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A preliminary report describing the first three numerical experiments carried out on the UK Meteorological Office (UKMO) mesoscale model using project WIND (Phase 1) data was prepared in September 1987. The final report incorporates the results described in that report and goes on to describe subsequent work carried out between October 1987 and March 1989. This included: (i) Further analysis of the results of experiments 1,2 and 3, (ii) Experiment 4, incorporating a change of surface albedo, (iii) Experiments with a single-column version of the MO model, and (iv) The development of a computer programme to carry out three-dimensional objective analyses of project WIND data. Items (i) and (ii) are described in the next two sections and (iii) in Section 4. The work carried out under (iv) (at Tel Aviv University) is described in Section 5. Section 6 states the conclusions drawn from these experiments, stressing the implications of the results for future development of the heirarchyof models, particularly SIGMET, at ASL. The documentation relating to the UKMO model has been supplied to ASL, together with computer tapes of the results of the model runs. Cont. overleaf......

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The personnel involved in the project are listed in the Appendix, together with an outline of the main meetings held over the period from May 1987.
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FINAL TECHNICAL REPORT

on

PROJECT WIND - EXPERIMENTS WITH THE UK METEOROLOGICAL OFFICE MESOSCALE MODEL

JUNE 1989

1. INTRODUCTION

A preliminary report describing the first three numerical experiments carried out on the UK Meteorological Office (UKMO) mesoscale model using project WIND (Phase 1) data was prepared in September 1987. This final report incorporates the results described in that report and goes on to describe subsequent work carried out between October 1987 and March 1989. This included:

(i) Further analysis of the results of experiments 1, 2 and 3;

(ii) Experiment 4, incorporating a change of surface albedo;

(iii) Experiments with a single-column version of the MO model;

and (iv) The development of a computer programme to carry out three-dimensional objective analyses of project WIND data.

Items (i) and (ii) are described in the next two sections and (iii) in Section 4. The work carried out under (iv) (at Tel Aviv University) is described in Section 5. Section 6 states the conclusions drawn from these experiments, stressing the implications of the results for future development of the heirarchy of models, particularly SIGMET, at ASL. The documentation relating to the UKMO model has been supplied to ASL, together with computer tapes of the results of the model runs. The personnel involved in the project are listed in the Appendix, together with an outline of the main meetings held over the period from May 1987.

2. THE UKMO MODEL EXPERIMENTS

The Meteorological Office (MO) mesoscale model has been run for the simulation of the summer flow on 27 June 1985 in the Sacramento Valley, California. The purpose is to examine its predictive capability using the meso-β high resolution observations that were obtained during Phase I of US Army Project WIND and compare with it similar runs made with the ASL SIGMET model. The simulated region is a 460 x 460 km area centred at (39.75°N, 121.8°W) as in the SIGMET simulation by Williams et al., (1986).

Four simulations were performed and their characteristics are summarised in Table 1. In the first simulation (referred to hereafter as Experiment 1) the MO model was modified to run with vertical levels as in the SIGMET run (36, 116, 213, 330, 471,.... 4779, 6219 m) while the other experiments, Nos.2, 3 and 4 were run with the vertical spacings and number of levels (16) used by the operational MO mesoscale model simulations (10, 110, 310, 610, 1010 ..... 10515, 12010 m). In the third run the evaporation resistance was increased from 100 to 500 s m^{-1} resulting in effectively reducing the evaporation to nearly zero. This reflects the relatively dry conditions over the Sacramento Valley at that time. In the fourth experiment the surface

89 9 13 114

albedo (reflectivity of solar radiation) was increased from 0.18 to a more realistic value (for dry grass) of 0.30.

The simulations were performed with the same topography, horizontal grid spacing ($\Delta x = \Delta y = 20$ km) and the same radiosonde initialization (that for Orchard, 1700 GMT, 1000 PDT) as in the SIGMET run. Fig. 1 illustrates the topography of the region, which includes an artificial apron as in the SIGMET run.

3. ANALYSIS OF RESULTS

(a) Winds and screen-level temperatures in experiments 1-3

Fig. 2 presents the full diurnal cycle of screen-level (1.3 m, linearly interpolated between the surface and 36 m) and soil temperatures as predicted by the model as well as the observed screen-level temperature at Corning station in Experiment 1. It clearly illustrates that the model captures correctly the minimum and maximum temperatures and follows the trend of the observations realistically. But compared with the observations the model amplitude is much too small. Also there is a strong, though too early, stabilization of temperature decrease after sunset. In the model this happens at about 20 PDT while in the observations about 4 hours later.

Another problem in Experiment 1 is the relatively low top (~ 7000 m) which causes in the model strong reflections near the top. Fig. 3 shows the cross-section of the vertical velocities (negative is shaded) and temperatures through the centre of the domain after 6 hours of simulation, i.e. at 1600 PDT. Unrealistic strong vertical velocities are formed at altitudes of about 4800 metres. In contrast, Fig. 4 shows the same cross-section for Experiment 2 where the model top is at about 12 km and the vertical circulations up to 6 km seem to be free of any disturbances reflected from the model top. As expected, these spurious vertical velocities affect the temperature and moisture vertical profiles as illustrated in Figs. 5 and 6 where the Hogsback model and observed tephigrams are compared for Experiments 1 and 2 respectively. Experiment 2 seems to better simulate the observed profiles - in particular it does not generate the temperature inversion at around 750 mb produced in Expt.1.

Although Experiment 2 (operational levels) yields a more realistic vertical structure, the amplitude of the screen-level temperature (Fig.7) remains too small, similar to that shown in Fig.2.

The model's screen-level temperature is largely determined by the earth's surface temperature, which is itself determined by the net incoming radiation at the surface (R), the fluxes into the atmosphere of sensible heat (H) and latent heat of water vapour (LE), and the heat flux into the ground (G). The third experiment was designed to test the hypothesis that the model's evaporative heat flux was too large resulting in surface and screen-level temperatures being too low during the daytime hours; the evaporative resistance was increased from 100 to 500 sm^{-1}, leading to the much improved screen temperatures shown in Fig. 8.

The surface winds in Experiment 2 for the full model domain (24 x 24) are shown for 1600 hours PDT (see Fig. 9). These may be compared with the objectivity analysed observed winds in Fig.20(a). It must be borne in mind, however, that the observations are clustered near the centre of the region - the central valley and surrounding slopes, so that no objective analysis scheme is capable of producing an acceptable analysis outside of this region. The forecast is successful in producing the broad southerly flow up the valley together with an upslope component on each side. Verification statistics for winds and temperature at the 850, 700 and 500 mb levels for all three experiments are given in Table 2. Also included are results from the SIGMET run (Williams et al. 1986). Apart from the wind results at 500 mb all results are generally better than those obtained by the SIGMET run. The poor values at 500 mb for Experiment 1 seem to be the result of reflections from the top boundary.

(b) The model's radiation balance - Experiment 4

Comparison of the model screen temperatures in Figs. 7 and 8 show that, although increasing the evaporative resistance lead to considerably more realistic temperatures during the day, they are still too high, by as much as 4 °C, at night. This suggests that, since the night-time cooling rate is determined largely by the outgoing long-wave radiation, the model's representation of radiative fluxes is the main source of error at night and may therefore also be contributing to the daytime error. The availability of WIND observations of net radiation (and solar radiation) makes it possible to study in detail the performance of the model's radiative scheme, which, like that used in SIGMET, is a relatively unsophisticated one. (See Golding, 1987). The observations were actually available from only two surface stations, however - Durham and Orlando; those from the other seven stations were not at the time available.

Fig. 10 shows the observed and model (Experiment 3) time sequences of solar radiation intercepted at the ground together with the net radiation. The main discrepancy is between the net radiation curves during the day, the model value being too high by about 200 Wm^{-2}. Since the errors in incoming solar radiation are small, this discrepancy can arise from either (a) the model albedo being too low, (b) a large underestimate by the model of the net outgoing long-wave flux or (c) a combination of (a) and (b). Since the night-time (long-wave) flux estimates are much closer to the observed, being in error by only about 40 Wm^{-2}, (a) would seem to be the major contributor to the discrepancy. Experiment 4 was therefore carried out with an increased surface albedo of 0.30. The results for the net radiative fluxes are shown in Fig. 11 and those for the screen temperatures in Fig. 12. The discrepancy between the model and observed net fluxes during the day is halved, but the screen temperatures are little different from those obtained in Experiment 3 (Fig. 8).

(c) Winds and temperatures - Experiment 4

Fig.13 shows the 10 m wind and screen temperature distributions predicted by the model for 2300 GMT (1600 PDT). The flow is generally southerly through the Sacramento valley and there is an upslope component on the western slope of the Sierra foothills as in Expt.2 (Fig.9); the maximum surface temperature in the valley is 34°C which is within about two degrees of the observed value. The objectively analysed 34°C contour based on the observations is shown in Fig.20(b).

Fig.14 shows the wind field predicted for 1300 GMT (0600 PDT). The valley winds are very light and there is now strong downslope flow off the mountain ridges. The objectively analysed winds for this time are shown in Fig.21(a). The forecast downslope winds off the ridge to the east are realistic, except for the tendency to concentrate into a narrow band near the middle of the region. There is also a downslope component off the ridge to the West but the general character of the light winds in the valley is not well predicted.

The predicted temperatures, shown in Fig.15, show a strong temperature gradient on the mountain slopes and temperatures of 16°C in the valley, close to the observed value. Fig.21(b) shows the objectively analysed isotherms for this time based on the observations.

(d) Further investigation of the model's physics

Increasing the earth's albedo in Experiment 4 went only about half of the way towards reducing the discrepancy between the modelled and the observed net radiation at the surface. This suggested that there were also errors in the model's representation of the long-wave fluxes as suggested under (b). An estimate of the long-wave fluxes at two-hourly intervals, was therefore made using a different, more-sophisticated, radiation scheme - that proposed by Rodgers and Walshaw (RW) (1966). A computer programme to implement the RW scheme was made available by the authors to the Department of Meteorology at Reading University several years ago. All it requires as input are vertical profiles of temperature and moisture (and cloud amount and level, although this was set to zero); it then solves the radiative transfer equation for upward and downward fluxes for each of 24 wavelength bands using assigned emissivities. (The input to the RW scheme was taken from the Hogsback (252 m) radiosonde whereas the UKMO model surface input was from Durham (38 m). The height difference between the two stations is not, however, sufficiently large to invalidate the conclusions drawn from the comparison.)

The results are shown in Fig. 16, implying that, if the RW scheme is correct, the UKMO scheme underestimates the outgoing long-wave radiation by between 60 and 120 Wm^{-2} during the day and about 120 Wm^{-2} during the night, largely as a result of overestimating the downwards flux. Whereas these estimates, together with the albedo correction, would together account nicely for the daytime discrepancy between the observed and model (Experiment 3) net radiative fluxes, during the night when only the outgoing long-wave flux is involved, the model error suggested by the RW comparison is much too large.

This last conclusion suggests that it might be either the ground heat flux which is poorly represented by the model, or the sensible and evaporative heat losses near the surface at night, or both. Also it is clear, both from the observations and model interpolated screen temperatures (Experiment 3) in Fig. 8 that a sharp decrease in the rate of fall of temperature occurs around midnight (2200 PDT in the model), implying a sharp change in the surface heat balance components at that time. In order to provide more insight into this phenomenon, the model temperatures at 10 m, at the surface and in the soil were plotted. These are shown in Fig. 17. These plots show the surface temperature leading the cooling after 2000 PDT, followed a little later at about the same rate by the 10 m temperature; both curves show a sharp levelling off at 2200 PDT. The soil temperature curve lags well behind both of the others and the cooling is much slower. These curves are consistent with the lowest 10 m of the atmosphere having a much smaller heat capacity than the effective modelled soil layer and responding rapidly to the radiative cooling until 2200 hrs. At that time the soil and/or the atmospheric heat flux becomes large and both the atmospheric layer and the soil cool at about the same rate.

A similar levelling-off of the surface cooling rate during the night has often been observed (e.g. Saunders, 1952) and is ascribed to latent heat release accompanying the deposition of dew. However no dew deposition was involved in either the model simulations or the WIND observations.

Further diagnostic studies of the individual surface heat balance components are needed to resolve this issue. With this purpose in mind, several experiments were carried out with a single column version of the model, and are described in the next section.

4. THE SINGLE COLUMN MODEL EXPERIMENTS

(a) Introduction

A single column version of the Meteorological Office Mesoscale model has been developed with the primary intention of testing the turbulence parametrization scheme - without the expense of running the full model. It differs from the full model in having no horizontal or vertical advection; no surface hydrology, precipitation or convective parametrization schemes. The only retained parts of the full model's physics package are;

(i) A parametrization of the turbulent transport of heat and momentum which involves predictive equations for the turbulent kinetic energy (based on Yamada and Mellor, 1979).

(ii) Parametrizations of the surface heat (sensible and latent) and momentum fluxes.

(iii) Radiative flux parametrizations (see below).

(iv) A two component soil model involving a 'surface' layer and a deep soil layer.

(v) Droplet cloud parametrization.

Two versions of the column model exist which differ only in the level of sophistication of their radiative flux parametrization. One has the operational model's scheme which only accounts for the effects of radiation at the surface and at cloud top. In this, Infrared radiation (IR) from the surface has a flux equal to that of a blackbody at the temperature of the surface soil layer. Downward IR incident at the surface is assumed to radiate at the mean temperature of the lowest 3 model levels with an emissivity which has some dependence on the total precipitable water in the column. The more sophisticated scheme is adapted from those due to Slingo and Schrecker (1982) and Roach and Slingo (1979).

The horizonal momentum equations are integrated in time assuming a prespecified pressure gradient force (or geostrophic wind). The column model's prognostic equations then take the form:

$$\frac{\partial \theta_L}{\partial t} = \frac{\partial}{\partial z} K_H \frac{\partial \theta_L}{\partial z} + Q$$

$$\frac{\partial q_T}{\partial t} = \frac{\partial}{\partial z} K_H \frac{\partial q_T}{\partial z}$$

$$\frac{\partial u}{\partial t} = f(v - v_g) - \frac{\partial}{\partial z} K_m \frac{\partial u}{\partial z}$$

$$\frac{\partial v}{\partial t} = -f(u - u_g) - \frac{\partial}{\partial z} K_m \frac{\partial v}{\partial z}$$

(b) Initial data

The initial vertical profiles of all prognostic variables were obtained for the point in the 3D model used for diagnostics i.e. point (11,12) or (200,260)km.

The initial soil and surface temperature were 20 and 26.6 °C respectively and surface pressure 998.1mb. The solar radiation was calculated assuming a latitude of 39.75°N and longitude of 121.80°E; the Coriolis parameter was based on the same latitude. The following physical constants were assumed:

albedo = 0.3

z_o = 0.1m

SRE = 500.0 (surface resistance to evaporation sm^{-1})

HTCOND = 950.0 (effectively the thermal capacity of the soil layer influenced by the diurnal cycle-MKS units)

The integrations were started from 17Z on 27 June 1985 and run for 24 hours with a time step of 120s.

(c) The numerical experiments

Experiment C1 - Operational radiation, geostrophic wind = zero.

In this experiment the pressure gradient force (or geostrophic wind) was set equal to zero and the model was run with the operational radiation scheme. Figs.18(a)-(c) show the soil, surface and 10 metre temperatures respectively throughout the integration and compare them with those found at the corresponding point inthe 3D model. Differences are rather minor until around sunset after which the temperature at 10m is higher than in the 3D model. By the end of the night the difference is as much as 10°C whereas the difference in surface temperature is about 4°C. Inspection of the 10m wind speed at T+21 hrs. in both models shows the column model to have a speed of 1.8ms^{-1} compared to 3.8 ms^{-1} in the full model. The primary effect of stronger winds is to increase the mixing in the lowest layers thereby weakening the static stability by warming the air adjacent to the surface and cooling air at the 10m level and higher. The different levels of turbulent mixing in the two cases can be seen by comparing their respective surface sensible (H) and latent heat (LE) fluxes. At time T+20 in the column model H=-3.1 Wm^{-2} and LE=4.7 Wm^{-2} compared to H=25.5 Wm^{-2} and LE=15.5 Wm^{-2} in the full model.

