HADLEY CENTRE
FOR CLIMATE PREDICTION AND RESEARCH

A Comparison of 11-Level General Circulation Model Simulations with observations in the East Sahel.

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CLIMATE RESEARCH TECHNICAL NOTE NO. 5

A COMPARISON OF 11-LEVEL GENERAL CIRCULATION MODEL SIMULATIONS WITH OBSERVATIONS IN THE EAST SAHEL

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1. Introduction.

Some success has been attained in simulating Sahel rainfall using a general circulation model (GCM) forced with observed sea surface temperatures (SSTs) for two wet years (1950 and 1958) and two dry years (1983 and 1984) in the Sahel (Owen & Folland, 1988) and more recently a fairly dry year (1976) and an average year (1988). These experiments produced realistic differences in rainfall between wet and dry years. Changes in model wind fields have been compared with those shown in the analysis of observed data in wet and dry Sahel years by Newell and Kidson (1984) and are also reasonably realistic.

Following this success, experimental forecasts have been run for 1988 and 1989 using the same GCM forced with fixed April and June SST anomalies (with a varying SST climatology added), again with reasonable success. A detailed description of the work to date is in Folland et al (1991).

Before the above experiments were carried out it was necessary to inspect the climatology of the GCMs available, as the ability of a model to simulate a specific year is partly dependent on the accuracy of its climatology. Two models were available (referred to as the 3rd and 4th annual cycle models) and some of the differences between them are described briefly in Schmitz & Owen, 1987 (S & O). The climatologies of these models have been studied in detail in the west Sahel (S & O) and as a result the 3rd annual cycle (3rd AC) model was found to be more realistic. This model has therefore been used for most of the subsequent simulations of individual years.

This discussion assesses the climatologies of these models and the performance of the 3rd AC in the 2 wettest and 2 driest years modelled, in the east Sahel, following S & O.

A detailed description of the 11-level model (but not the differences between individual versions of the 11 level model) is given in Slingo (1985).

2. A comparison of 3rd and 4th AC rainfall, temperature and cloud climatologies.

(i) Rainfall.

Figure 1 shows the model and observed rainfall climatologies averaged over the west Sahel (12.5°N to 17.5°N, 15°W to 11.25°E) and east Sahel (12.5°N to 17.5°N ,11.25°E to 37.5°E). In the east Sahel the models both simulate well the total rainfall during the rainy season, errors being small compared with the west Sahel where both models, but particularly the 4th AC, are too dry.

The 3rd AC climatology is based on a 12 year intergration of the model forced with an SST climatology only approximately representative of the 1951 to 1980 period. Generally the SST data are too cold, except in parts of the north Pacific and north Atlantic, compared with a more accurate 1951 to 1980 SST climatology. The 4th AC climatology is based on a 4 year integration forced with a more accurate 1951 to 1980 SST climatology, althougth the SST climatology in the southern ocean is still uncertain (for details see Bottomley et al, 1990).

The observed rainfall climatology is based on climate data for 1951 to 1980 and is probably more accurate in the west than in the east Sahel. In the analysis that follows it must be realised therefore, that some of the differences between the 3rd and 4th AC models may not be intrinsic to the models themselves, but may reflect the different SSTs used and/or sampling errors.

Figure 1 shows only the mean values over the east and west Sahel regions. It is also necessary to inspect the spatial patterns of modelled and observed rainfall. Figure 2 shows the observed, 3rd AC and 4th AC rainfall climatologies for June to October.

It can be seen that both models are a little wet in June, the 3rd AC being least accurate. The north/south rainfall gradient in the 4th AC model is noticably sharper than in the 3rd AC model.

In July and August the 4th AC simulation is slightly more accurate than the 3rd AC model, although both are fairly good (fig. 1). Note that it is during these months that the 4th AC model is very poor in the west Sahel (fig. 1). As in June the north/south rainfall gradients are too sharp in the 4th AC model; hence there is too much rain in the south of the east Sahel but this is compensated by too little rain in the north of the region (figs. 2b and 2c). The 3rd AC model shows a more realistic northward decrease in rainfall over the Sahel itself, although further north there is too much rainfall. In August it can also be seen that in reality the contours are orientated east-west, but in the 3rd AC model they lie in a northwest/southeast orientation over the east Sahel. To the south of the Sahel region in August a large region of greater than 8mm/day is observed. The 3rd AC simulates this more accurately than the 4th AC model.

In September, the 3rd AC is generally more accurate than the 4th AC which gives too much rain over the southern east Sahel.

In October, although the 4th AC moves the rain area too far south, the simulation is realistically dry in the east Sahel. The 3rd AC is also quite accurate in the east Sahel and further south as the positioning of the rain area is more realistic.

In summary both models are quite accurate in the east Sahel throughout the season, although both are a little wet in June. The differences between the two models and between each model and observed climatology are smaller and less coherent than those found in the west Sahel. The northern edge of the rain area tends to be too diffuse in the 3rd AC model, but too sharp in the 4th AC.

It should be noted that a model climatology generated using climatological SSTs is not strictly comparable with observed climatological data, since there is no anomalous (compared with the annual cycle) SST forcing during the control integration. If interannual variability in SST is important for interannual variability in rainfall in a particular region, then the model's rainfall variance is likely to be too low compared with observations in this region. For the same reason it is unlikely that the control integration could simulate any asymmetry in the observed rainfall frequency distribution. In the Sahel the observed rainfall frequency distribution is positively skewed, so the control integration may underestimate the frequency of extreme wet years, producing a dry bias in the model's rainfall climatology.

(ii) Surface Temperature.

The amount of moisture at the ground surface (soil moisture content) affects the temperature that the surface reaches during the day. A wet surface will have a lower temperature than a dry one (in the absence of other differences) since loss of heat through evaporation will be greater in the former. The 3rd and 4th AC models both include feedback between modelled rainfall and soil moisture content (interactive soil moisture) and therefore it is necessary to inspect the surface temperature climatologies of the two models in addition to their rainfall climatologies.

The observed climatology shown here is a mean of surface air maximum and minimum temperature (ie. screen temperature) for the period 1951 to 1980, again based on climate data. This quantity is not calculated in the models, hence observations must be compared with model ground surface temperature averaged over each timestep throughout the model day. As a result, it is not possible to compare actual values of observed and model temperature but the comparison of gradients and positions of maxima is valid, although not precise, as the observed temperatures are not true 24 hour means.

The 4th AC model has a tendency to be hotter than the 3rd AC north of around 14°N (S & O also found this for the west Sahel). Figure 3 shows August temperatures, but this tendency is also true in July and September. The largest differences are in the westernmost region of the east Sahel where the 3rd AC tends to produce unrealistically large amounts of rainfall (S & O).

Inspection of the observed August climatology in figure 3 shows that the meridional temperature gradients across the east and west Sahel are too great in both models, the errors being worst in the 4th AC, and that the highest temperatures over the Sahara are positioned a little too far southwest. Both models simulate the cool temperatures over the Ethiopian highlands well, and the small maximum to the north (over the Nubian desert) is also evident, although positioned too far south in both models. However this difference may be within the uncertainty of the observations.

Inaccuracies in the strength and position of meridional temperature gradients in the tropics have important implications for the model's vertical wind profile. This is due to the sensitivity of the thermal wind in the tropics to the local horizontal surface or near surface temperature gradient (Newell and Kidson, 1984). For example a change in the surface temperature gradient of around 0.5°C in 10° latitude at 15°N would change the vertical zonal wind shear between 1000 and 500mb by about 1.5 m/s. In addition, it has been found that the latitude and strength of the mid-tropospheric African Easterly Jet (AEJ) in the model is correlated with model rainfall amounts in the Sahel. The further south and weaker the AEJ in the model, the lower the rainfall in the Sahel shown by the model. A similar relationship between the strength of the AEJ and Sahel rainfall has also been found from observed data (Newell and Kidson, 1984). Further studies are needed to show how changes in the AEJ in the model are physically related to variations in modelled Sahel rainfall; both effects could be related to a third factor.

(iii) Total cloud cover.

Higher surface temperatures in the 4th AC model compared with the 3rd AC model have been noted in a region north of 14°N, from 15°W to 15°E (S & O and section (ii)). S & O suggested that lower cloud cover in the 4th AC model could be responsible for higher surface temperatures in this region.

The 4th AC model has an interactive cloud scheme, while the 3rd AC model uses prescribed zonal mean cloud anmounts (Slingo, 1985). Figure 4 shows the 4th AC total cloud cover averaged over July to September compared with an observed cloud climatology for 1971 to 1981, compiled from daily weather observations (Warren et al,1986). Because this was generally a dry period in the Sahel it is likely that the observed data under-estimate rather than over-estimate cloud cover relative to a longer period of data. (The model values have been interpolated from the model grid (2.5°lat. x 3.75°long.) to that used in the observational data (5° x 5°), after checking this had no spurious effects on the cloud cover values). The 3rd AC total cloud amounts for July to September are shown on the right hand side of figure 4. The effect of the diurnal cycle is removed from both the observed and modelled data, since the data are meaned over several points throughout the day and night.

Coincident with the region of high surface temperatures in the 4th AC model is an area from 15°W to 15°E and 15 to 20°N where the 4th AC model generally underestimates total cloud cover. The observed cloud cover is around 40% to 80% while the 4th AC model produces around 30%. The 3rd AC cloud cover value of 45% in this area is generally accurate, apart from between 5°W and 15°W where the observed cloud amounts increase to about 70%. Hence, lack of cloud cover in the 4th AC model could explain the higher surface temperatures.

Further south (10°N to 15°N) over the whole Sahel the 4th AC model has cloud values from 70 to 80% which agree well with observations. The 3rd AC however, uses a values of only 53% for these latitudes. In this region the 4th AC temperatures are actually a little higher than the 3rd AC values, despite the higher cloud cover.

Also evident in figure 4 is the small north/south gradient in cloud cover in the 3rd AC model and the much larger gradient in the 4th AC model. Generally the gradient in the 3rd AC is too weak compared with observations, especially in the east Sahel. The more gradual northward decrease in cloud cover in the 3rd AC model might explain both the more diffuse northern edge to the Sahel rainfall area and the smaller north/south temperature gradients in the climatology of this model (see figs. 2a to 2e).

3. Simulation of individual years.

Figure 5 shows the observed and modelled rainfall for June to October averaged over the east and west Sahel for 1950 and 1958 (wet) and 1983 and 1984 (dry). It shows clearly the 3rd AC model's ability to simulate the difference between very dry and very wet years.

There is a tendency for the model to produce too much rain in these years over the east Sahel, especially in August, September and October. Given the earlier remarks about likely biases in the model's climatology, this bias is likely to be real. In addition June is too wet in three out of the four years. In 1984 the east Sahel experienced extremely dry conditions and rainfall was overpredicted throughout the season.

As was done for the rainfall climatologies, the spatial patterns of rainfall have also been inspected for these four years.

(i) Wet years (figures 6 and 7).

During June in 1950 and 1958 there is too much rain over the whole of the east Sahel with the worst errors in the eastern part of the region. July is more accurately simulated, although in 1950 the east Sahel is a little dry, especially between 20°E and 25°E. In August the simulation is also quite accurate, particularly in 1958. In 1950, west of 15°E, there is too much rain produced by the model. The months of September and October are both too wet in the model.

There is a tendency in all months for the northern edge of the rain area to be too diffuse in the model, as noted in the 3rd AC climatology. This results in too much rain in areas just to the north of the east Sahel.

(ii) Dry years.

Differences between observed and modelled rainfall are less consistent in 1983 and 1984 so they will be discussed separately.

The simulation in 1983 is quite accurate in June and August (figs. 8a and 8c) over the east Sahel, but in July the northern edge of the rain area is too far south and the region is too dry (fig. 8b). In reality the maximum rainfall occurred during July, rather than during August which is more usual. The 3rd AC model is not able to reproduce this. In September and October (figs. 8d and 8e) the region is a little wet. There are a few small areas of particularly high rainfall in the model during September (for example 24°E,13°N, fig. 8d, which is in the mountainous Darfur region of western Sudan).

In 1984, during June and August the northern edge of the modelled rain band is positioned too far north and is too diffuse, making the Sahel and regions to the north too wet (figs. 9a,c and d). July however is more accurate, although still a little wet (fig. 9b). As in 1983 the maximum rainfall in the Sahel as a whole occured in July and then it decreased in August. Again the model is unable to simulate this. In September over most of the region the simulation is quite accurate, but, as in 1983, there is too much rainfall around 24°E,13°N. From September to October the model moves the rain band too far south, especially in the west of the east Sahel. Further east however the model is too wet (fig. 9e).

Discussion.

There is a tendency in the individual year experiments for August, September and October to be too wet in the 3rd AC model (fig. 5). The reasons for this excess rainfall are not obvious, but it may be due to an anomalous northerly position of the region of strongest convergence (known as the ITCZ) in the model. In both the model and observations maximum rainfall occurs some distance to the south of the ITCZ. Excessive rainfall in August, September and October compared with observations is a feature of each of the individual year simulations discussed here and suggestes a problem with the climatology of the 3rd AC model. However the 3rd AC climatological rainfall is in fact quite accurate in these months (fig. 1). Although, as discussed in section 2(i), figure 1 may not be a true representation of the 3rd AC model's climatology.

There is also the problem that the model, because of its coarse resolution, may not adequately simulate mechanisms such as easterly waves (scales of 2000 to 4000km) and squall lines (length scales of order 100km, width scales of order 10km), which are especially important for rainfall production in the west Sahel (Hastenrath, 1988). This may partly explain the more accurate simulation of rainfall in the east Sahel compared with the west.

4. 10 day mean model rainfall and soil moisture content.

Figure 10 shows time series of 10 day mean rainfall and soil moisture content for four regions to the south of the east Sahel which all lie along the area of highest modelled rainfall in August 1950.

S & O noted for the west Sahel that the onset of the rains in the model became earlier as one moved eastward. This is not true for the east Sahel. It could be possible however, that the trend found by S & O is not a real one, but due instead to the underestimated rainfall in the extreme western Sahel.

Figure 10 also shows the effect of rainfall on the soil moisture content. Soil moisture appears to respond very quickly to rainfall at the beginning of the season when the soil is dry. Once the soil is wet however, quite large variations in rainfall do not affect the soil moisture a great deal and there is some lag in the response. It is only at the end of the rainfall season when there is a more severe drop in rainfall that the soil moisture content decreases significantly.

The difference between wet and dry years decreases eastwards, a trend also found by S & O. Again it is not clear whether this feature is realistic, although in the east Sahel it could be explained by the existence of the Ethiopian highlands which enhance rainfall production in both wet and dry years.

In the first 2 regions the rainfall season in wet years starts earlier than in dry years (figs. 10a and 10b), but this is not apparent in the easternmost regions (figs. 10c and 10d).

5. Summary.

The simulation of rainfall and temperature is more accurate in the east Sahel than the west in both the 3rd and 4th AC models. Errors in rainfall are less consistent from month to month than in the west Sahel. The northern edge of the rain area is too diffuse in the 3rd AC model's climatology which results in too much rainfall in areas north of the Sahel. Over the east Sahel itself however, both models are of similar accuracy.

The climatological meridional temperature gradients across the Sahel region are too great in both models, but the errors are worst in the 4th AC. This is probably due to the more rapid northward decrease in cloud cover in the 4th AC model. This difference in cloud cover gradients may also explain the more diffuse rain edge in the 3rd AC model. To the north of the Sahel the higher temperatures in the 4th AC model can be attributed to reduced cloud cover. The northern edge of the rain area also tends to be too diffuse in the individual year experiments, strongly indicating that this is a permanent feature.

A common feature of the individual year experiments is the over-prediction of rainfall in August, Septmeber and October, but this tendency does not appear in the 3rd AC climatology. The climatology of the 3rd AC model presented here may not be a true representation of the model's climatological state however, because of inaccuracies in the SSTs used.

References.

Bottomley, M., Folland, C.K., Hsiung, J., Newell, R.E. and Parker, D.E. 1990. Global Ocean Surface Temperature Atlas "GOSTA". Joint Meteorological

Office / Massachusetts Institute of Technology Atlas. Project supported by US Dept of Energy, US National Science Foundation and US Office of Naval Research. Publication funded by UK Depts of Environment and Energy. Printed by HMSO, London. 20pp + iv, plus 313 plates. Magnetic media versions available.

Folland, C.K., Owen, J.A., Ward, M.N. and Colman, A.W. 1991. Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods. J. Forecasting 10.

Hastenrath, S. 1988. Climate and Circulation of the Tropics. Dordrecht, D. Reidel, pp164-166.

Newell, R.E. and Kidson, J.W. 1984. African mean wind changes between Sahelian wet and dry periods. J. Clim.,4,27-33.

Owen, J.A. and Folland, C.K. 1988. Modelling the influence of sea-surface temperatures on tropical rainfall. Recent Climatic Change, (ed. S. Gregory), Belhaven Press, Chapter 13, pp 141-153.

Schmitz, G. and Owen, J.A. 1987. Comparison of GCM simulations of western Sahel rainfall with observational results. Met O 13 Branch Memorandum No. 169

Slingo, A. 1985 Handbook of the Meteorological Office 11-layer atmospheric general circulation model. Dynamical Climatology Tech. Note No. 29, Meteorological Office, Bracknell.

Ward, M.N. and Owen, J.A. 1988 Experimental Sahel rainfall forecast for 1988. A preliminary assessment. Met O 13 Branch Memorandum No. 170.

Warren, S.G.; Hahn, C.J; London, J; Chervin, R.M. and Jenne, R.L. 1986. Global Distribution of Total Cloud Cover and Cloud Type Amounts Over Land. NCAR Tech. Note TN:273+STR. Natl. Cent. Atmos. Res.,Boulder,Col.

