1 = 3.72$ and $C_2 = 7.4$. If we set $C_2 = 0$ and let $C_1 = \sqrt{\pi}$ then (5.1) reduces to the expression used by Rowntree (1975) in the 11-level model. Deardorff(1977) has investigated the behaviour of many different schemes for G. He found that the inclusion of a deep soil temperature had a beneficial effect and that the results were better than for the formulations where there is a diagnostic equation for T_0. Therefore (5.1) has been used in our model and we have followed Blackadars suggestion that T_g is taken to be the mean air temperature over the previous 24 hours. This suggestion was checked using 30 cm soil temperatures from Cardington and found to be surprisingly accurate.

Inserting (5.1) in (1.1) yields a differential equation for T_0 which was solved with the Crank-Nicholson method. Hence

$$\frac{\partial T_0}{\partial t} \text{ becomes } \frac{T_0^{(n+1)} - T_0^{(n)}}{\Delta t}$$

where the indices refer to the time level and Δt is the time step. Wherever T_0 appears in the forcing function

$$T_0 \text{ becomes } \frac{T_0^{(n)} + T_0^{(n+1)}}{2}$$

The advantage of using this method is that it is unconditionally stable.

6. The calculation of the 10 m values of T, q and V

In order to calculate the fluxes of heat and moisture we require values of temperature, mixing ratio and wind speed at a level which is always in the surface layer. We choose a level which is 10 m above the ground. Unfortunately the only low level information about T and q

from the large scale model is at 950 mb (denoted by T_{950} and q_{950}), and even T_{950} is actually derived from a 1000-900 mb thickness. A highly pragmatic approach has been adopted in deriving the 10 m values and this is espeically true of the temperature.

During the day we assume that the 10 m temperature is related to the temperature both at the surface and at 950 mb. T_1 is derived from a linear interpolation between T_0 and T_{950}, so

$$T_1^{(n+1)} = \left(T_{950}^{(n+1)} - T_0^{(n)}\right)\frac{10}{h_{950}} + T_0^{(n)} = T_1[\mathrm{day}] \qquad (6.1)$$

where the suffix denotes the time level and where necessary we have used the surface temperature from the previous time step ($T_0^{(n)}$); h_{950} is the height of the 950 mb level above the ground. This procedure should be an improvement upon that used in the 10-level model because it allows T_1 to change as the surface temperature changes.

During the night we assume that the 10 m temperature will not be affected by what happens at the surface, and so T_1 is only altered by the advective changes which take place at 950 mb. Therefore we have

$$T_1^{(n+1)} = T_1^{(n)} + \left(T_{950}^{(n+1)} - T_{950}^{(n)}\right) = T_1[\mathrm{night}] \qquad (6.2)$$

After dusk we allow a 3 hour adjustment period between the day and night regimes. If τ is the time relative to dusk in hours then we use

$$T_1^{(n+1)} = \frac{(3-\tau)\,T_1[\mathrm{day}] + \tau\, T_1[\mathrm{night}]}{3} \qquad (6.3)$$

This procedure allows a smooth transition between the two regimes. At dawn we allow the night time regime to continue until

$$T_1[\mathrm{day}] > T_1[\mathrm{night}]$$

and then the day time procedure takes over.

In order to derive the mixing ratio at 10 m we follow the procedure used in the 10-level model and assume that the relative humidity at 10 m is the same as that at 950 mb.

Parker and Jonas (1976) investigated ways of estimating the surface wind (ie 10 m wind) from the 10-level model forecast data. They only considered weather ship data and so their recommended method is not directly applicable over land. However they did find that V_1 was closely related to the 1000 mb wind from the rectangle (V_{1000}) and that V_{1000} tended to overestimate V_1. Therefore we have used

$$V_1 = \frac{3}{4} V_{1000}$$

The height of the 950 mb level above the ground (h_{950}) is computed from the 1000 mb height (h_{1000}), the 1000-900 mb thickness (h'_{950}) and the height of the ground above msl (h_0)

$$h_{950} = 0.5\, h'_{950} + h_{1000} - h_0$$

The pressure at the ground is computed from

$$p_0 = 1000 \exp\left[g(h_{1000} - h_0)/RT_1\right]$$

In these calculations we have used the height of the 950 mb level above the ground so that the calculated surface temperatures are representative of those at the ground rather than at some fictituous 1000 mb or msl surface.

7. The calculation of C_L, C_M and C_H

Since cloud is not carried explicity as a model variable it is necessary to infer the cloud amount from the forecast humidity and temperature fields. In the 10-level model empirical relationships based on the work of Ricketts (1973) are used to derive the cloud cover from the relative humidities of the moistest 100 mb layer in the 1000-800 mb, 800-500 mb and 500-300 mb groups (see Gadd and Keers (1970) for further details). However there have been several indications that these linear relationships tend to overestimate the amount of cloud, and so following Walker (1978) we use a quadratic relationship of the form

$$C(p) = \left\{ \frac{H - H_c(p)}{1 - H_c(p)} \right\}^2 \quad H \geqslant H_c \qquad (7.1)$$

and $C(p) = 0$ when $H < H_c$ with

$$H_c(p) = p(mb) \times 5 \times 10^{-4} + 0.115 \qquad (7.2)$$

Here H the relative humidity and H_c the critical relative humidity below which there is no cloud. The expression for H_c is such that when $H = H_c$ and $H = 1$ we get the same values of C as when the Gadd and Keers relationships are used. The value of C_L is then defined as the largest value of C in the 1000-800 mb group of layers; a similar procedure is adopted for C_M and C_H.

The amount of stratocumulus has a marked effect on temperature variations and so it is necessary to include an estimate of how much of this type of cloud is present. Walker (1978) used observations taken during GATE to relate the stratocumulus cover to the lapse rate of potential temperature in the most stable layer (Γ say). Here we follow this approach and use

$$C_L = -16.67\,\Gamma - 1.167 \qquad (7.3)$$

provided that (i) $\Gamma = (\theta(950) - \theta(850))/100 \geq -0.07$

(ii) $H(950) \geq 59\%$

(iii) $(H(950) + H(850))/2 \geq 59\%$

The coefficients in (7.3) and condition (i) is taken directly from Walker, and the lower limit on the relative humidity in conditions (ii) and (iii) is $H_c(950)$ given by (7.2). If both (7.1) and (7.3) indicate low cloud then the larger of the two estimates is used.

8. The calculation of the screen temperature

In section 4 we outlined how the fluxes of heat and moisture are computed with the aid of the Monin-Obukhov similarity theory. The same theory is used to estimate the screen temperature T_s from the surface temperature T_0. According to the theory

$$\frac{\partial T}{\partial z} = \frac{T_*}{kz}\,\phi_H(\zeta) \qquad \zeta = \frac{z}{L} \qquad (8.1)$$

where T_* is a scaling temperature, K the Von Karman constant, L the Monin-Obukhov length and ϕ_H the similarity function for heat.

In order to proceed it is necessary to calculate T_*. By definition T_* is given by

$$T_* = \frac{-H}{\rho C_p u_*} \qquad (8.2)$$

where H is the heat flux given by (4.1) and u_* is the friction velocity computed from

$$u_* = \sqrt{C_D}\, V_1 \qquad (8.3)$$

where $C_D = C_D(R_{ib}, Z_1/Z_0)$ is the drag coefficient for momentum which is calculated in a similar manner to those for heat and moisture.

Using (8.3) in (8.2) yields

$$T_* = \frac{-H}{\rho C_p \sqrt{C_D}\, V_1} \qquad (8.4)$$

We also use (8.3) and (8.4) to give L

$$L = \frac{T_1}{g}\frac{u_*^2}{T_*} = -\frac{T_1}{g}\frac{(\sqrt{C_D}\, V_1)^3}{(H/\rho C_p)}$$

Having found T_* and L, (8.1) is integrated between Z_0 and screen height Z_s

$$\int_{T_0}^{T_s} dT = \frac{T_*}{K}\int_{Z_0}^{Z_s} \phi_H(\zeta)\,\frac{dz}{z}$$

Although this can be integrated exactly it is probably sufficient to replace $\phi(\zeta)$ by a mean value $\phi(\bar{\zeta})$ so

$$T_s = T_0 + \frac{T_*}{K}\phi_H(\bar{\zeta})\ln\left(\frac{Z_s}{Z_0}\right) \qquad (8.5)$$

with

$$\bar{\zeta} = \frac{Z_s + Z_0}{2L}$$

We use the same similarity functions as were used by Carpenter to derive the drag coefficients (Webb (1970) in stable conditions and Dyer and Hicks (1970) in unstable conditions).

Therefore we have

$$\phi_H = \begin{cases} 1 + 5\zeta & 0 < \zeta < 1 \\ 6 & \zeta > 1 \end{cases}$$

$$\phi_H = (1 - 15\zeta)^{-0.55} \qquad \zeta < 0$$

9. The data

The model uses rectangle forecasts to provide 6 hourly values of

(i) partial thickness

(ii) mixing ratio

(iii) 1000 mb wind and height

Since a time step of 1 hour is used in the temperature model these fields are interpolated linearly to give hourly values. Tests were carried out using hourly values direct from the forecast and also a 12 minute time step, but neither of these had any significant effect on the temperature forecasts.

Temperatures are derived from the partial thicknesses and these are used in conjunction with the mixing ratios to give relative humidities which are used in the cloud calculations. The 950 mb temperature and mixingratio and the 1000 mb wind are used in the calculations of the fluxes of heat and moisture.

The temperature model always uses data from midnight forecasts because it is desirable to start the model when the surface temperature is not changing rapidly. The initial surface and 10 m temperatures are taken to be the same as the observed midnight screen temperature in the vicinity of the gridpoint considered.

In the following sections we compare forecast temperatures using the model with those observed at Cardington. Also comparisons are made with the simple scheme devised by Wickham (1978) for use with the worded forecast. Effectively this diagnostic scheme imposes a diurnal variation of temperature whose amplitude is derived from the forecast fields.

Results from three sets of experiments will be described. The first two experiments investigated the usefulness of the model in basically cloudy and cloudless conditions. The third experiment consisted of investigating cases where a front crossed the country.

It is worth noting that the comparisons described here are not really a fair test of the model because the model temperatures are representative of those in a 100 km square whereas the actual temperatures refer to a single location.