Experiment C2 - Operational radiation, imposed geostrophic wind

In order to examine the effect of mixing in the nocturnal boundary layer when a large-scale pressure gradient exists, a height-dependent geostrophic wind was introduced into the column model. This was chosen such that above 1.51km the geostrophic wind was set equal to the initial wind; below this the geostrophic wind was assumed height-independent and set equal to its 1.51km value $(u_g, v_g) = (-0.65, 7.04)ms^{-1}$. The observed geostrophic wind may not have been as large as this but other effects such as katabatic drainage and channeling may contribute to forcing a super-geostrophic flow.

The daytime variation of temperature (soil, surface and 10m) was very similar to that in Expt. C1 but the night-time phase was in much better agreement with the full model with a minimum 10m temperature of 19.4°C at

T+21. The surface temperature at the same time was 19.2°C showing that the 10°C difference in Expt.C1 has been completely eroded. The wind speed at 10 and 110m at T+21 in this experiment were 2.5 and 7.3ms^{-1} compared 1.5 and 3.7 ms^{-1} in Expt.C1 showing the consistency of stronger near-surface wind and boundary layer shear with extra mixing.

Experiment C3 - Interactive radiation, geostrophic wind = zero

The comparison of the observed and modelled net radiation during the night (Section 3(d)) revealed a considerable discrepancy with a tendency for too much surface radiational cooling in the model in spite of the fact that the diurnal screen level temperature variation was satisfactorily simulated. Some compensation between errors in the soil model parameters and the crude radiation scheme was inferred. A comprehensive radiation scheme (Slingo and Schrecker, 1982, and Roach and Slingo, 1979) is currently being tested for inclusion in the operational Mesoscale model. Experiment C1 was repeated using this scheme instead of the current operational radiation scheme. The resulting simulation was very similar in the daytime with surface and 10m temperature maxima different by less than 0.5°C. The surface temperature minimum for the following night was, however, almost 6° colder though with a similar difference between 10m and surface temperature (≃9°C). The net radiation during the night was found to be similar to that in the 3D model at ≃ -70 Wm^{-2}. Since, in this case, the column model's temperature and humidity profiles are considerably in error due to the lack of sufficient mixing near the surface we are limited in what we can say about the above result. It should be noted that the net radiation in the column model with the operational radiation scheme was some 20 Wm^{-2} higher (i.e. -47 Wm^{-2}) than in the full model simulation due to the unrealistically large temperature inversion in the lowest layers. The effect of additional mixing in this experiment therefore may further decrease the net radiation and widen the discrepancy between model and observations. Some light could be thrown on the problem by using observed and model profiles (with surface temperature) in a diagnostic test of the interactive radiation scheme.

A possible explanation for the apparent model error in the net radiation is that the surface soil layer temperature is inappropriate in the evaluation of the blackbody radiation emitted from the surface. Since infrared radiation is emitted from a very thin layer near the surface there can be a large difference between this 'skin temperature' and the mean temperature of the surface soil layer (which can be thought of as a few centimetres thick). Since the surface soil layer will be warmer than the skin temperature at night and vice versa by day the net radiation should be overestimated by day and underestimated by night (i.e. more negative - as in the model). The deep soil layer is apparently able to compensate for this by supplying extra heat to the surface by night after receiving more than is appropriate from the previous day's sunshine.

5. OBJECTIVE ANALYSIS OF PROJECT WIND DATA

(a) Introduction

The following steps were carried out at Tel Aviv University with the assistance of Ms Rachel Rosenthal and Ms Shoshana Adler.

(i) The three-dimensional objective analysis program provided by Dr J. Purser (Met O 11) was put on the local CDC computer and run with various parameters in order to make it suitable for mesoscale analysis. The modification of the program was not successful and following correspondence with Dr Purser and further experiments we discontinued this route.

(ii) Ms Shoshana Adler ran a two-dimensional Cressman type interpolation. The basic scheme calculates an interpolated value, ϕ_A, at point A of any scalar $\phi(x,y)$ using the formula

$$\phi_A = \sum_{L=1}^{N} W_{iA}\phi_{oi}$$

where ϕ_{oi} are observed values of ϕ at all (N) points within some specified radius R (the 'radius of interpolation'), and W_{iA} are weighting functions defined by

$$W_{iA} = N_{iA} \frac{(R^2 - d_i^2)}{R + d_i^2}, \quad d_i < R$$

$$W_{iA} = 0, \ d_i > R.$$

Here d_i is the distance between A and the i^{th} observation point and the constants N_{iA} are chosen so that

$$\Sigma W_{iA} = 1$$

The objective analysis was carried out by successive applications of the scheme over a rectangular grid of points A with a gradually decreasing radius of interpolation for both winds (individual components) and temperatures. With most of the observation points clustered near the centre of the grid area, this enabled the outer grid values to be calculated with large values of R, in some cases using only one observation, while those near the centre of the region used several observations even with small values of R. Fields were calculated for isobaric surfaces and for a terrain-following surface.

(b) Results

In a series of experiments with various parameters the optimum interpolation was found to be as follows:

(i) A grid of 51x51 points with an interval of 4kms.

(ii) An initial radius of interpolation of 116km successively reduced to 112,108,104,....20kms, i.e. by the grid length of 4Km. Further reduction resulted in too irregular a field.

Figs.19a,b show the location of the radiosonde and surface stations respectively with the general topographical background of the study domain.

Figs.20a,b show the surface analysis of the 10m wind and screen temperature distributions for 2300 GMT (1600 PDT). The flow is generally southerly through the Sacramento Valley and is in good agreement with the model results from Fig.13 at the central region where the observations are available.

(c) Discussion

In the Sacramento Valley region where most observations are located, the analysis works well and the wind flow and temperature distributions are in good agreement with the simulated fields. The upper-level flow variations were found in general to be small and since the departures from the simulations were insignficant, they are not shown.

It is not expected that the interpolation scheme can realistically represent the wind flow and temperature distributions outside of the observational region, particularly over a complex terrain where appreciable variations occur over small horizontal distances. An alternative approach which can do better is by a 3-D mesoscale model initialization procedure which considers the topographical effects over the appropriate horizontal scale.

(d) Future plan

The Penn-State/NCAR model will be applied for the 3-D analysis of the WIND data. The analyses will serve both for initializing and for verification of the mesoscale model. At first, single radiosonde initialization - similar to these performed by the SIGMET and the UKMO - will run and be compared to the other model simulations. Next, the initialization including the five radiosonde available and all surface reports will be applied.

6. CONCLUSIONS

The conclusions to be drawn from these experiments fall into two categories (a) those relating to the behaviour of the UKMO model itself and (b) those which relate to the overall strategy of mesoscale model development based on project WIND data. The former are listed under (a) below. The latter have held to sets of recommendations being drawn up at two subsequent Mesoscale Meteorology Advisory Panel meetings, one a mini-panel at ASL, 14-16 September, 1988, and the other, a full panel meeting in Las Cruces 10-14 April, 1989. Both sets of recommendations are shown under (b) below. Obviously those of the April 1989 meeting supercede those of the September, 1988, meeting.

(a) Specification of model parameter values

1. The model parameters involved in the surface energy balance need to be chosen with great care if forecasts of the surface diurnal cycle are to be made with acceptable accuracy. In the experiments carried out so far with the UKMO model, a surface labedo of 0.3 and an evaporative resistance of 500 sm^{-1} yielded good results.

2. The UKMO model's radiation scheme, when compared with the more sophisticated scheme of Rodgers and Walshaw, gives a larger value (by about 100 W m^{-2}) of the downwards long-wave flux. Modification of the model scheme leading to a reduction of the downward flux by this amount would considerably reduce the discrepancy between the model and observed net incoming radiation during daytime.

3. Experiments with a single column version of the model suggest that the sharp rate of change of the rate of fall of temperature in the model around midnight is linked primarily with the surface net radiation change. The surface soil layer temperature is inappropriate in the evaluation of the emitted black body radiation. Further study of the soil heat balance is needed.

4. Experiments with the single column version of the model, which suppresses any effects of temperature advection in the surface layer by the flow near the ground, indicate, when the results are compared with WIND data, that these latter effects are important and need to be modelled.

(b) Future modelling strategy

The experiments with the UKMO model were undertaken to provide a standard of comparison for the performance of the SIGMET model - clearly the highest possible accuracy of SIGMET products is required if the heirarchal concept is to work at all. Mesoscale predictability based on numerical models has only recently been subject to detailed testing, and only then at one or two centres, such as the UKMO, with major computing facilities. It is therefore necessary to ensure that the simplifications imposed on the design of SIGMET by computer constraints are those having minimal effect on its performance, and this can only be done by comparing it with results from using a much more sophisticated model.

One of the main reasons for the delay in development of mesoscale forecasting, despite the availability for some time of computers adequate for this purpose, has been the lack of a good observational data base for model testing. The WIND project has provided just the kind of data the modellers need. For this reason the first experiments carried out at the UKMO using the data have been directed towards understanding the model's performance an making 'tuning' adjustments. A broad measure of its overall behaviour is provided by the statistics in Table 2 (but comparisons with observations based on statistics alone can only provide a measure of the progress made in model improvement and not the nature of the modifications needed to achieve it!)

The studies carried out so far have concentrated mainly on the prediction of near-surface conditions. There is much more information in the outputs from the 4 UKMO experiments to be examined in detail, so that the first recommendation is that:

> Further diagnostic studies be carried out on the UKMO runs in order to identify as far as possible the reasons for the errors in forecast winds. These will require further experiments to examine, for example, the errors resulting from the 'single station' initialisation of the model.

RECOMMENDATIONS OF THE SEPTEMBER 1988 MINI-PANEL MEETING

Experiments with the UKMO model and those using the SIGMET model were discussed in detail at a 'mini-panel' meeting at ASL, 14-16 September, 1988. These led to the following set of recommended tasks to be carried out on the SIGMET model before it is used in an extensive series of integrations using WIND data for validation purposes:

1. Complete the modification of the programme using the perturbation technique in order to substantially increase the time-step.

2. Carry out minor adjustments of parameter values, based on the UKMO model experiments and move the lowest level of the model to 10 m above the surface.

3. Run SIGMET for both Phase I 24-hour cycles and compare the main features of its output with WIND observations.

4. If the results are satisfactory, document the SIGMET model in full detail.

5. Examine the UKMO output (Experiment 4) and compare with SIGMET output for June 27/28 (u, v, w, T, radiation).

At the same time SIGMET must be revised to interpolate sensible heat fluxes and 50 m winds (instead of surface temperatures and winds) for input into VARYME.

On completion of these tasks, the hierarchy should be run using the same sets of WIND data, and outputs from HRW compared with observation.

Work on the objective analysis scheme already commenced by Mrs Zak-Rosenthal in Tel-Aviv should be completed. It is also desirable that an alternative objective analysis scheme incorporating mass conservation be developed at ASL.

Work should continue using WIND data on development of procedures for representating the basic physics in the model. This could proceed under Dr Alpert's supervision at Tel Aviv using the most advanced version of the NCAR/PENN STATE model which is now operational there. An assistant may be available to carry on these studies from March 1989.

The proposed time-table for all of these activities is:

88	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	89
ASL	←Revision of SIGMET→		←SIGMET→		←Hierarchy→ runs ←SIGMET→ Documentation	Technical Assessment Meeting(ASL) (Alpert,Pielke)		Panel Meeting	
Tel Aviv University		Objective analysis scheme → Examples of flow fields				← Model physics development			

RECOMMENDATIONS OF THE APRIL, 1989, PANEL MEETING

R2. All development work on SIGMET should cease forthwith.

R3. SIGMET should be replaced by a state-of-the-art validated mesoscale model (see Appendix 4 for discussion of specific available models).

R4. ASL should write software to reformat the output from the new model so that it resembles output from SIGMET. The new model should be inserted into the Hierarchy.

R5. ASL should make arrangements for a suitable scientist with meteorological modelling skills to be responsible for the implementation and maintenance of the new model. The chosen individual should work alongside scientists at the donor institute and manage a long term contract to ensure continued input of expertise into ASL's mesoscale modelling effort.

R6. The research program should actively explore the initialisation of the hierarchy using data from operational models from USAF Global Weather Center, which is the primary source of forecast information to the Staff Weather Officer and to the US Army.

R7. The possibility should be explored of a USAF Staff Weather Officer being assigned to ASL to assist in the implementation of recommendation R6 and complement ASL's research efforts.

The above recommendations make no reference to the testing of the models using data from the other three phases of project WIND. This is deliberate since it is essential that the models first be thoroughly tested, compared and refined, and properly understood, along the lines proposed above under the relatively stable atmospheric conditions of Phase 1. There is nothing to be gained in going ahead at this stage in examining their performances under the more disturbed and complex conditions of the other phases, when moisture, for instance, plays a more crucial role.

There is no reason, however, why this strategy should delay testing the other models in the hierarchy. The project WIND data can be used to provide input into VARYME on the scale corresponding to SIGMET's resolution and tests of its performance carried out. Indeed, it is desirable that this be done quite apart from using input from SIGMET.

Acknowledgement

The major part of Section 4 was prepared by Dr G J Shutts of the Meteorological Office, and that of Section 5 by Dr P Alpert of Tel Aviv University.

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Slingo, A. and Schrecker, H.M., 1982. On the shortwave radiative properties of stratiform water clouds. Ibid, **108**, 407-426.

Williams, Michael D., Cionco, Ronald M. and Ohmstede, William D., 1986. Construction and validation of meso- and micro-scale meteorological model. [Presented at the 79th Annual Meeting of the Air Pollution Control Association, 19 June 1986, Minneapolis, Minnesota].

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TABLE 1. Summary of the four model simulations.

Experiment	Vertical spacing (Number of levels)	Evaporation resistance ($s\ m^{-1}$)	Surface albedo	Period of integration (hours)
1	as in SIGMET (15)	100	0.18	24
2	as in operational MO mesoscale model (16)	100	0.18	6
3	" " " "	500	0.18	24
4	" " " "	500	0.30	24

Table 2. Statistics for winds and temperatures in the model simulations and the observations at 850, 700 and 500 mb. The Table is based on 54 available soundings at 5 radiosonde stations and 12 times (19, 21, 23, ... 17 GMT).

Parameter	Height (mb)	Observations Mean		Model Mean			Expt. 2	
		(MO)	(Williams)	Exp.1	Exp.3	(Williams)	Model mean	Obs. mean
T(°K)	850	293.74	293.3	291.37	291.62	291.6	291.03	293.64
u(ms^{-1})	850	-0.45	-0.4	-1.00	0.08	-3.7	-0.35	0.18
v(ms^{-1})	850	5.67	5.6	6.72	9.39	9.7	9.62	6.74
T(°K)	700	280.79	280.3	281.33	281.39	278.6	281.4	281.48
u(ms^{-1})	700	3.22	3.1	1.77	5.71	3.6	5.18	3.65
v(ms^{-1})	700	7.35	7.2	4.18	7.39	7.4	7.56	7.35
T(°K)	500	263.81	263.6	263.1	264.52	269.2	264.37	264.94
u(ms^{-1})	500	10.71	10.9	2.29	8.40	8.3	8.08	9.96
v(ms^{-1})	500	9.83	10.2	-5.78	4.05	8.7	4.47	8.85

COMMENTS:

1. Experiment 2 needs separate calculation of the obs. mean because the simulation was for only 6 hours.

2. Obs. mean is slightly different for MO (Met Office) compared to Williams (Dr M Williams simulation) due to small changes in the raw data available.

Appendix 4

Personnel involved in experimentation with UKMO model and meetings held to monitor progress

Personnel:

Meteorological Office	Dr. P. White Dr. G.S. Shutts Dr. B.W. Golding Mrs. Sue Ballard
Dept. of Atmospheric Science Tel Aviv University	Dr. P. Alpert Mrs. Rachel Zak-Rosenthal Ms Shoshana Adler
Department of Meteorology, Reading University	Prof.R.P. Pearce

Meetings:

Frequent consultations were carried out between Dr Alpert, Mrs Zak-Rosenthal and the Meteorological Office (MO) meso-scale modelling staff whilst they were working at the MO between May 1987 and January 1988.

In addition, the following meetings were held between most or all of the personnel in order to monitor progress.

At Meteorological Office:	5 Aug/87, 10 Sep/87, 23 Oct/87, 27 Nov/87, 6 Dec/87, 6 Jan/88.
At University of Reading:	27 Jul/87, 30 Sep/87, 18 Jan/88, 1 Feb/88 14, 15, 16 Jun/88. Dr R Cionco of ASL also attended the latter three meetings. A meeting to finalise Section 5 was held between Dr Alpert and myself at the University of Reading on 11/8/89.
At ASL:	14-16 Sep/88. Mini-panel meeting. 10-14 April 1989. Full panel meeting.