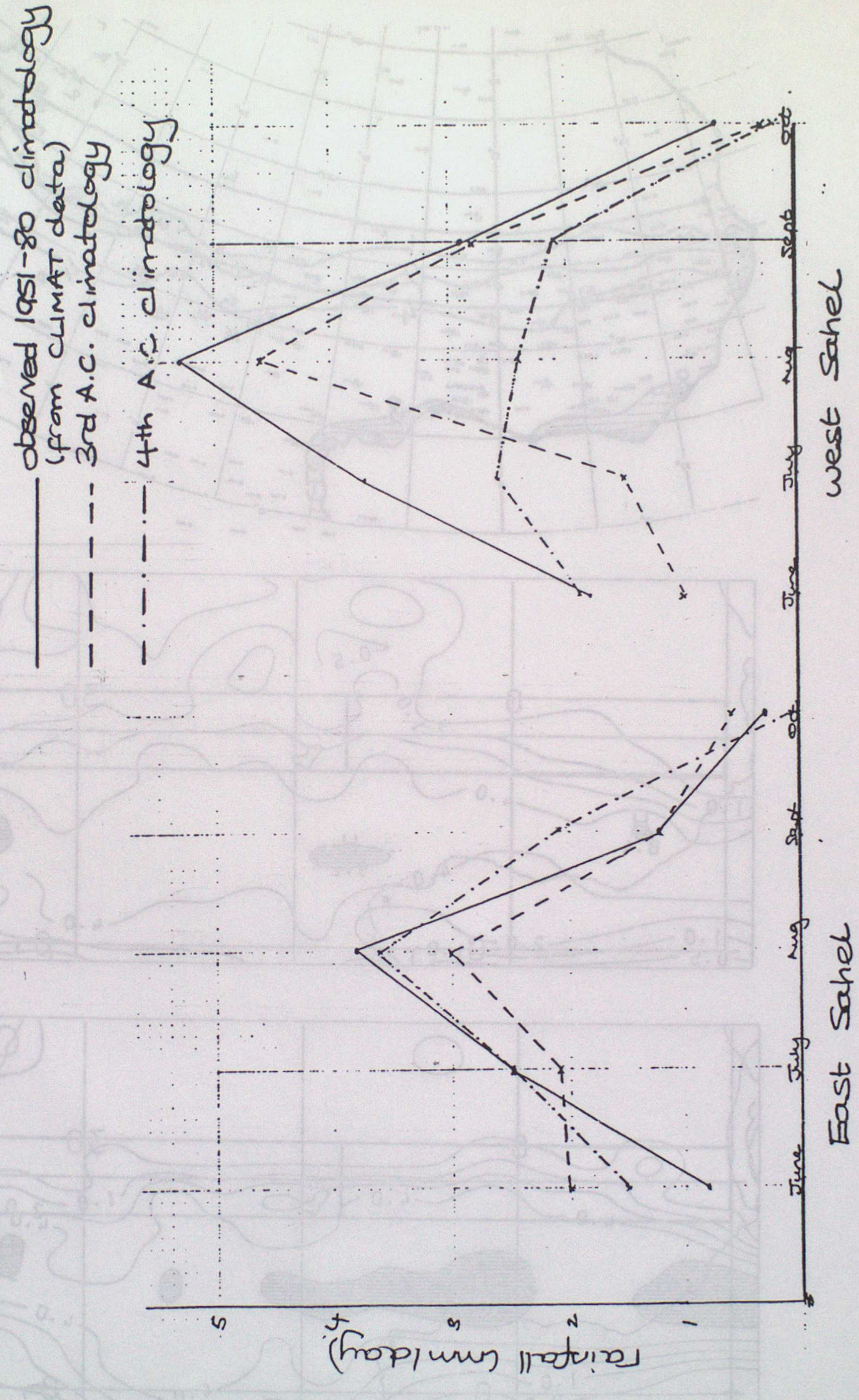


Fig. 1 Observed (1951-80), 3rd AC and 4th AC rainfall climatology averaged over the west and east Sahel (mm/day).

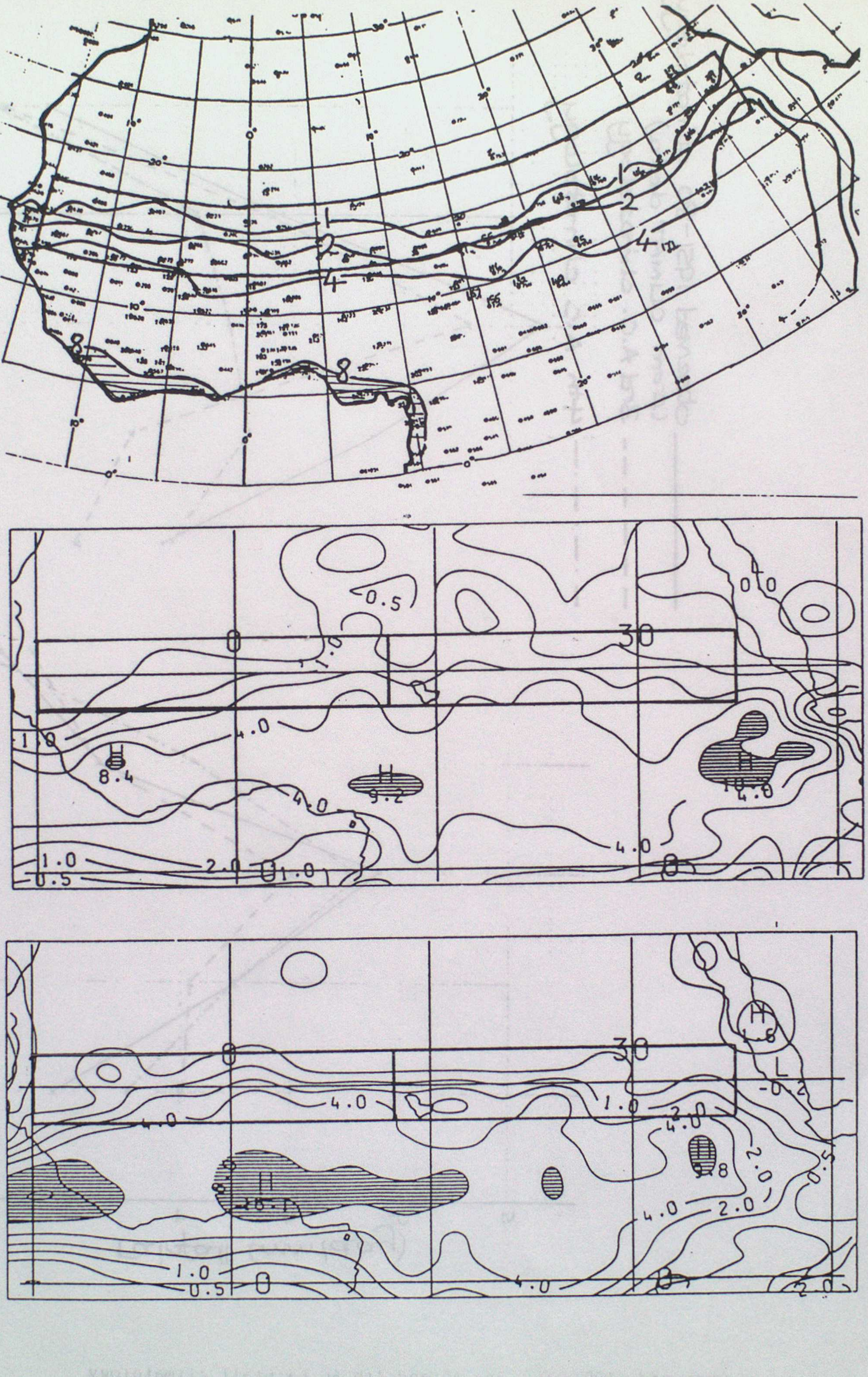


Fig. 2a (i) Observed (1951-80), (ii) 3rd AC and (iii) 4th AC rainfall climatology for June. Contours at 0, 0.5, 1, 2, 4, 8 and 16 mm/day.

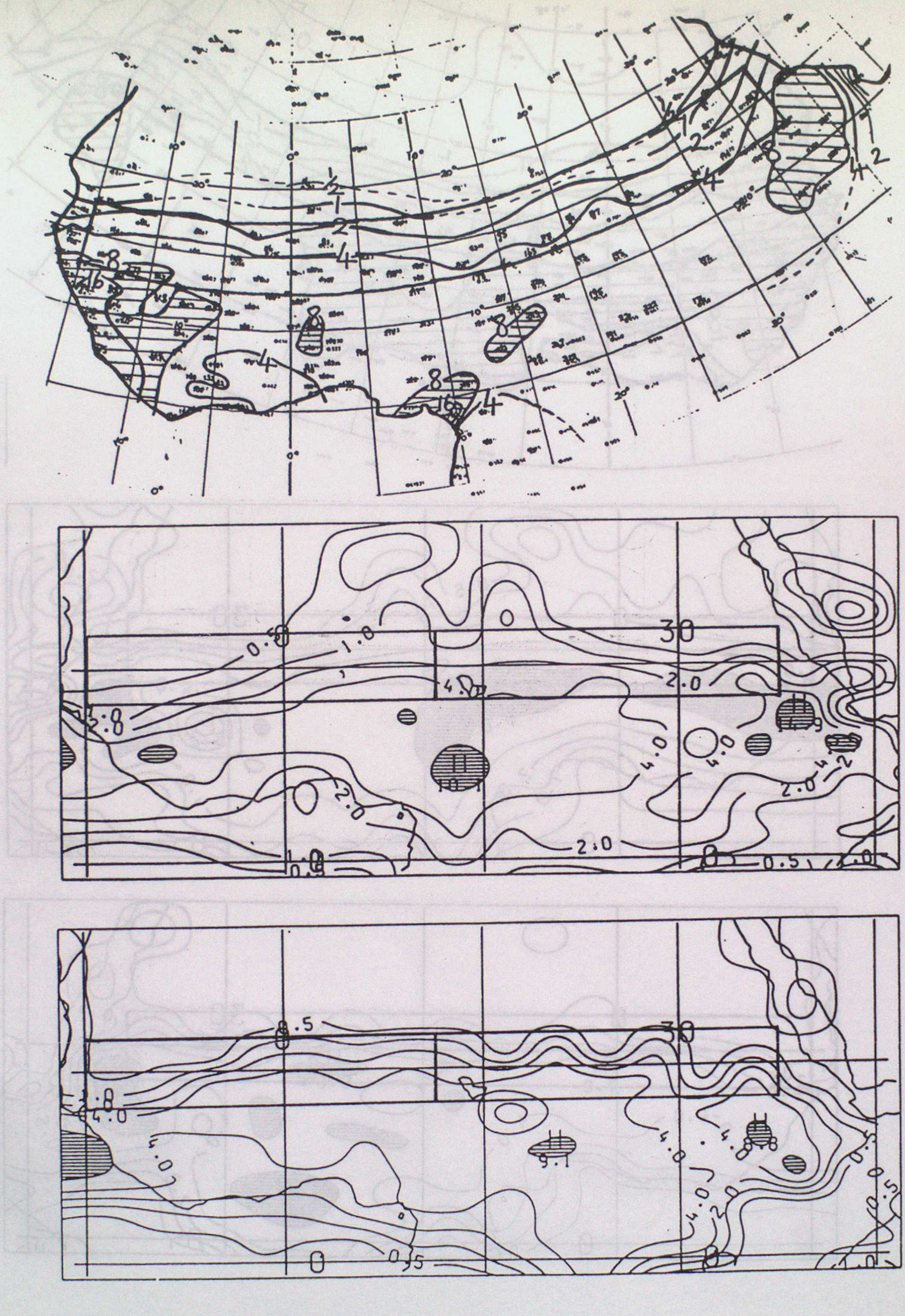


Fig. 2b As in fig. 2a but for July.

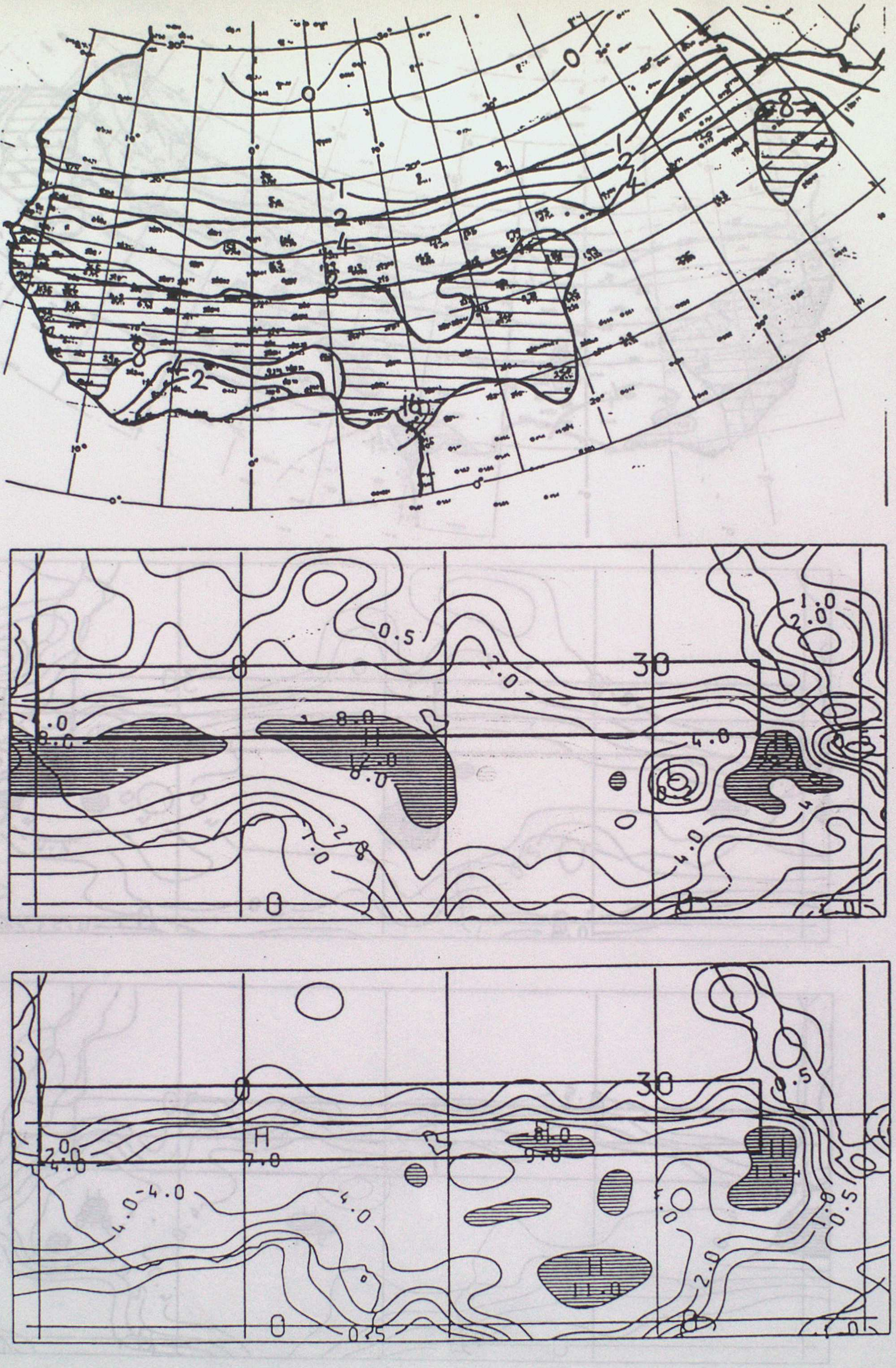


Fig. 2c As in fig. 2a but for August.

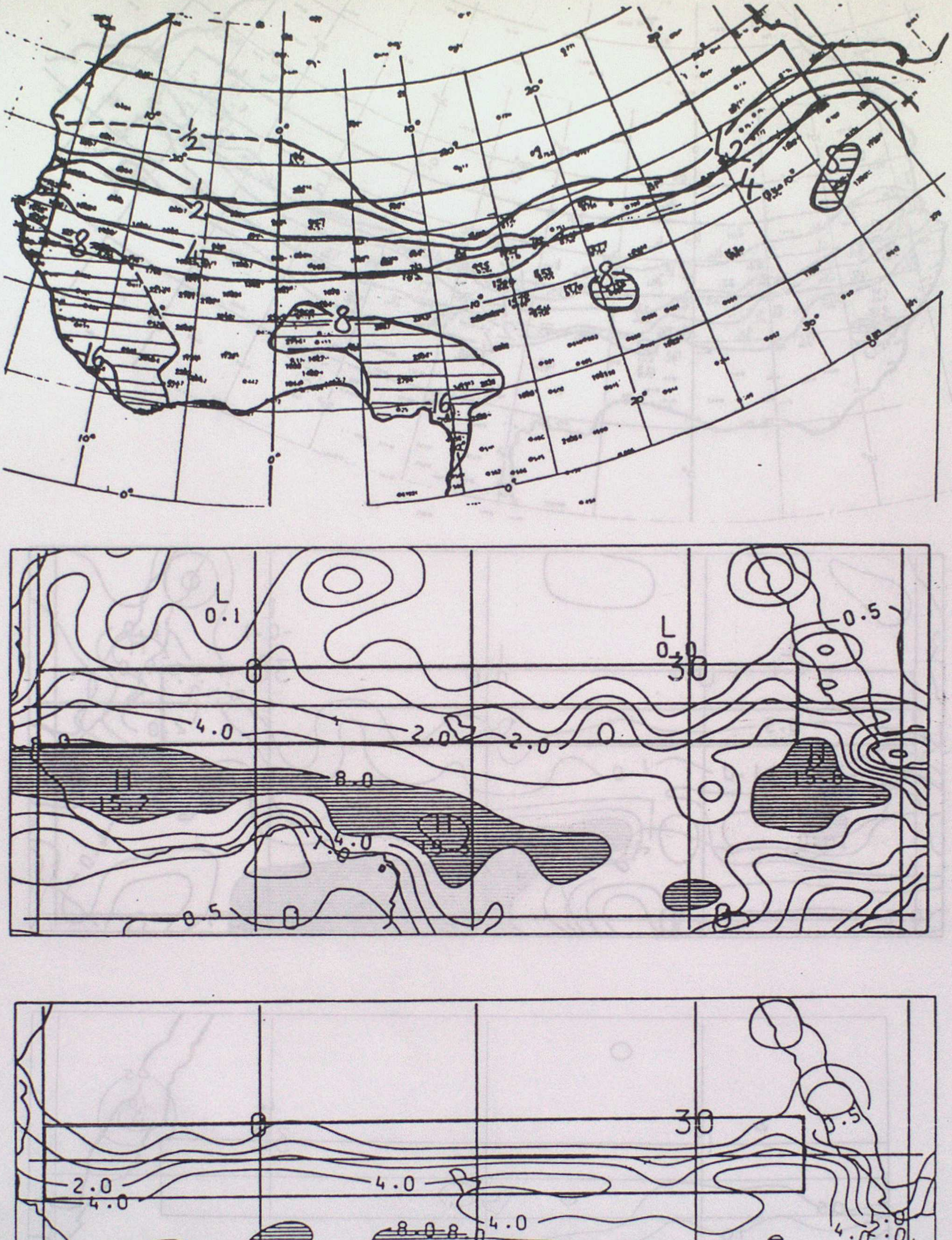


Fig. 2d As in fig. 2a but for September.