10. The first experiment

The behaviour of the model in cloudy conditions was tested by running a series of experiments using rectangle forecasts from a period when the weather over the UK was slow moving and predominately cloudy. Results of four 36 hour integrations using data from midnight on 21-24 March 1977 will be presented here. The charts in figures 1 to 4 illustrate the weather during this period. In the first part of the period there was high pressure to the north and low pressure to the south of the UK which maintained a cloudy east or northeast wind over the country. There was almost complete cloud cover all the time with virtually no diurnal variation in temperature. During the last two days the anticyclone moved east as an Atlantic low moved towards the UK. On the 24th a shallow low developed in the North Sea leaving most of the country in a col. During most of the day South East England was covered in a layer of St or Sc but a limited diurnal variation in temperature still developed.

The forecast temperatures from the model and the Wickham scheme are shown in Figures 1 to 4 along with the observed temperatures from Cardington; Table 1 has various statistics derived from these forecasts.

The results from the first integration are shown in Figure 1. The model reproduces the almost constant temperatures observed during the period. It follows that the parameters given in Table 1 (maximum, minimum, maximum-minimum and mean temperatures) correspond closely to those observed. The root mean square error between the model and observed temperatures (denoted by rmse) is a measure of how well the forecast temperature follows the observed variations in temperature throughout the forecast period. In order to compare the rmse in different cases is is convenient to introduce a normalised rmse given by the ratio of the rmse to the difference between the observed first maximum and following minimum; in the first case the normalised rmse is 37%.

The second integration (Figure 2) is also reasonably good although the model predicts a higher daytime rise in temperature than that observed and does not predict the odd behaviour of the observed temperature between T + 21 and T + 25. Examination of the observations near midnight shows that there was a marked reduction in the surface wind which resulted in a sudden drop in temperature. At about midnight wind started to increase and the temperature rose by about 2°C so at T + 25 the temperature was similar to that at T + 21. Since the large scale model would know nothing about this short period fluctuation it is not surprising that the temperature model does not reproduce the observed behaviour of the temperature.

The third integration (Figure 3) predicts temperatures which are consistently too low, although over most of the forecast the variation in temperatures reproduced quite well. For example, the mean temperature is underestimated by 2.4°C whereas the predicted max-min of 4.4°C is almost exactly that observed. The main reason for this behaviour is that the initial surface temperature used in the model is not representative of the general level of temperature at that time; as discussed earlier there was a 2°C rise in temperature at the start of the forecast period probably due to mesoscale effects. When the model started off with the observed temperature at T + 1 (which is a representative temperature) there is an improvement over most of the forecast and the normalised rmse is reduced from 69% to 60%.

The results from the fourth integration (Figure 4) show that the temperature model overestimated the maximum temperature by 5.6°C; this was due to an underestimate of the cloud amount. The minimum temperature was also underestimated by the model but the max-min was similar to that observed. Once again the model predicts the general variation in temperature quite well.

Now consider the performance of the Wickham scheme. Results from the first two cases illustrate how this scheme imposes a marked diurnal variation in temperature even when there is virtually none (Figures 1 and 2). Also the poor quality of temperatures during the early part of the forecast illustrates the inadequacy of deriving screen temperatures from only the 950 mb temperature (the observed screen temperature at the start of the forecast is not used in Wickhams scheme). In both these cases the rmse is much larger than that from the temperature model.

For the third and fourth cases (Figures 3 and 4) the rmse's are comparable to those from the temperature model. However examination of the details of the forecasts shows that there are some serious deficiencies in the temperatures from the Wickham scheme and that its superiority over the temperature model (in terms of the rmse) may be rather fortuitous. In the third case the Wickham scheme forecasts a daytime rise in temperature of 10.1 $^{\circ}$C compared with an observed value of 4.3°C and a predicted rise of 3.9°C from the temperature model. Thereafter the Wickham scheme and temperature model predict similar variations in temperature. However it must be remembered that overall the results from the temperature model would be better than those from Wickhams scheme if a more representative initial temperature is used. In the fourth case both schemes overestimate the diurnal variation in temperature. However it is likely that during the last part of the forecast the similarity of the Wickham temperatures to those observed (and its superiority over the temperature model) is due to chance; during the first 24 hours of the forecast the Wickham scheme underestimates the initial night temperature by about 3°C, overestimates the daytime rise by about 7°C and overestimates the following fall in temperature by about 3°C. All these errors tend to cancel to give a reasonable night temperature on the 25th.

The results presented here show that in cloudy conditions the proposed model appears to perform reasonably well and is capable of predicting the general variation in temperature. However in the fourth integration the effect of cloud was not handled as well as in the previous cases. It is not clear if this is due to

(i) a poor forecast of the humidities

(ii) inadequacies in the way in which cloud amounts are derived from humidity fields.

(iii) the way in which the effect of cloud on radiation is parameterised.

The results from the third case also show the importance of using a representative temperature at the start of the forecast.

A comparison of the temperature model with the Wickham scheme has shown that in two of the cases the temperature model was definitely superior. This also applies to the third case if an improved initial temperature is used. There is doubt about the significance of the apparent superiority of the Wickham scheme in the fourth case. Overall the average normalised rmse for the temperature model is almost half that for the Wickham scheme.

11. The second experiment

A second set of integrations were performed in order to examine the behaviour of the model under less cloudy conditions where a reasonable diurnal variation might be expected. Here we consider a set of 6 forecasts based on midnight data from 24th to 29th May 1977 (see Figures 5 to 10).

At the start of the period the weather was under the influence of an anticyclone to the north of Scotland and a low pressure region over Spain. The easterly windbrought North Sea stratus and stratocumulus into Southern England, but this tended to dissipate during the day. The Spanish low moved northwards and by the 26th this had brought cloud into some parts of Southern England, especially the Southwest. The low then filled and this, with the migration of the anticyclone southwards into the North Sea, resulted in a reduction in the amount of cloud over most of Southern England; South East England was almost cloudless during the 27th and 28th. During the 29th a weak cold front moved southwards across the country bringing further cloud into Southern England. This was followed by a northeasterly airstream bearing Sc and so Southern England was covered in cloud for most of the 29th and 30th.

In the first integration of this series (Figure 5) the temperature model predicted the maximum and minimum temperatures quite accurately, as well as the general behaviour of the temperature. However there is still a relatively large rmse of 2°C because of the small timing errors during the periods of maximum change and because of the poor quality of the forecast during the last 6 hours. This illustrates how difficult it is to get a small rmse when there are rapid changes in temperature.

The second integration (Figure 6) again illustrates the sensitivity of the temperature model to the predicted cloud. During the 25th rectangle forecast brought rain into South East England and the associated cloud restricted the predicted daytime rise in temperature; in reality the low to the south of the country had little effect on the cloud in the vicinity of Cardington. The predicted cloud during the night of the 26th was similar to that observed due to the return of the stratocumulus and so the predicted max-min is quite accurate although the maximum was 5.9°C too low.

The next three integrations (Figures 7, 8 and 9) predicted the general behaviour of the temperature quite well although there was a tendency for both the maxima and minima to be underestimated.

The large errors in the last case (Figure 10) were due to the inability of the rectangle forecast to handle the weak cold front that crossed the country. At the grid point from which data was extracted the estimated cloud cover was only about 10% whereas large amounts of cloud were observed. Therefore the predicted temperatures were similar to these for the previous day but the observed temperatures had a restricted diurnal variation with a maxinum temperature of 13.7°C (23.7°C predicted) and a minimum of 8.1°C

(2.6°C predicted).

The Wickham scheme did not perform particularly well in any of the integrations and in all cases the rmse was greater than that from the temperature model; the average normalised rmse for the temperature model was 40% compared with 60% for the Wickham scheme.

These results indicate that the temperature model is capable of providing useful information about temperature variations in situations with small amounts of cloud. The errors in the second and sixth forecasts could be traced to deficiencies in the information passed to the temperature model from the rectangle forecast.

12. The third experiment

Three further integrations were carried out for cases in which the rectangle correctly forecast the movement of a front across the country.

In the first case (Figure 11) a weak cold front moved southwards across the country and passed Cardington at about midday on the 4th. The front was associated with an enhanced band of cloud which restricted the daytime rise in temperature. Behind the front there was a brief reduction in cloud before a wave on the front brought further rain and cloud into Southern England.

The temperatures at Cardington were forecast quite well by the model. It is worth mentioning that this is the first case discussed so far in which the inclusion of a stratocumulus estimate had a marked effect on the forecast; its omission increased maximum temperature by about 9°C.

In the second case (Figure 12) Southern England was initially covered in Sc but later a cold front moved quickly southwards across the country bringingthicker cloud. After the passage of the front there was a break in the cloud but convective cloud soon formed in the northwesterly airstream.

The temperature curves show that during the first few hours there were marked variations in the observed temperature and this again raises the problem of the representativeness of the initial temperature; nearby observations suggest that an initial temperature of $7^{\circ}C$ would have been more suitable and this would have produced an improvement in the forecast up until T + 15. At T + 16 the model forecasts a disappearance of the Sc leaving little cloud and so the forecast temperature dropped until arrested by the arrival of the front in the late evening. In reality there was no break in the cloud before the front arrived and so the actual temperature remained almost constant until after the passage of the front when there was a slight drop. During the 24th the constancy of the temperature was forecast accurately although its value was about $5^{\circ}C$ too low.

We now consider a case where there was a marked movement of warm air across the country (Figure 13). At the start of the period Southern England was covered in a layer of Sc , but during the afternoon an occlusion travelled northeasterly across Southern England leaving this area in a warm cloudy southwesterly airstream. Over the sea typical temperatures in the warm air were about $14^{\circ}C$ and as this air was advected over the land the observed temperature rose from about $3^{\circ}C$ to $12^{\circ}C$. This marked rise in temperature due to a change in air mass was not forecast by the model because the 950 mb temperature derived from the rectangle only changed by $0.8^{\circ}C$ during the last 18 hours of the forecast. This failing was probably due to an underestimate of the 950 mb temperature of the warm air in the original analysis.

The inadequacy of the Wickham scheme is apparent in all 3 cases and will not be discussed further.

The results from these forecast show that in one case the temperatures were predicted quite accurately with a normalised rmse of 22% (lower than for some of the cases described in the other two experiments). However the other two cases had substantial errors, but the indications are that these were mainly due to deficiencies in the forecast rectangle fields rather than in the temperature model itself.