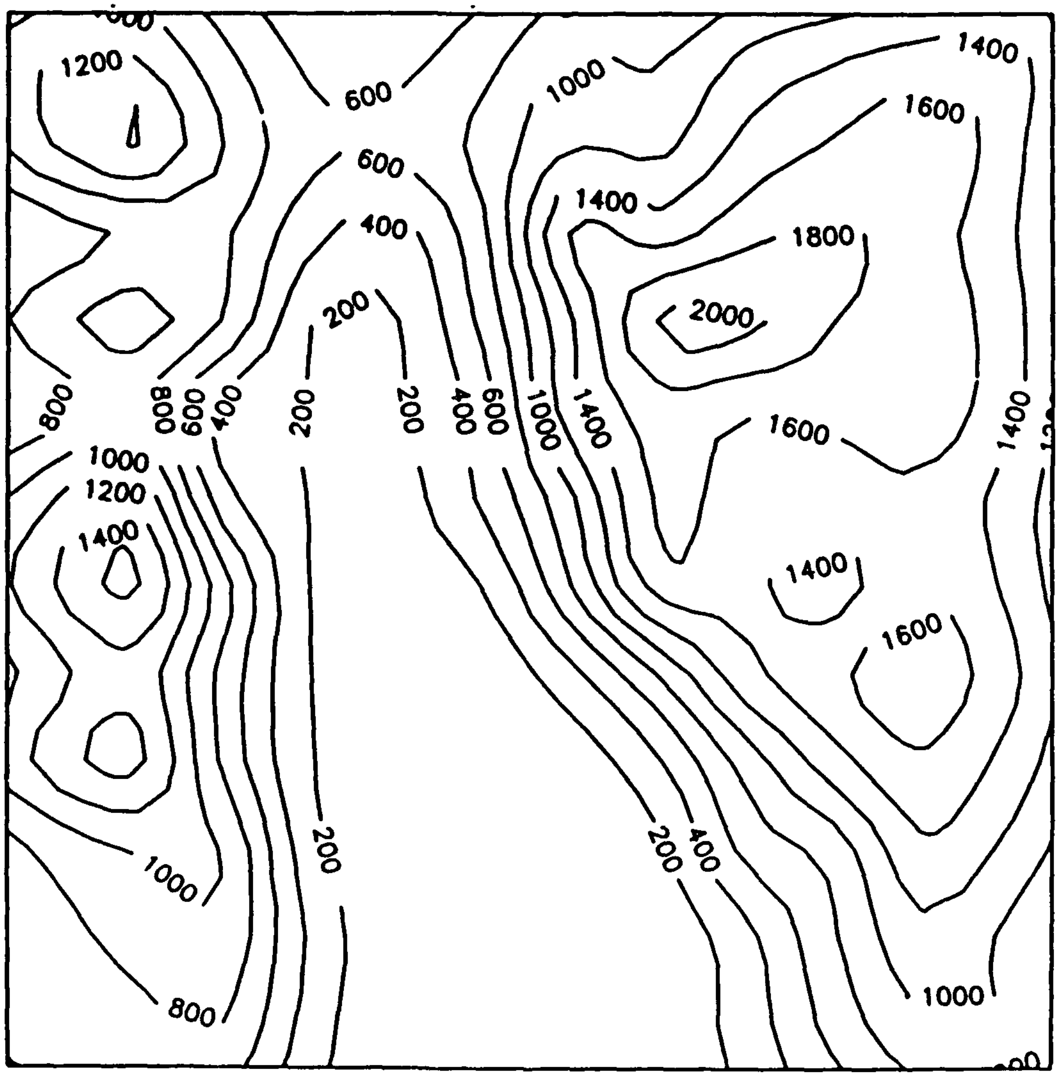


FIGURE 1

Contours of the Sacramento valley area (m) used for the model experiments

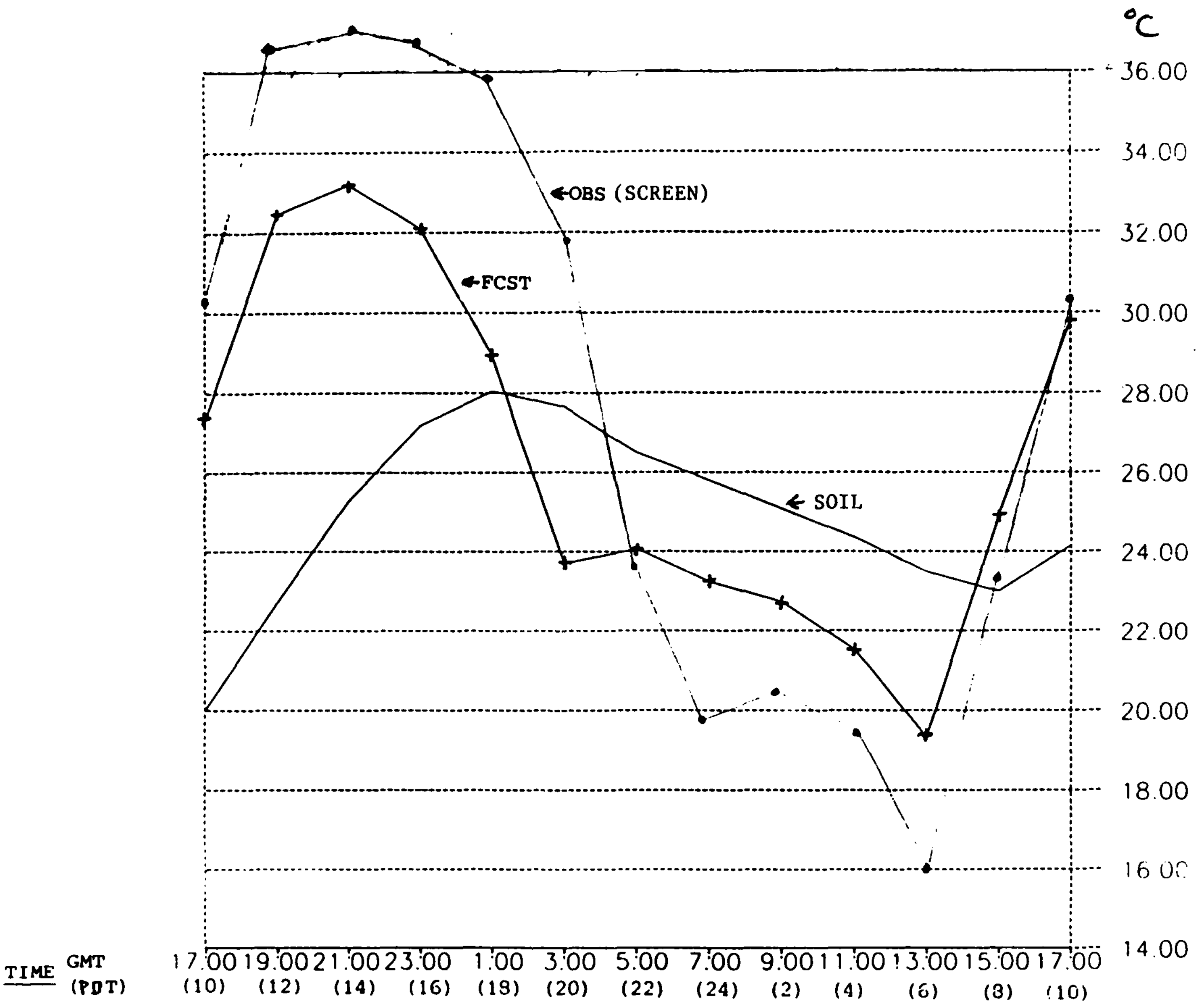


FIGURE 2. SIGMET levels run - Corning Airport (Experiment 1)

Observed and forecast screen temperatures and forecast soil temperatures (°C)

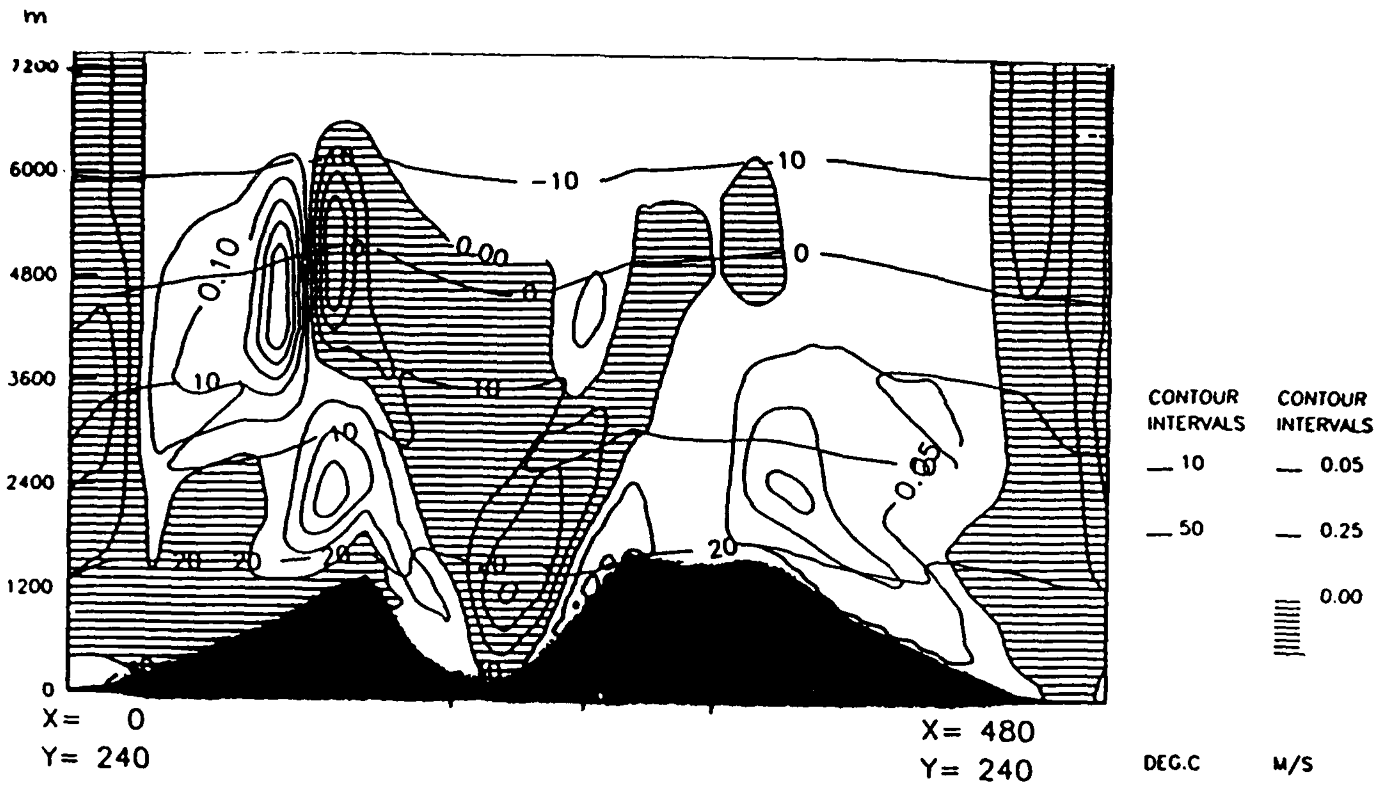


FIGURE 3. SIGMET levels run: temperature and vertical velocity (Experiment 1)