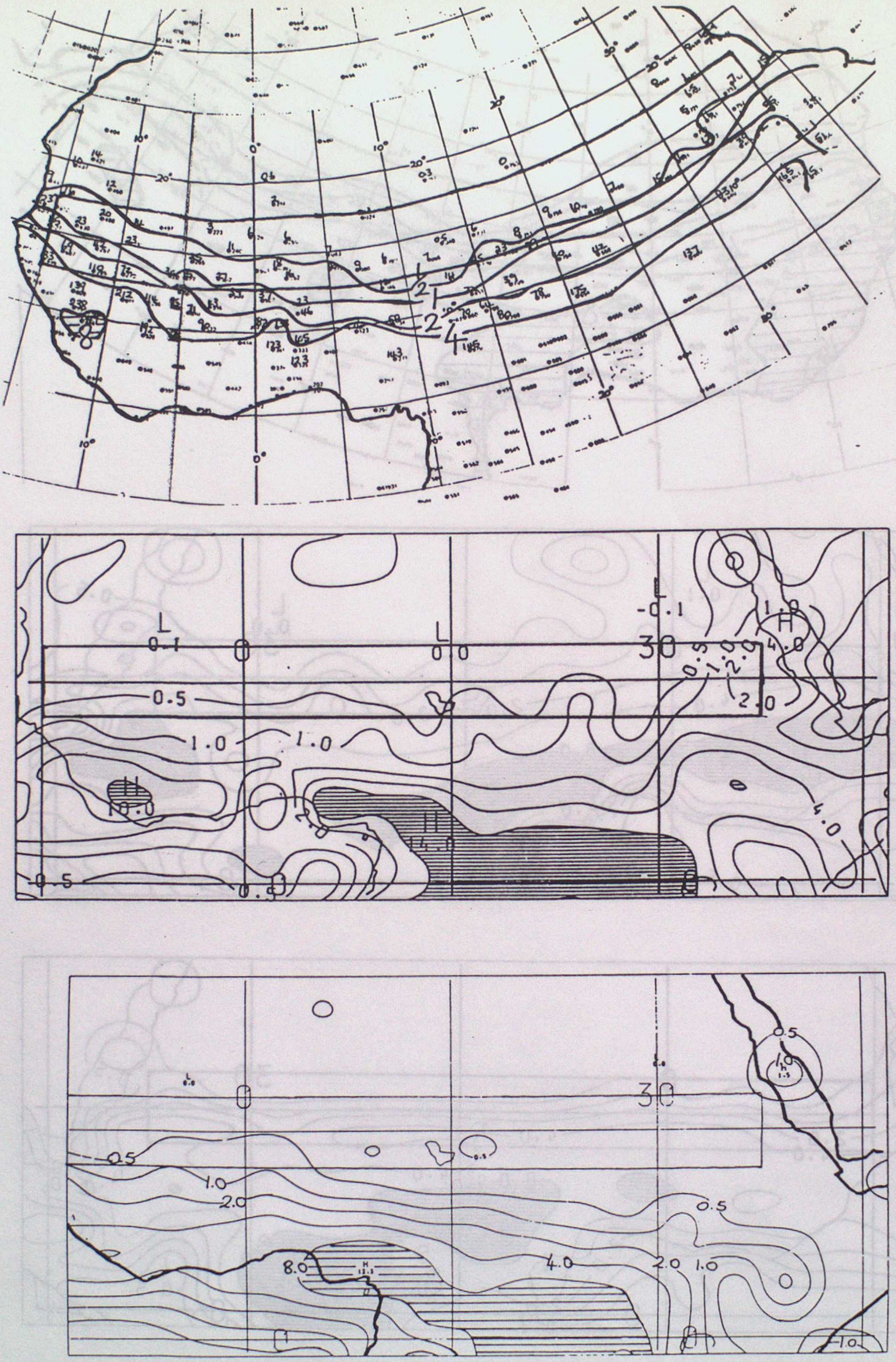


Fig. 2e As in fig. 2a but for October.

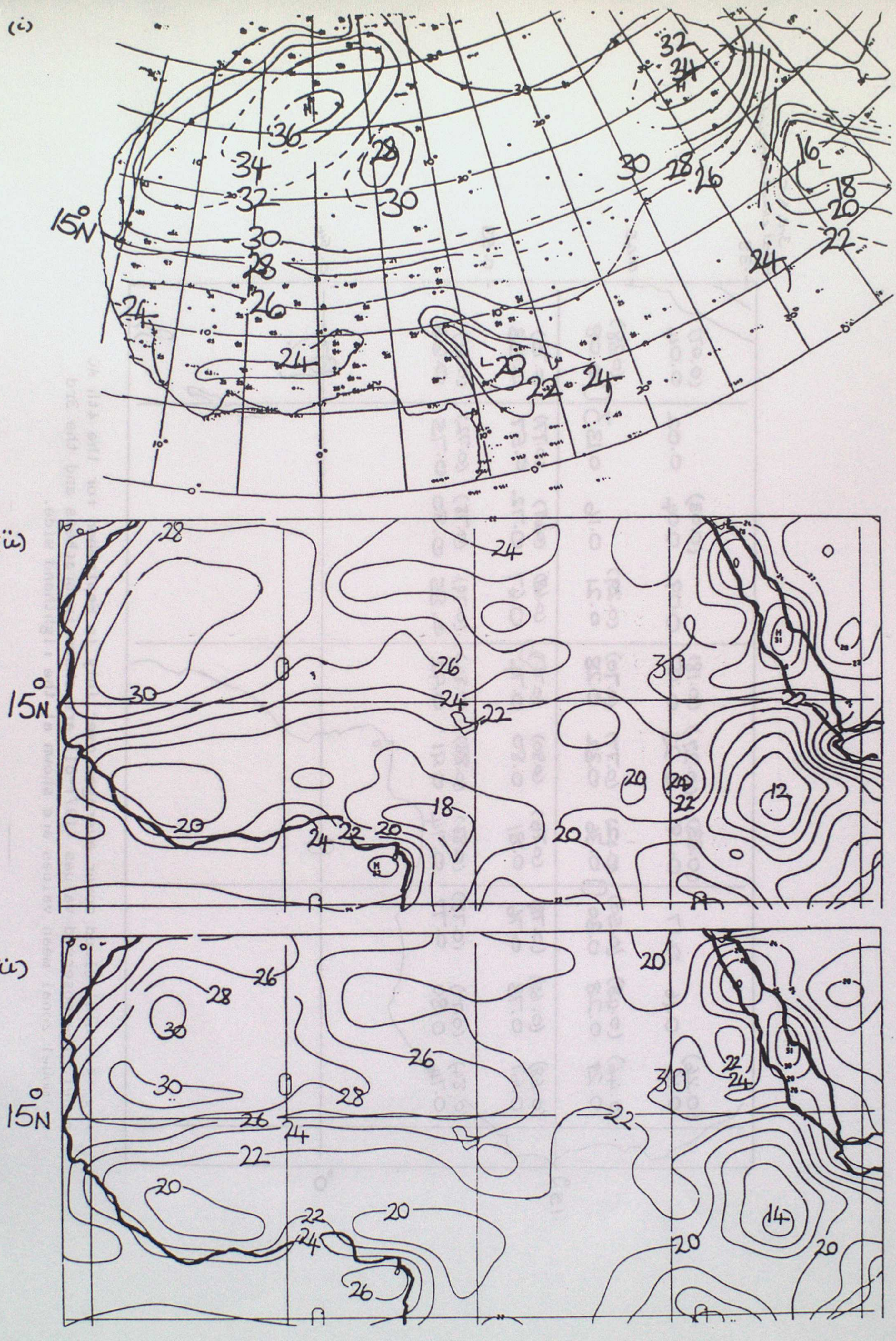


Fig. 3 (i) Observed (1951-80), (ii) 3rd AC and (iii) 4th AC mean surface temperature for August in °C. The observed data is a mean of maximum and minimum surface air temperature. The model values are surface land temperature meaned over each timestep throughout each model

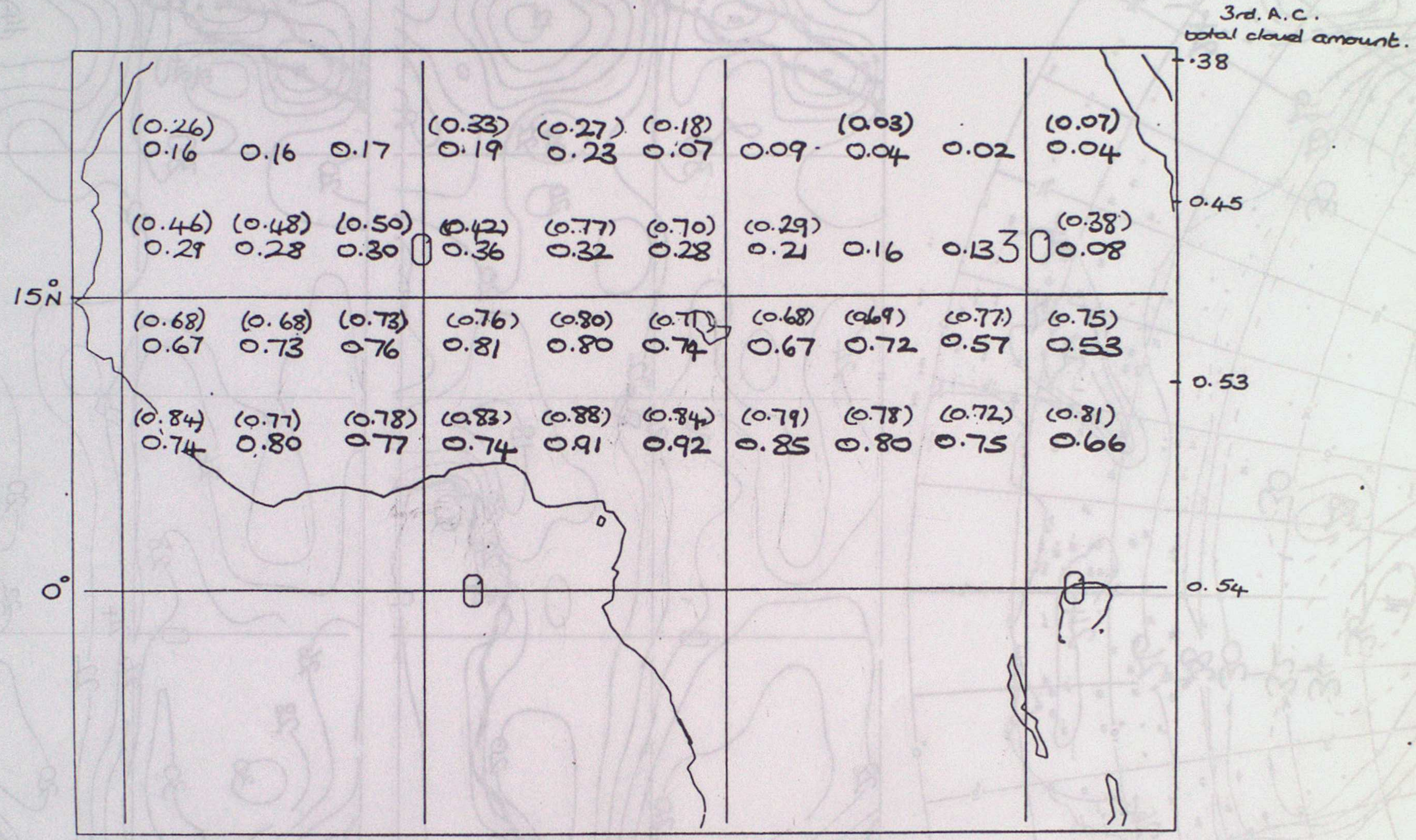


Fig. 4 Total cloud cover averaged over July to September for the 4th AC model. The observed values (1971-81) are shown in brackets and the 3rd AC model zonal mean values are shown at the righthand side.

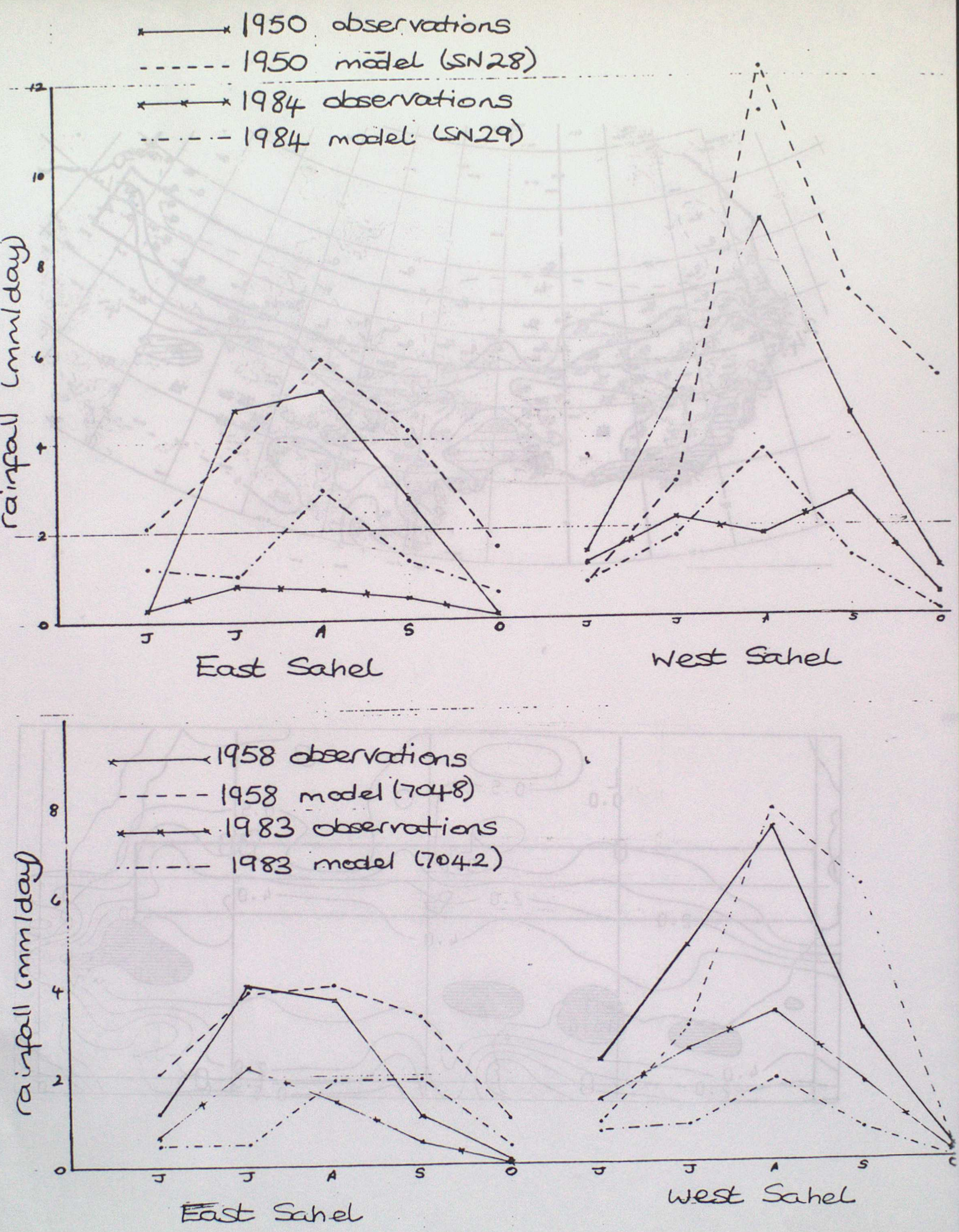


Fig. 5 Observed and 3rd AC rainfall for June to October, averaged over the west and east Sahel for 1950, 1958, 1983 and 1984 (mm/day).

