Some Effects of Topography, Soil Moisture, and Sea-Surface Temperature on Continental Precipitation as Computed with the GISS Coarse Mesh Climate Model [1]

J. Spar and C. Cohen

The City College
New York, N.Y. 10031

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Abstract

The effects of ~~The contributions of~~ terrain elevation, soil moisture, and zonal variations in sea/surface temperature to the mean daily precipitation rates over Australia, Africa, and South America in January were ~~are~~ evaluated. ~~with the GISS coarse mesh global general circulation model.~~ It was found that Evaporation of soil moisture may either increase or decrease the model generated precipitation, ~~apparently~~ depending on the surface albedo. A flat, dry continent model best simulates the January rainfall over Australia and South America, while over Africa the simulation is improved by the inclusion of surface physics, specifically soil moisture and albedo variations.

1 This research was carried out at the Goddard Institute for Space Studies (GISS) under Grant NGR 33-016-086, NASA, Goddard Space Flight Center.

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Introduction

The GISS climate model (Hansen et al., 1980) is a coarse mesh (8° of latitude by 10° of longitude), 7-layer global general circulation model that has been used for experimental simulations of the global climate, including, among other things, the annual cycle (Christidis and Spar, 1981). The model has also been run in a "perpetual January" mode to generate a presumably stable model climatology for that month. This is done by computing 25 successive mean January states with constant solar declination and then averaging the outputs for only the last 20 months of the run (Spar, 1981; Spar et al., 1981a; Cohen, 1981).

In the course of the perpetual January experiment, the model was run with (a) flat, dry (no soil moisture) continents, and a zonally symmetric pattern of sea-surface temperature (SST), (b) dry but mountainous continents, with zonally symmetric SST, (c) mountainous and "wet" continents, capable of moisture storage in two soil layers from which evaporation can take place, with zonally symmetric SST, and (d) mountainous, wet continents, with a climatologically realistic SST pattern (i.e., zonal as well as meridional gradients of SST).

For historical reasons, these four computations have been designated as runs 2, 3, 4, and 5, respectively. For runs 3, 4, and 5, the model was initialized with a dry isothermal, motionless atmosphere, and allowed to generate its own humidity and temperature fields while "spinning up", whereas in run 2 initial meridional and vertical gradients of humidity and temperature were specified. However, the model soon "forgets" its initial conditions, and, as the first 5 months are discarded before averaging, the transient effects of the initial conditions are hardly reflected in the model climatologies (Spar et al., 1981b).

In runs 2 and 3, one constant value was used for the surface albedo of all continents (except where snow covers the ground, causing a jump in the albedo to that of snow), whereas for runs 4 and 5 a geographically variable albedo (high over deserts, low over jungle, etc.) was employed. Thus, differences between runs 4 and 3 represent effects of both spatial albedo variations and the evaporation of soil moisture resulting from the storage of rainwater on the continents.

The global characteristics of the climatologies generated by the model with different surface boundary conditions have already been described in earlier reports (e.g., Cohen, 1981). In the present paper, attention is focused on the precipitation over the continents, and, specifically, on the influences of topography, soil moisture, albedo variations, and zonal SST gradients on that particular element of the model-generated January climate. As noted recently by Miyakoda and Strickler (1981), for example, model calculations of precipitation are clearly sensitive to the physical characteristics of the earth's surface, especially soil moisture. However, relatively little is known about the precise quantitative role of the surface physics in the actual hydrologic cycle.

In the perpetual January computations with the GISS climate model, precipitation amounts over the extratropical continents of the Northern Hemisphere were found to be small compared with the rainfall over the continents in the tropics and in the summer hemisphere. For this reason, the present study is concentrated on the three continents where the most abundant precipitation appears in the January climate simulations: Australia, Africa, and South America.

Australia

From climatological data, the mean daily precipitation rate over Australia in January is known to increase from less than 1 mm day^{-1} in the southwest to more than 7 mm day^{-1} around the Gulf of Carpentaria in the north, with values probably greater than 10 mm day^{-1} on the northeast coast. (See, e. g., Kendrew, 1942.) Figure 1, based on run 2, shows the January precipitation rate computed with the flat, dry continent model. The result is in fairly good general agreement with the observed climatology, showing less than 1 mm day^{-1} over the southwestern desert region and a maximum of 7.5 mm day^{-1} south of the Gulf of Carpentaria, but with the rainfall rate decreasing unrealistically to the north and northeast of Australia.

The addition of smoothed mountainous terrain, mainly in the east and northwest, alters the rainfall pattern to that of run 3, shown in figure 2. The difference between the last two computations, presented in figure 3, indicates that the effect of the mountains is to increase the precipitation in the east and northwest, and to decrease the precipitation around the Gulf of Carpentaria, leaving the low rainfall rate over the southwestern desert essentially unchanged. The inclusion of terrain thus spreads the heaviest precipitation more uniformly (and more realistically) along a band from northwest to southeast, but reduces the intensity of the rainfall unrealistically in the northern part of Australia.

The effects of a geographically variable surface albedo and of soil moisture are both reflected in figure 4, which shows the result of run 4, and in figure 5, which displays the difference between the precipitation calculated in runs 3 and 4. The dominant effects of the continental