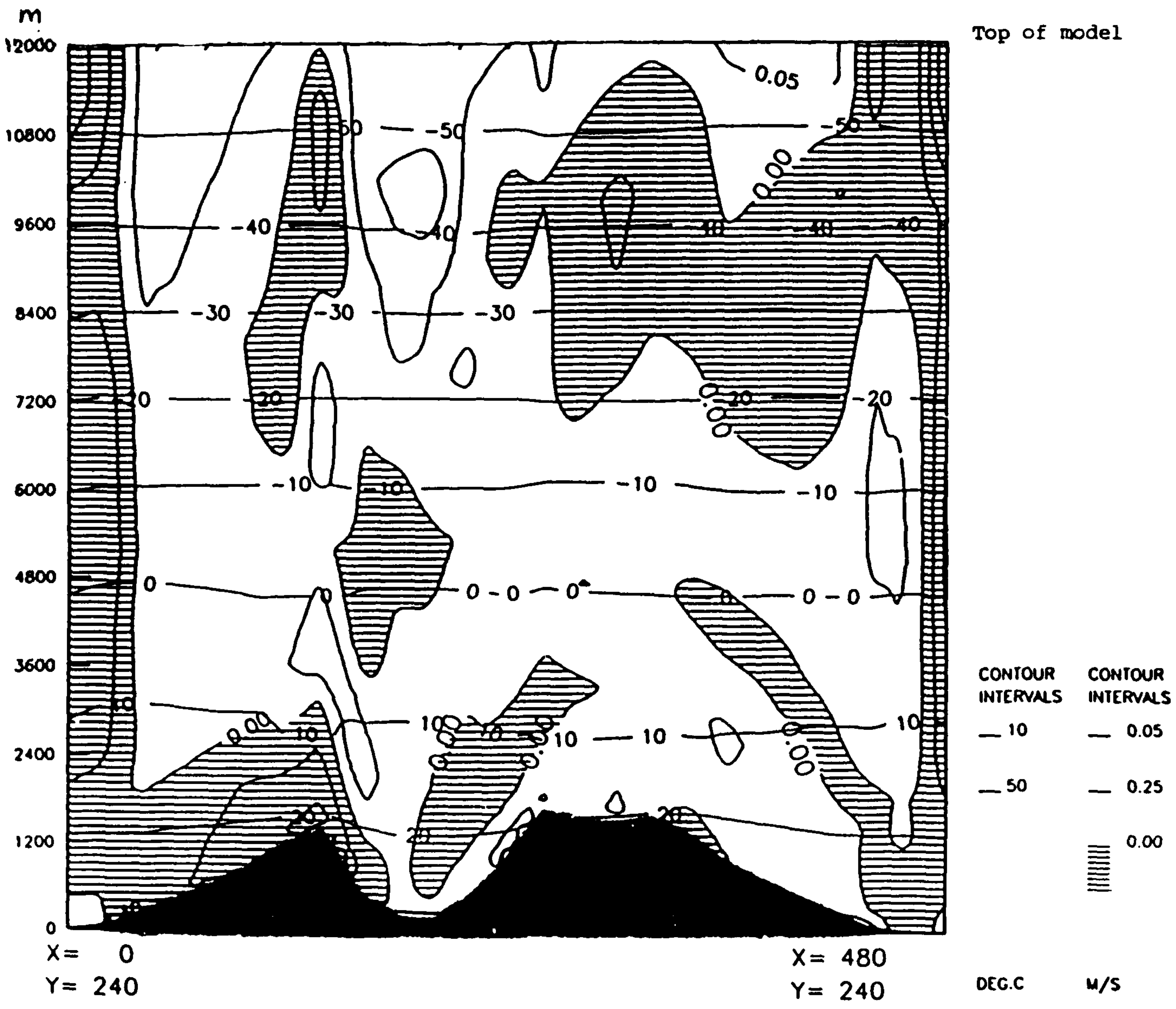


FIGURE 4. Experiment 2: vertical velocity and temperature

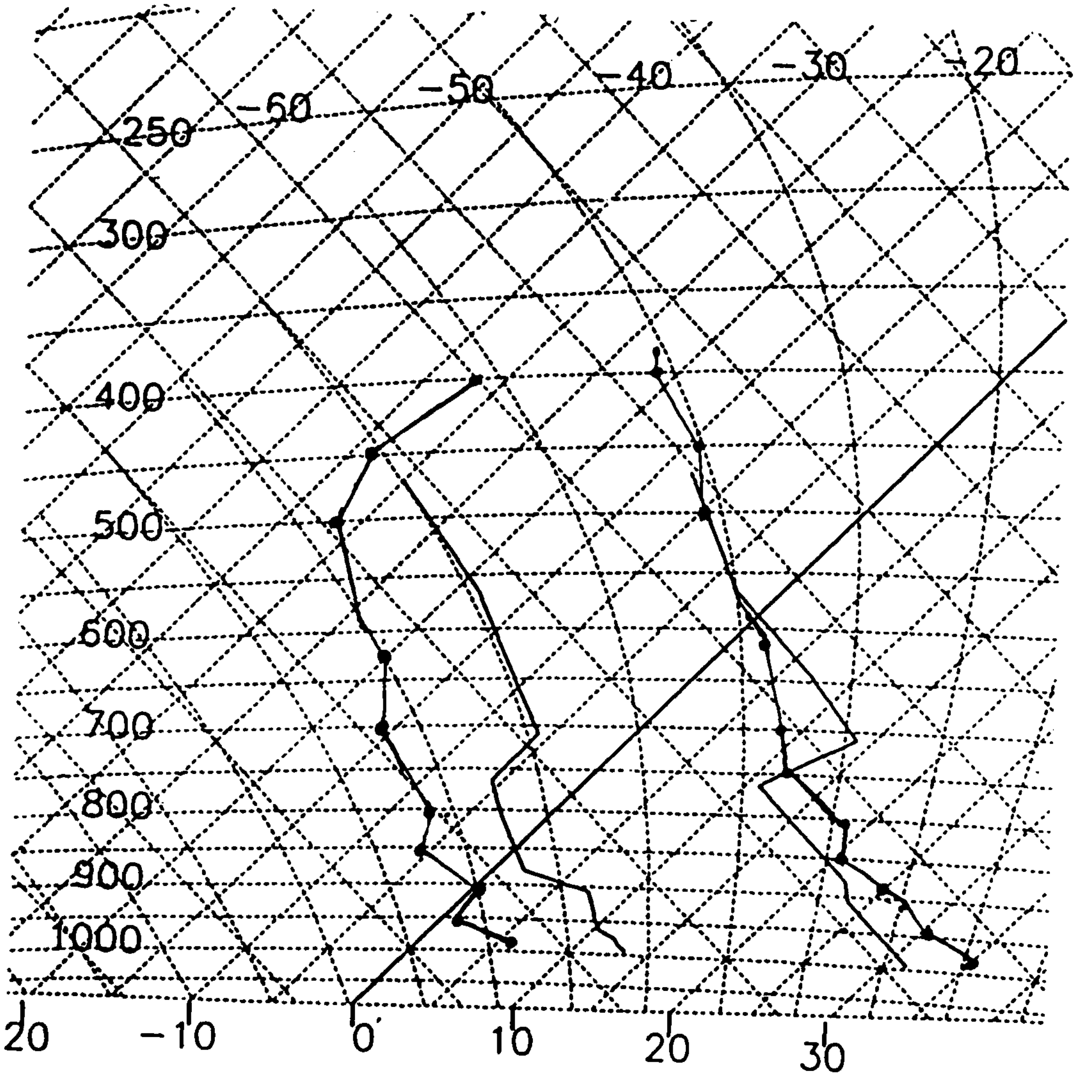


FIGURE 5

Tephigrams of temperature (°C) and dew point (on left), observed (•) and computed for 1600 PDT at Hogsback - Experiment 1.

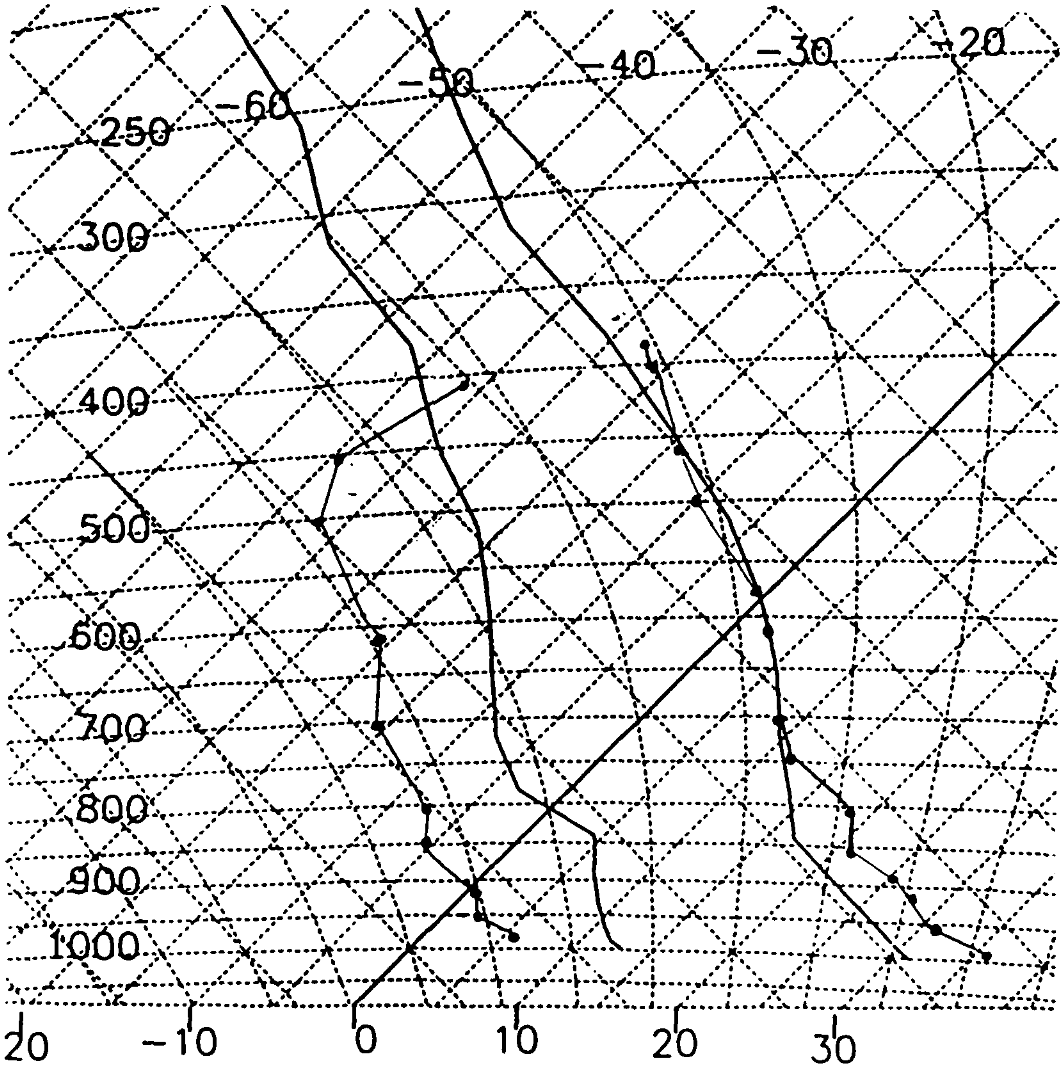


FIGURE 6

As for Fig.5, but for Experiment 2

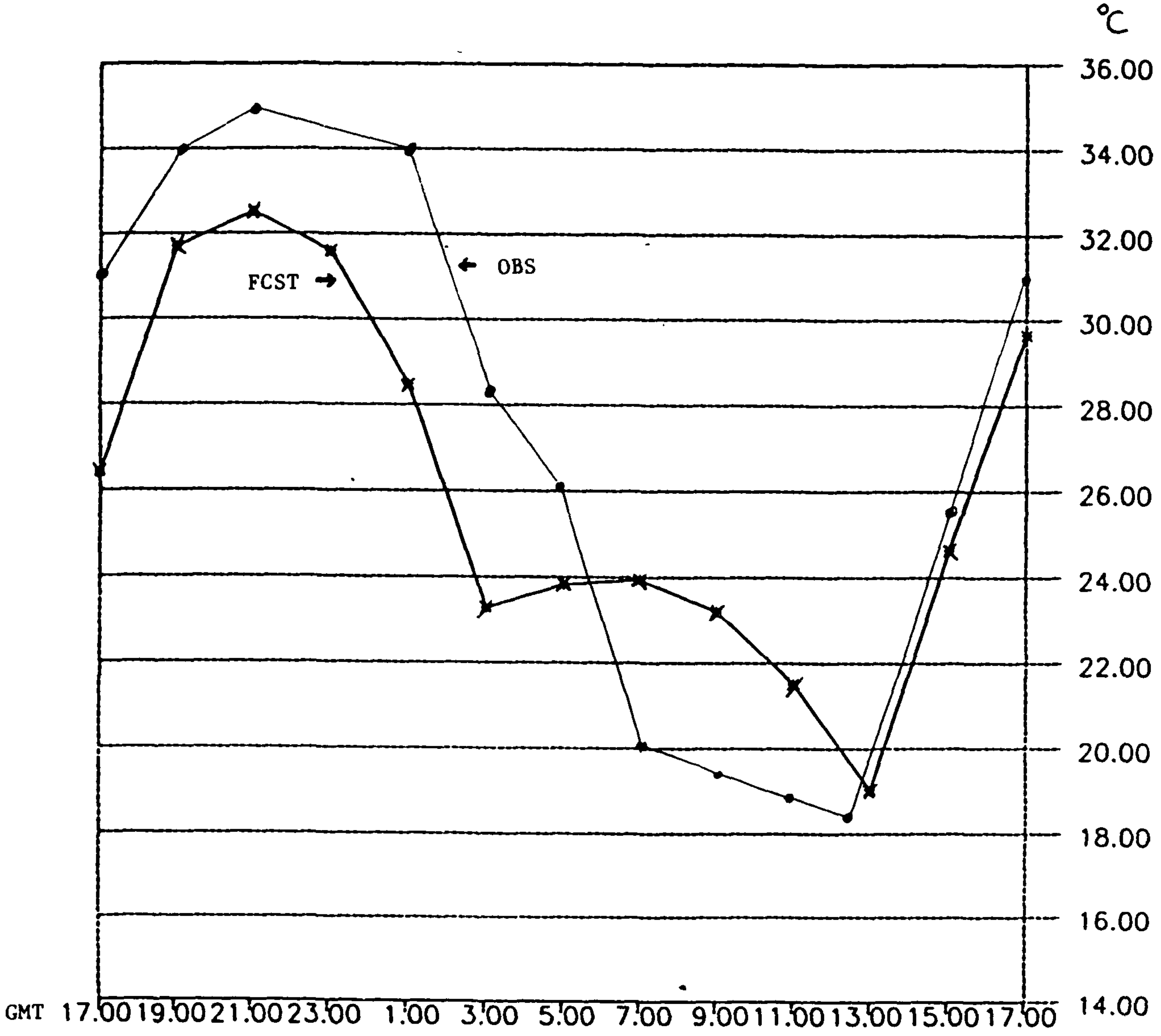


FIGURE 7. Observed (●) and forecast screen temperatures - Hog's Back Experiment 2.

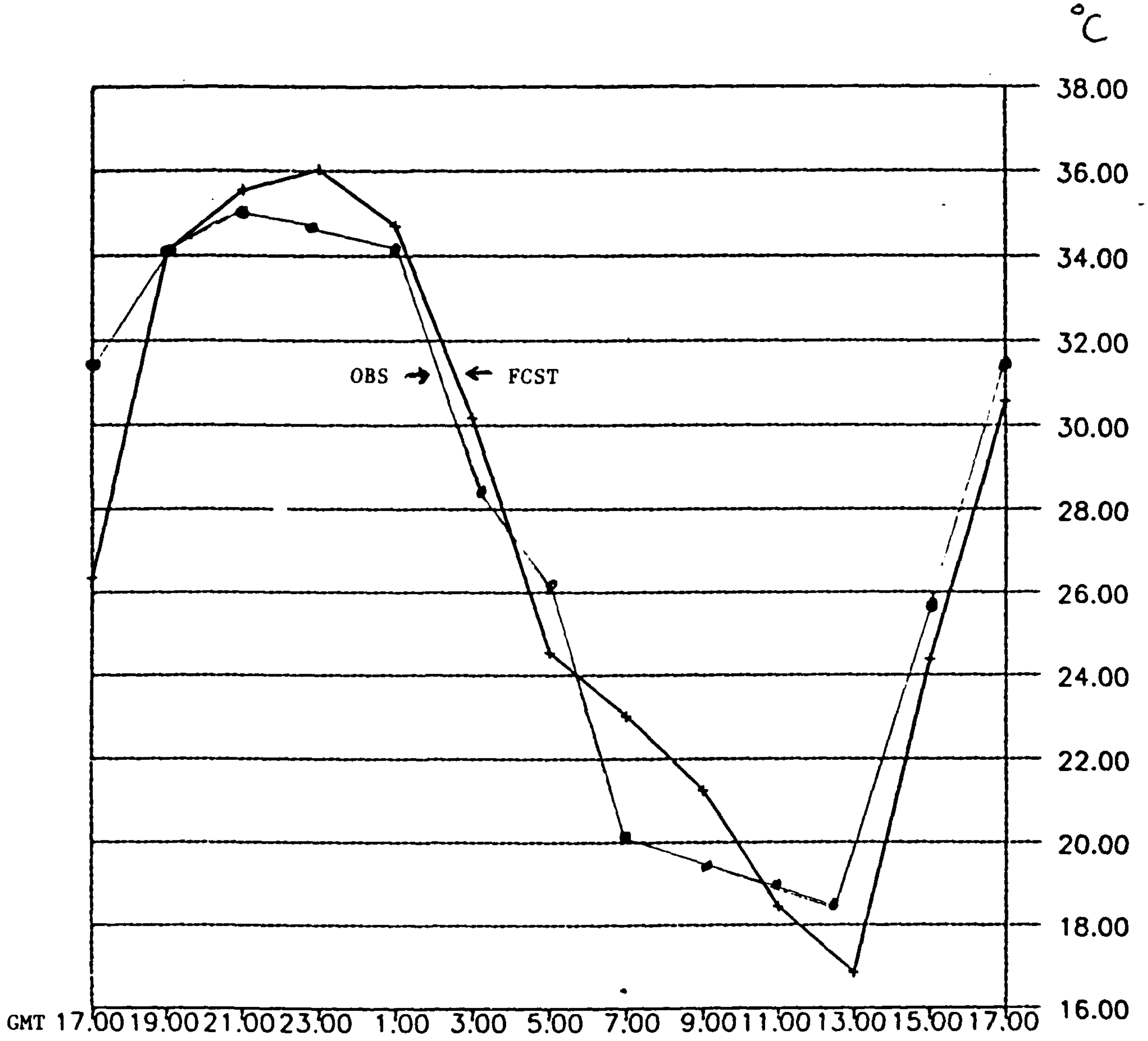


FIGURE 8. As Fig.7, but for Experiment 3

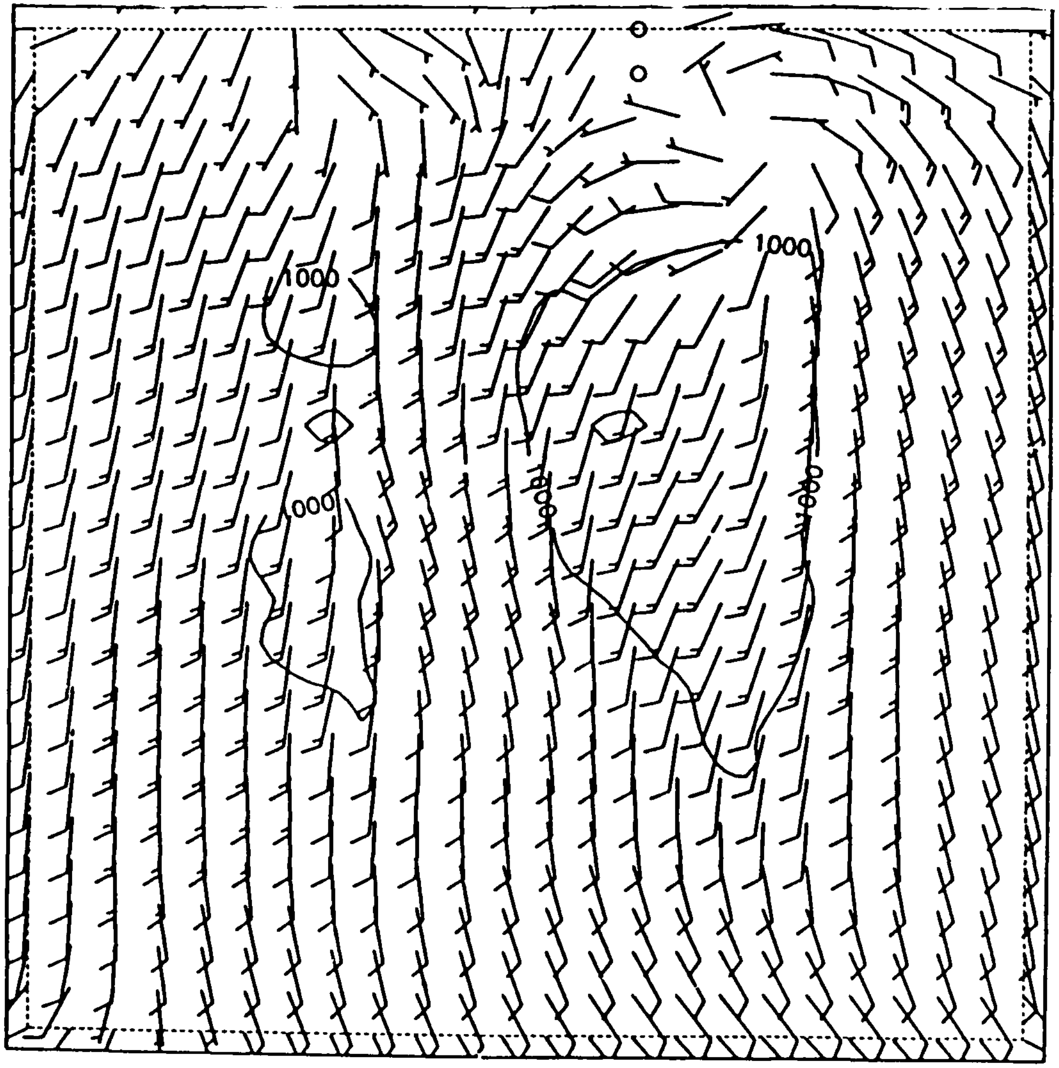


FIGURE 9. Forecast 10m wind vectors for 1600 PDT and 1000 m height contour - Experiment 2.