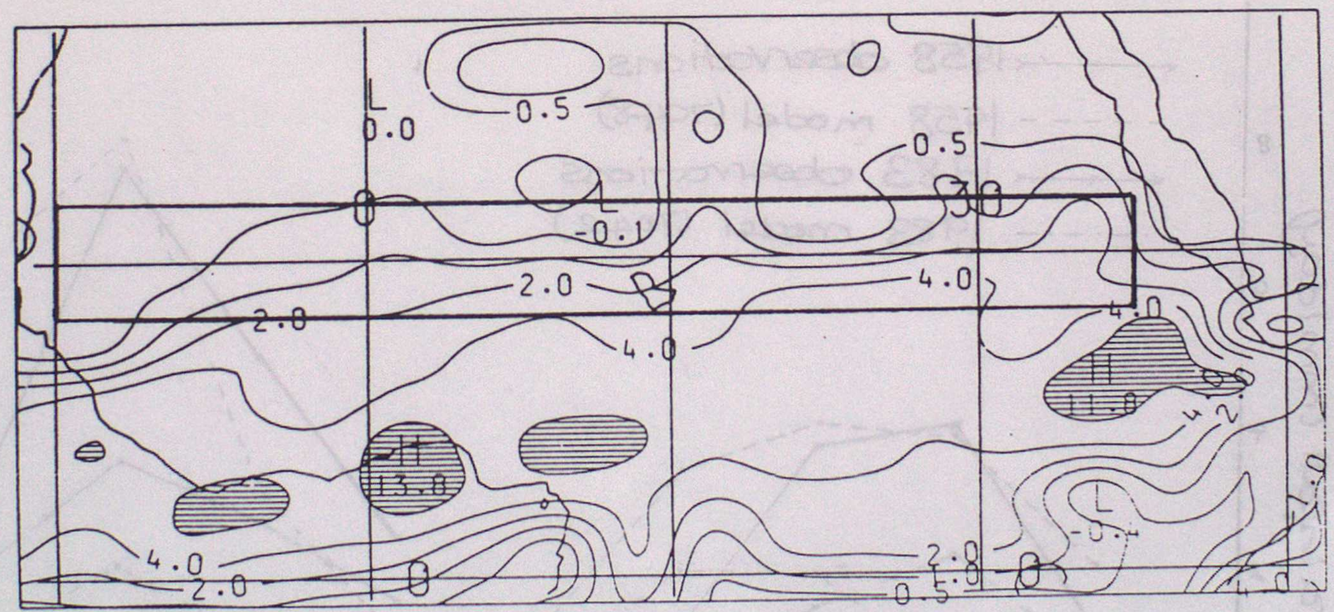


Fig. 6a (i) Observed and (ii) 3rd AC model rainfall for June 1950. Contours at 0, 0.5, 1, 2, 4, 8 and 16 mm/day.

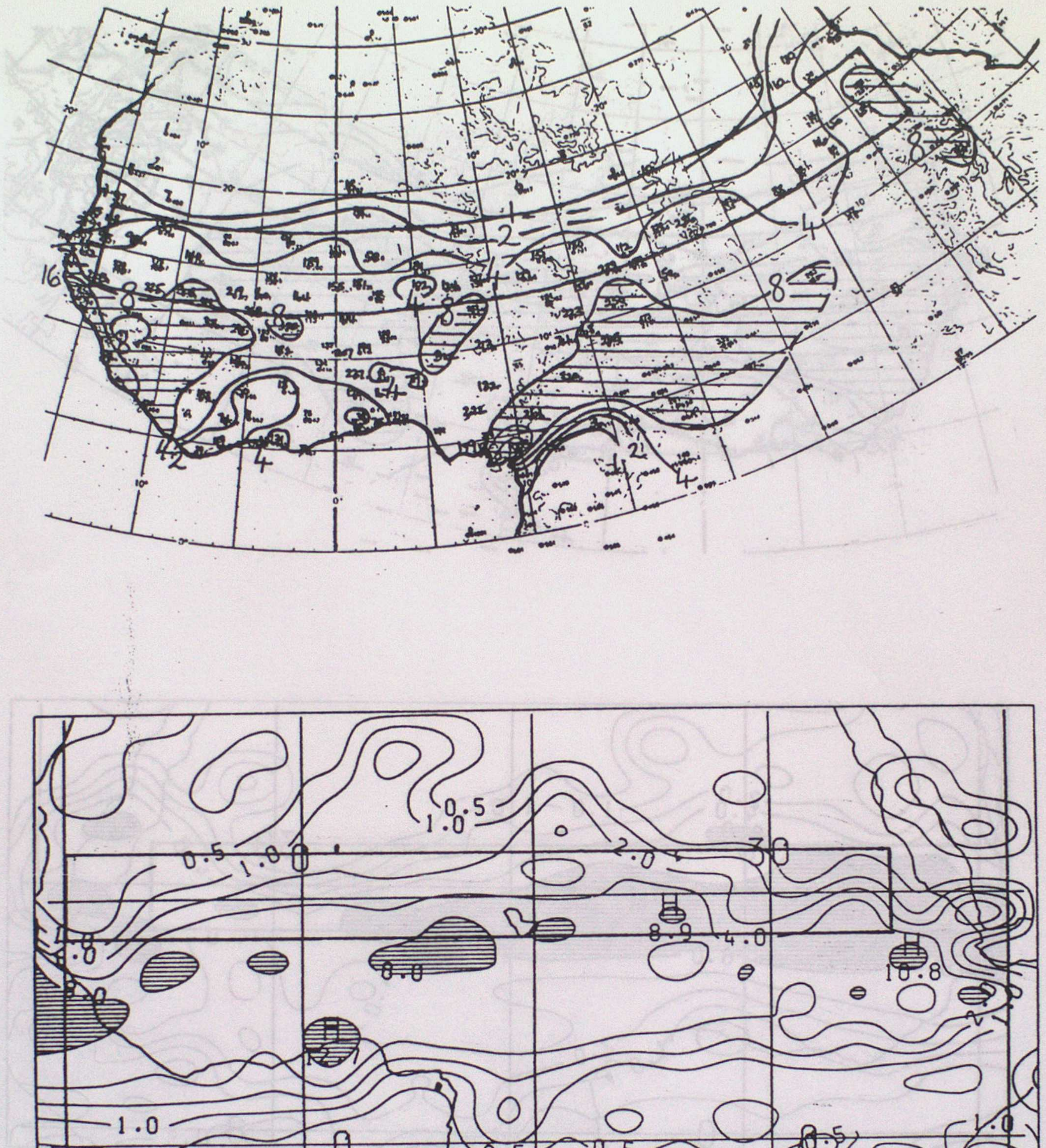


Fig. 6b As in fig. 6a but for July.

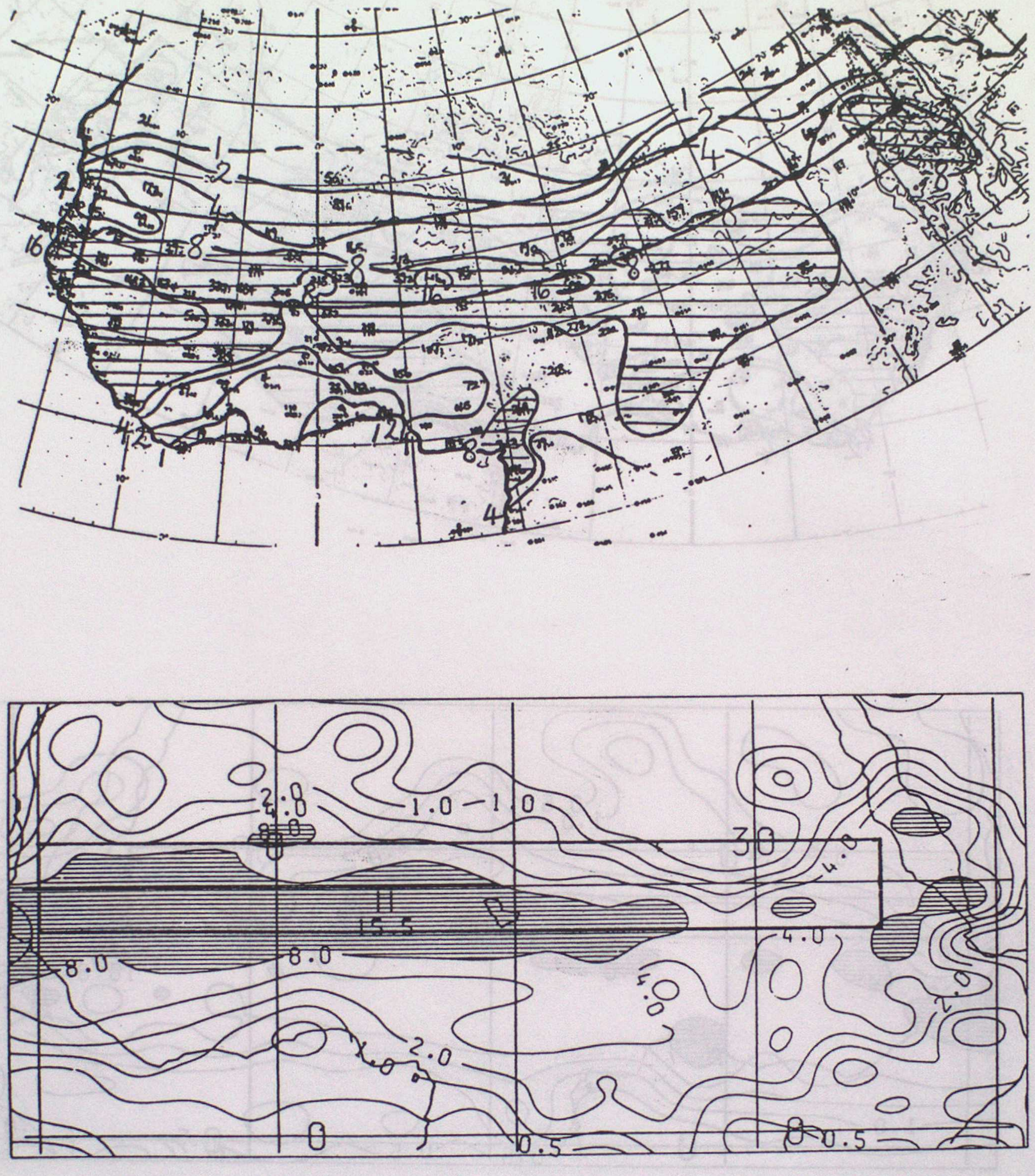


Fig. 6c As in fig. 6a but for August.

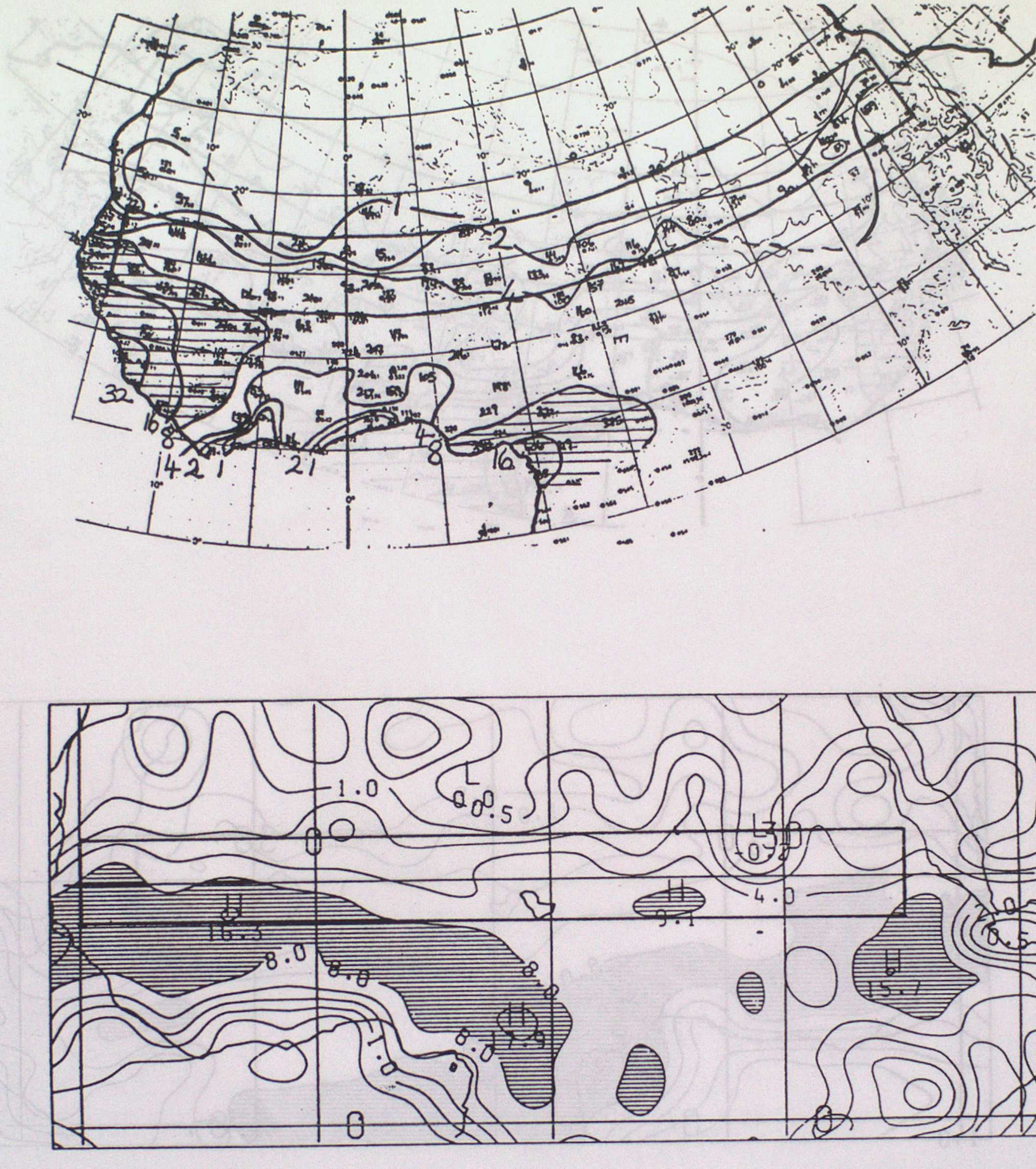


Fig. 6d As in fig. 6a but for September.

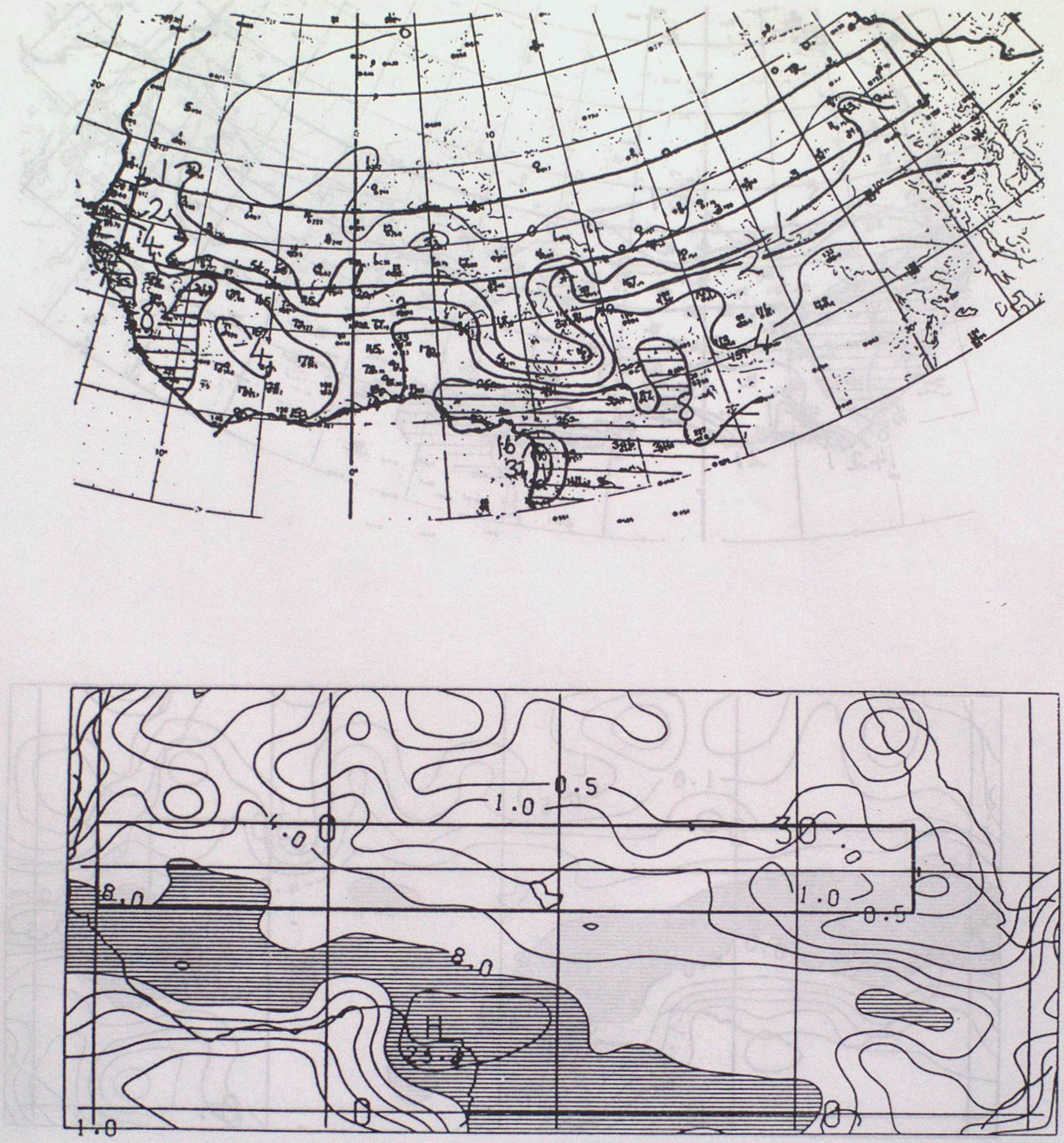


Fig. 6e As in fig. 6a but for October.