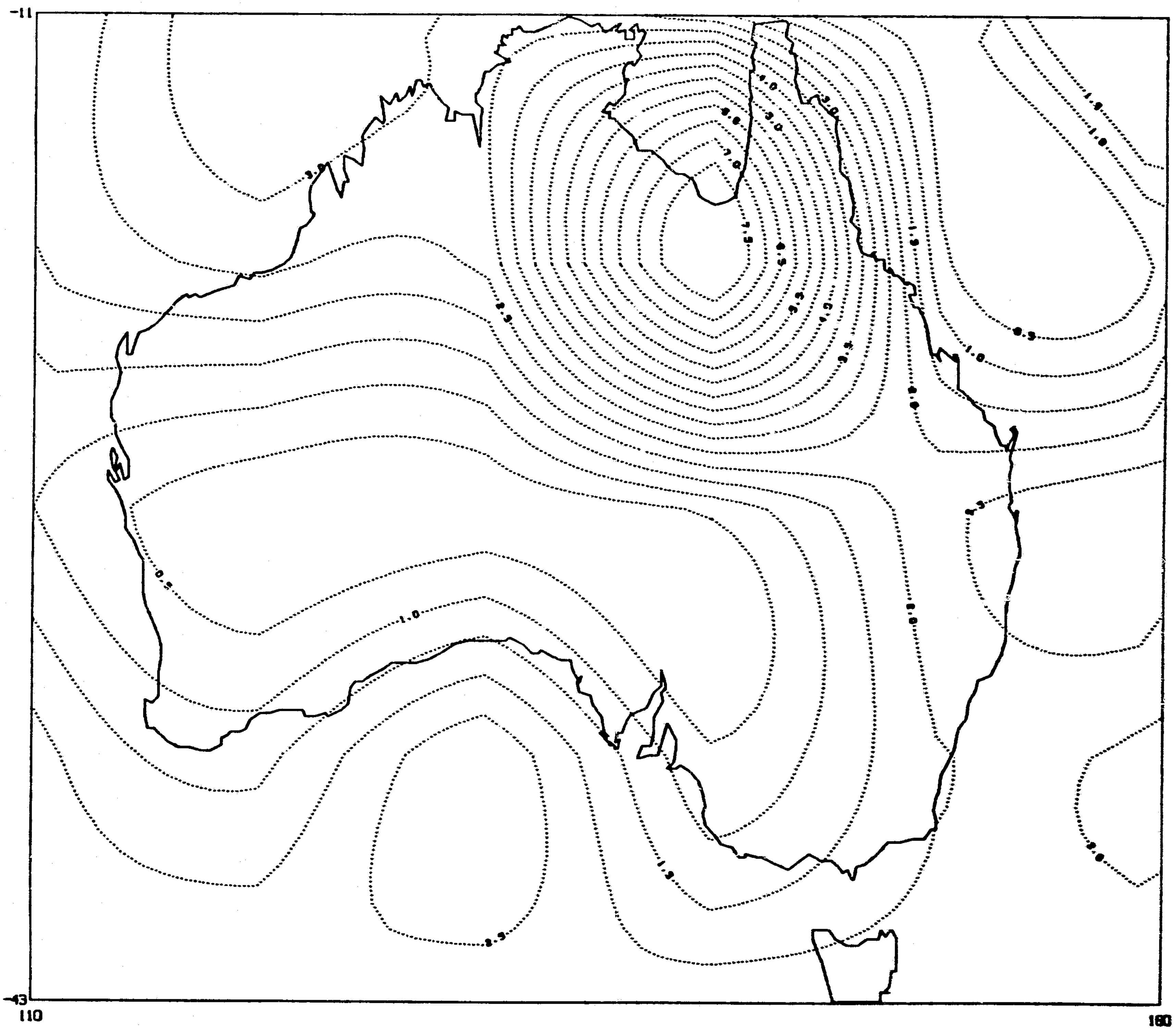


Fig. 1 PRECIPITATION (MILLIMETERS PER DAY) RUN 2

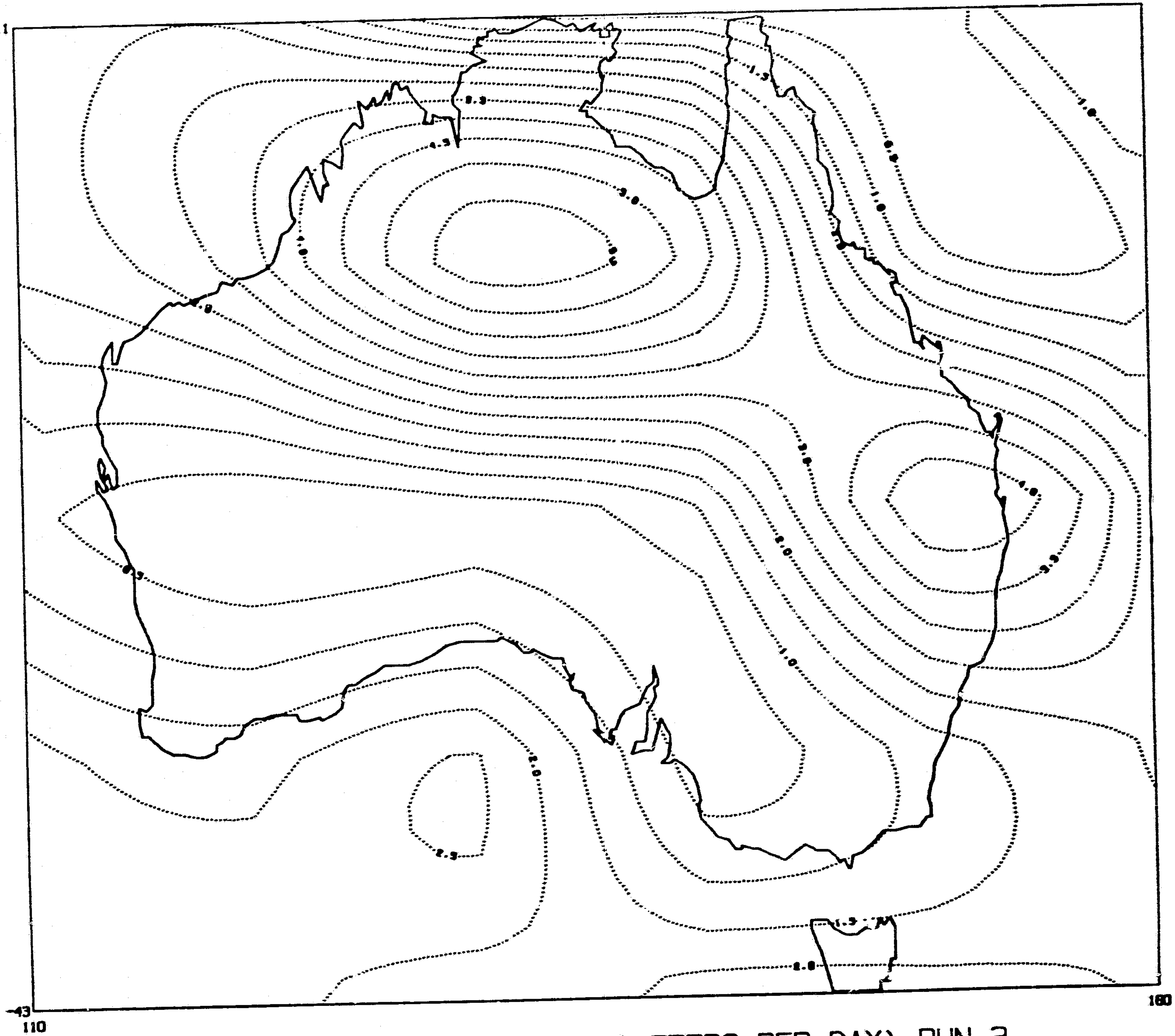


Fig. 2 PRECIPITATION (MILLIMETERS PER DAY) RUN 3

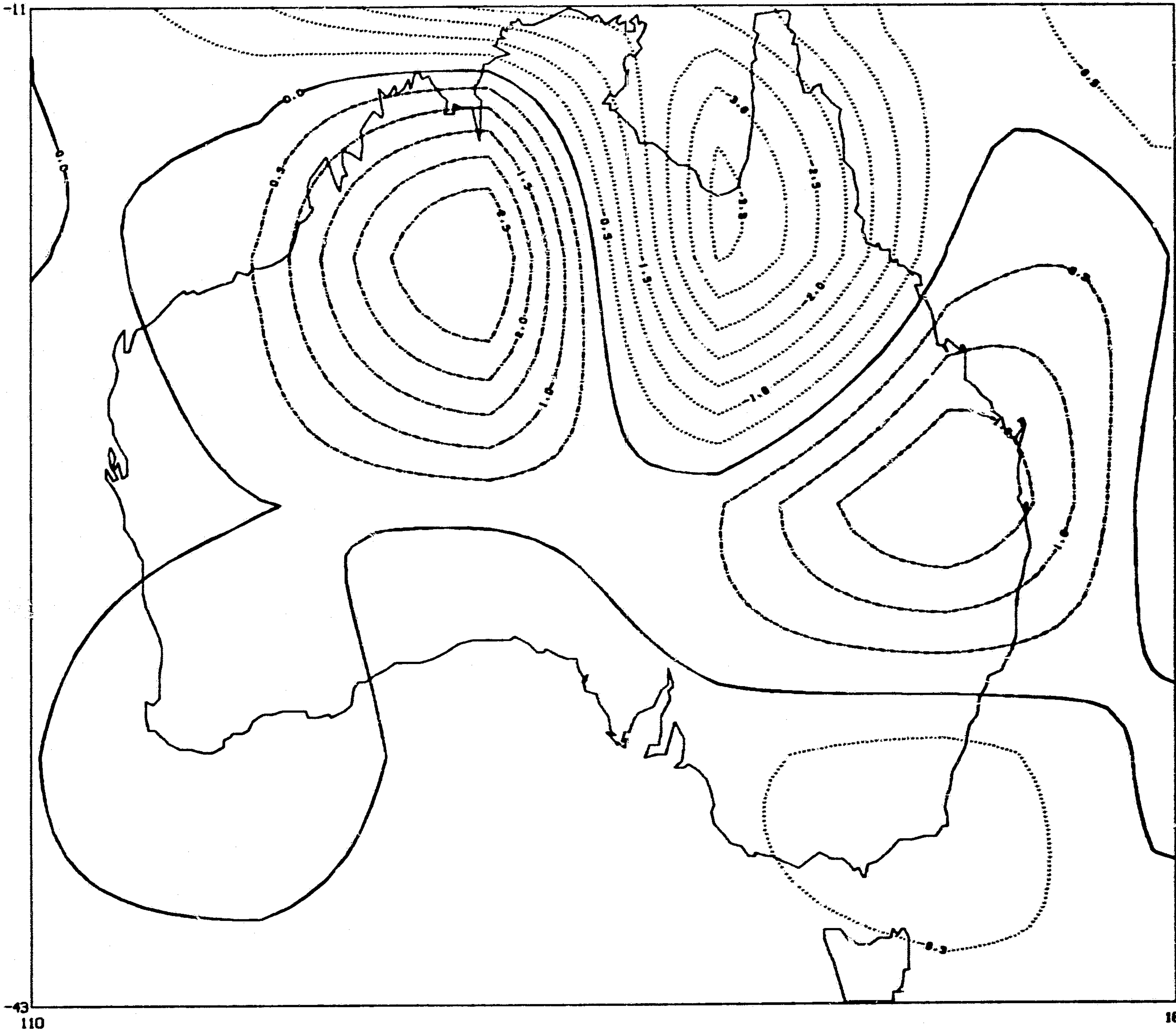


Fig. 3 PRECIPITATION (MILLIMETERS PER DAY) RUN 3 MINUS RUN 2

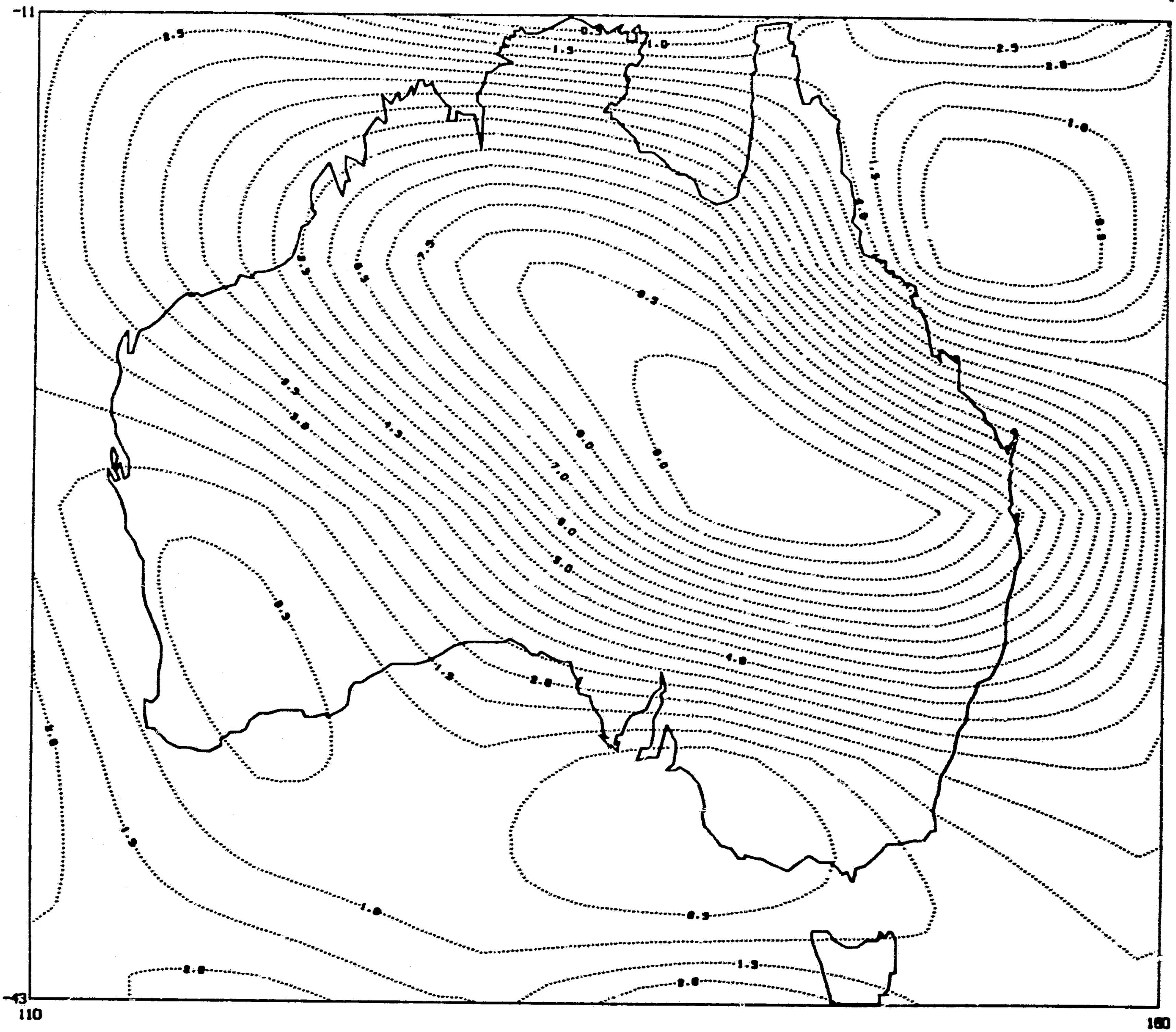


Fig. 4 PRECIPITATION (MILLIMETERS PER DAY) RUN 4

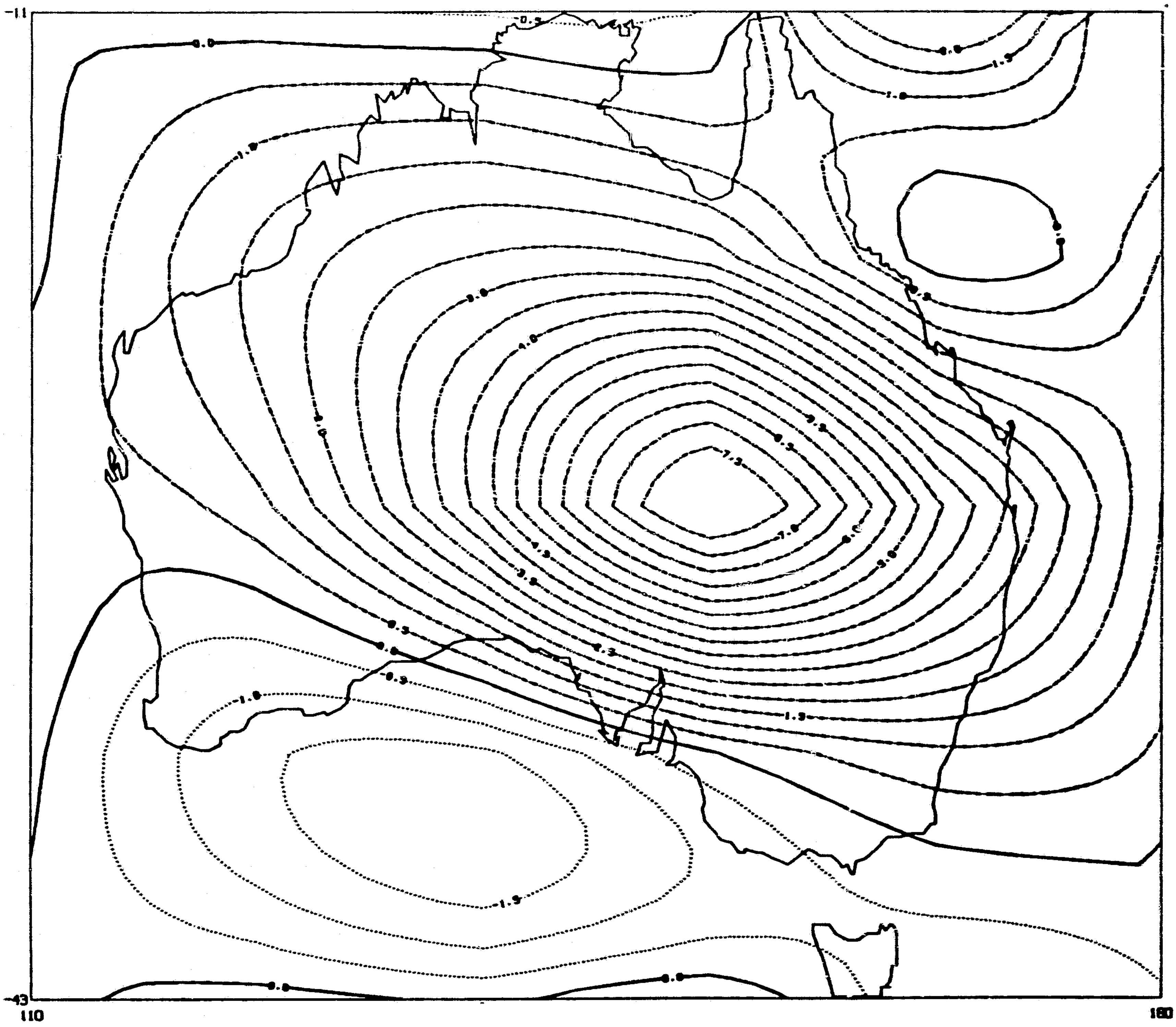


Fig. 5 PRECIPITATION (MILLIMETERS PER DAY) RUN 4 MINUS RUN 3

surface physics are an excessively large increase in the precipitation rate over most of the continent, and a shift of both the wet and dry belts too far south. This is probably due more to the evaporation of soil moisture than to the variable surface albedo, and indicates that there may be an exaggerated positive feedback of rainwater in the model calculation.

The inclusion of zonal gradients of SST has a relatively small effect on the computed precipitation pattern for January over Australia, slightly decreasing rainfall on the east coast and increasing it in the northwest and northeast, as seen in figures 6 and 7. The increased rainfall over the ocean northeast of Australia, apparently due to an increase of SST above the zonal mean of the model, is a noteworthy improvement in the climate simulation, but the rainfall minimum closer to the northeast coast remains as a serious defect.

In general, the main features of the mean January precipitation pattern over Australia are reproduced reasonably well by the dry, flat continent model, while the contributions of topography, soil moisture (as well as variable albedo) and zonal variations of SST add little or nothing of beneficial value to the quality of the simulation.

Africa

As shown in figure 8, the January rainfall rate over Africa computed with the dry, flat continent model is less than 1 mm day^{-1} over the desert regions in the north (Sahara) and south (Kalahari), more than 11 mm day^{-1} north of the Equator over central Africa (northern Zaire) and more than 8 mm day^{-1} south of the Equator over the region of Angola, with light precipitation elsewhere, including coastal areas.