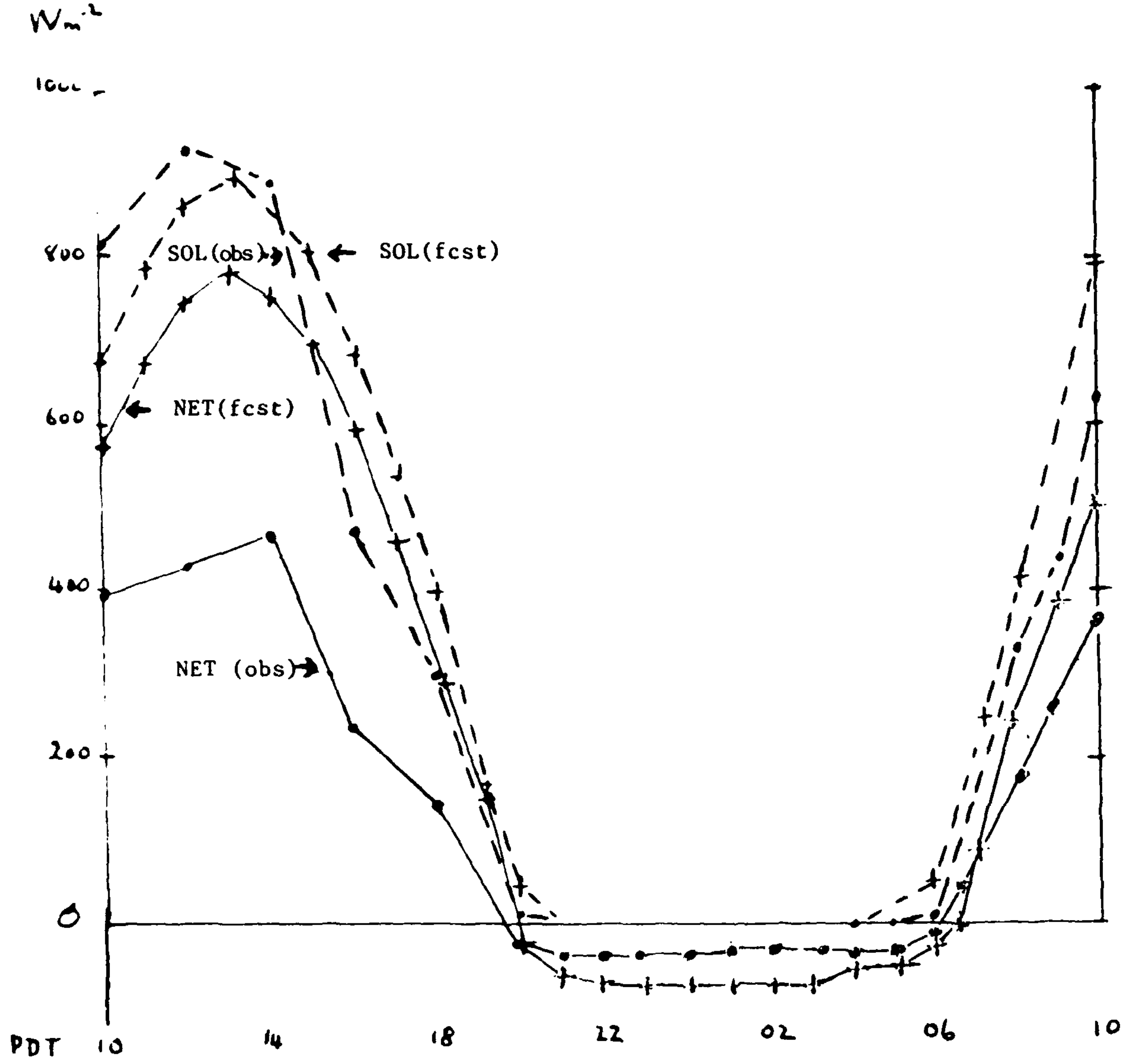


FIGURE 10. Computed solar and net radiative fluxes (W m^{-2}) at the surface - Experiment 3 and observed (●) values (Durham)

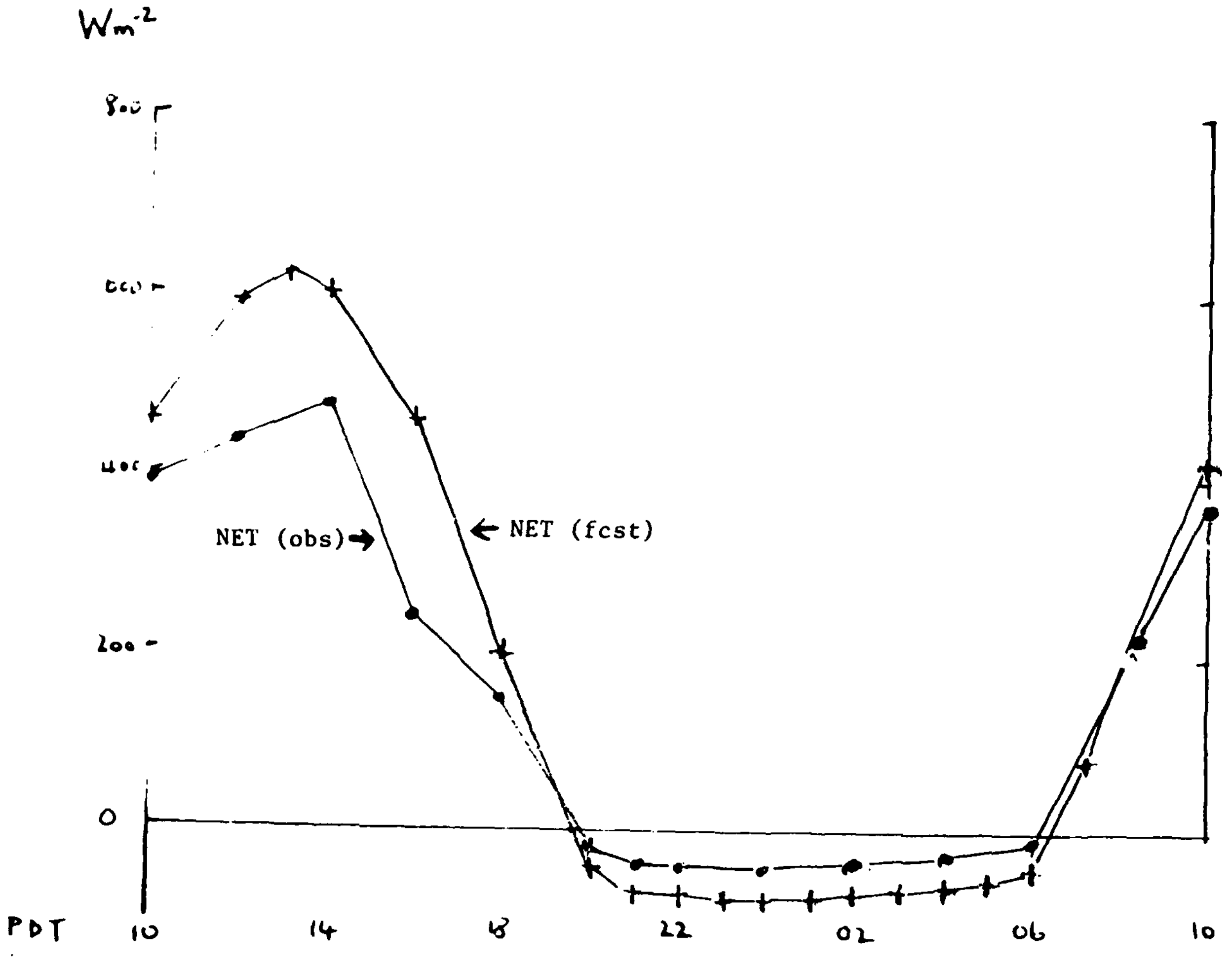


FIGURE 11. Computed net radiation (W m^{-2}) at the surface - Experiment 4 and observed (●) values (Durham).

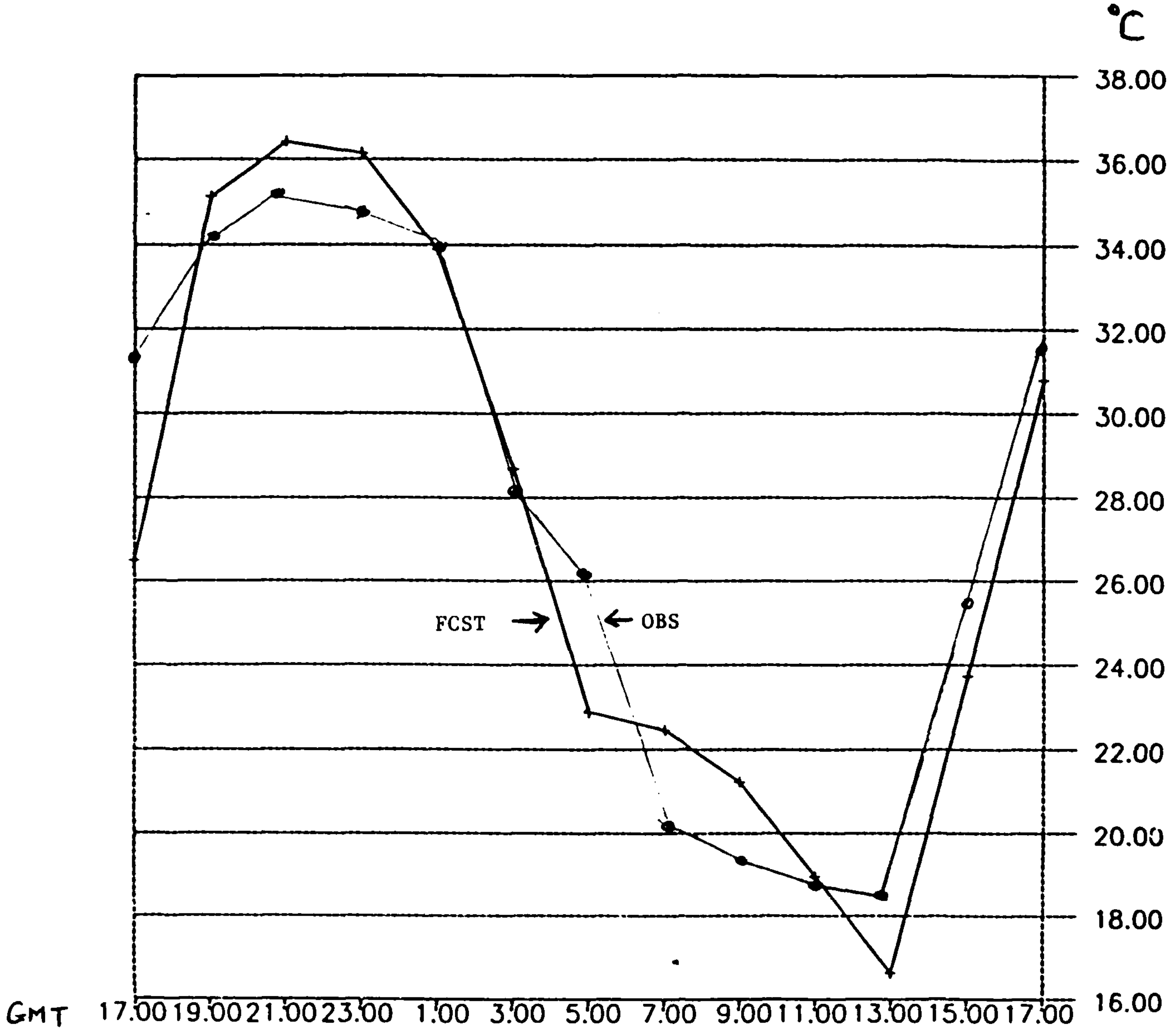


FIGURE 12. Observed and forecast screen temperatures - Experiment 4.

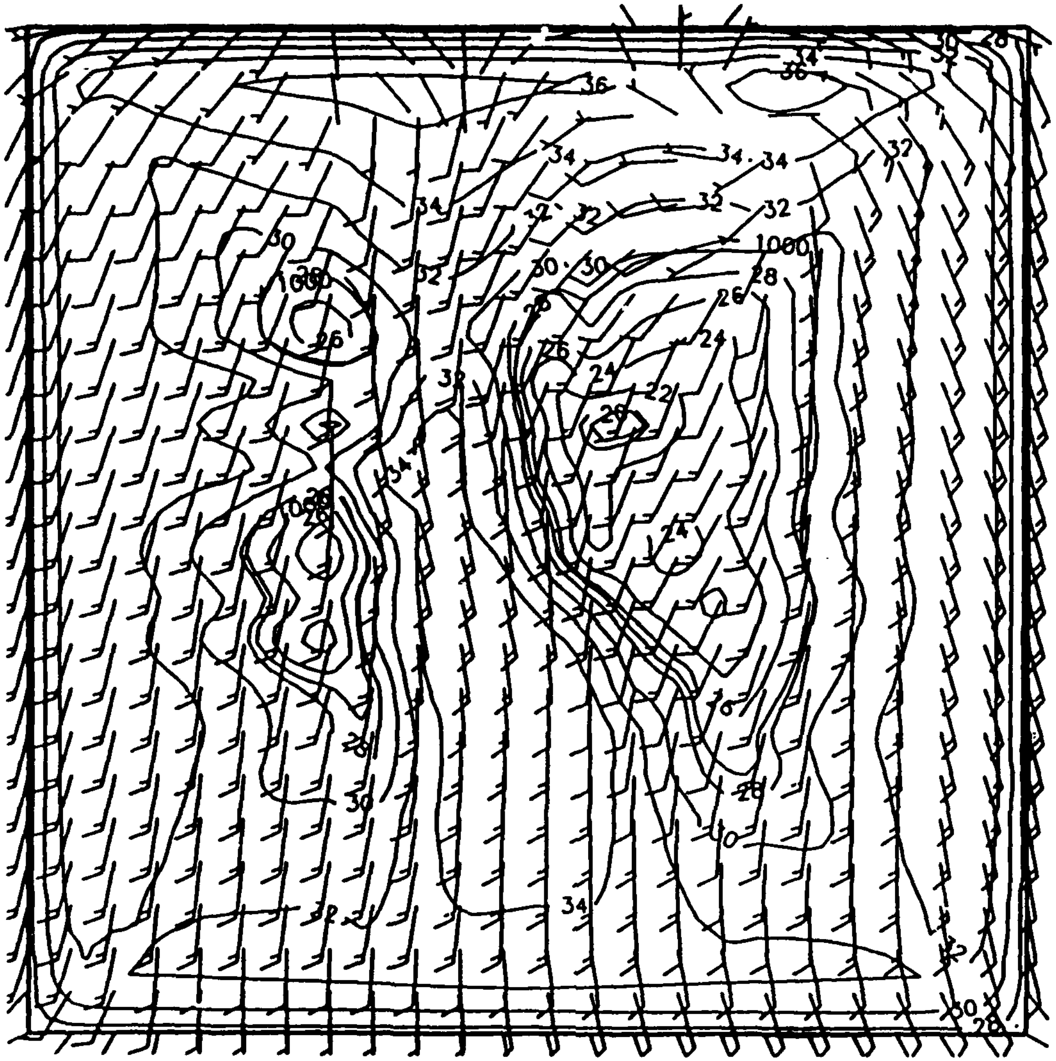


FIGURE 13. Forecast 10 m winds and screen temperatures 1600 PDT and 1000 m contour - Experiment 4.