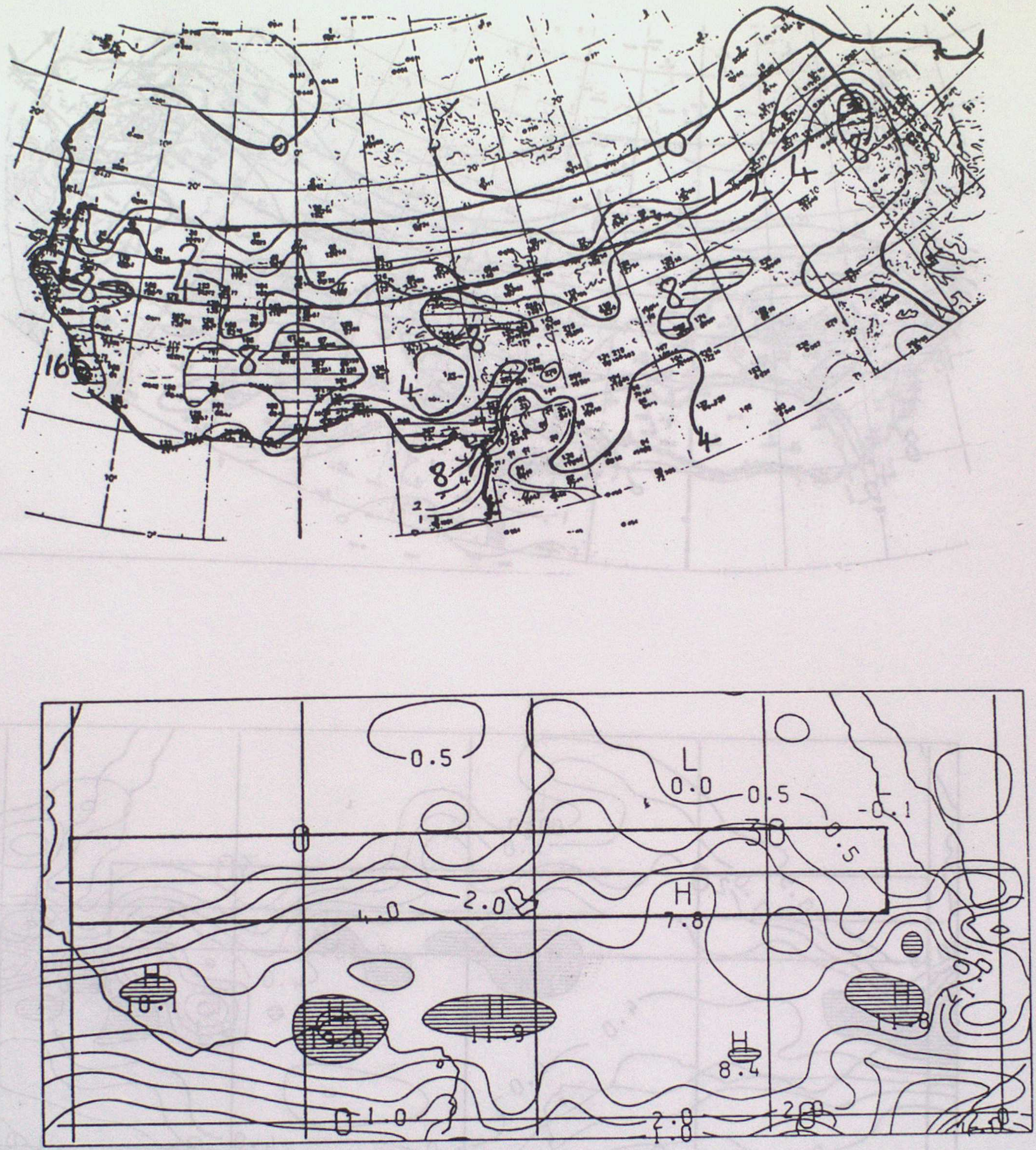
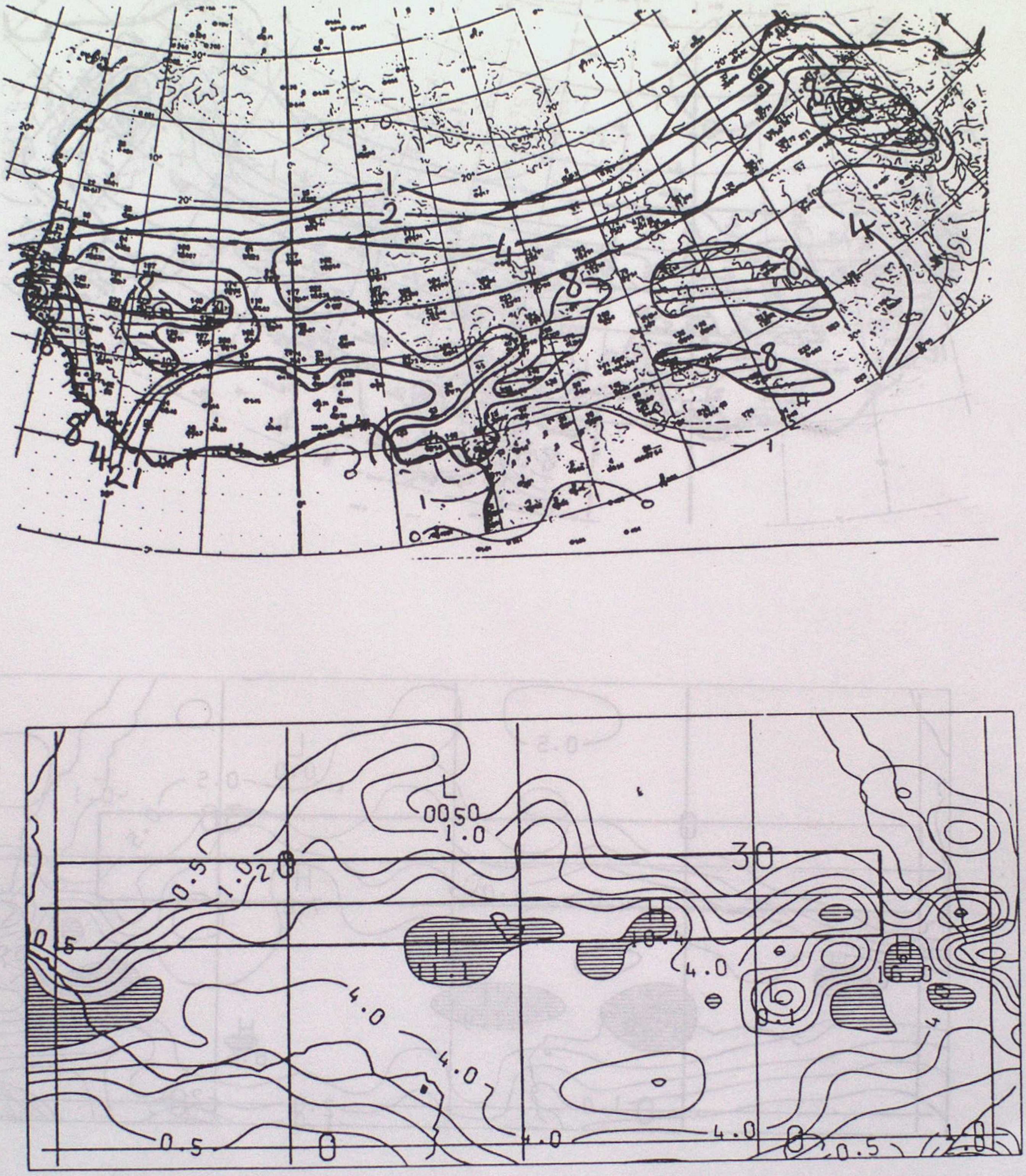


Fig. 7a (i) Observed and (ii) 3rd AC model rainfall for June 1958.
Contours at 0, 0.5, 1, 2, 4, 8 and 16 mm/day.



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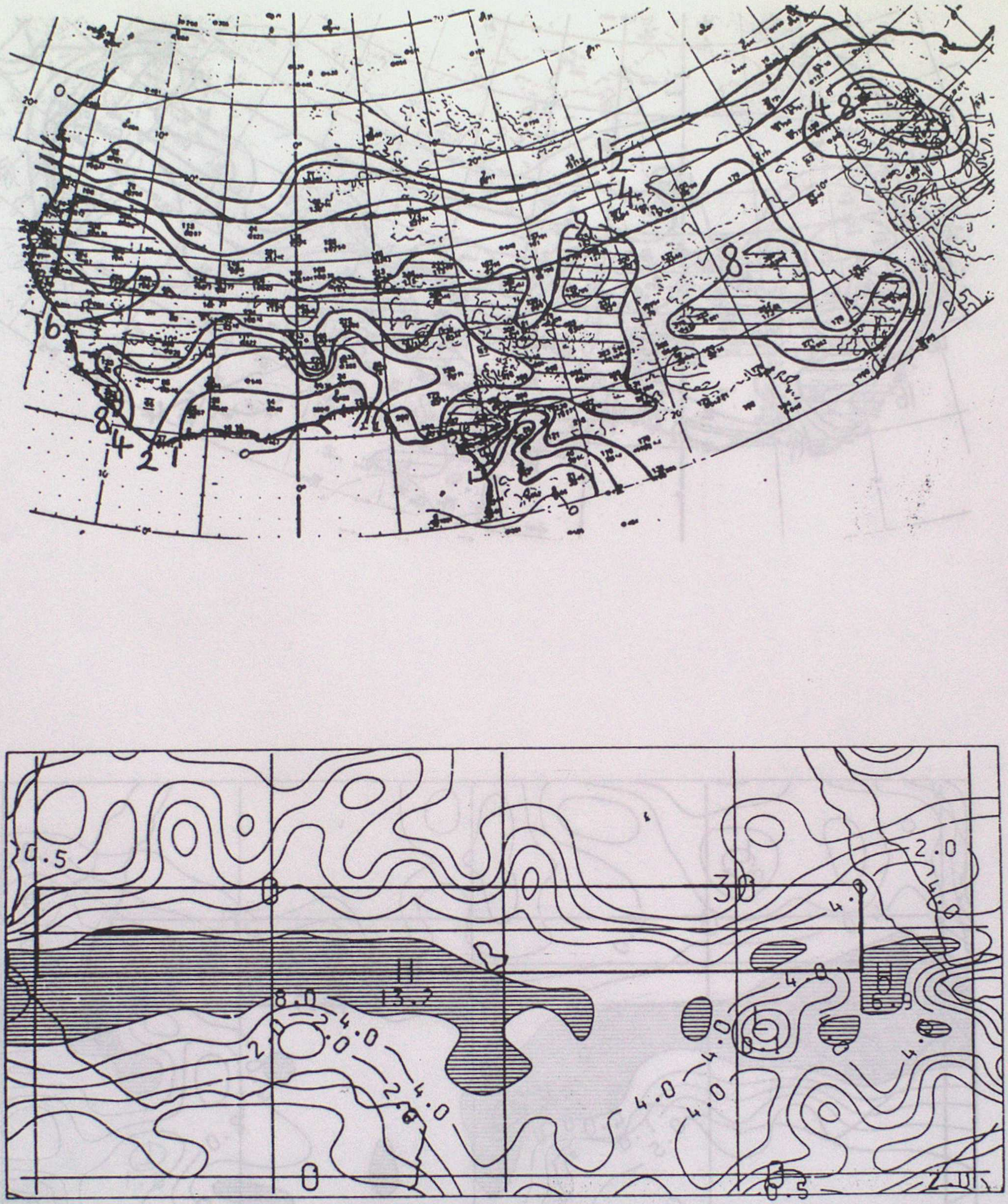
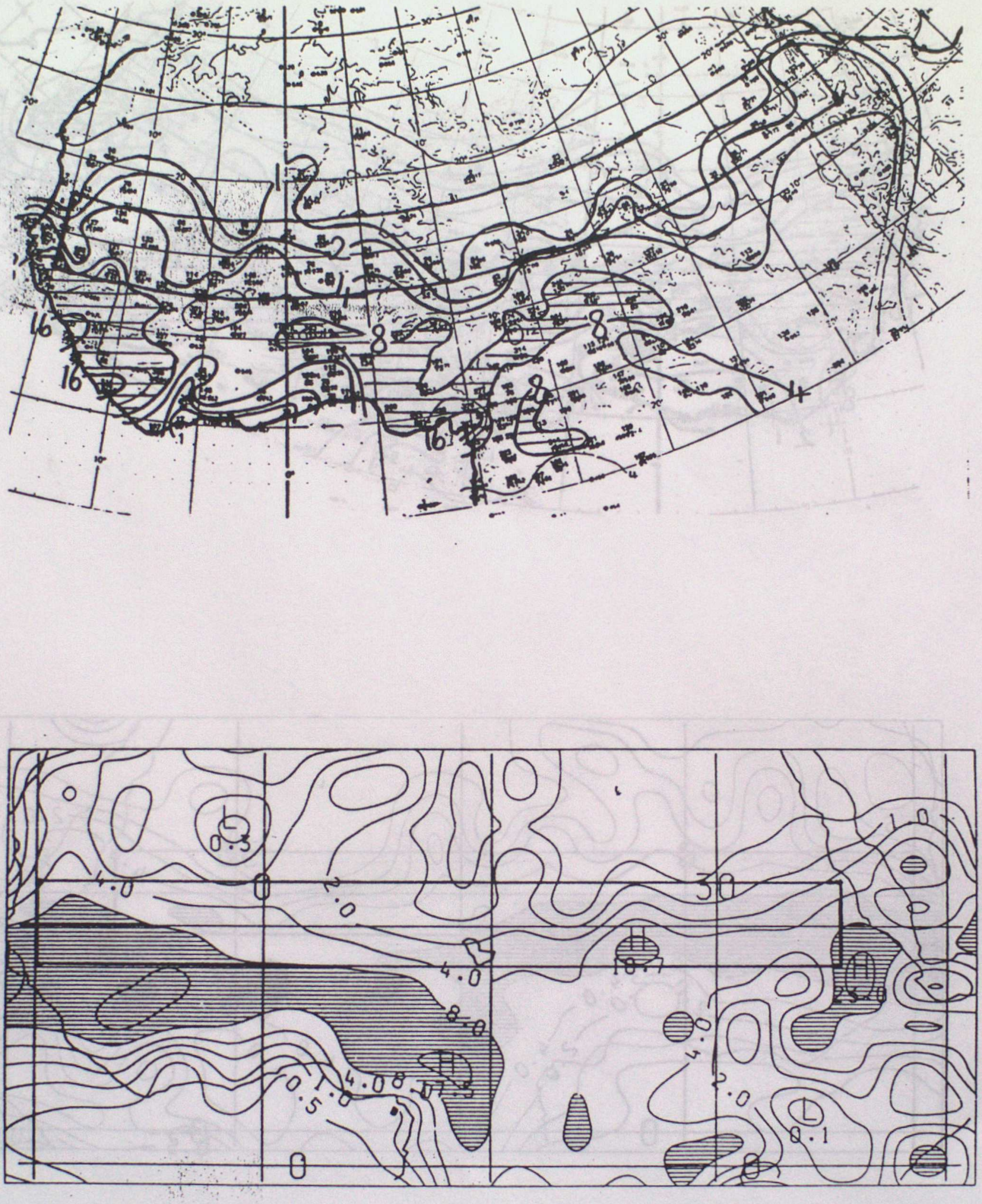


Fig. 7c As in fig. 7a but for August.



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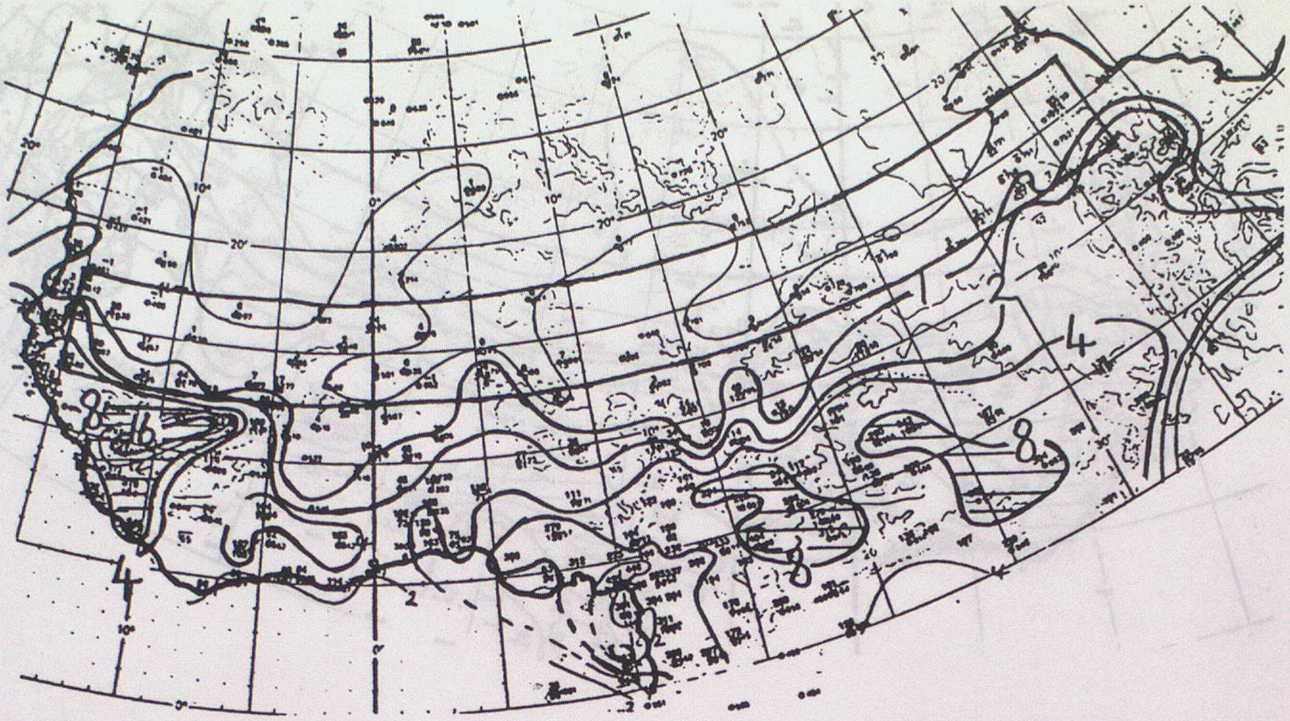


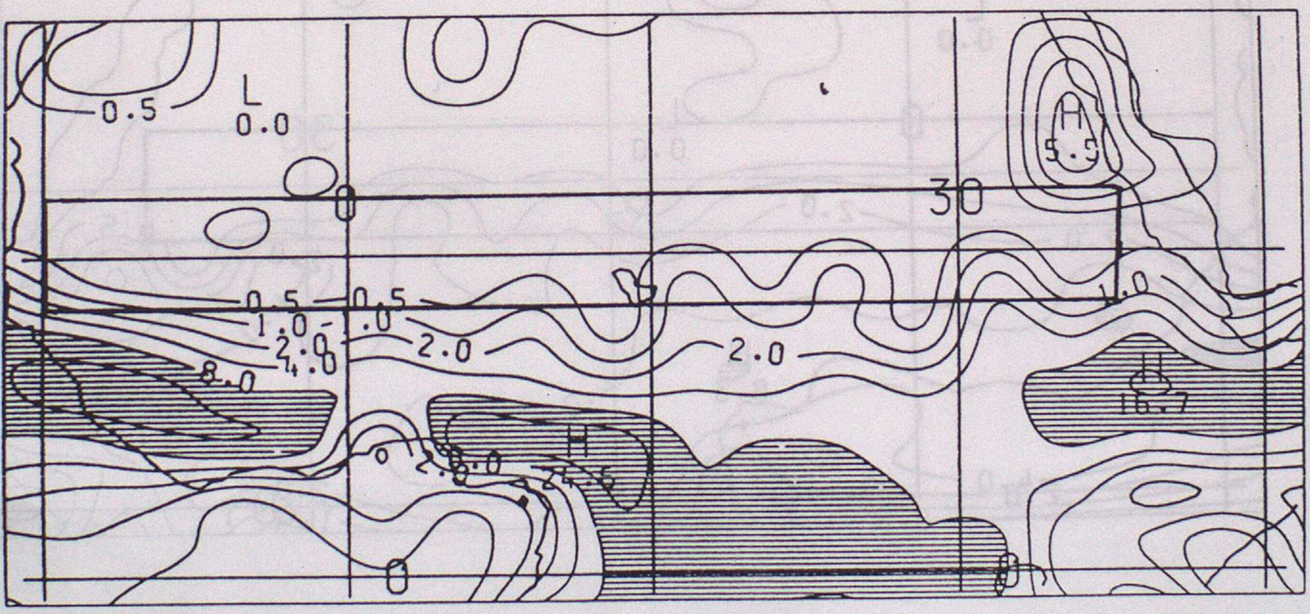


Fig. 7e As in fig. 7a but for October.