13. Conclusions

The three experiments described above indicate that this simple model has some skill in forecasting temperatures in several different types of synoptic situation. Even when the temperatures are not predicted accurately it is often possible to extract useful information about temperature variations. The results suggest that most of the substantial errors are due to the large scale model rather than the temperature model itself.

Several aspects of the model could be improved. These include

(i) the method of deriving cloud, especially Sc

(ii) the scheme used to derive the 10 m temperature and wind, and the transitions from the day and night regimes.

(iii) the specification of the soil parameters which should be a function of soil moisture content.

(iv) the choice of representative initial temperatures.

It is hoped shortly to predict the maximum and minimum temperatures over the whole of the UK on a semi-operational basis. For this (iv) will be improved by using the mean midnight screen temperature from three stations in each rectangle gridbox ($\bar{T}_s$ say). The 24 hour forecast values of the differences between the surface and 10 m temperatures, and the screen temperature ($[T_1 - T_s]_f$ and $[T_0 - T_s]_f$ say) will be used to initialise T_0 and T_1

$$T_1 = [T_1 - T_s]_f + \bar{T}_s$$

$$T_0 = [T_0 - T_s]_f + \bar{T}_s$$

Thought is being given to how other improvements may be made.

The skill of the model in predicting temperatures suggests that in mid-latitudes the boundary layer schemes which incorporate a prognostic equation for the surface temperature are capable of predicting the surface fluxes of heat and moisture reasonably well.

The temperature model may be useful as a forecasting aid although careful monitoring would be required in order to take into account deficiencies in the rectangle forecast (a chart of forecast temperature and cloud maybe useful for this). Also it is possible that the model could be used in conjunction with octagon forecasts to provide guidance up to 3 days ahead.

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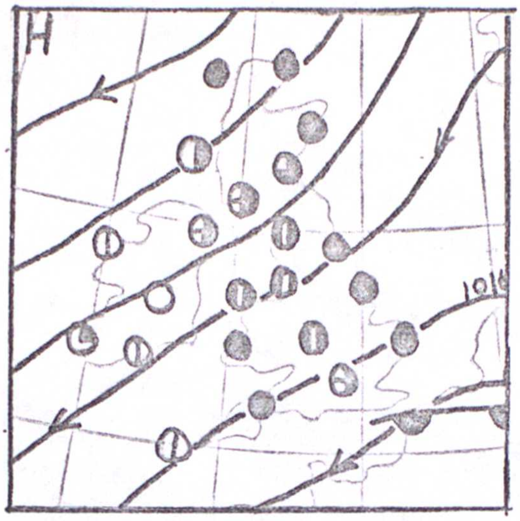
TABLE 1

Figure	Data Time	Max			Min			Max-Min			Mean			r.m.s.e. Obs (max-min)	
	00Z	obs	temp model	Wickham	obs	temp model	Wickham	obs	temp model	Wickham	obs	temp model	Wickham	temp model	Wickham
1	21/3/77	6.0	6.3	9.7	4.3	4.6	2.3	1.7	1.7	5.4	5.2	5.4	4.9	37	165
2	22/3/77	5.5	8.0	9.1	3.2	5.2	1.6	2.3	2.8	7.5	5.1	5.8	4.3	52	113
3	23/3/77	9.3	6.0	12.2	4.9	1.7	6.6	4.4	4.3	5.6	6.1	3.7	7.6	69	68
4	24/3/77	7.5	13.1	10.6	0.7	4.4	2.0	6.8	8.7	8.6	5.1	7.5	5.5	44	31
5	24/5/77	18.3	19.1	24.7	7.4	6.6	14.8	10.9	12.5	9.9	11.6	10.6	18.4	18	65
6	25/5/77	21.2	15.3	26.6	9.8	3.2	16.4	11.4	12.1	10.2	13.4	8.2	20.1	54	61
7	26/5/77	23.1	18.7	25.0	5.4	4.3	13.9	17.7	14.4	11.1	13.9	10.3	18.9	25	31
8	27/5/77	20.7	18.3	24.2	3.7	3.5	13.3	17.0	14.8	10.9	12.6	9.3	17.7	24	33
9	28/5/77	23.1	23.6	26.0	5.9	2.6	15.0	17.2	21.0	11.0	13.3	11.1	19.2	30	40
10	29/5/77	13.7	23.7	25.8	8.1	2.6	9.1	5.6	21.1	16.7	10.3	11.1	16.5	90	129
11	4/6/77	19.4	22.4	24.1	7.6	9.1	10.9	11.8	13.3	13.2	13.4	12.9	16.6	22	33
12	23/11/77	9.3	6.2	19.5	5.8	0.9	6.9	3.5	5.3	12.6	6.8	2.8	11.9	128	175
13	21/12/77	5.5	5.7	15.3	3.2	2.9	7.0	2.3	2.8	8.3	6.2	3.9	10.0	174	245



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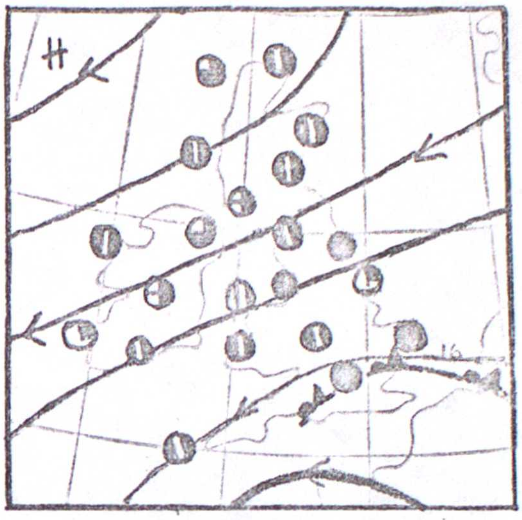

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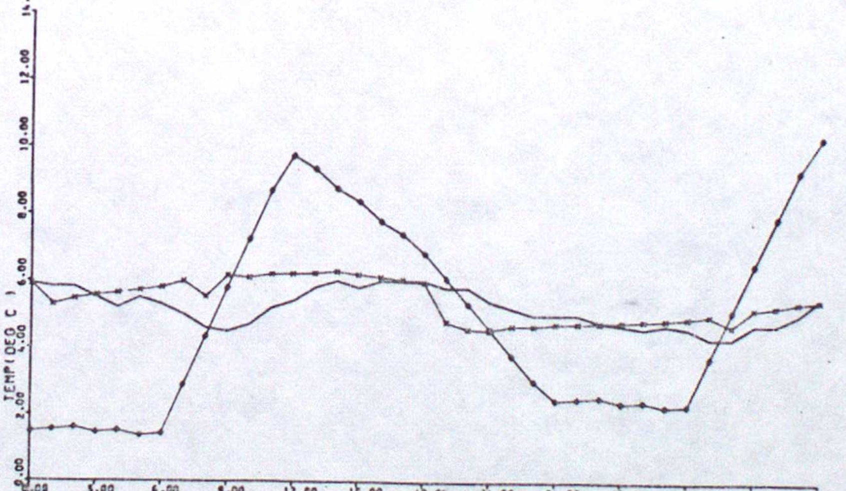
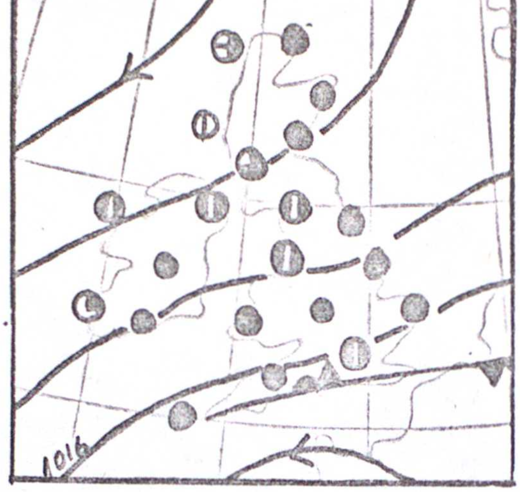


Figure 1



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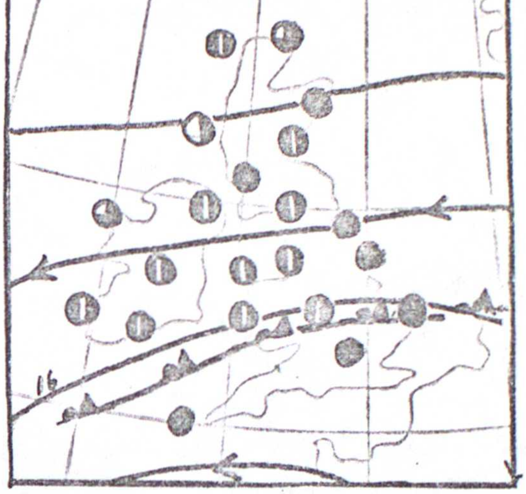

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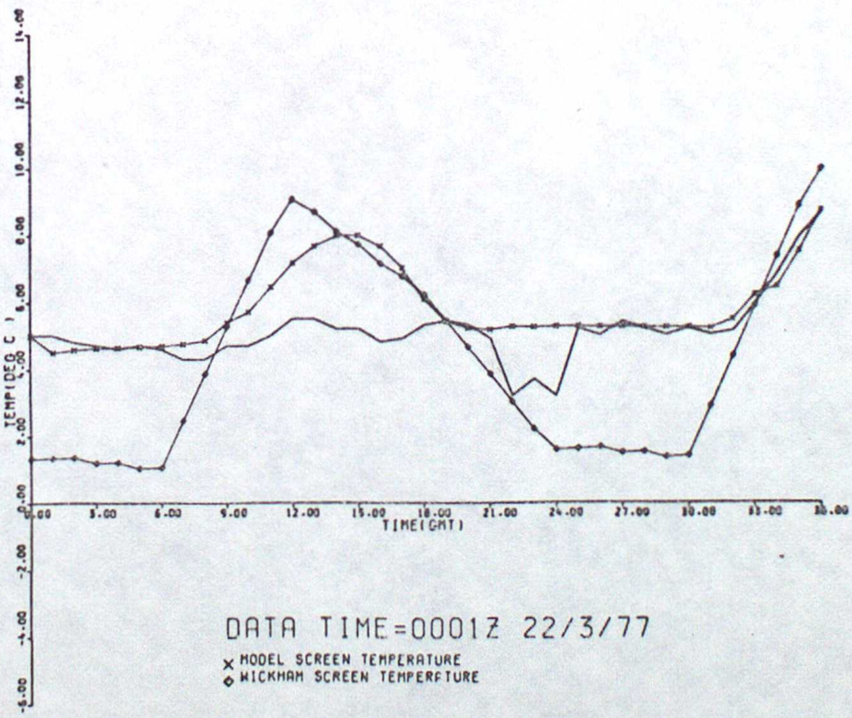