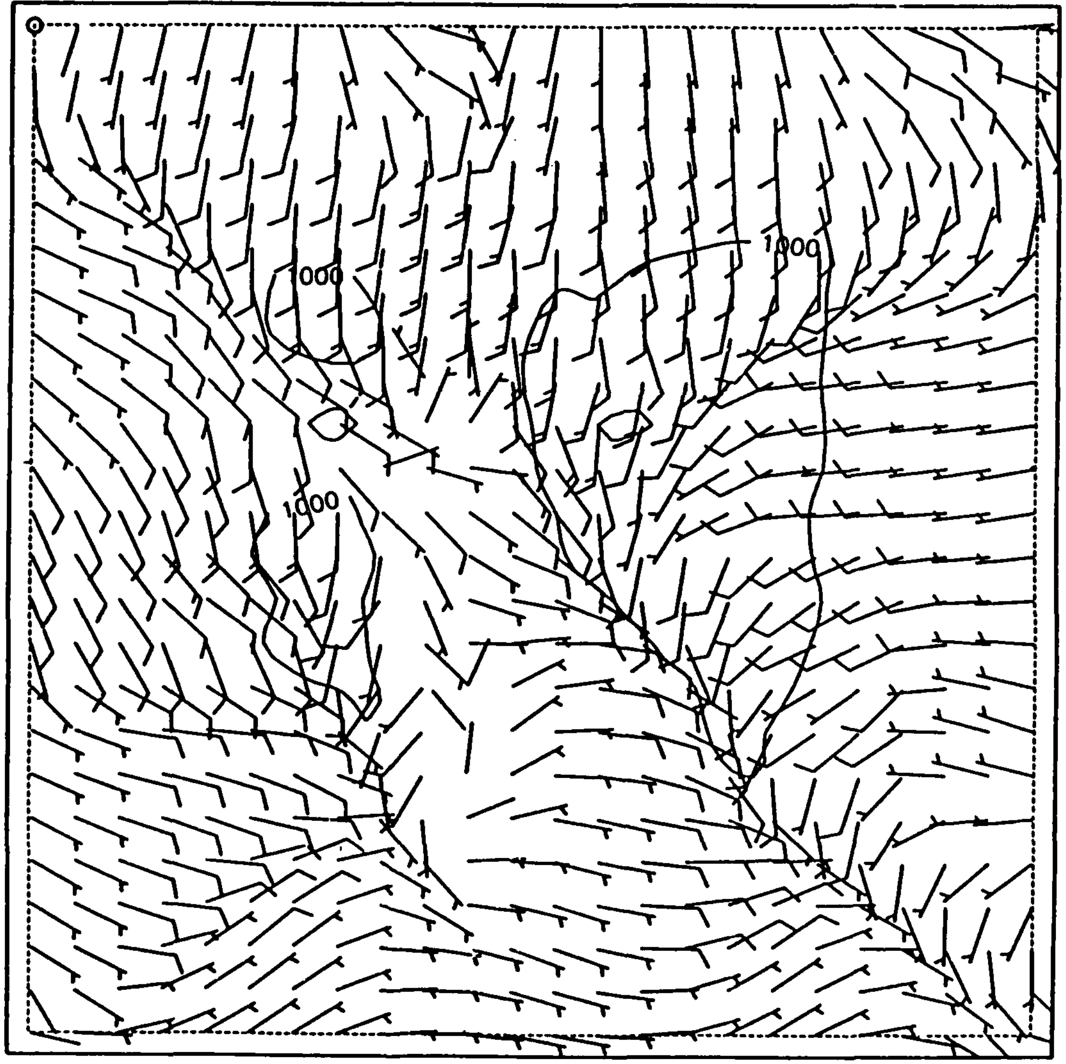


FIGURE 14. Forecast 10 m winds for 0600 PDT and 1000 m contour - Experiment 4.

FIGURE 15. Forecast screen temperature (°C) for 0600 PDT and 1000 m contour - Experiment 4.

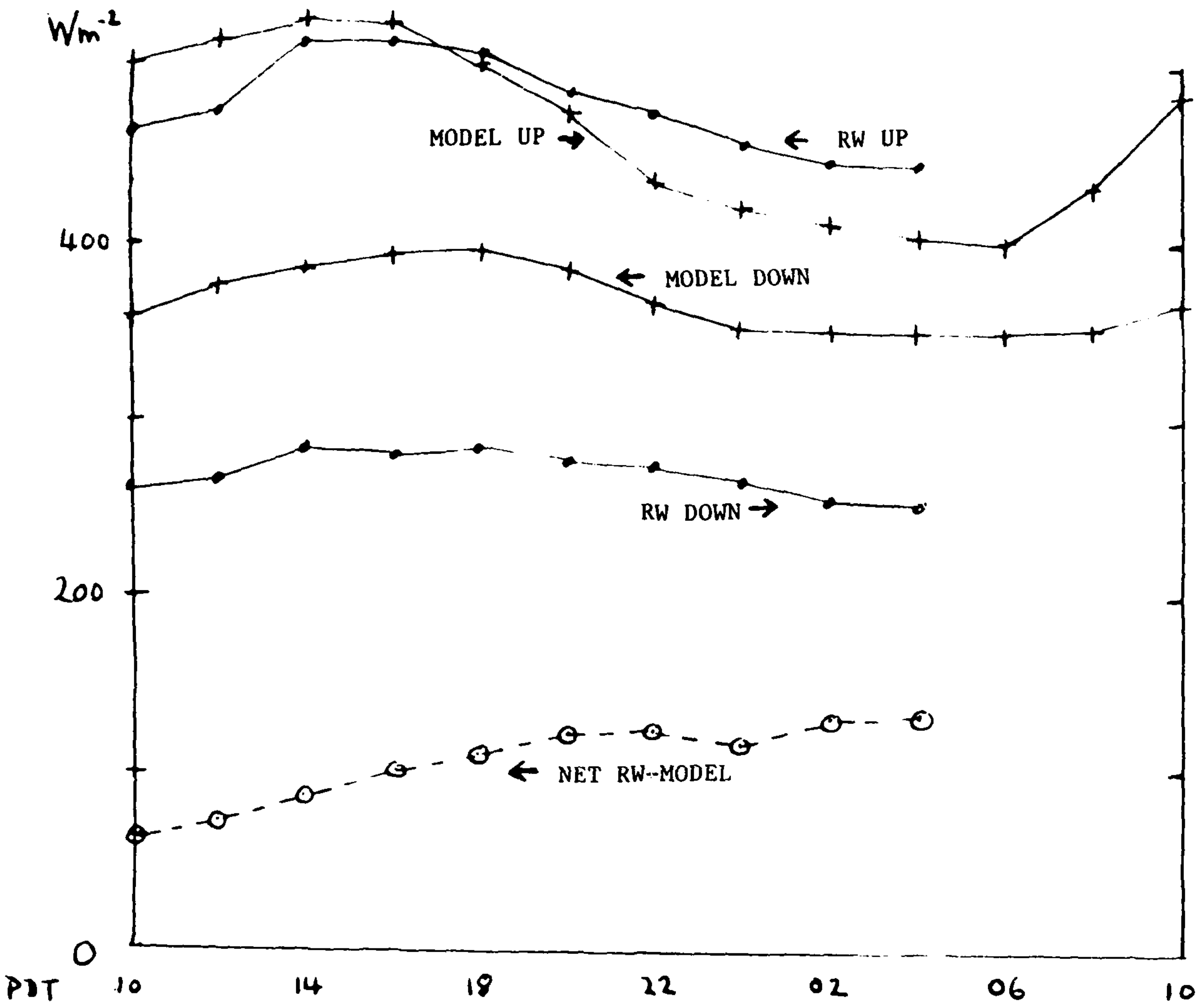


FIGURE 16. Modelled upwards and downwards long-wave radiative fluxes at the surface using the UKMO model radiation scheme (Experiment 4) and Rodgers' and Walshaw's scheme. Also shown is the difference between the values of the net long-wave outgoing flux given by the two schemes.

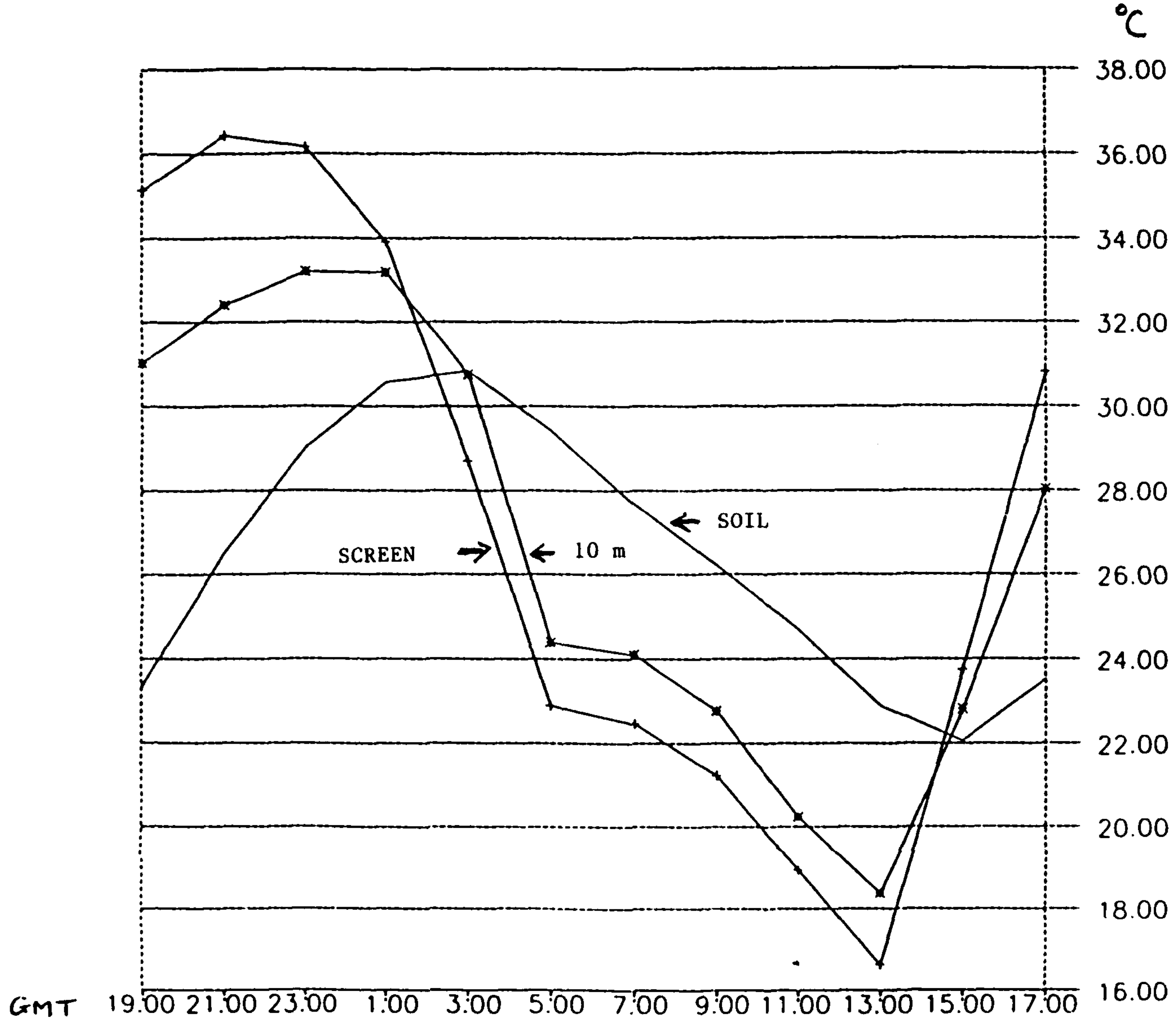


FIGURE 17. Soil, screen and 10 m temperature - Experiment 4.

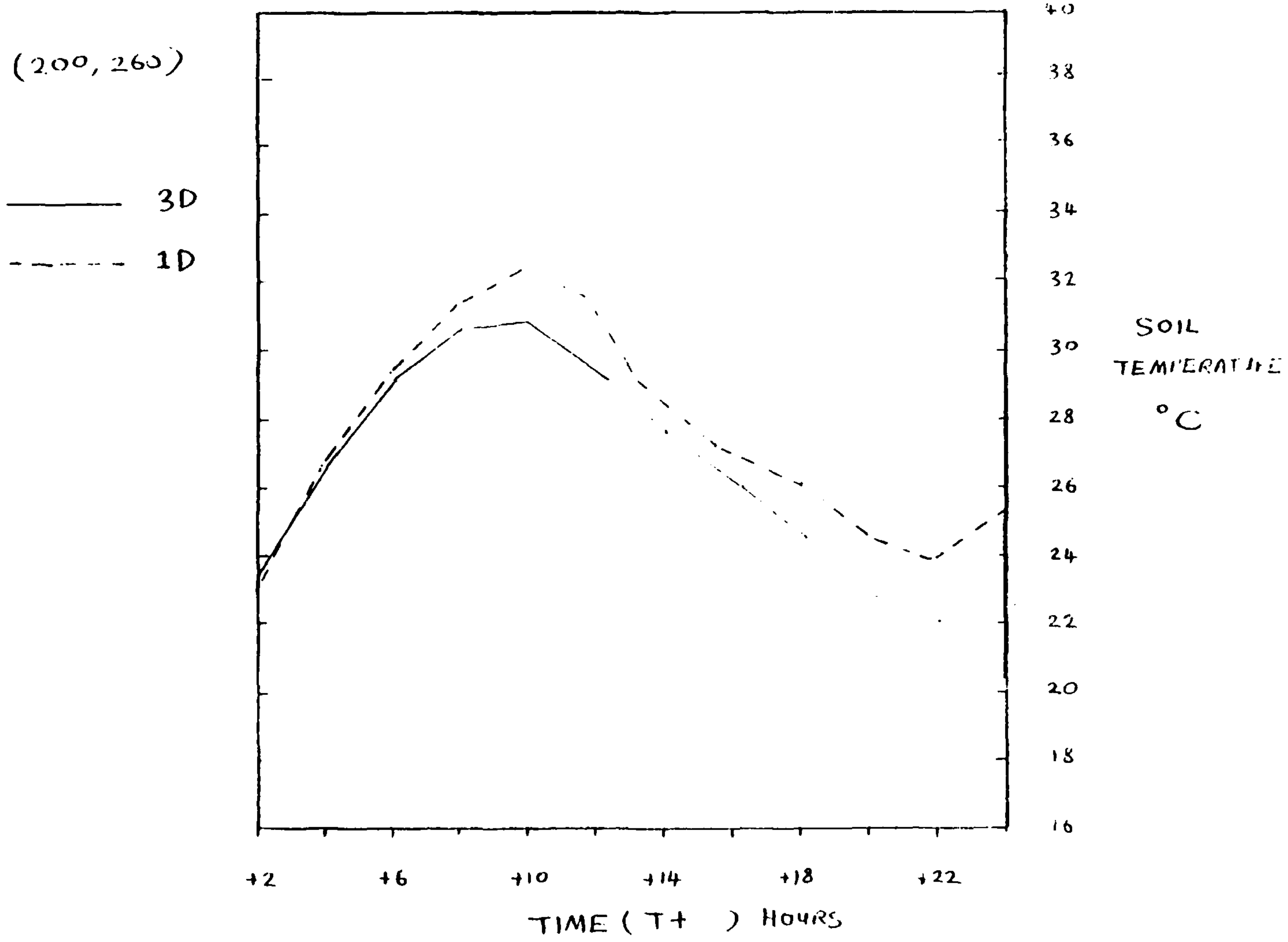

(200, 260)
3D
1D
40
38
36
34
32
30
28
26
24
22
20
18
16
SOIL
TEMPERATURE
°C
+2
+6
+10
+14
+18
+22
TIME (T+) HOURS

FIG.18(a)