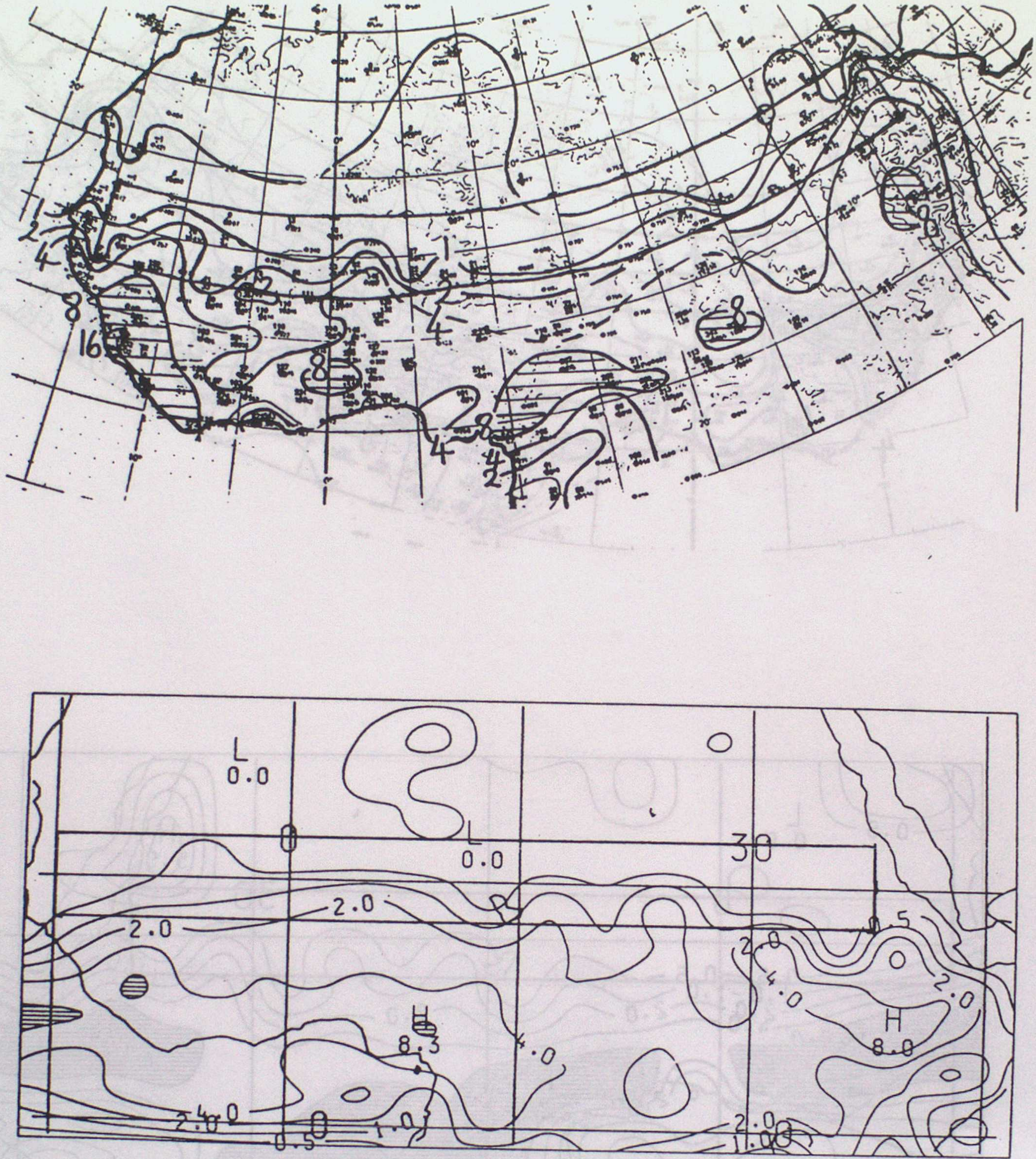
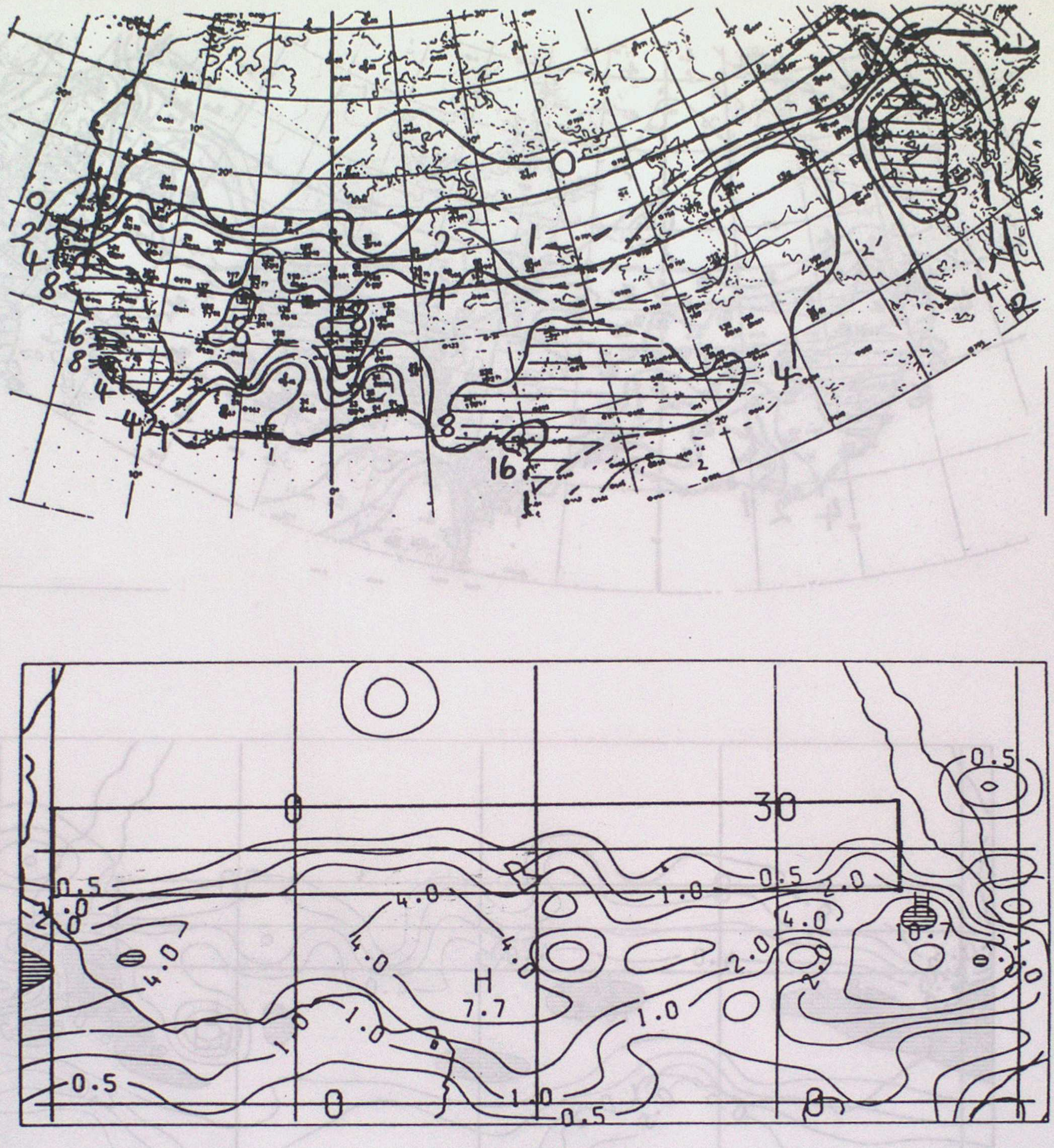


Fig. 8a (i) Observed and (ii) 3rd AC model rainfall for June 1983.
Contours at 0, 0.5, 1, 2, 4, 8 and 16 mm/day.



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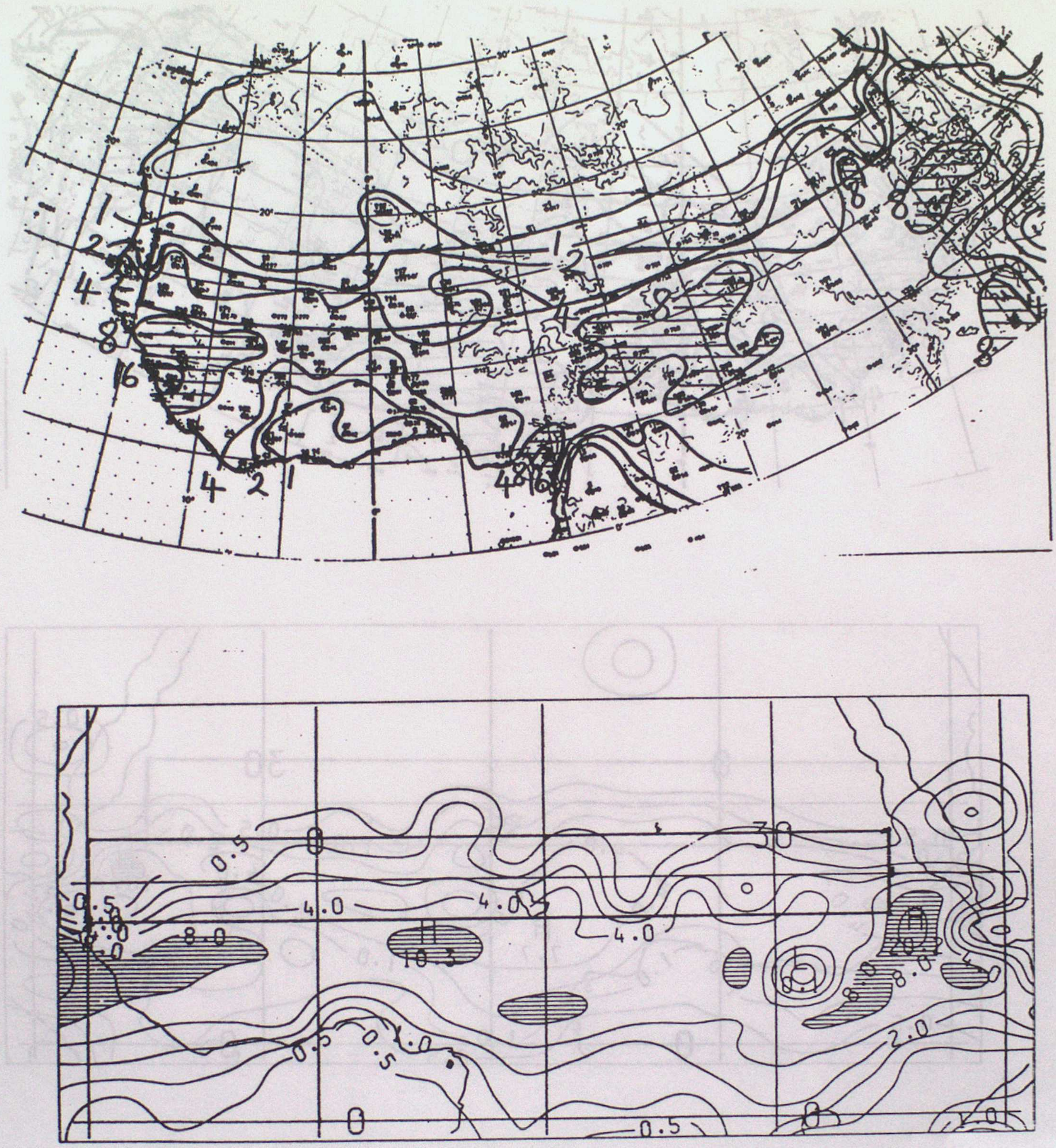


Fig. 8c As in fig. 8a but for August.

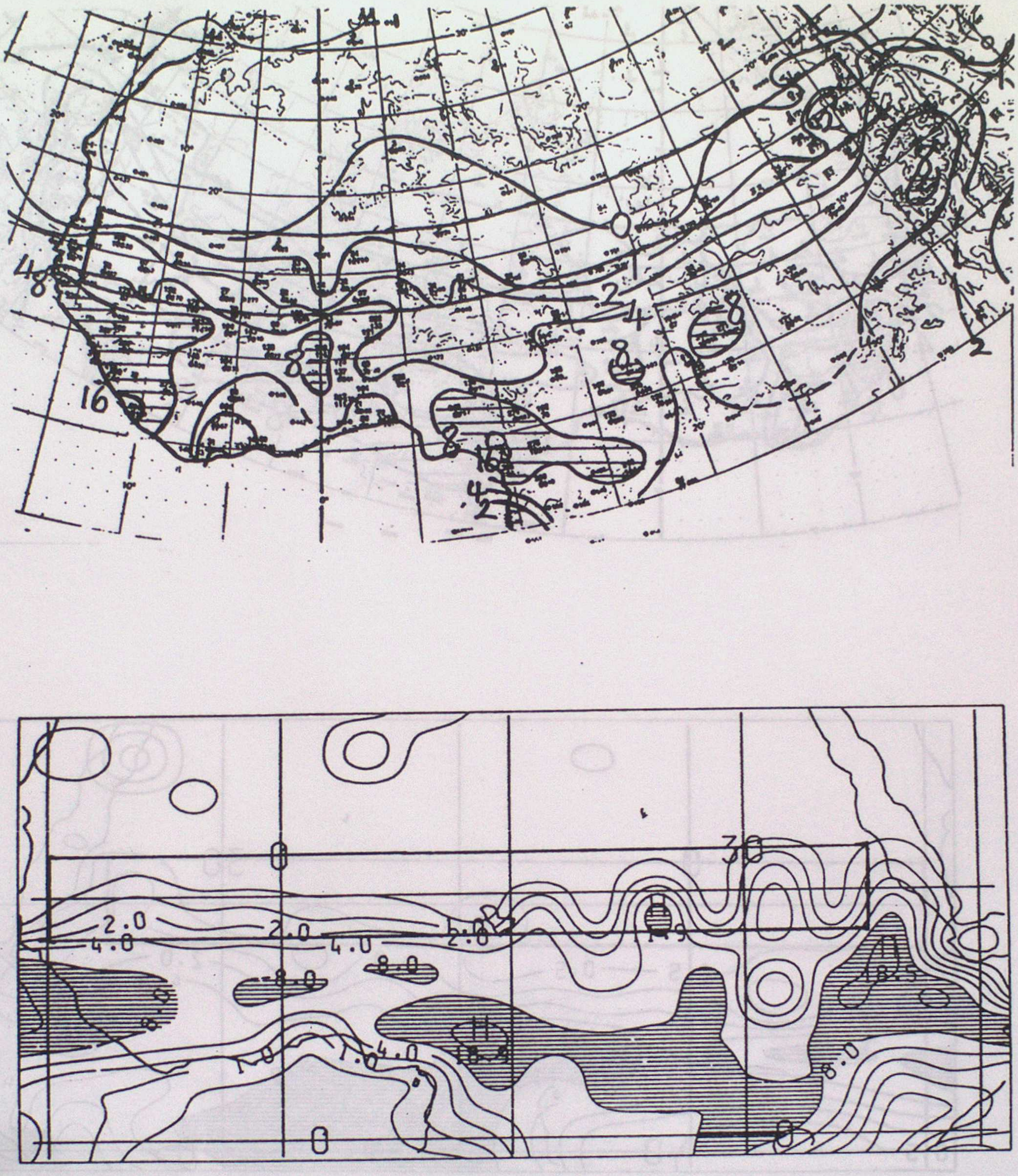


Fig. 8d As in fig. 8a but for September.