When topography is introduced (fig. 9), the desert and coastal rainfall are almost unaffected. However, the Angolan maximum almost

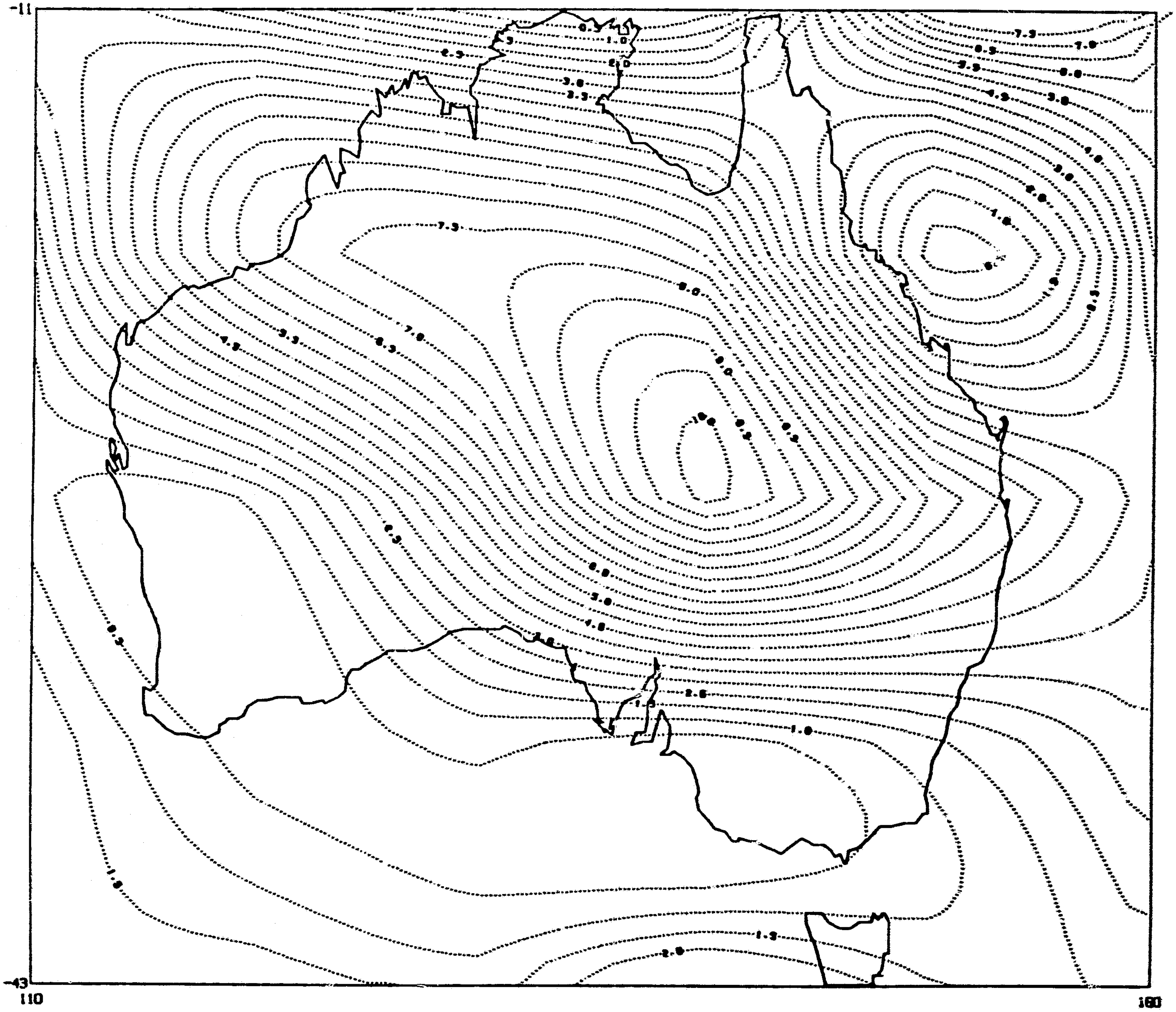
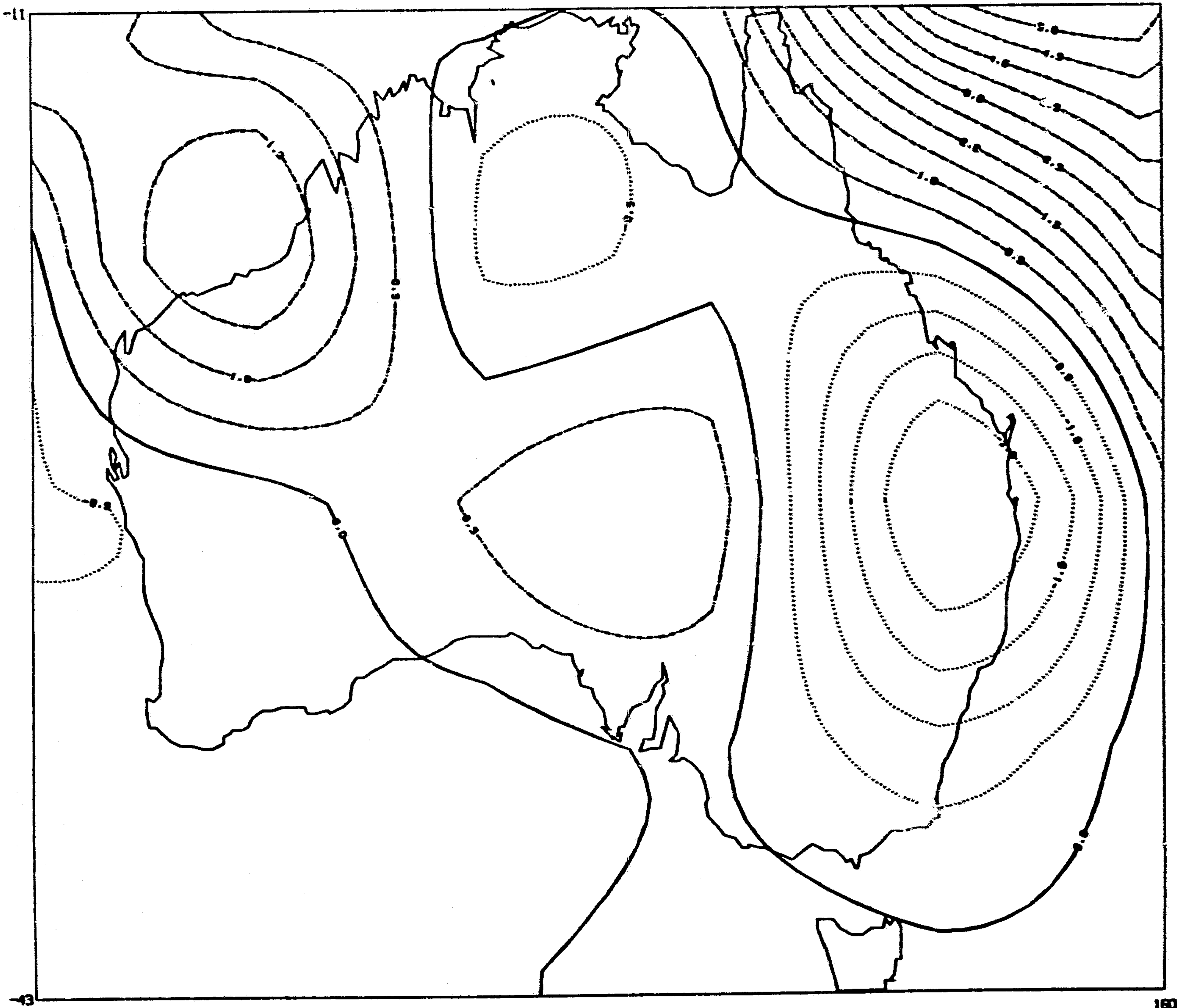