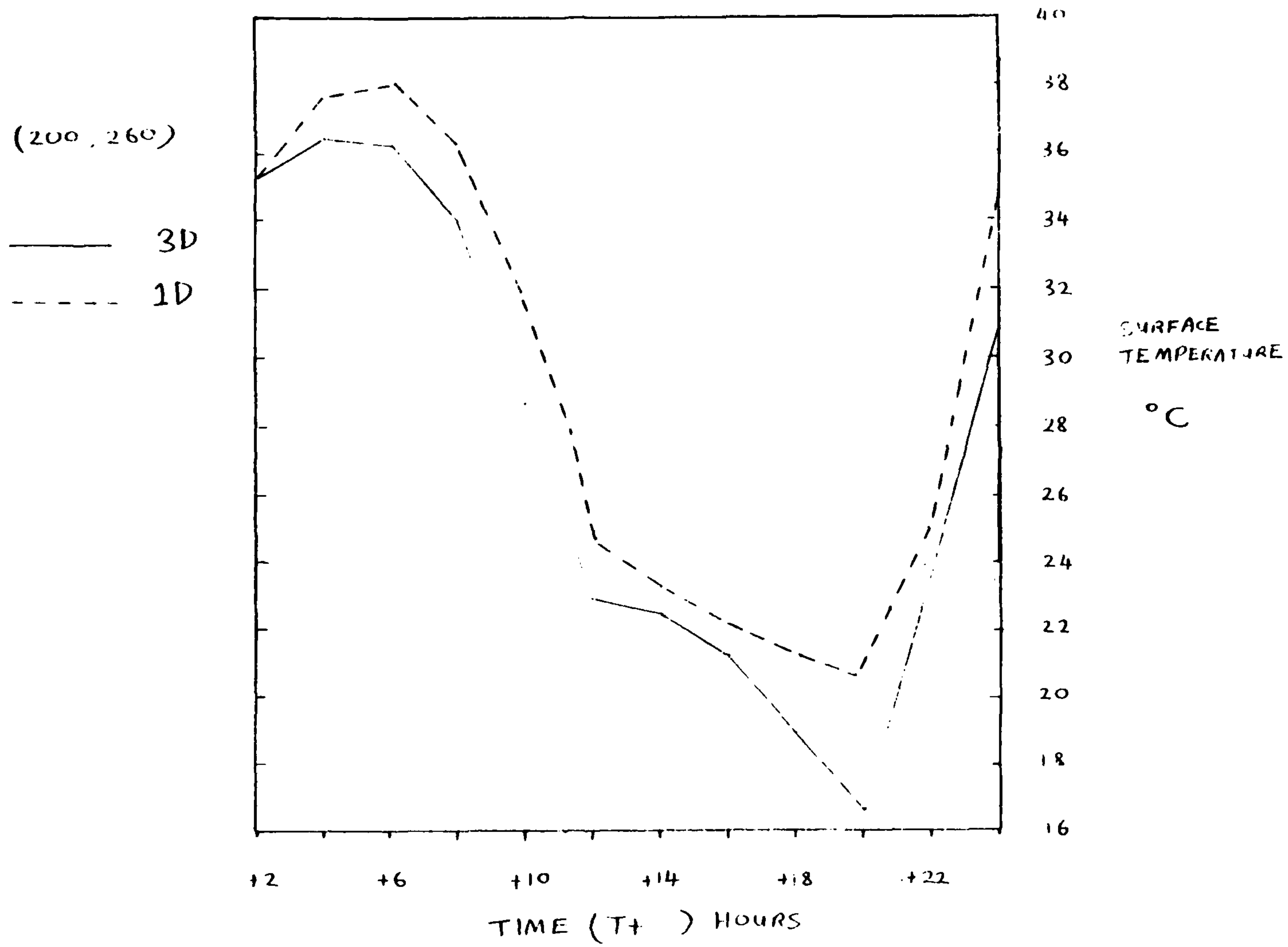

(200, 260)
3D
1D
40
38
36
34
32
30
28
26
24
22
20
18
16
SURFACE TEMPERATURE
°C
+2
+6
+10
+14
+18
+22
TIME (T+) HOURS

FIG.18(b)

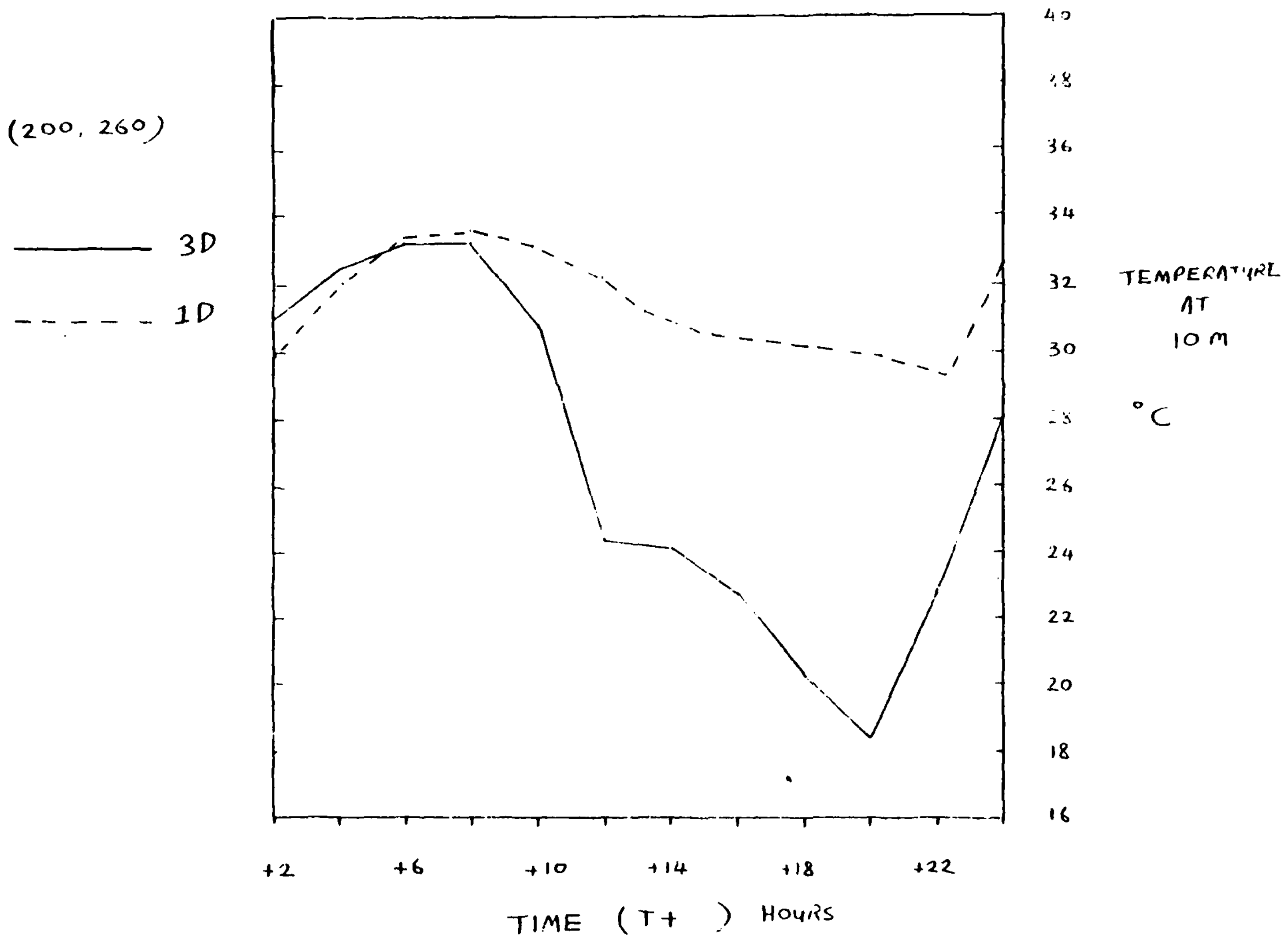

(200, 260)
3D
1D
40
38
36
34
32
30
28
26
24
22
20
18
16
TEMPERATURE
AT
10 m
°C
+2
+6
+10
+14
+18
+22
TIME (T+) HOURS

FIG.18(c)

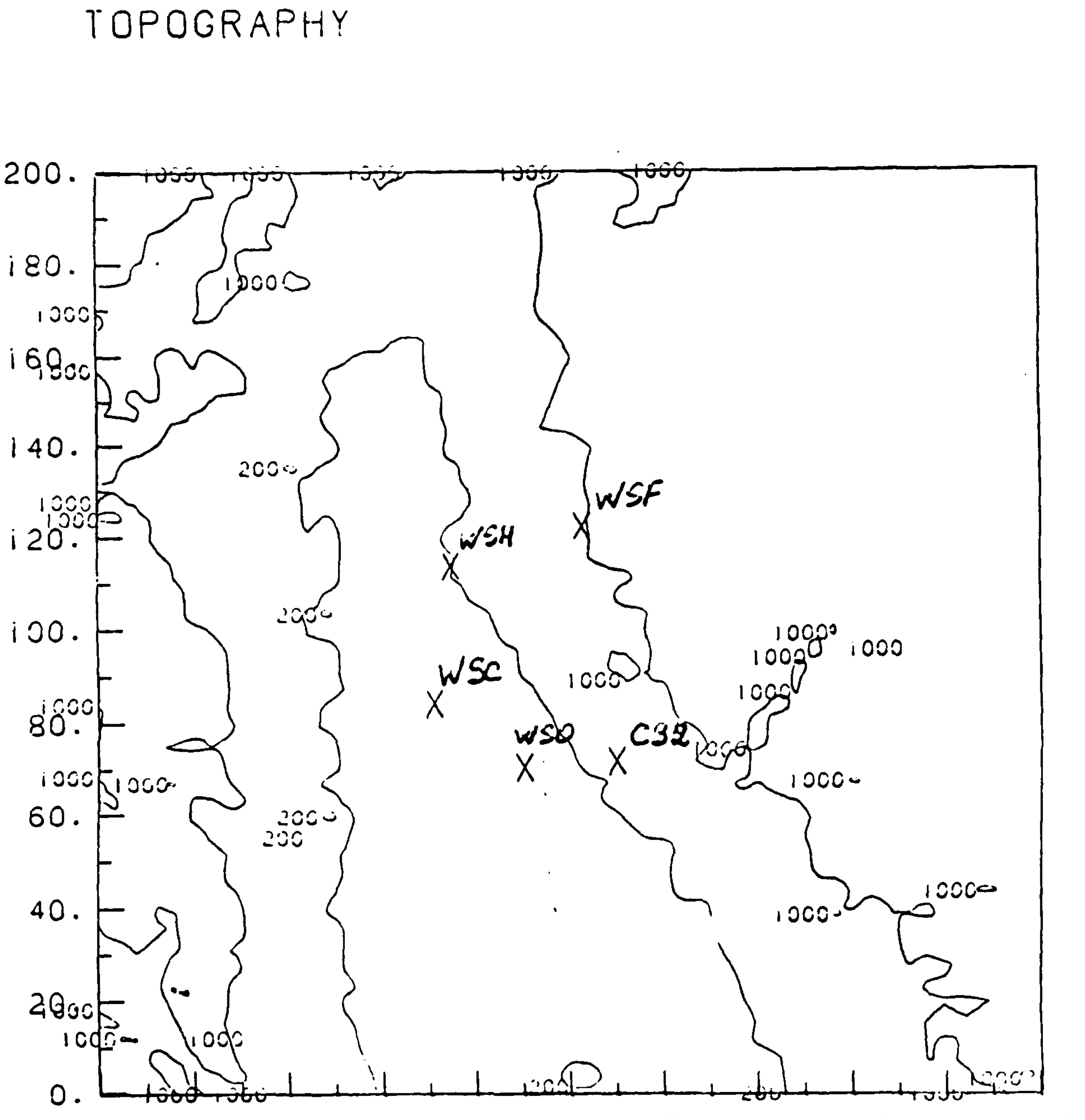


Fig.19(a) Topography of the study region with contours of 200 and 1000m. Location of the 5 radiosondes is indicated with an x and the abbreviated name.

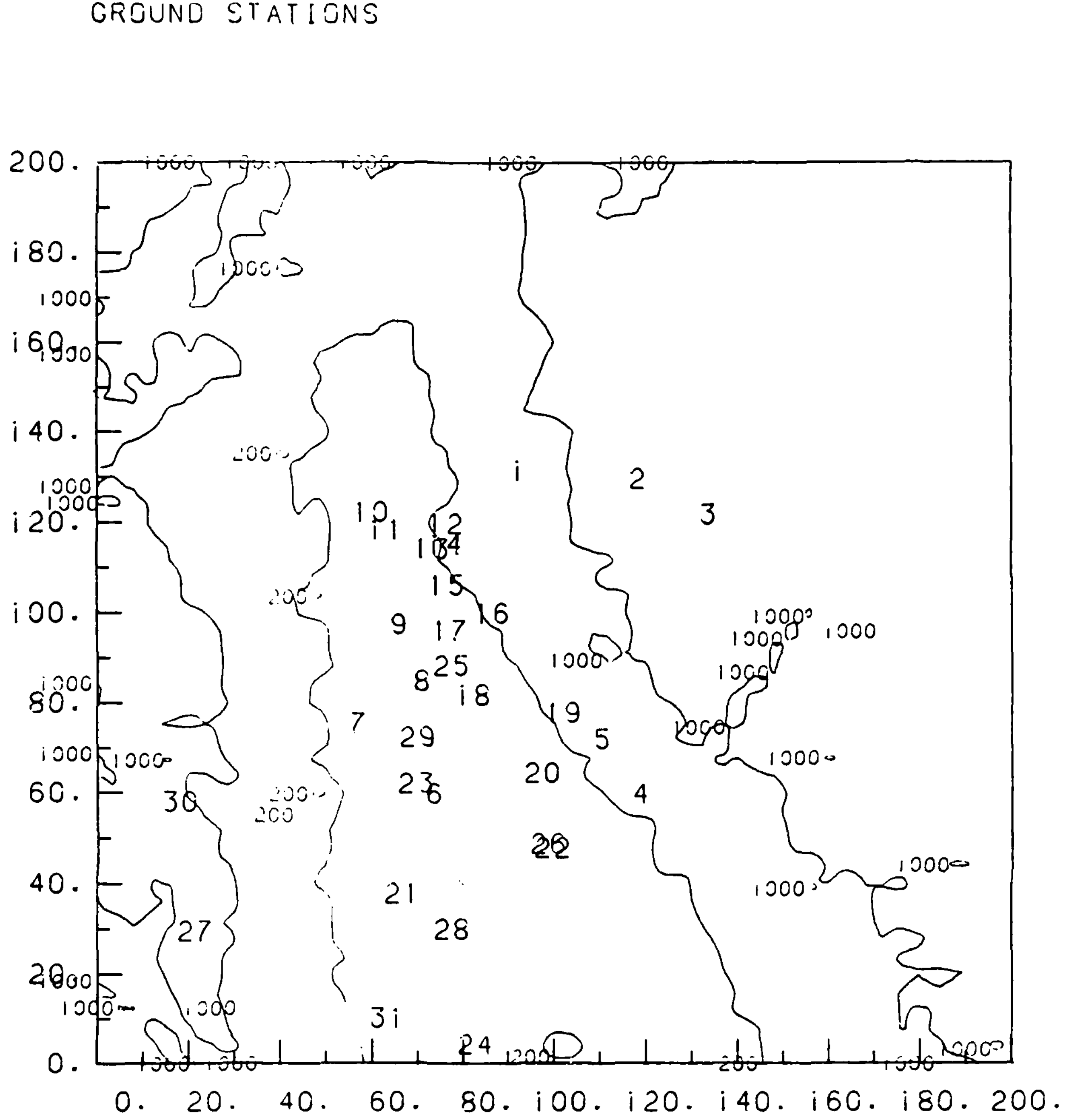


Fig.19(b). As in (a) with the 31 stations indicated by their index number from the list of stations.