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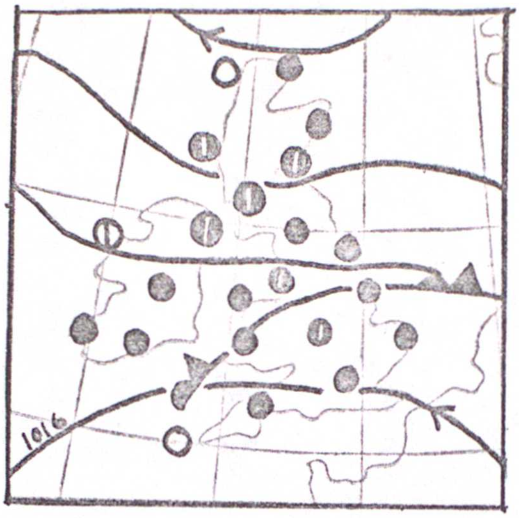

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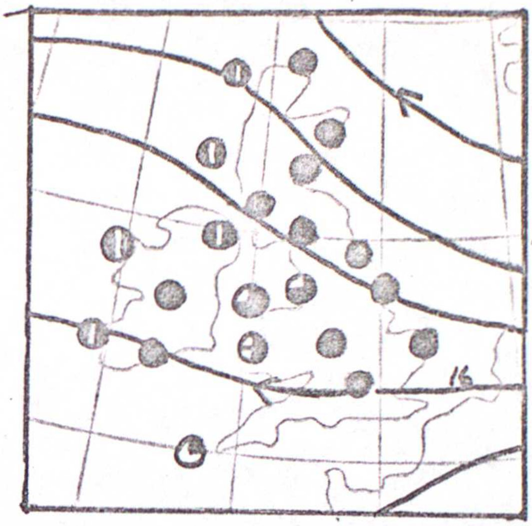

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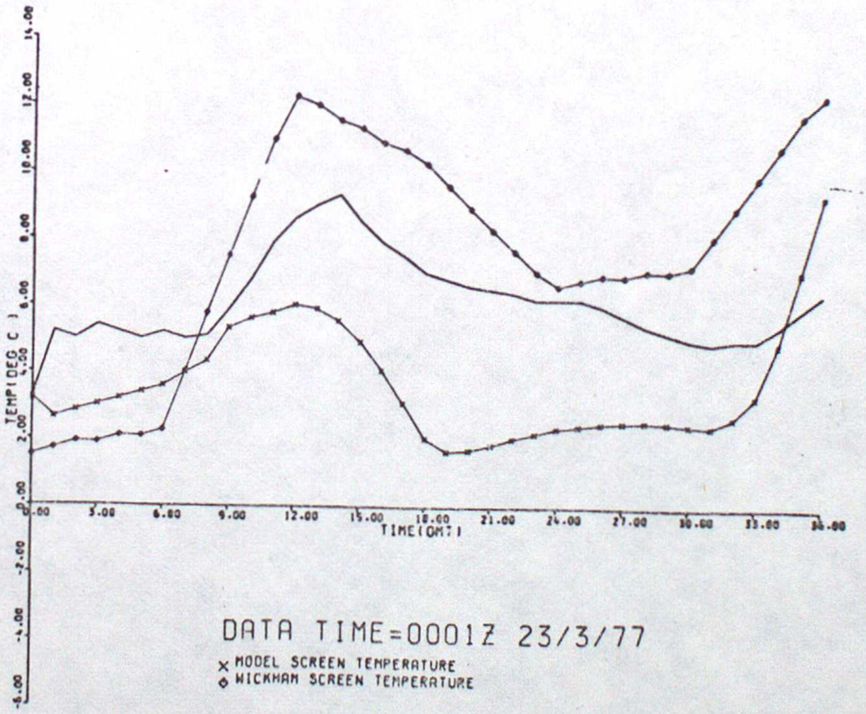

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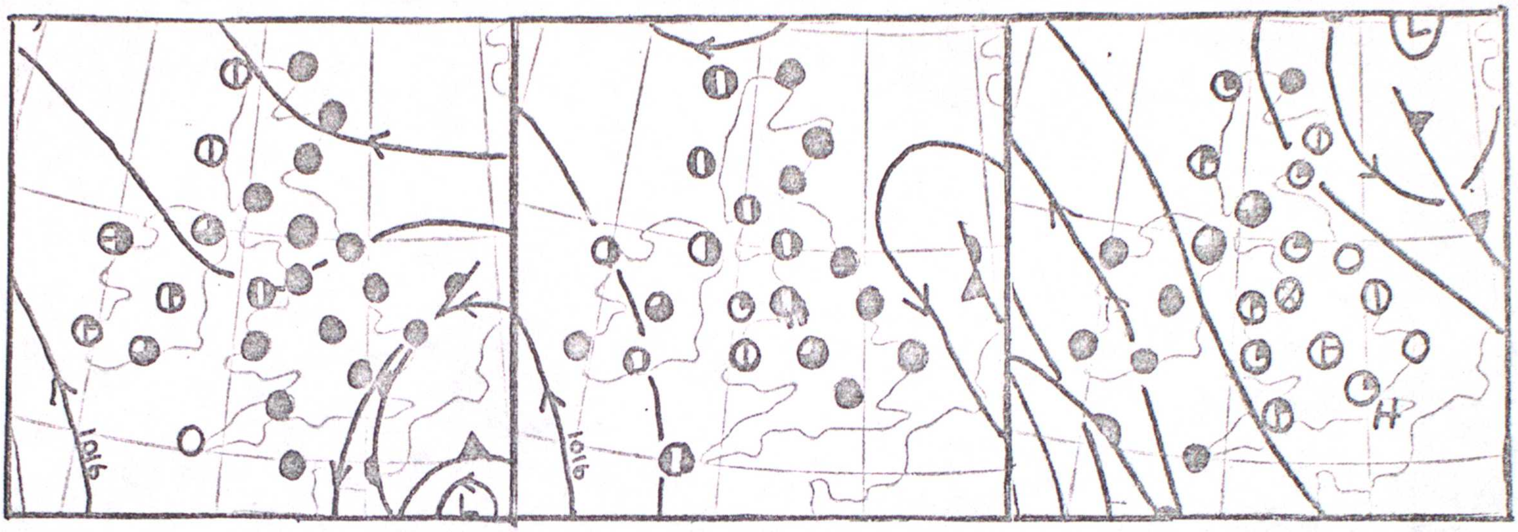

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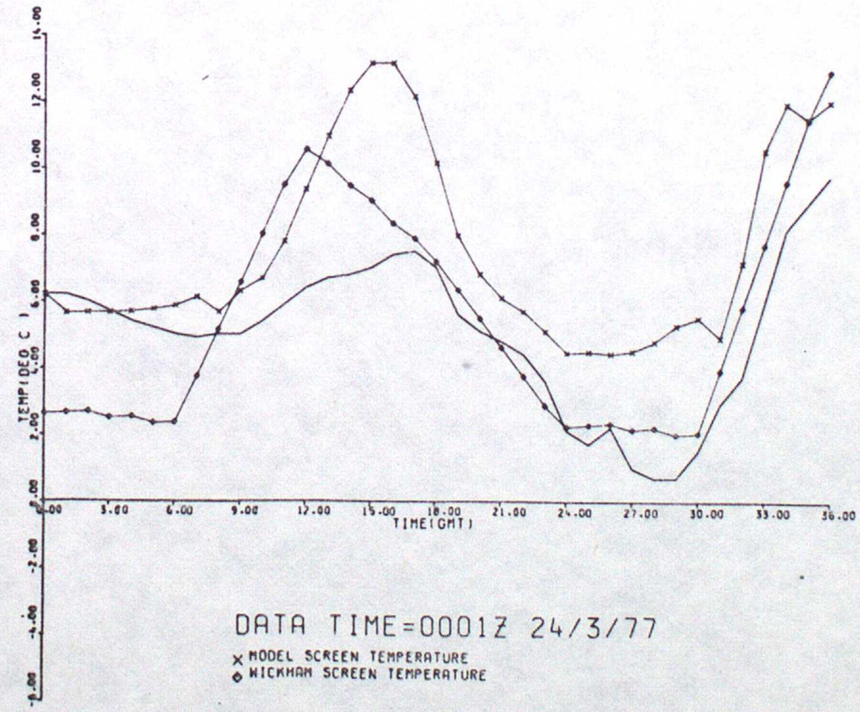

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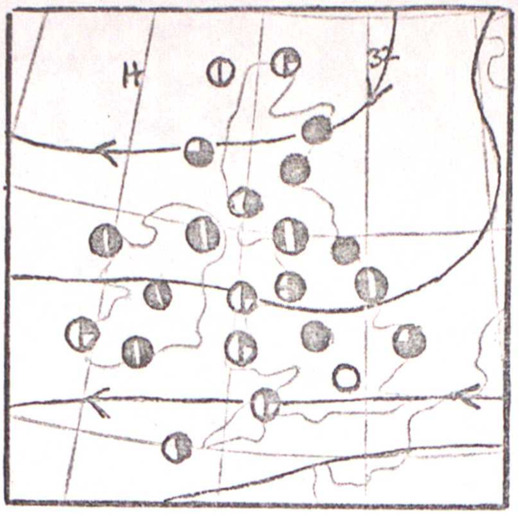

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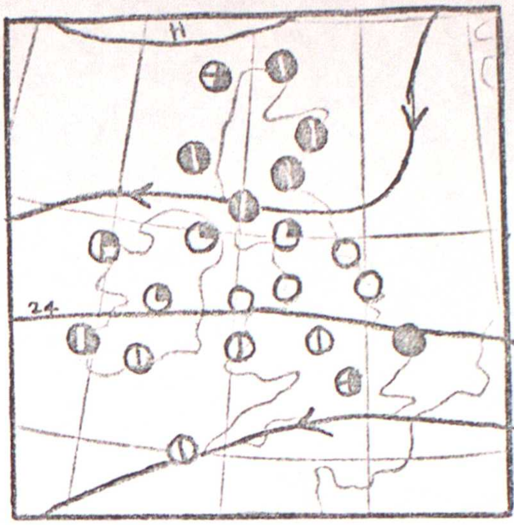