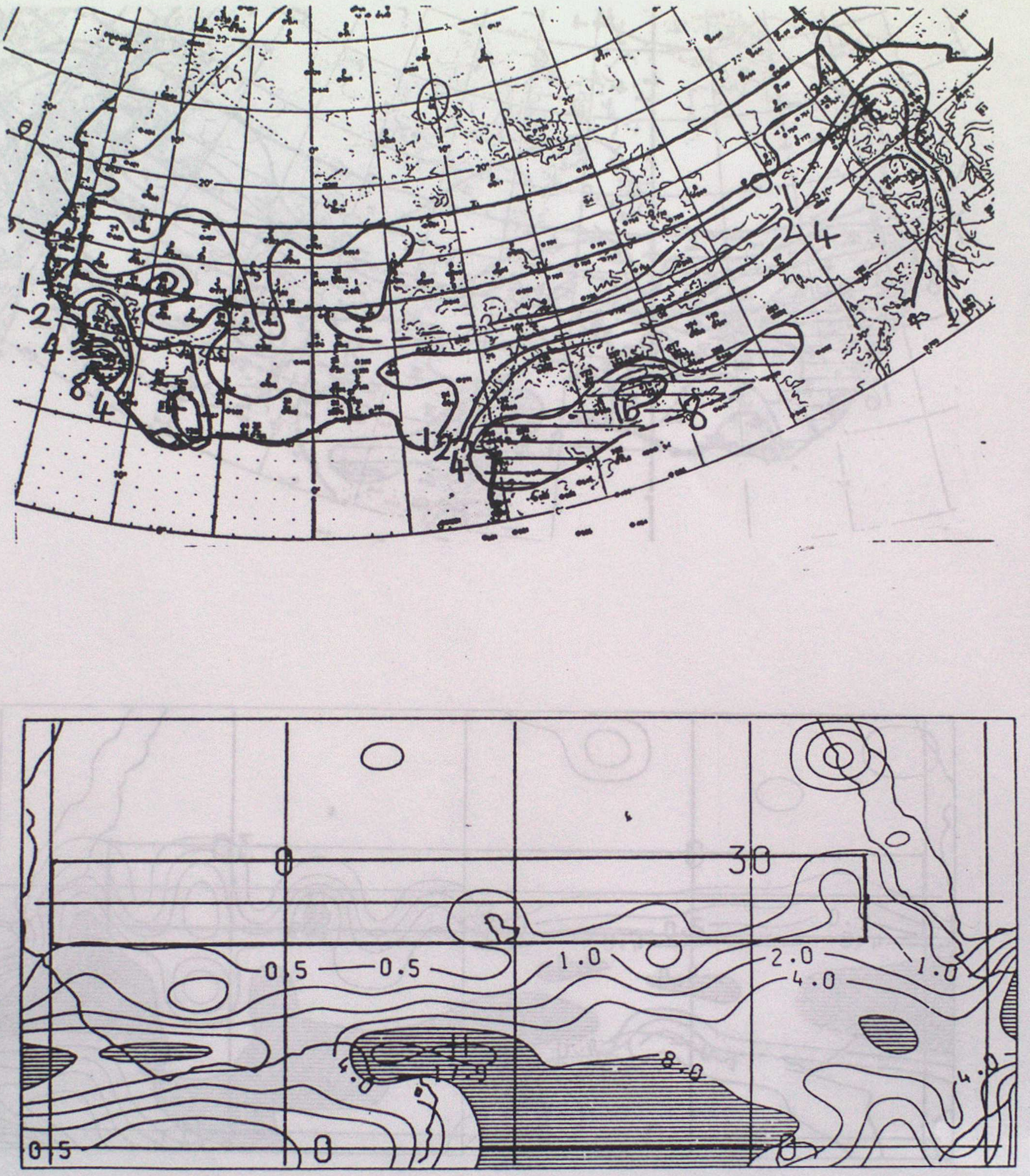


Fig. 8e As in fig. 8a but for October.

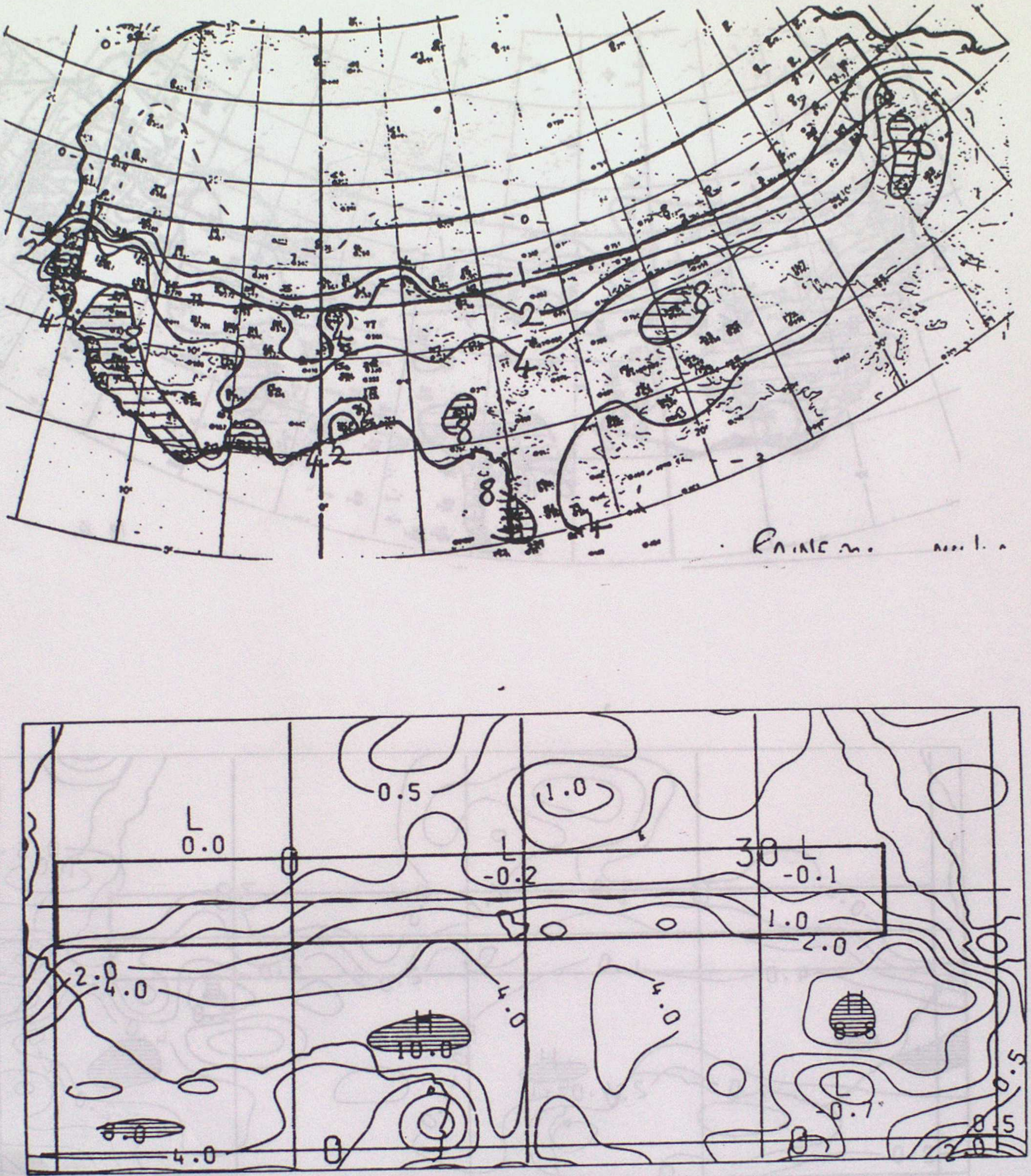


Fig. 9a (i) Observed and (ii) 3rd AC model rainfall for June 1984.
Contours at 0, 0.5, 1, 2, 4, 8 and 16 mm/day.

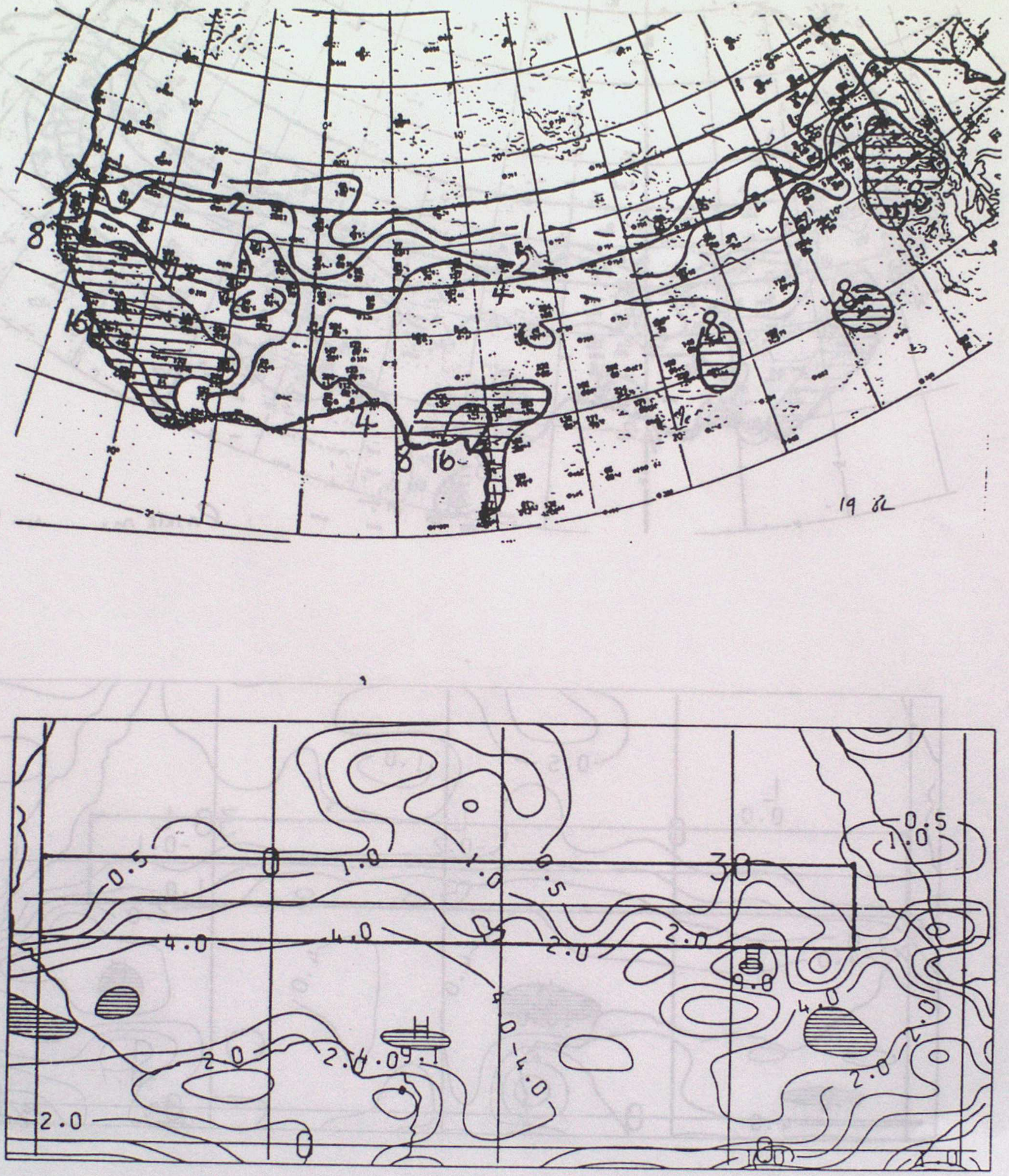


Fig. 9b As in Fig. 9a but for July.

Fig. 9c As in fig. 9a but for August.

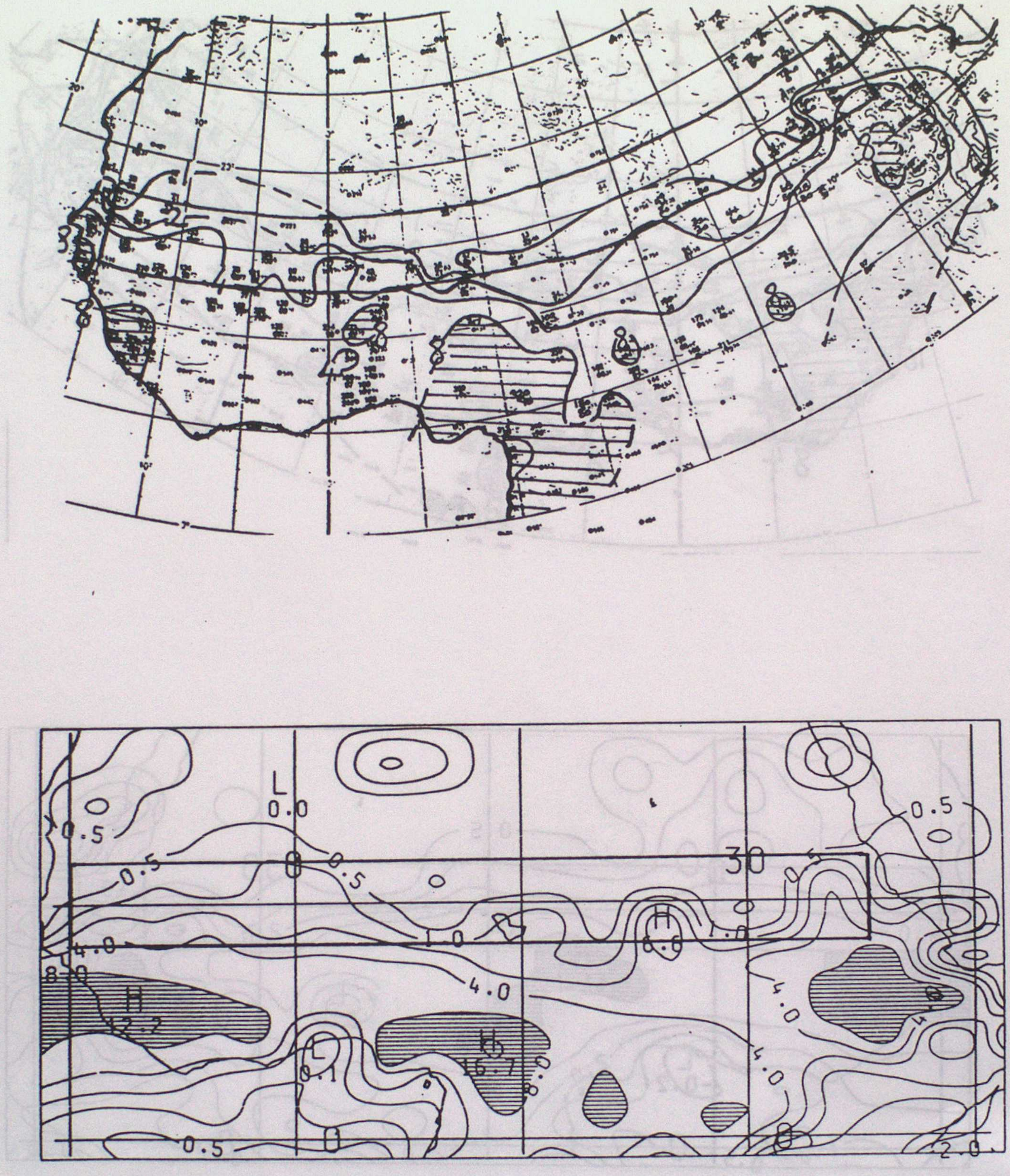


Fig. 9d As in fig. 9a but for September.

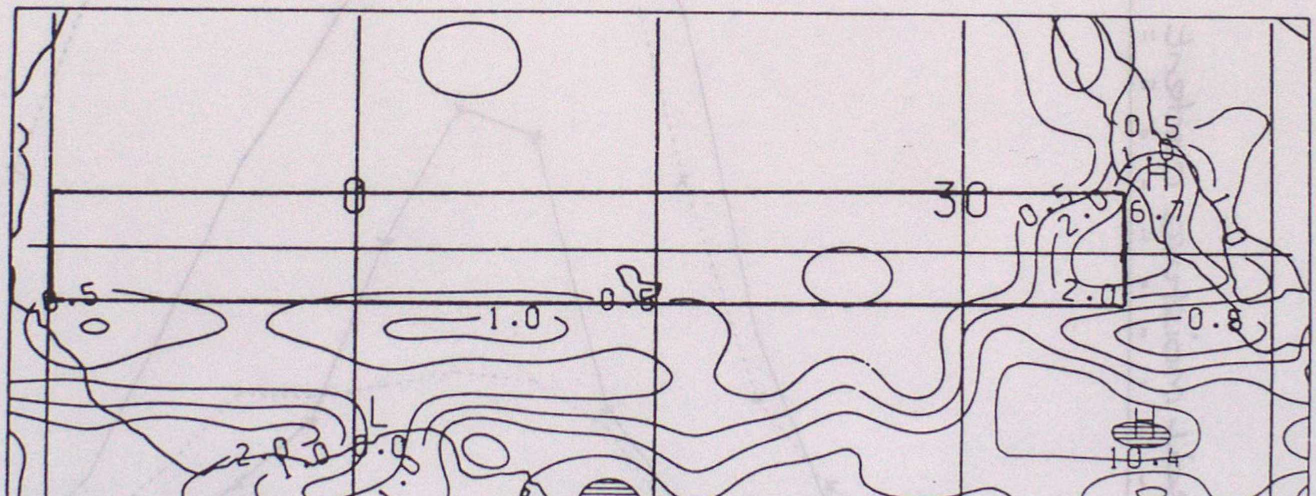


Fig. 9e As in fig. 9a but for October.