16.00 WINDS R1=20

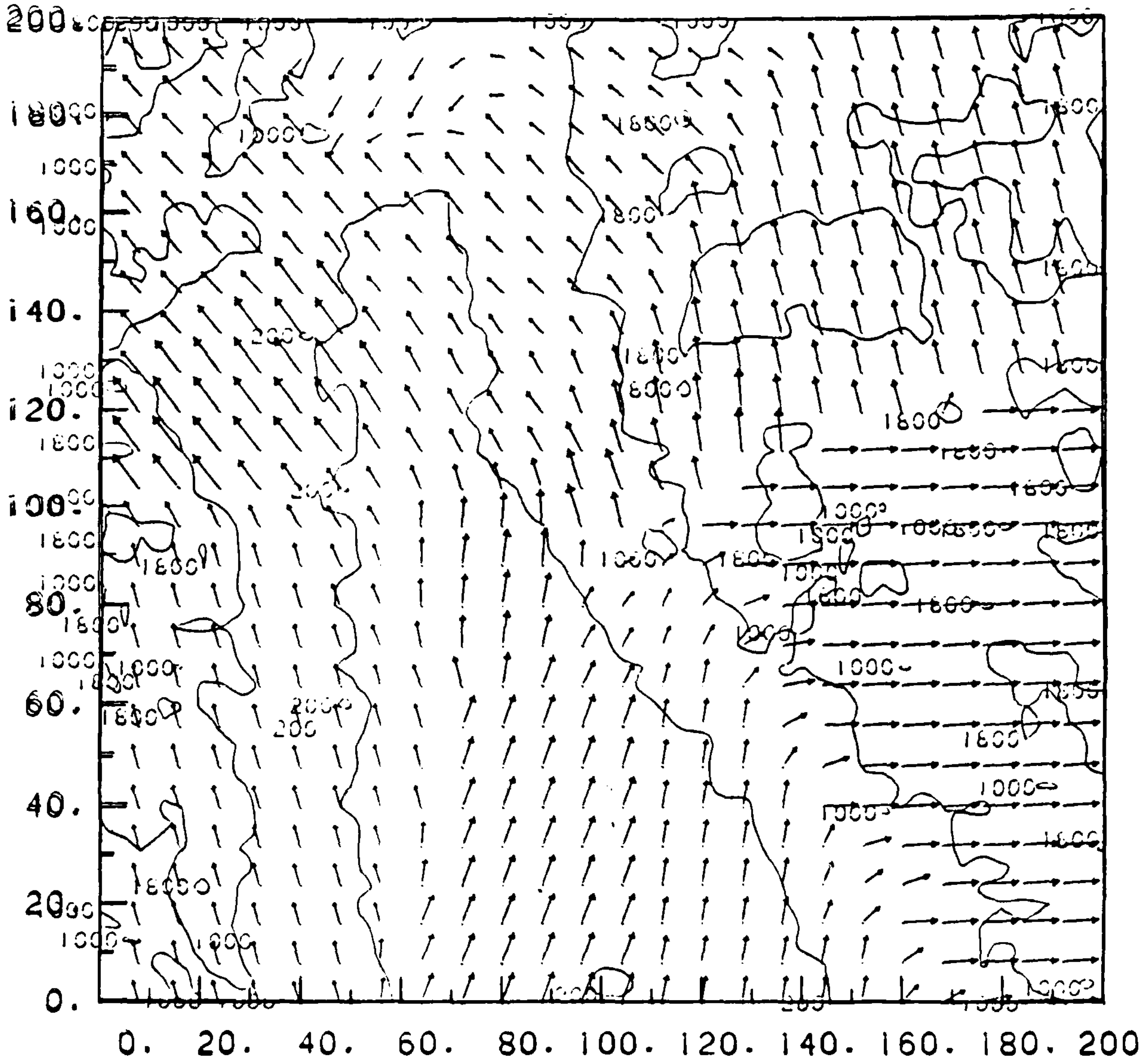
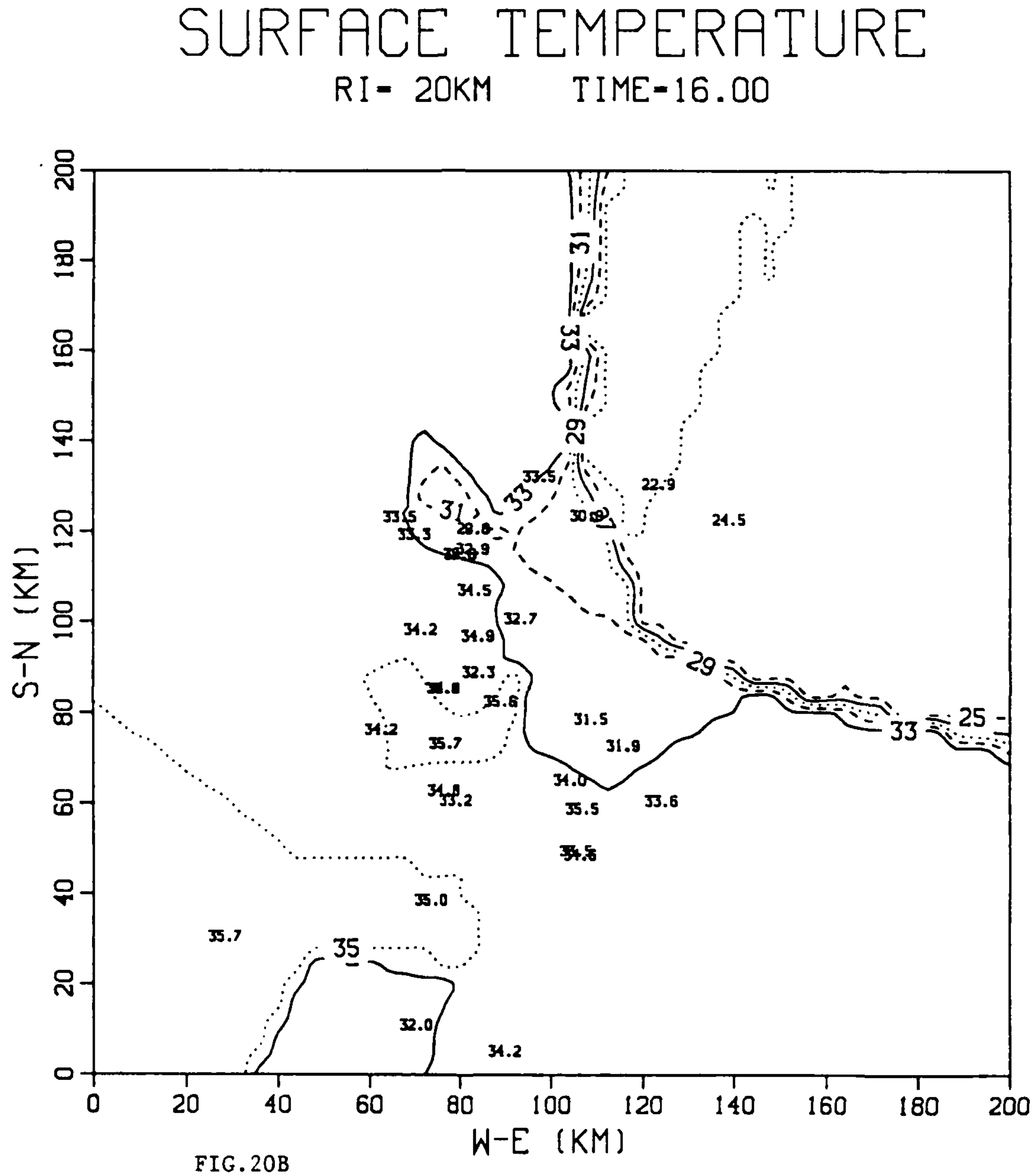


FIG.20A

Fig.20 Surface analysis of (a) the 10m wind, and (b) screen temperature distributions for 2300 GMT (1600 PDT). Coordinates indicate distance in kms. Topographical contours of 200, 1000 and 1800m are plotted. Isotherm interval is 2°C. Contours change from dotted to dashed and to a full line in sequence. Observed temperatures at the available stations are also indicated. The radius of interpolation (R) was 20km.



SURFACE TEMPERATURE

RI= 20KM TIME=16.00

FIG.20B

06.00 WINDS RI=20

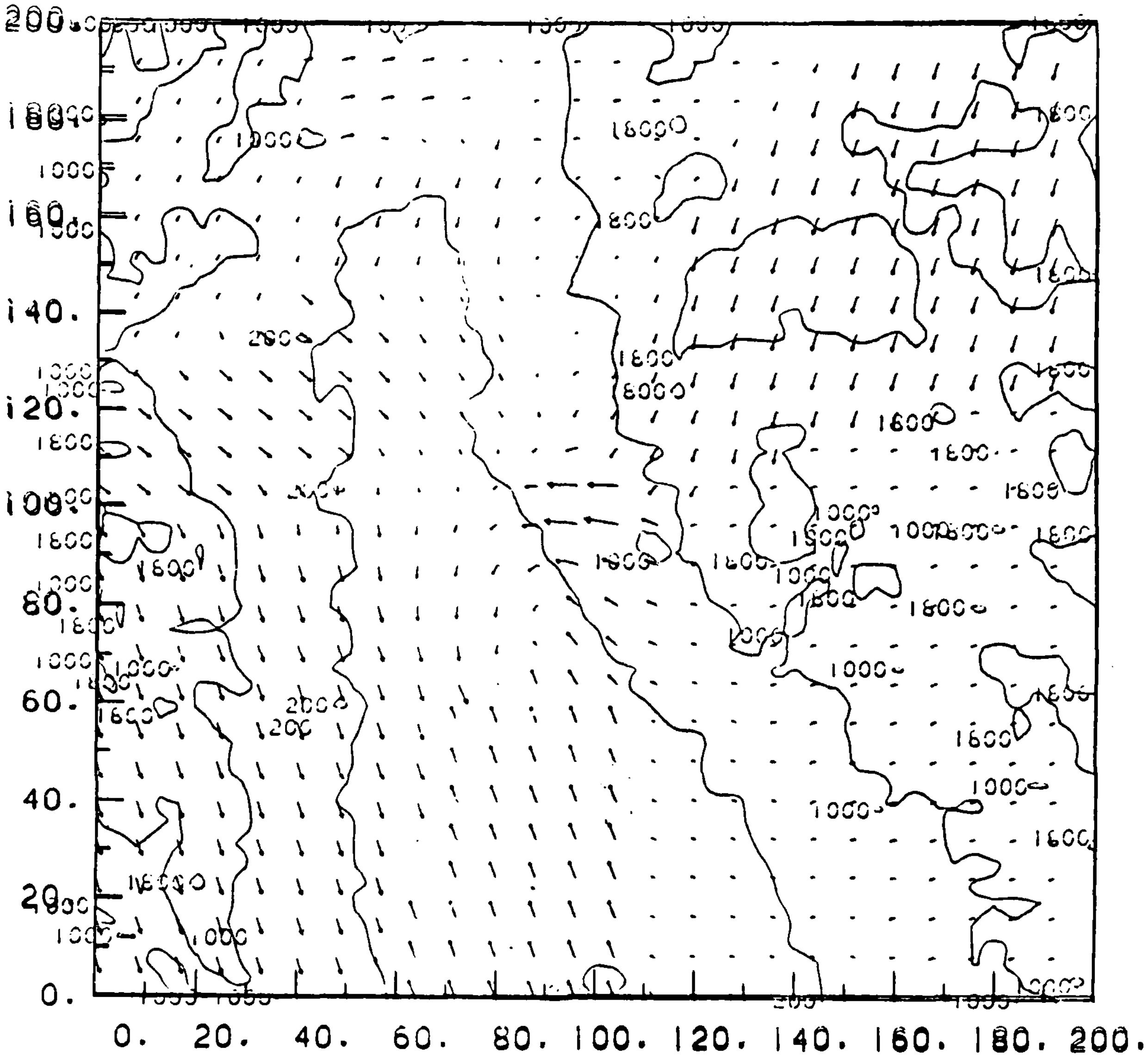


Fig.21(a). As in Fig.20 but for 0600 PDT

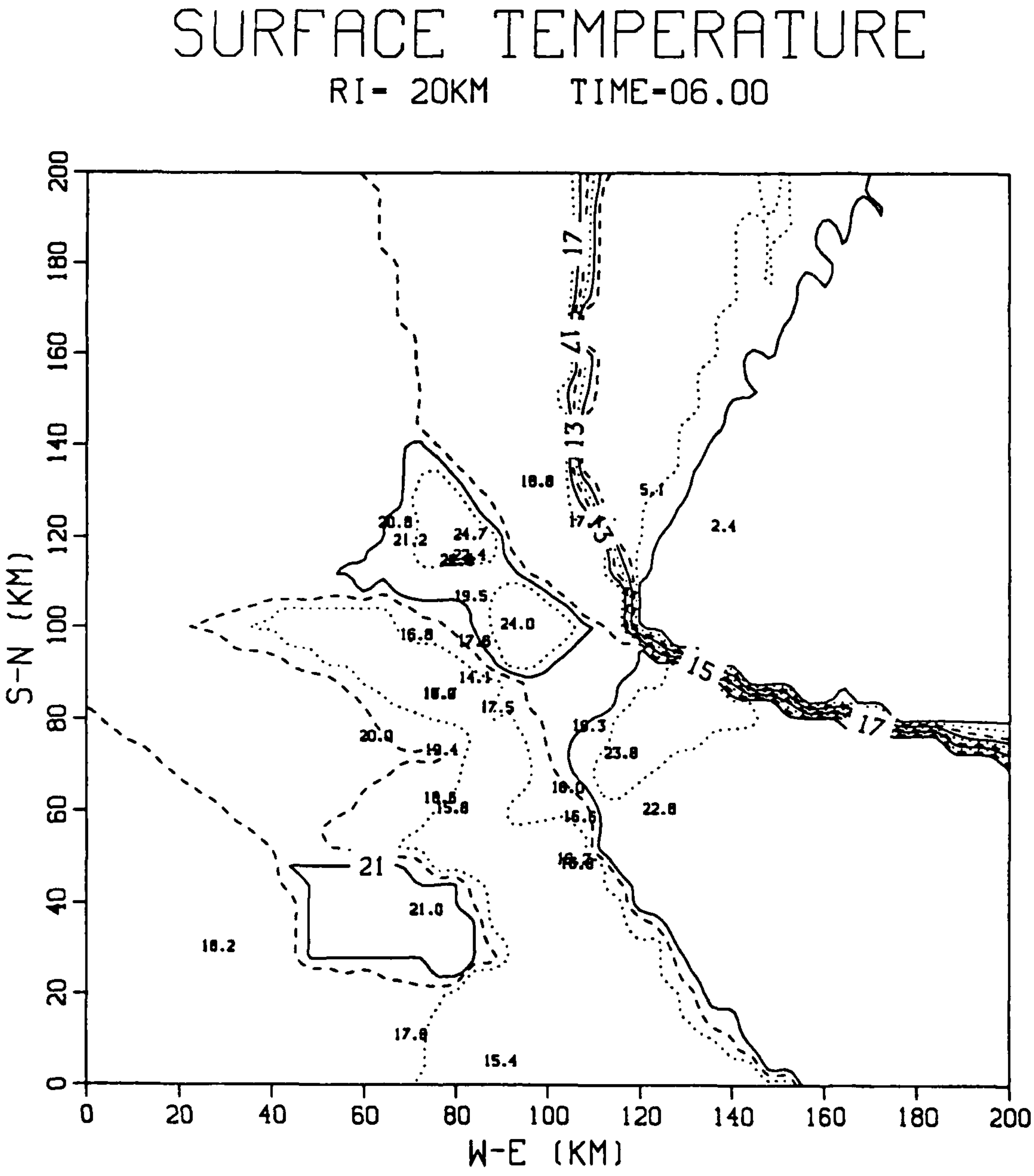


Fig.21(b). As in Fig.20 but for 0600 PDT.

LIST OF STATIONS

X (KM)	Y (KM)	NAME	NO.
[illegible]	131.2	C1	1
110.0	129.5	C2	2
[illegible]	121.6	C3	3
[illegible]	59.6	C4	4
[illegible]	71.8	C7	5
[illegible]	59.7	S1	6
57.0	75.4	S2	7
70.7	84.6	S3	8
65.7	97.4	S4	9
63.1	122.2	S5	10
64.3	118.3	S6	11
[illegible]	119.6	S7	12
74.4	114.0	S8	13
[illegible]	115.1	S9	14
[illegible]	106.0	S10	15
[illegible]	99.8	S11	16
76.4	96.0	S12	17
83.4	81.6	S13	18
103.3	77.7	S14	19
90.7	64.2	CIC	20
66.0	37.7	WLW	21
100.9	47.7	DUR	22
70.9	61.9	ORL	23
[illegible]	4.3	COL	24
76.6	66.1	ABK	25
[illegible]	48.6	AMO	26
[illegible]	29.5	BGG	27
[illegible]	72.3	CPY	28
101.4	57.9	CSF	29
[illegible]	10.1	MAX	30
[illegible]	122.5	WSF	31
[illegible]	64.5	WSC	32
[illegible]	113.9	WSH	33
90.1	70.7	WSO	34
109.9	72.1	C32	35