Fig. 6 PRECIPITATION (MILLIMETERS PER DAY) RUN 5



PRECIPITATION (MILLIMETERS PER DAY) RUN 5 MINUS RUN 4 Fig. 7

PRECIPITATION (MILLIMETERS PER DAY) RUN 2

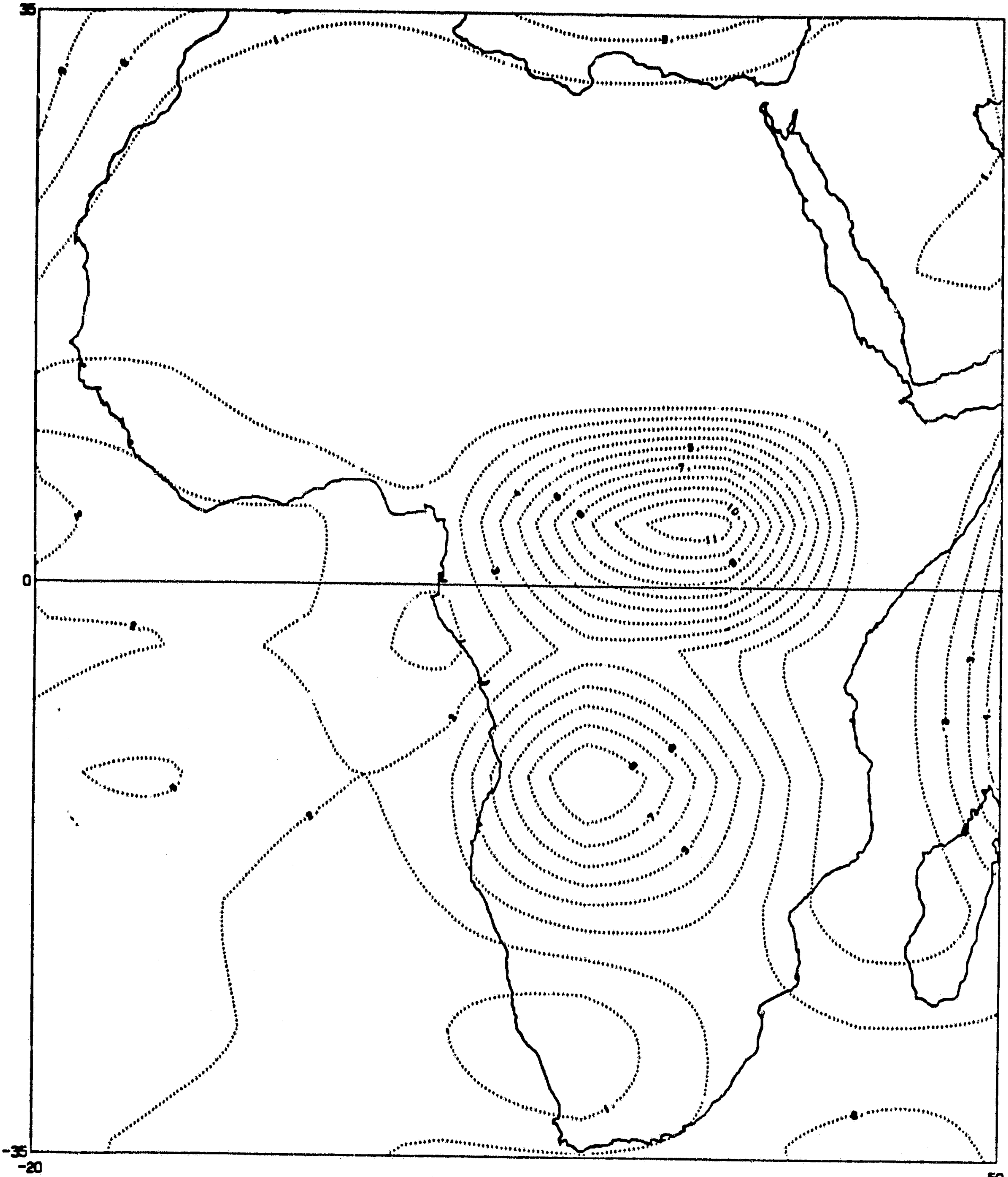


Fig. 8

PRECIPITATION (MILLIMETERS PER DAY) RUN 3

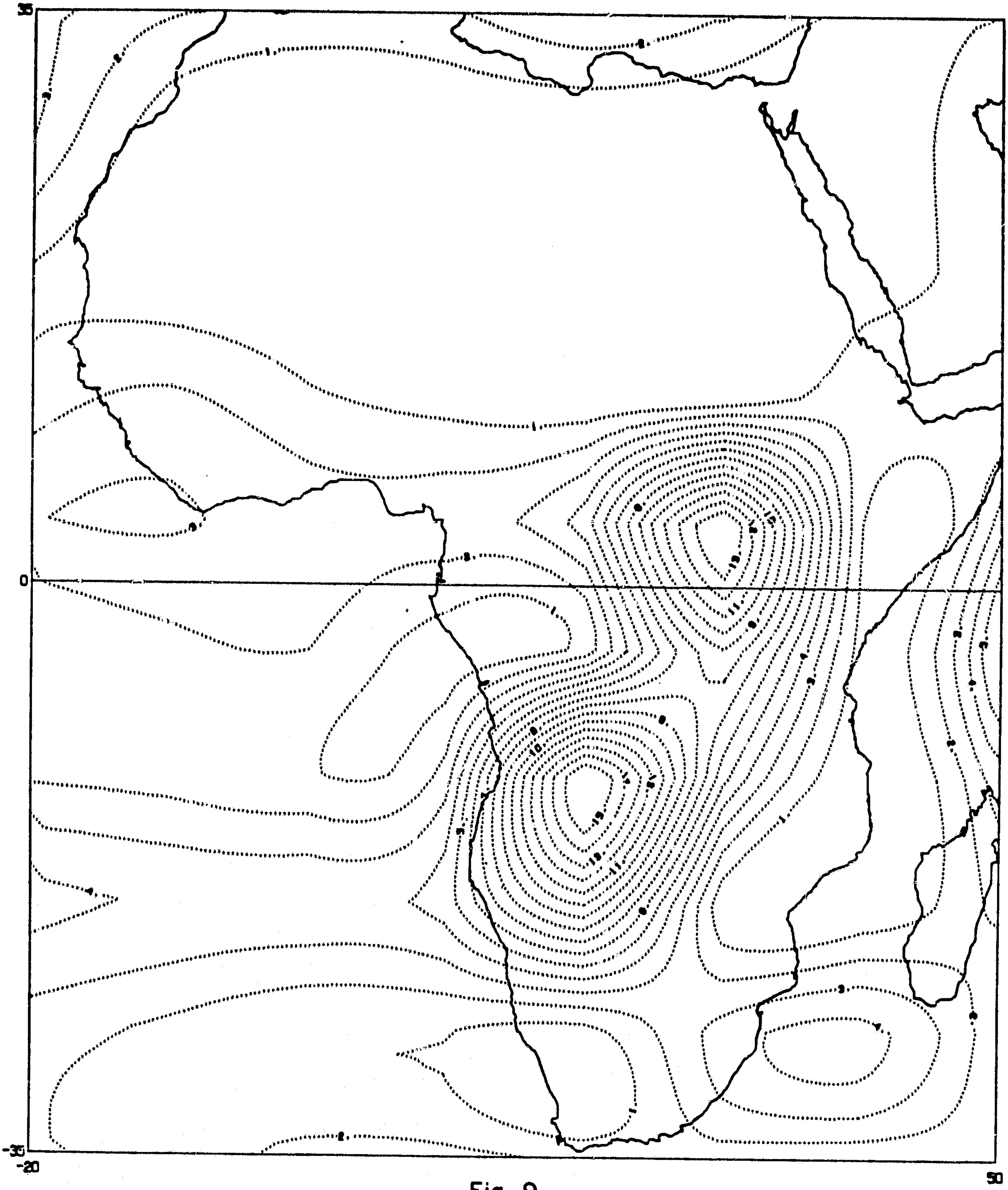


Fig. 9

doubles (to more than 15 mm day^{-1}), while the central African maximum shifts closer to the Equator and increases slightly (to 13 mm day^{-1}). The net effect of topography, as shown in the difference map (fig. 10) between runs 3 and 2, is a band of increased rainfall oriented northeast-southwest parallel to the highlands of southern Africa.

The influence of variable albedo and soil moisture on the computed January rainfall over Africa, illustrated in figures 11 and 12 (the latter being the difference map for run 4-minus-run 3), is rather complex. Again, the Sahara is hardly affected. However, the equatorial maximum in the north is severly reduced, while the Angolan maximum in the south, also slightly diminished, is shifted southeastward, toward Zambia, Zimbabwe, and Mozambique.

The principal effects of zonal SST gradients on the computed precipitation, as shown in figures 13 and 14, are a decrease around the Somali peninsula, where the SST is colder than the zonal mean, and an increase in the Gulf of Guinea, where the SST used in the model is (perhaps unrealistically) slightly warmer than the zonal mean SST of the model. Cold water off the southwest coast of Africa appears to have reduced the rainfall maximum over southern Africa. However, the cold water off the west coast of Africa near Senegal has apparently no effect on the already low precipitation there.