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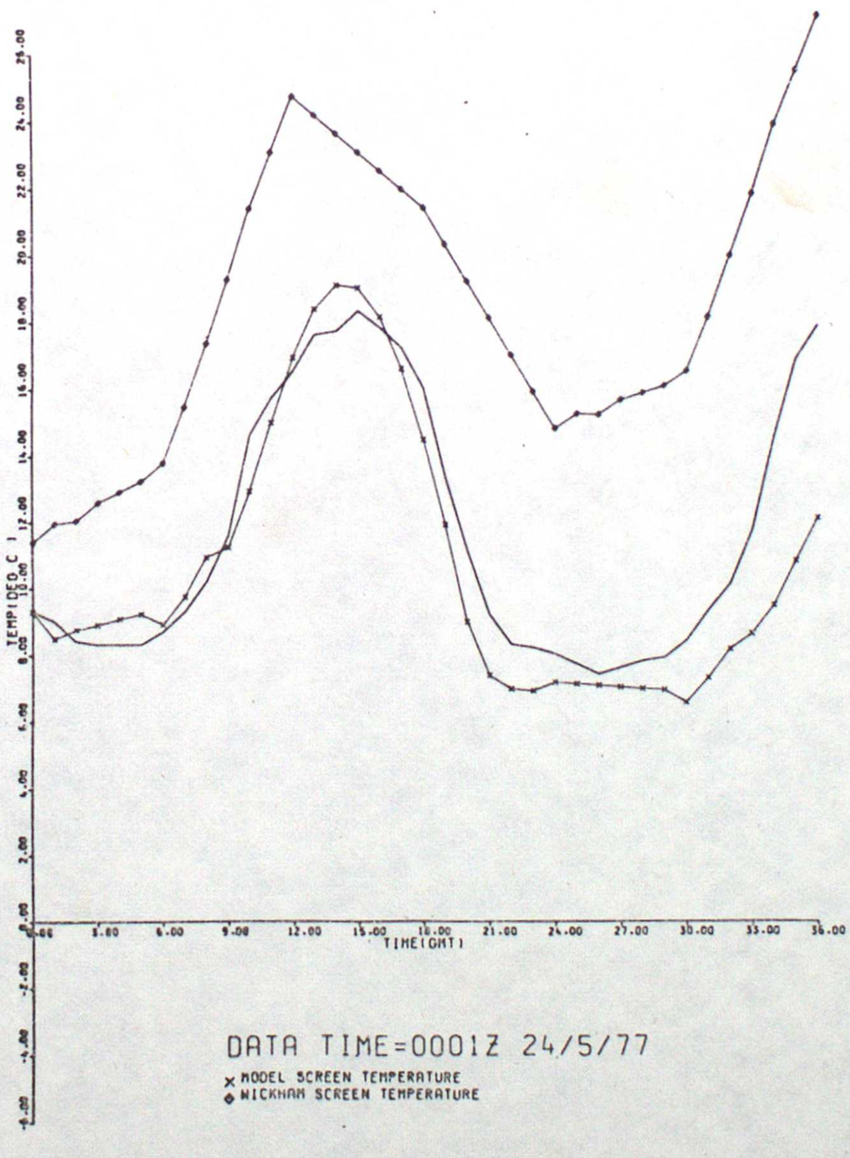

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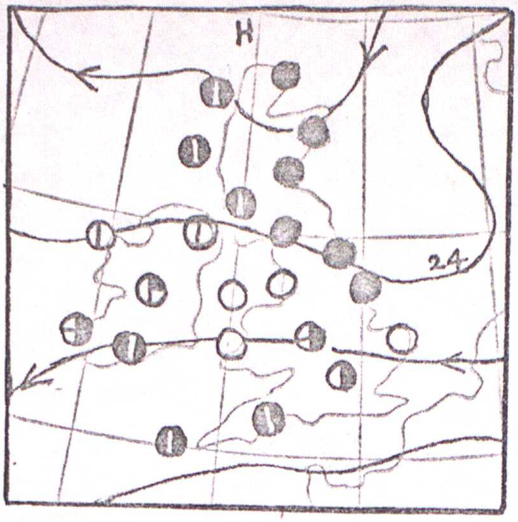

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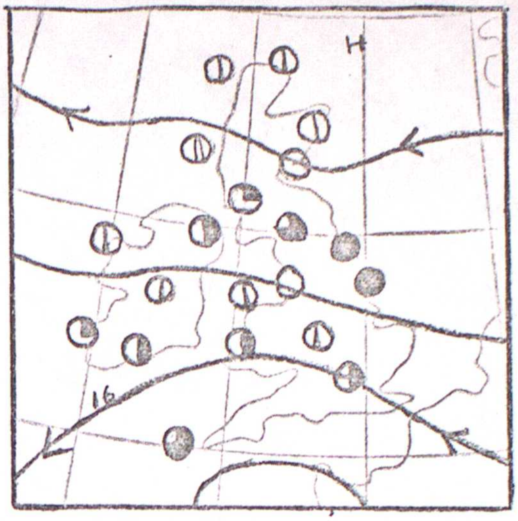

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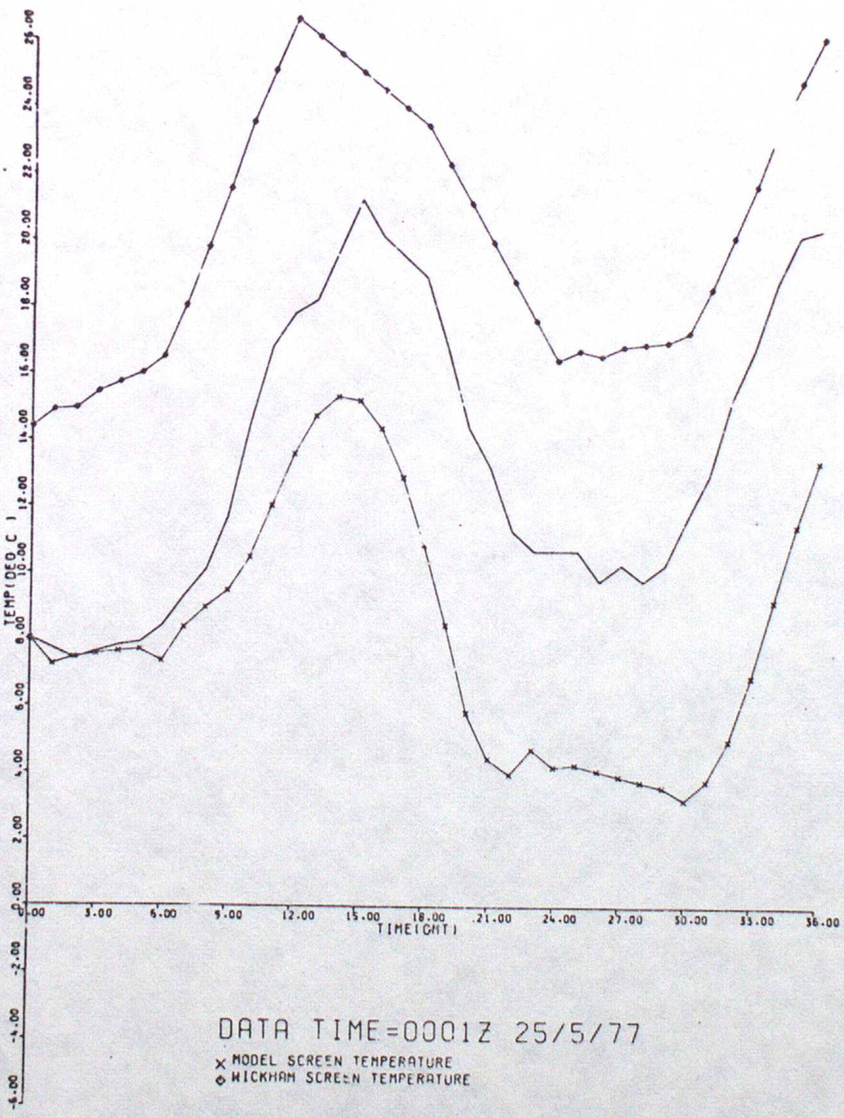

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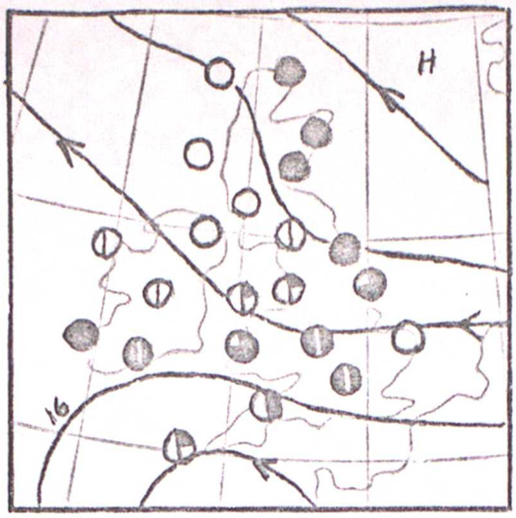

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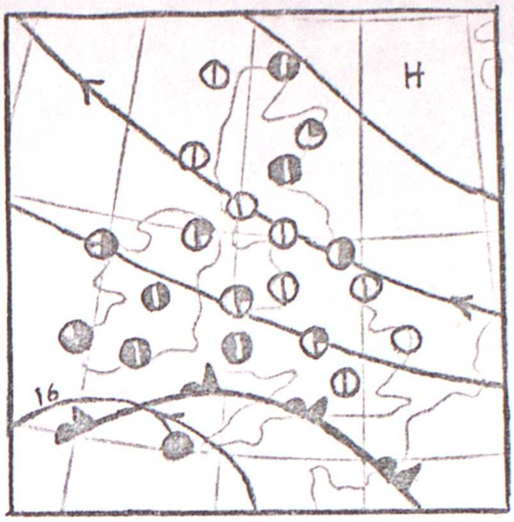