11.25 to 15°E, 10 to 15°N

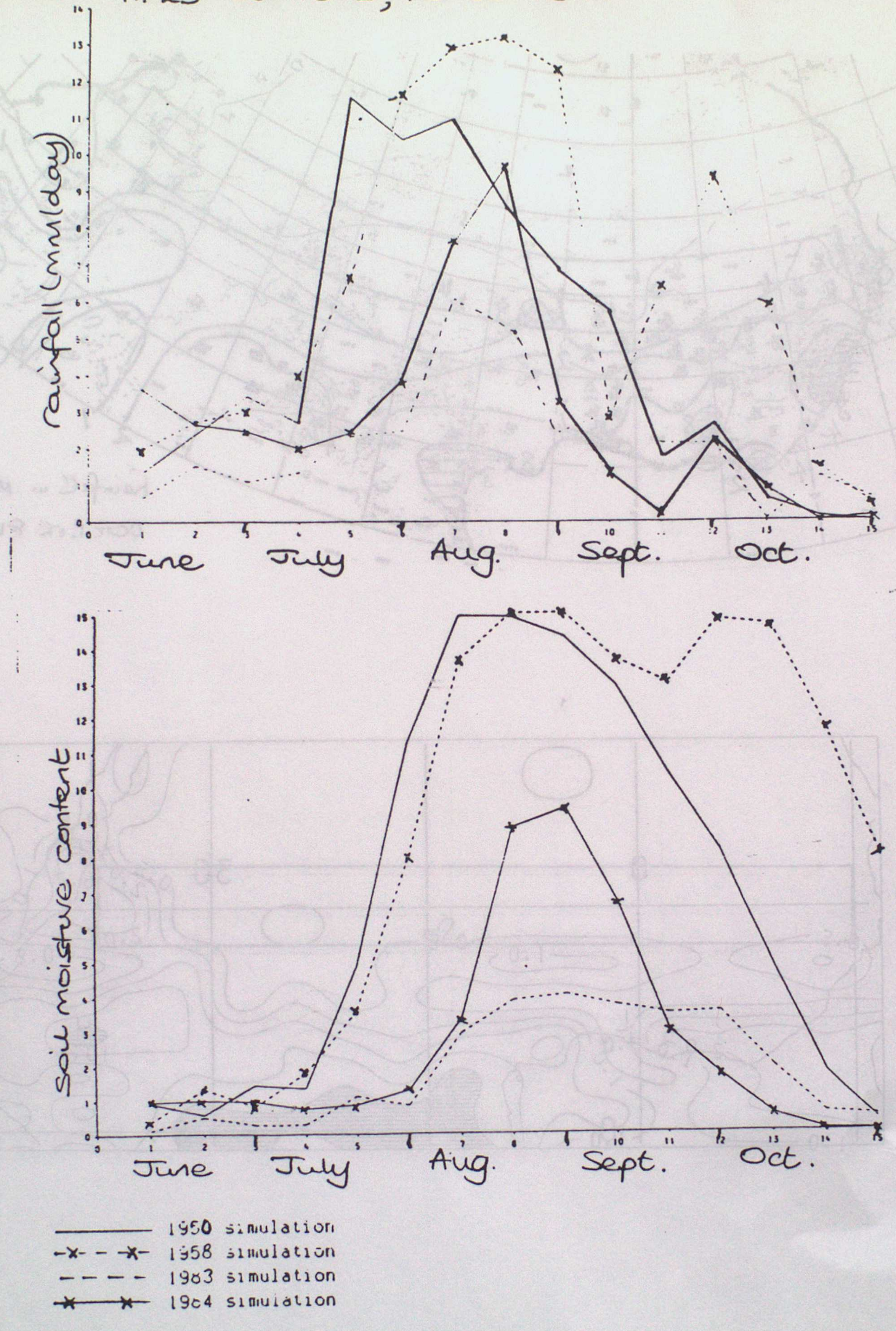


Fig. 10a Time series of rainfall and soil moisture content from June to October for the region 11.25 to 15°E, 10 to 15°N.

18.75 to 22.5 E, 10 to 15N

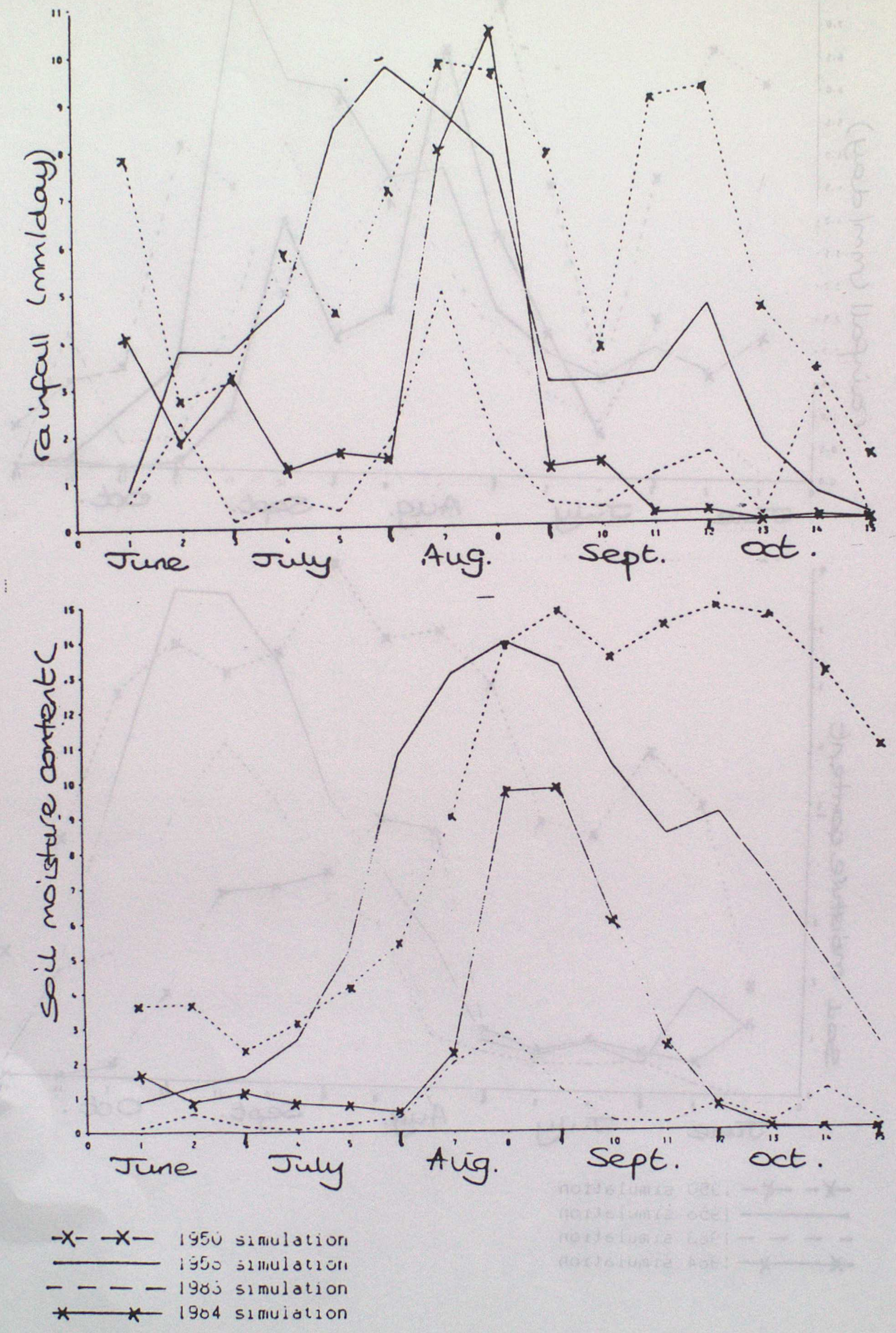
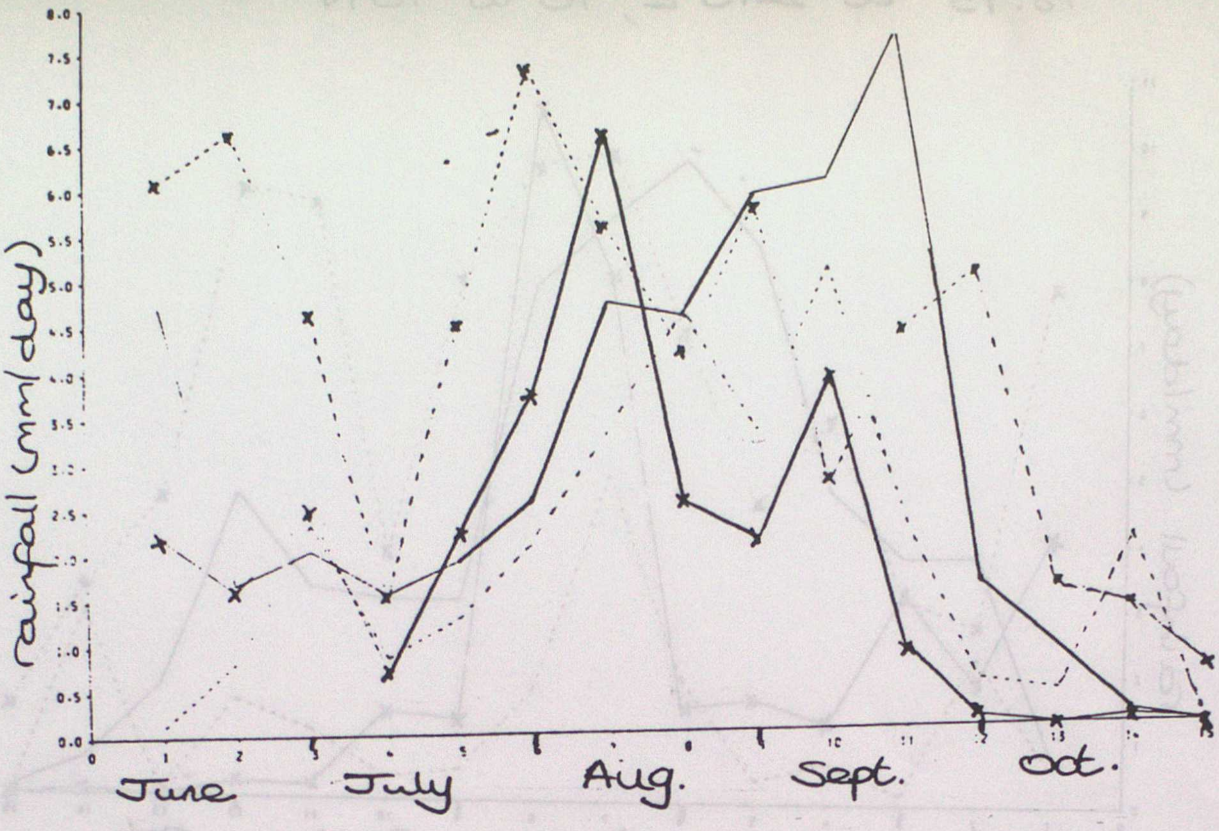


Fig. 10b Time series of rainfall and soil moisture content from June to October for the region 18.75 to 22.5°E, 10 to 15°N.

26.25 to 30 E, 10 to 15 N



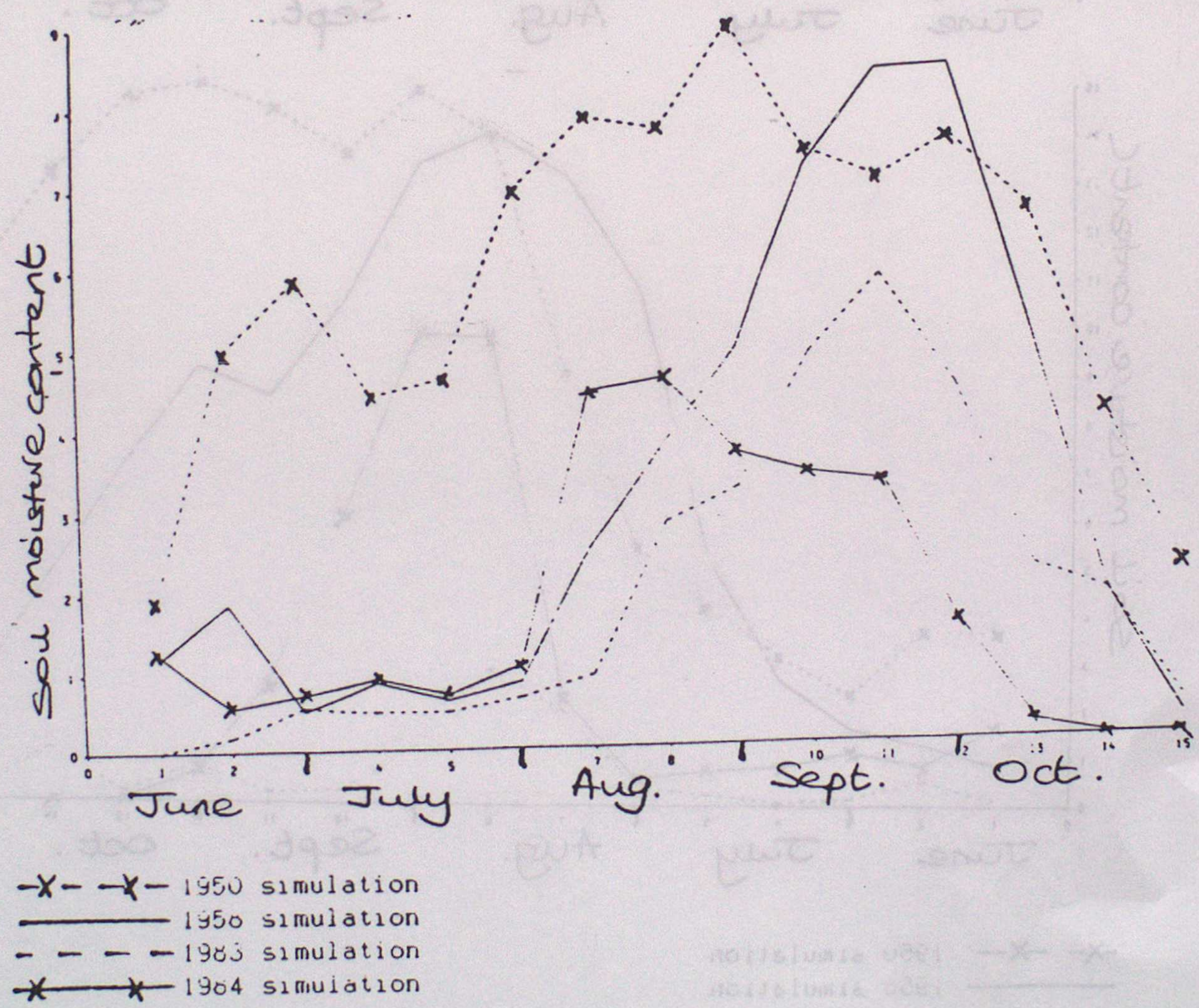


Fig. 10c Time series of rainfall and soil moisture content from June to October for the region 26.25 to 30°E, 10 to 15°N.

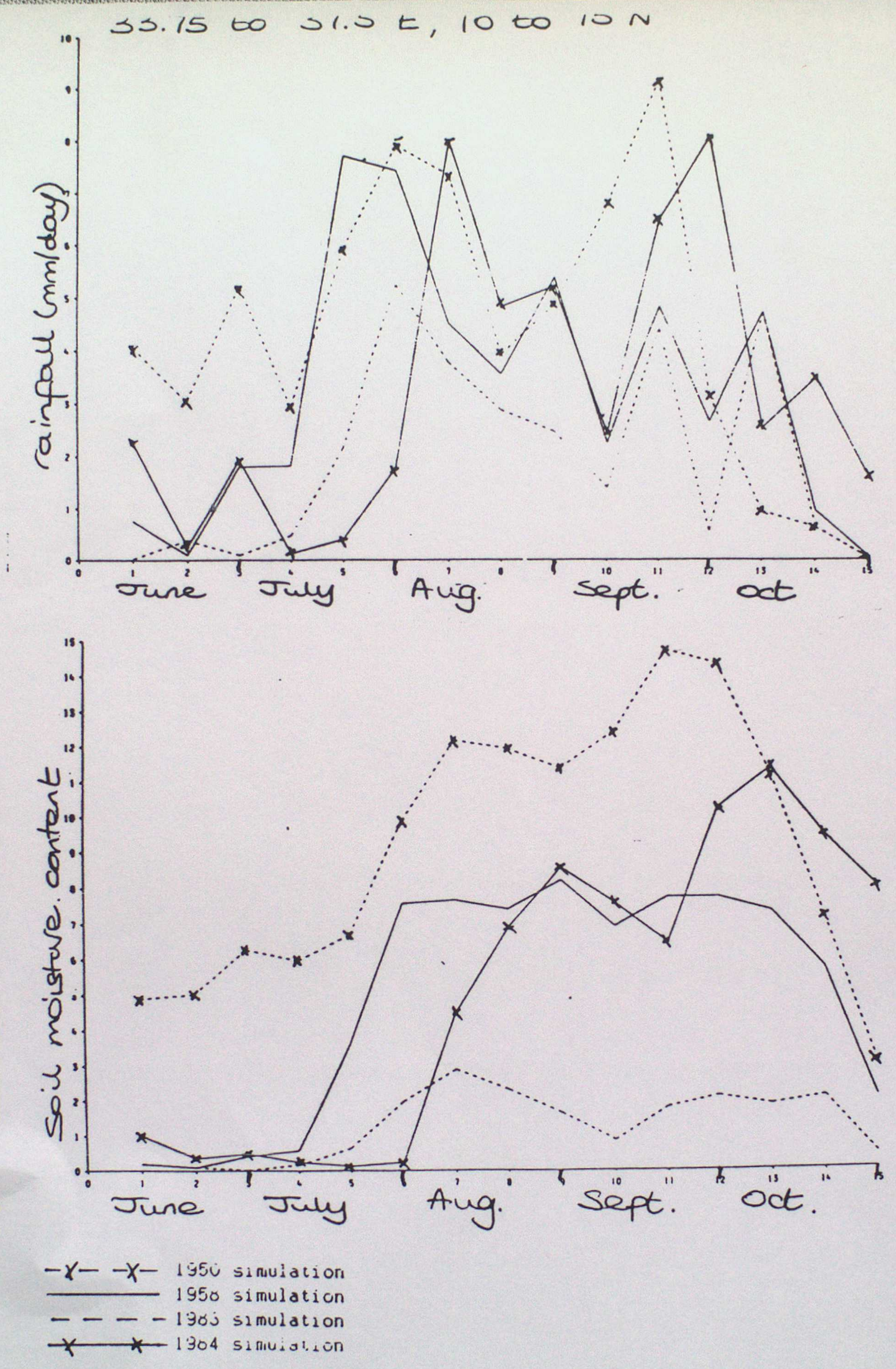


Fig. 10d Time series of rainfall and soil moisture content from June to October for the region 33.75 to 37.5°E, 10 to 15°N.