Compared with the observed mean January precipitation over Africa (e.g., Kendrew, 1942), the most unrealistic feature of the dry, flat continent simulation (fig. 8) is the north equatorial maximum. The introduction of terrain (fig. 9) further increases this error and also exaggerates the magnitude of the realistic maximum in southern Africa. However, when the continental surface physics, including geographical variations of surface albedo and soil moisture, are incorporated in the

PRECIPITATION (MILLIMETERS PER DAY) RUN 3 MINUS RUN 2

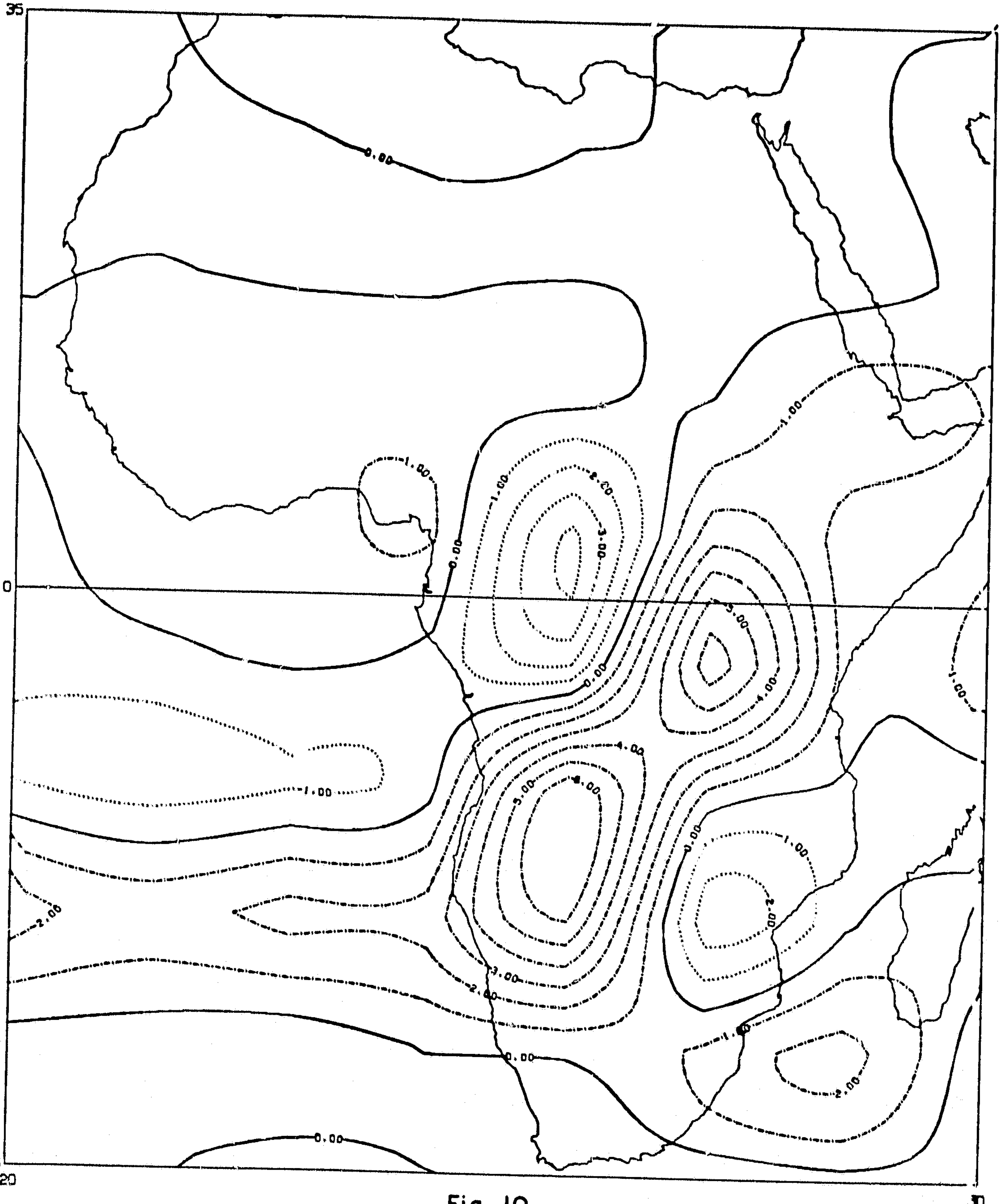


Fig. 10

PRECIPITATION (MILLIMETERS PER DAY) RUN 4

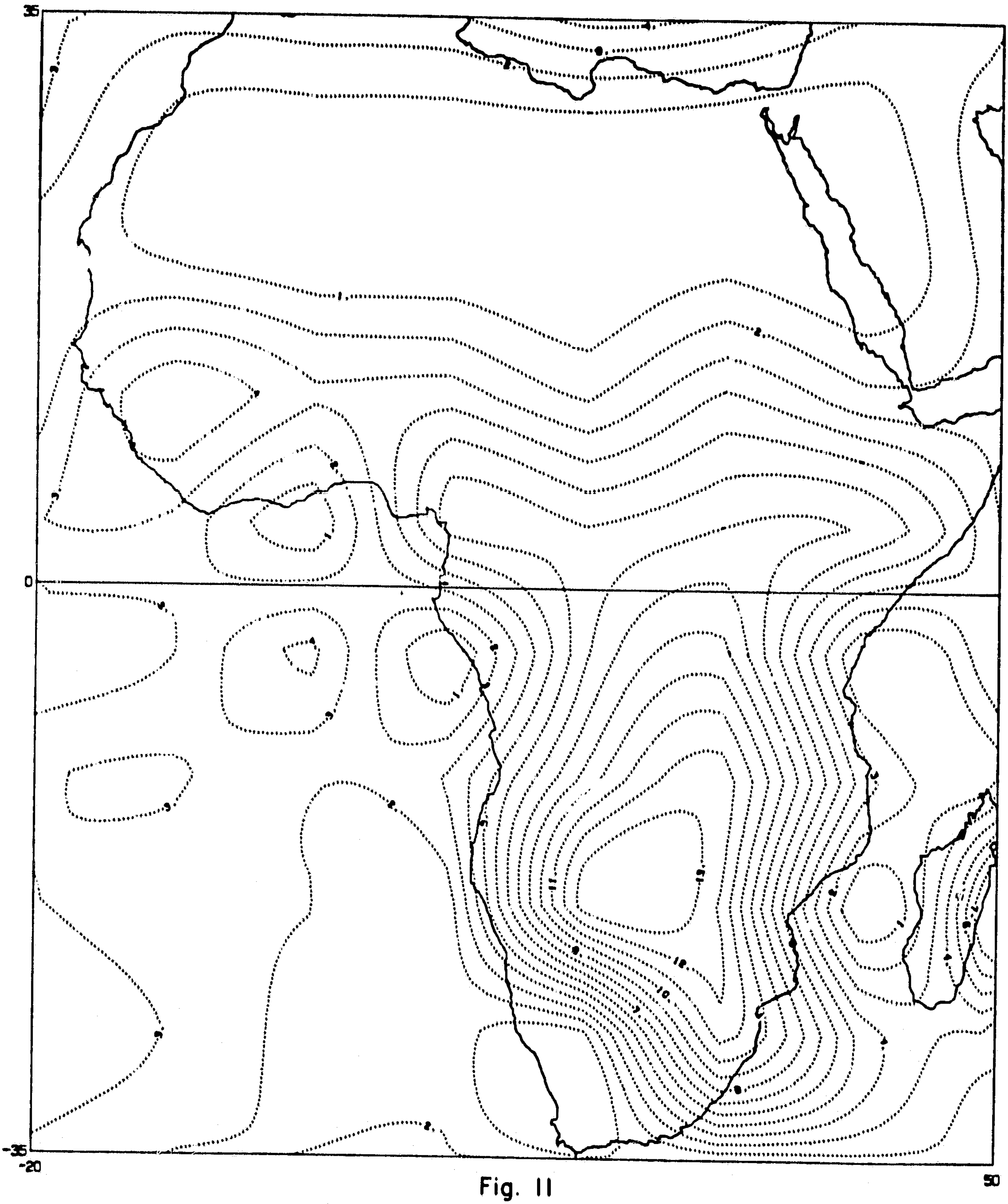


Fig. 11

PRECIPITATION (MILLIMETERS PER DAY) RUN 4 MINUS RUN 3

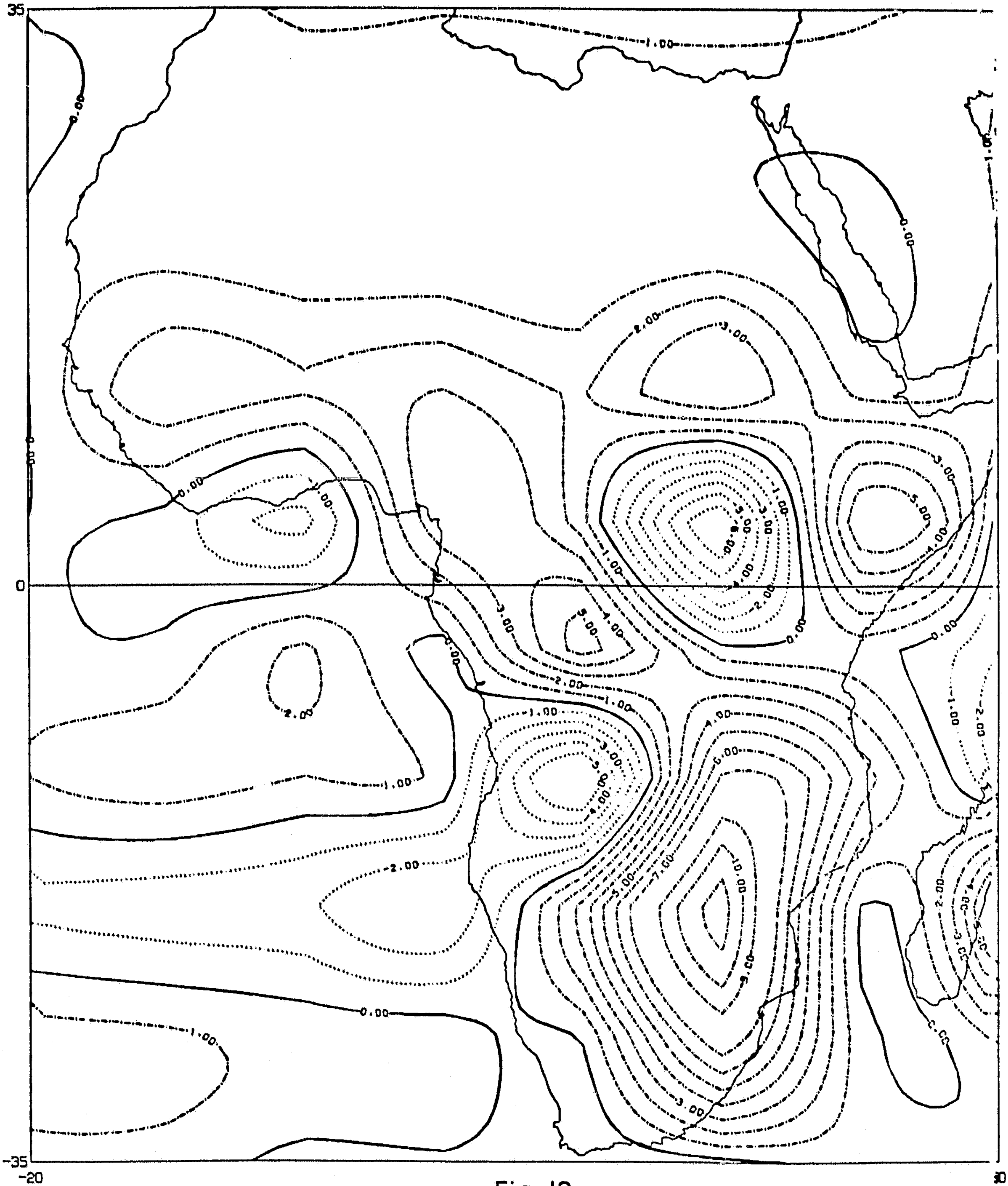


Fig. 12

PRECIPITATION (MILLIMETERS PER DAY) RUN 5

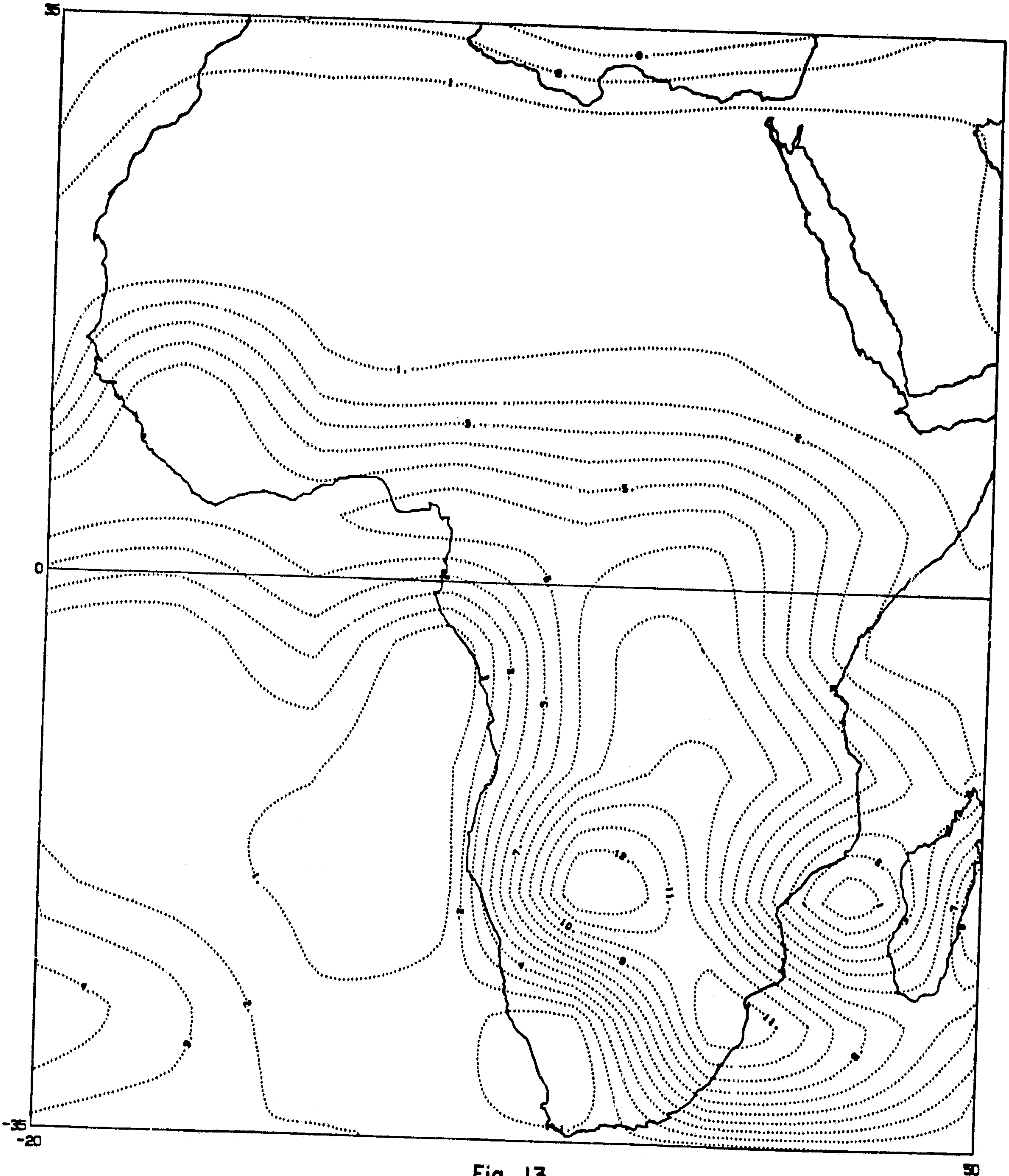


Fig. 13

model (fig. 11), the result is a rainfall pattern that is, qualitatively, at least, much closer to that of the observed climatology, except for excessive precipitation over the Horn of Africa. The north equatorial maximum disappears, and the maximum in southern Africa, while still too intense, shifts, realistically, towards the southeast. A further improvement in the simulation, notably restoration of dry conditions over the Horn of Africa, follows the introduction of the climatological SST field (fig. 13).

The marked change in the computed January precipitation pattern over Africa resulting from the surface physics, compared with the rather different response over Australia, indicates the complexity of the precipitation process in the model simulation, and probably in nature as well. Evaporation of water from rain-moistened soil has the positive feedback effect of increasing the local water vapor content of the atmosphere, thus possibly augmenting precipitation, as indicated over Australia. On the other hand, evaporative cooling lowers the surface temperature and inhibits convection, thus possibly reducing precipitation, as computed, for example, over central equatorial Africa. The process is undoubtedly complicated by the role of the specified surface albedo, which is clearly different over the verdant terrain of central Africa than over the bright surface of Australia, and can apparently tip the effect of soil moisture toward either increased or decreased precipitation.