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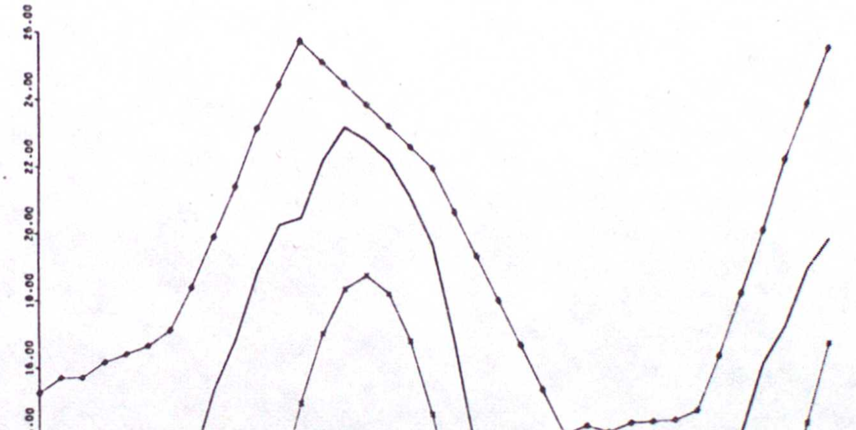

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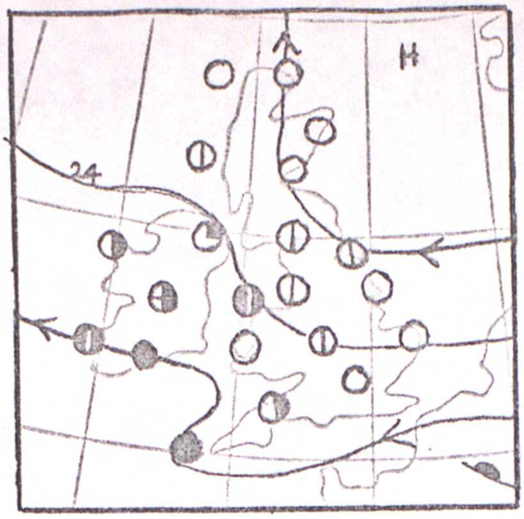

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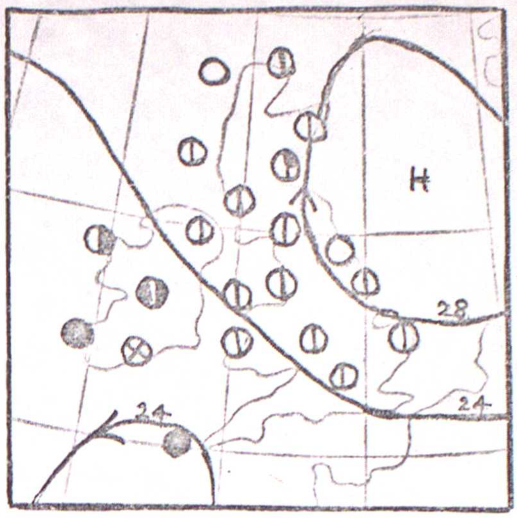

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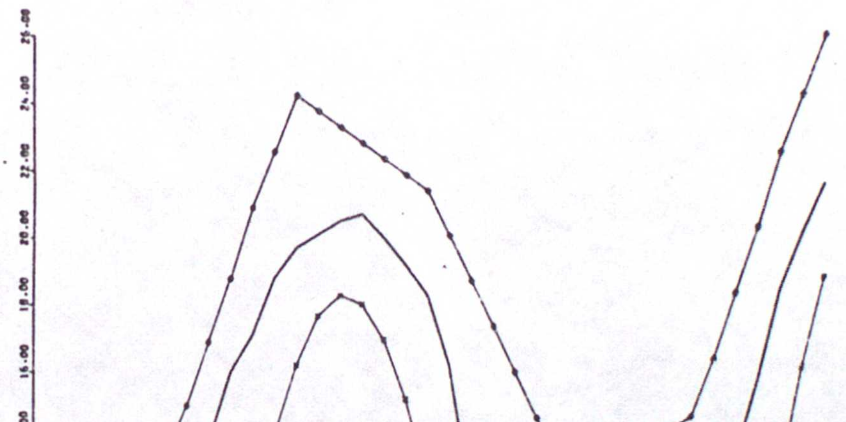

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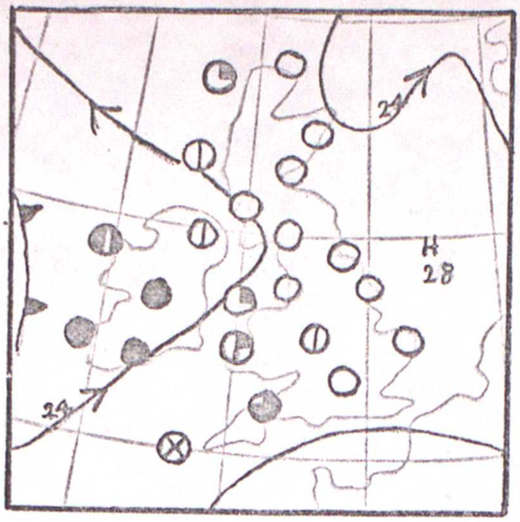

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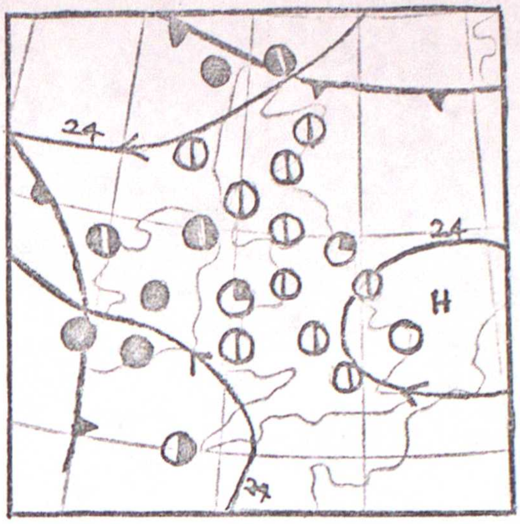

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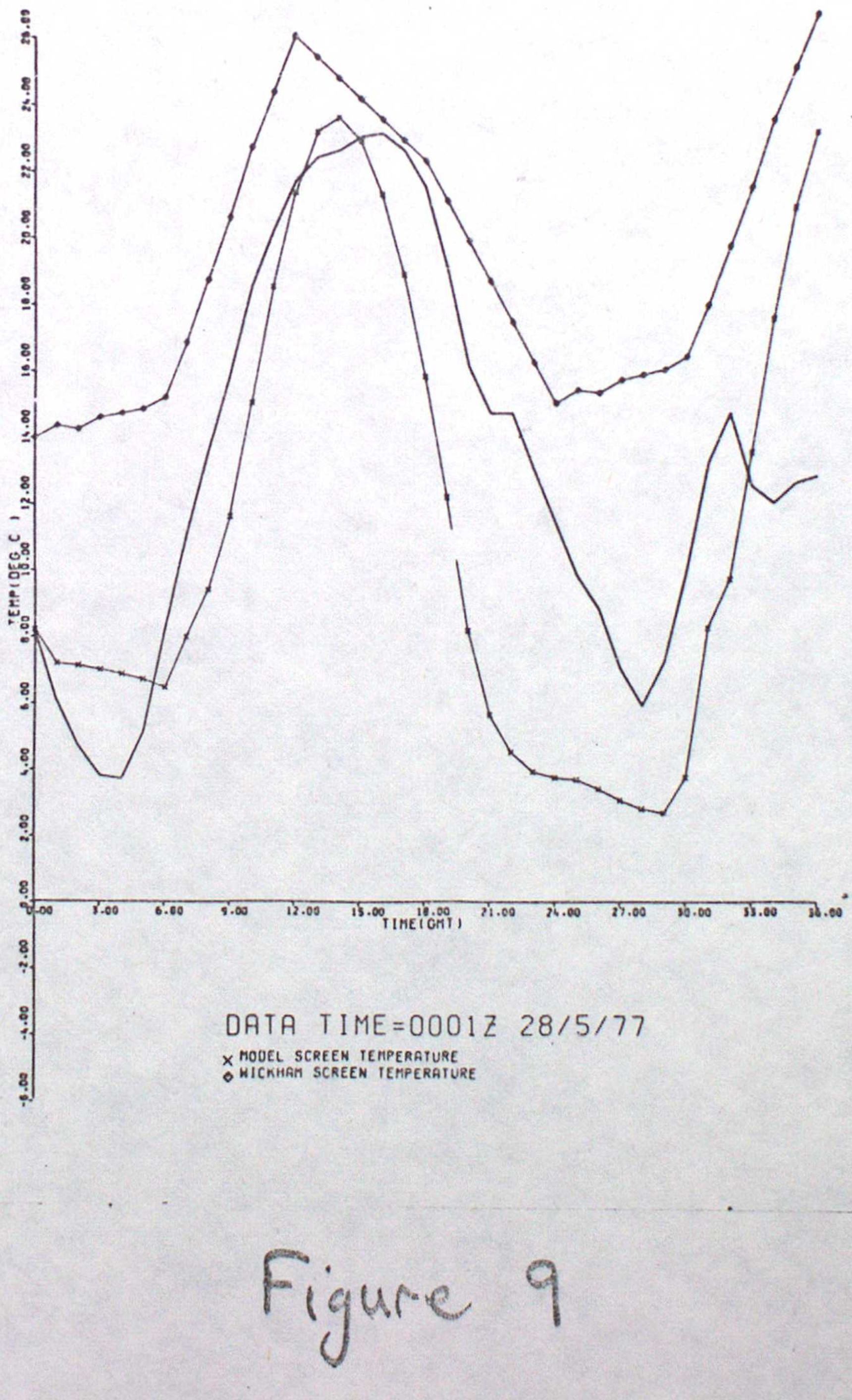

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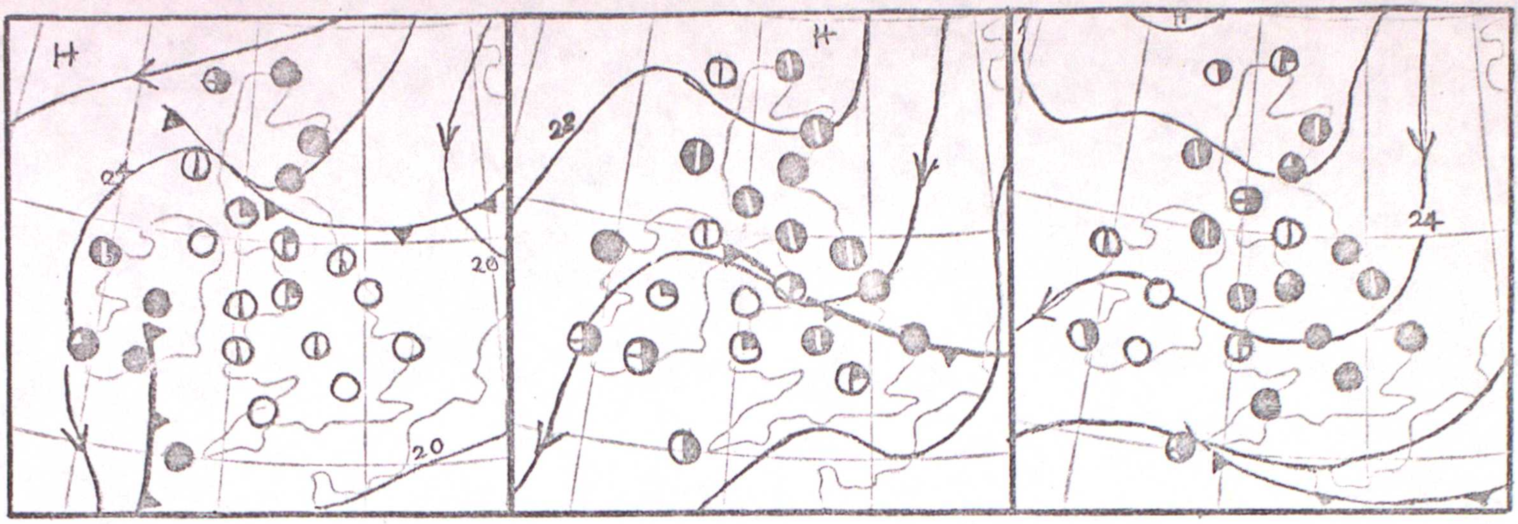

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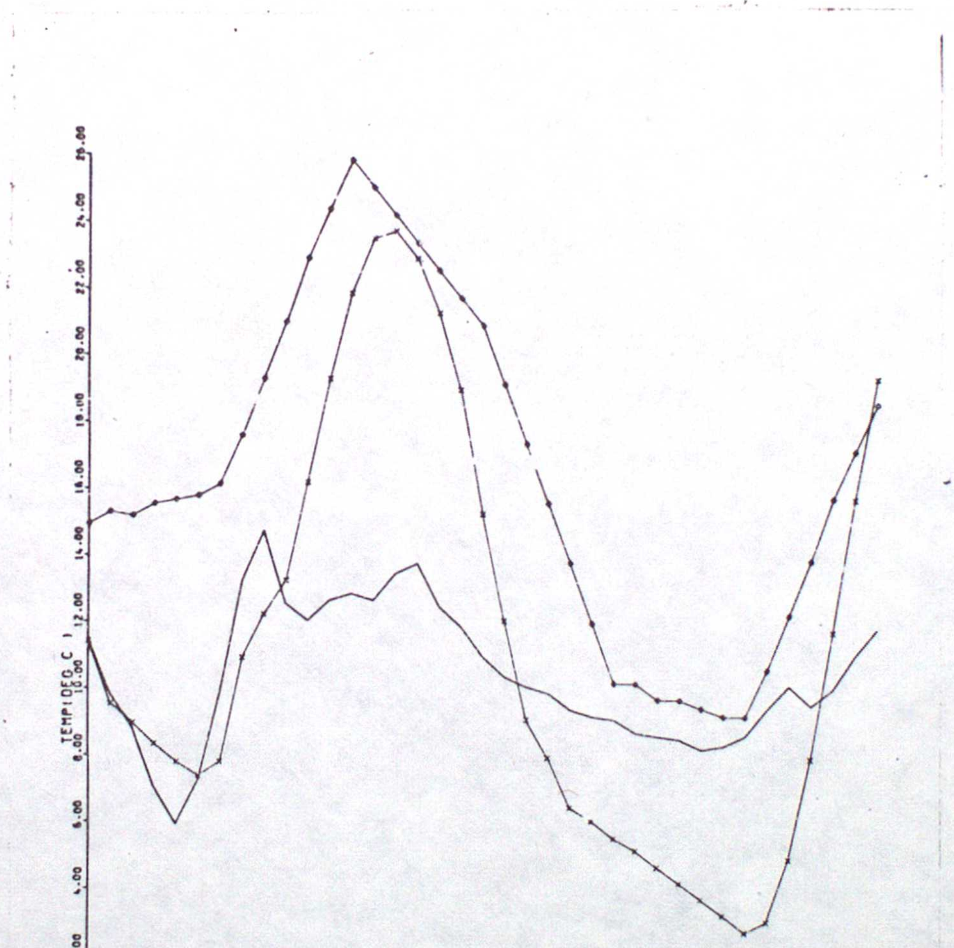

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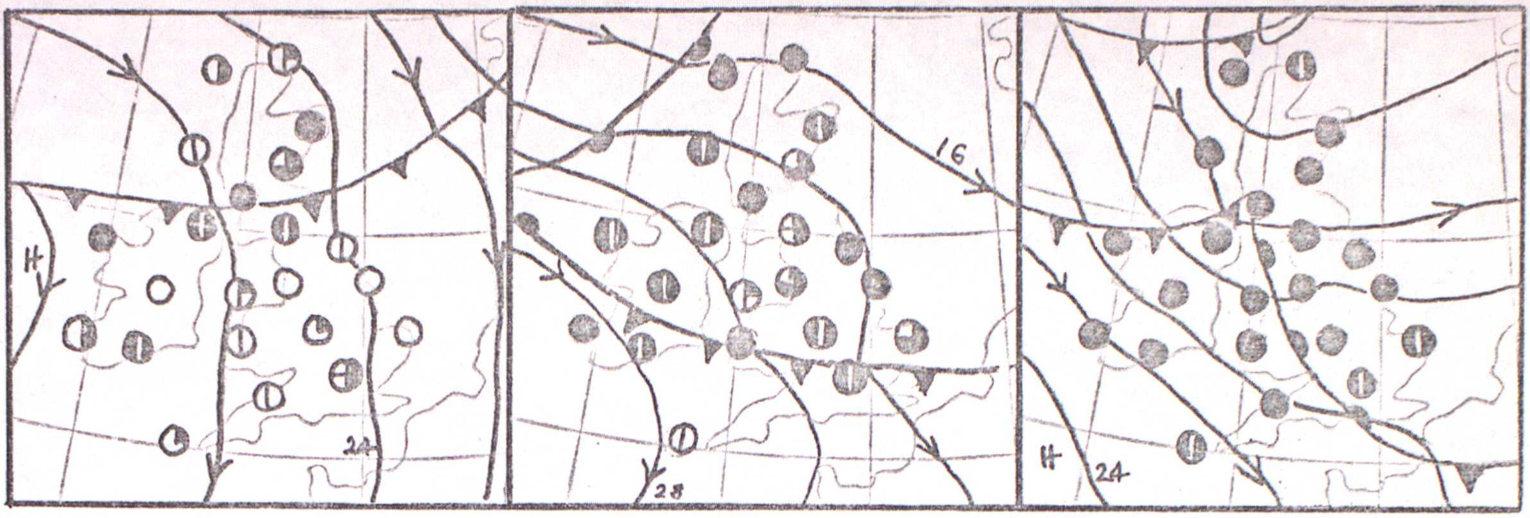

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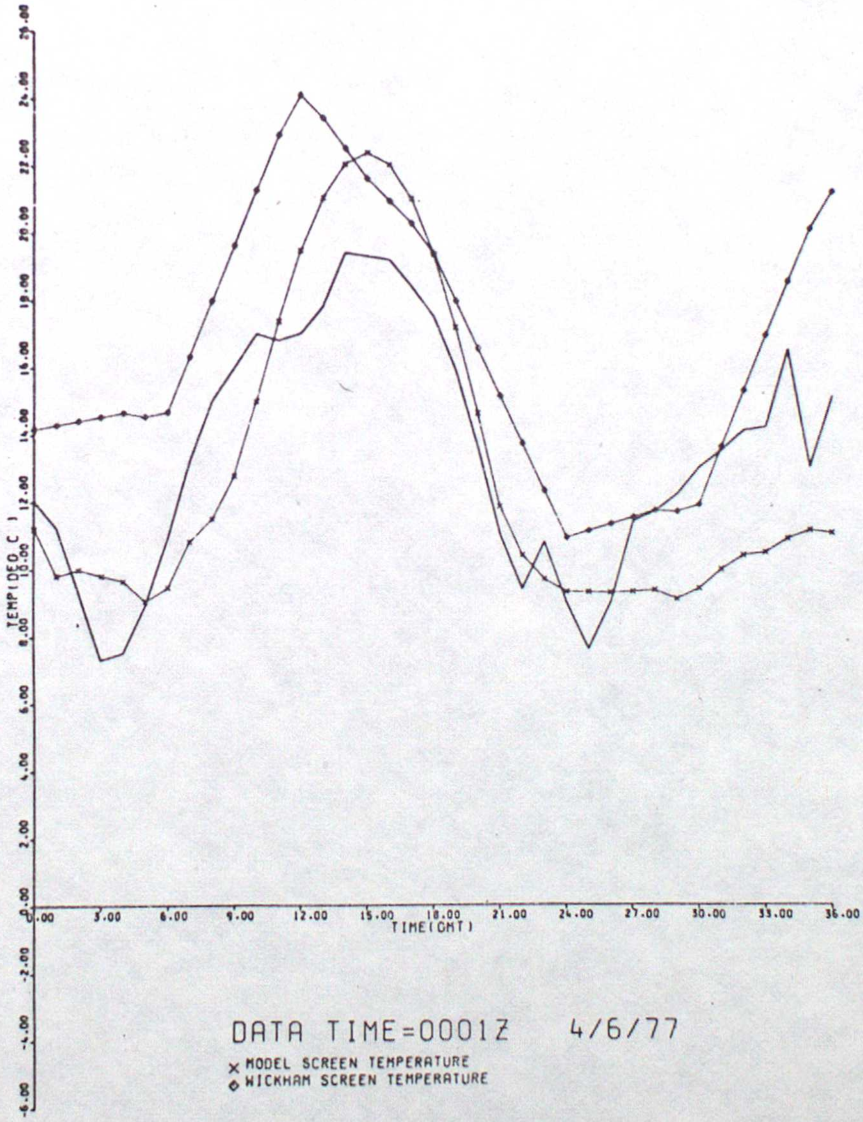

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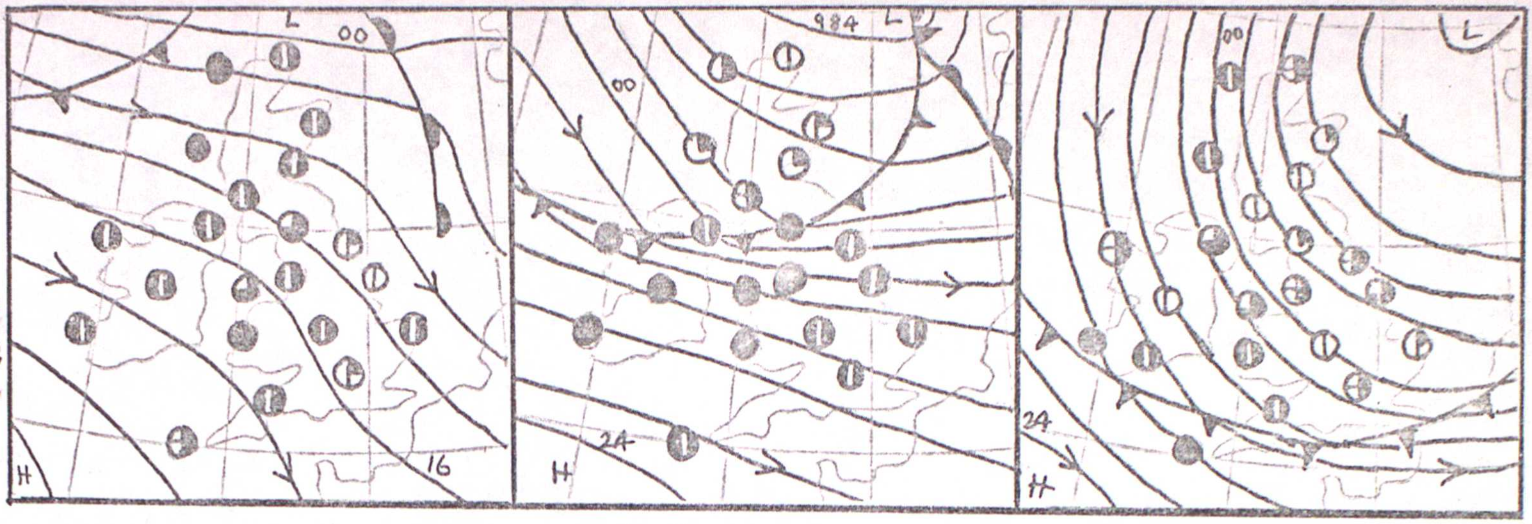

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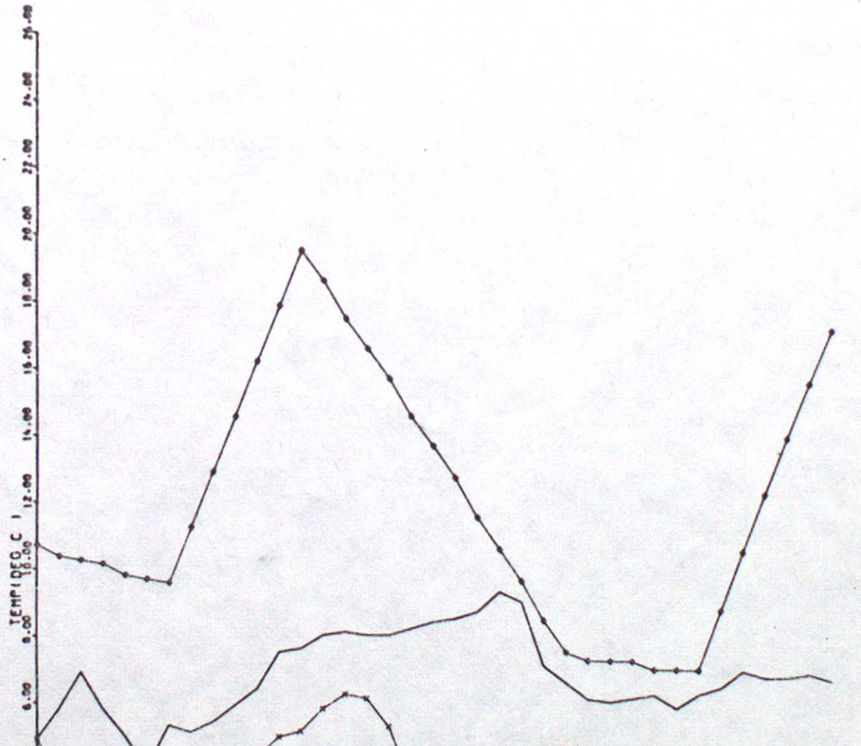

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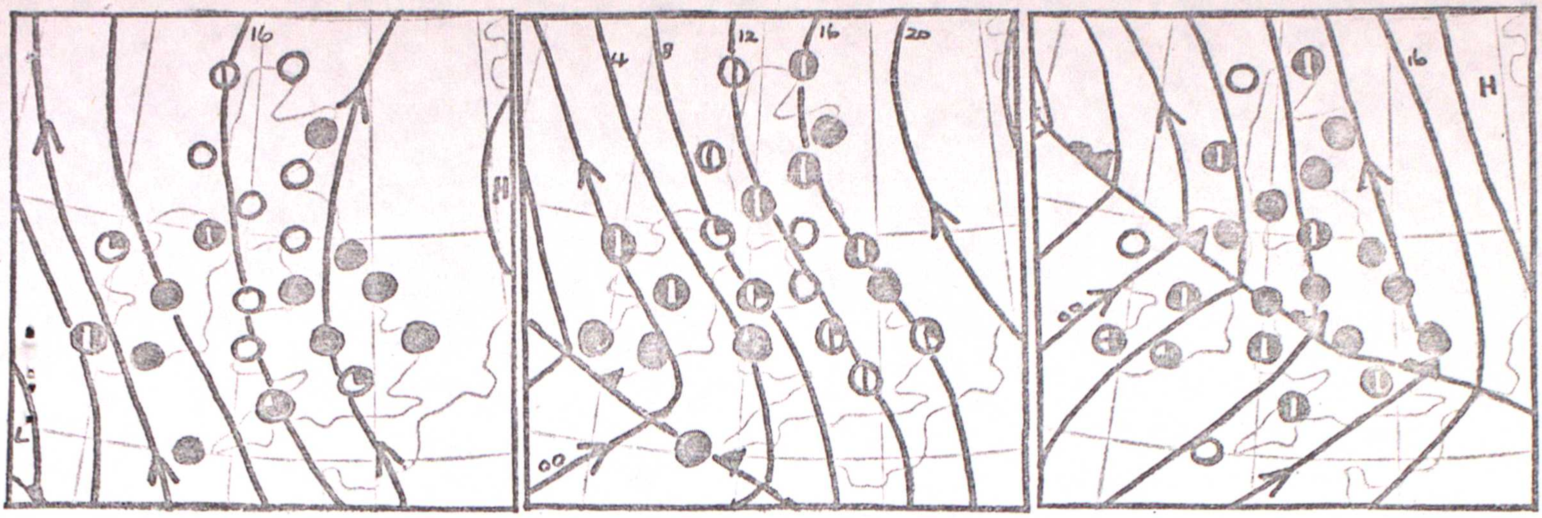

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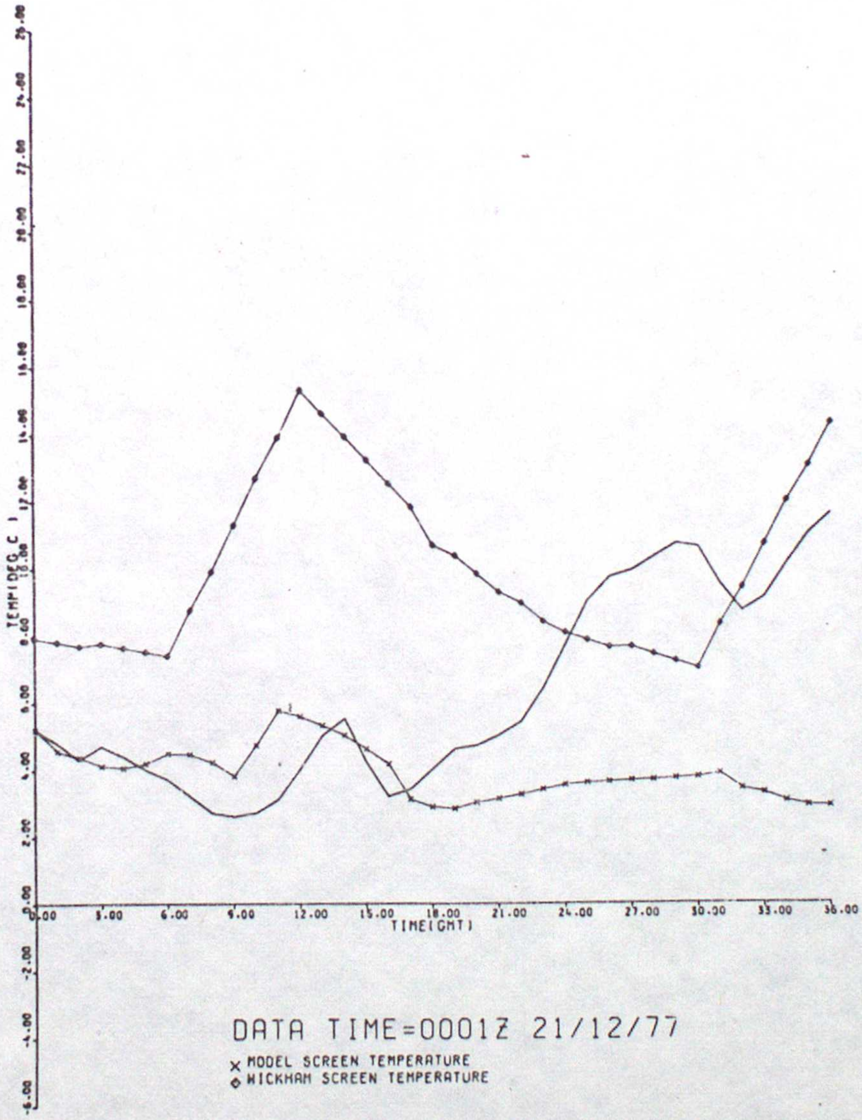

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× MODEL SCREEN TEMPERATURE

◇ WICKHAM SCREEN TEMPERATURE

Figure 13