South America

The observed mean precipitation in January over South America (see, e.g., Kendrew, 1942) is characterized by an extensive area of heavy rainfal in the north (maximum at least 8 mm day^{-1}) centered over Brazil, and a narrow band of moderate rainfall on the extreme southwestern coast of Chile, with dry conditions in between over Argentina and Uruguay as well

PRECIPITATION (MILLIMETERS PER DAY) RUN 5 MINUS RUN 4

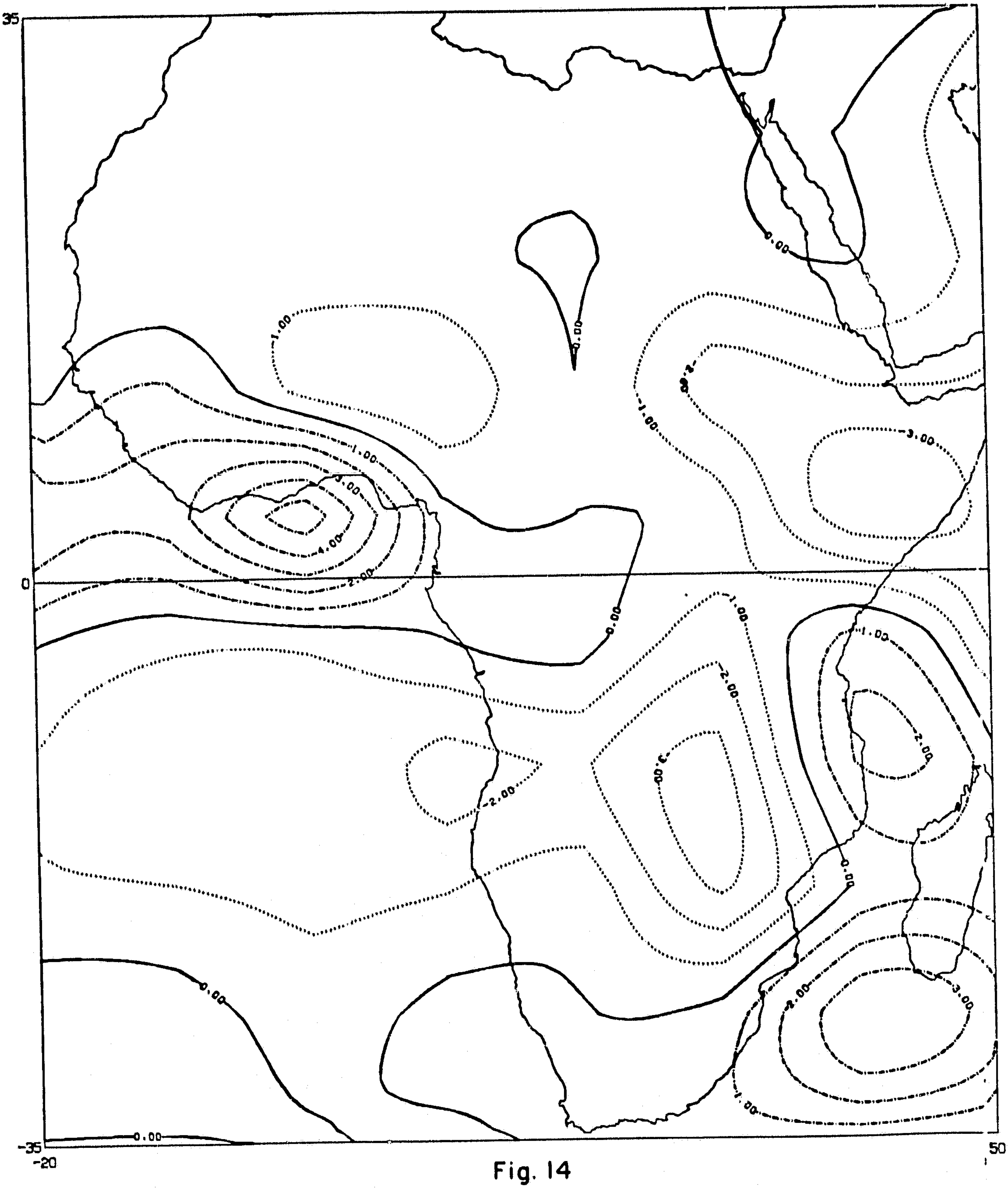


Fig. 14

PRECIPITATION (MILLIMETERS PER DAY) RUN 2

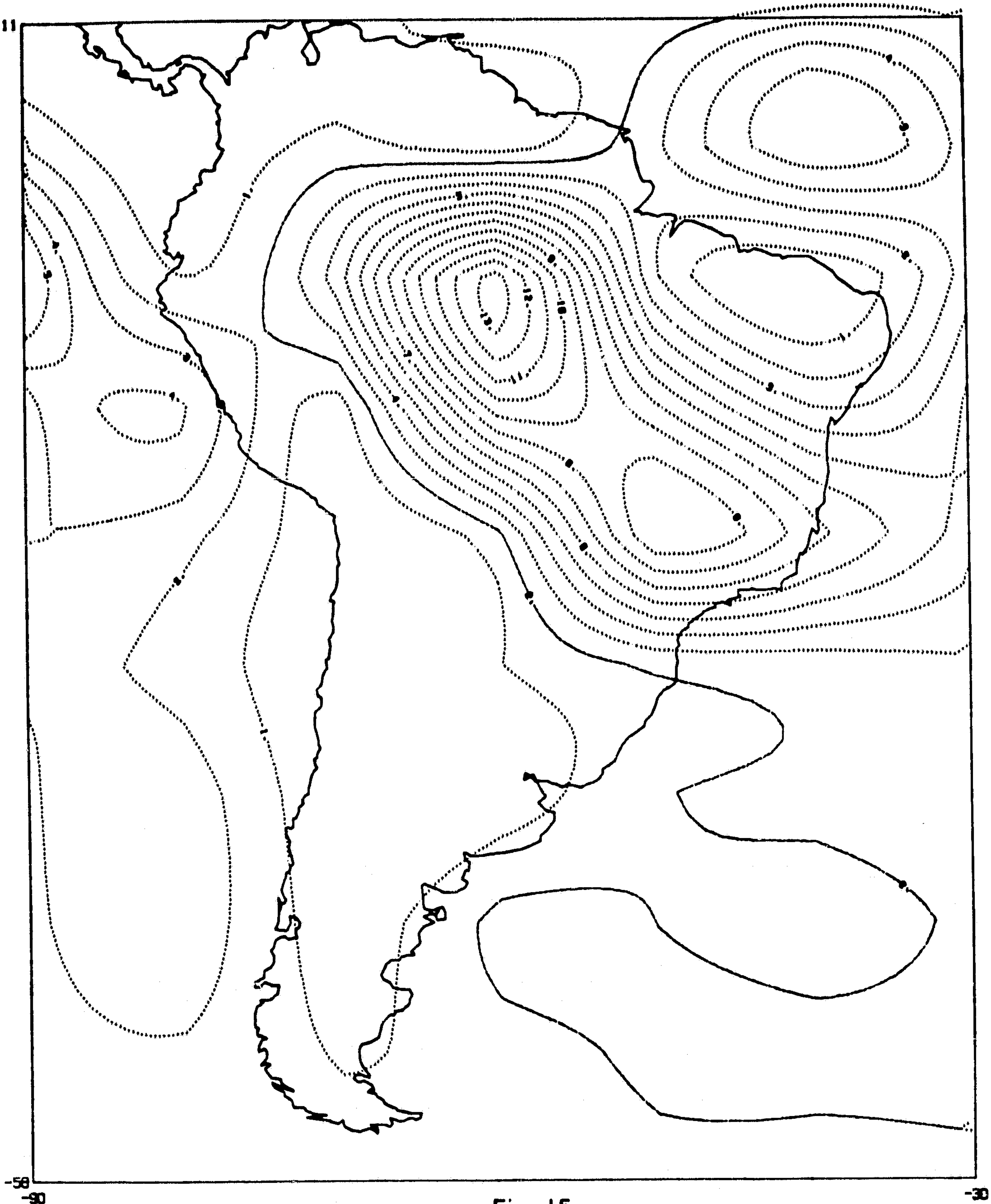


Fig. 15

as over northeastern Brazil south of the Equator and northwestern Colombia.

With the principal exceptions of the southwest coast of Chile, where too little rainfall is generated by the model, and the coast of Peru, where the computed rainfall is too large, the general pattern of the observed January rainfall climatology is reasonably well-simulated by the flat, dry continent model, as shown in figure 15, although the computed maximum over the Amazon Basin (13 mm day^{-1}) is probably too high.

With the addition of topography in run 3, mainly the Andes in the west, but also the highlands of southeastern Brazil, the model rainfall pattern is distorted in an unrealistic way, as illustrated in figure 16. The difference map for run 3 - minus-run 2 (fig. 17) shows that the model terrain diminishes the Amazon maximum excessively, shifting the heaviest rainfall to the southwest and southeast, while increasing the precipitation over Colombia in the northwest. The heavy rainfall in southeastern Brazil in figure 16 is, qualitatively, not unrealistic, although the magnitude is excessive. However, the maximum in Peru in figure 16, due to the Andes Mountains, is totally in error.

The computed precipitation over South America is further distorted by the inclusion of soil moisture and variable surface albedo (run 4), which generates even heavier rainfall on the west coast and increases the model rainfall over northwestern Colombia and northeastern Brazil, as shown in figures 18 and 19. The net result is a precipitation pattern that is in very poor agreement with climatology, with a minimum over west-central Brazil in figure 18. The complexity of the contribution of continental surface physics to the computed precipitation is apparent from the difference map in figure 19, which defies a simple interpretation.

A radical alteration of the model-generated rainfall distribution over South America follows the replacement of the zonally symmetric SST pattern with the climatological SST's, as shown both in figure 20 for run 5 and

PRECIPITATION (MILLIMETERS PER DAY) RUN 3

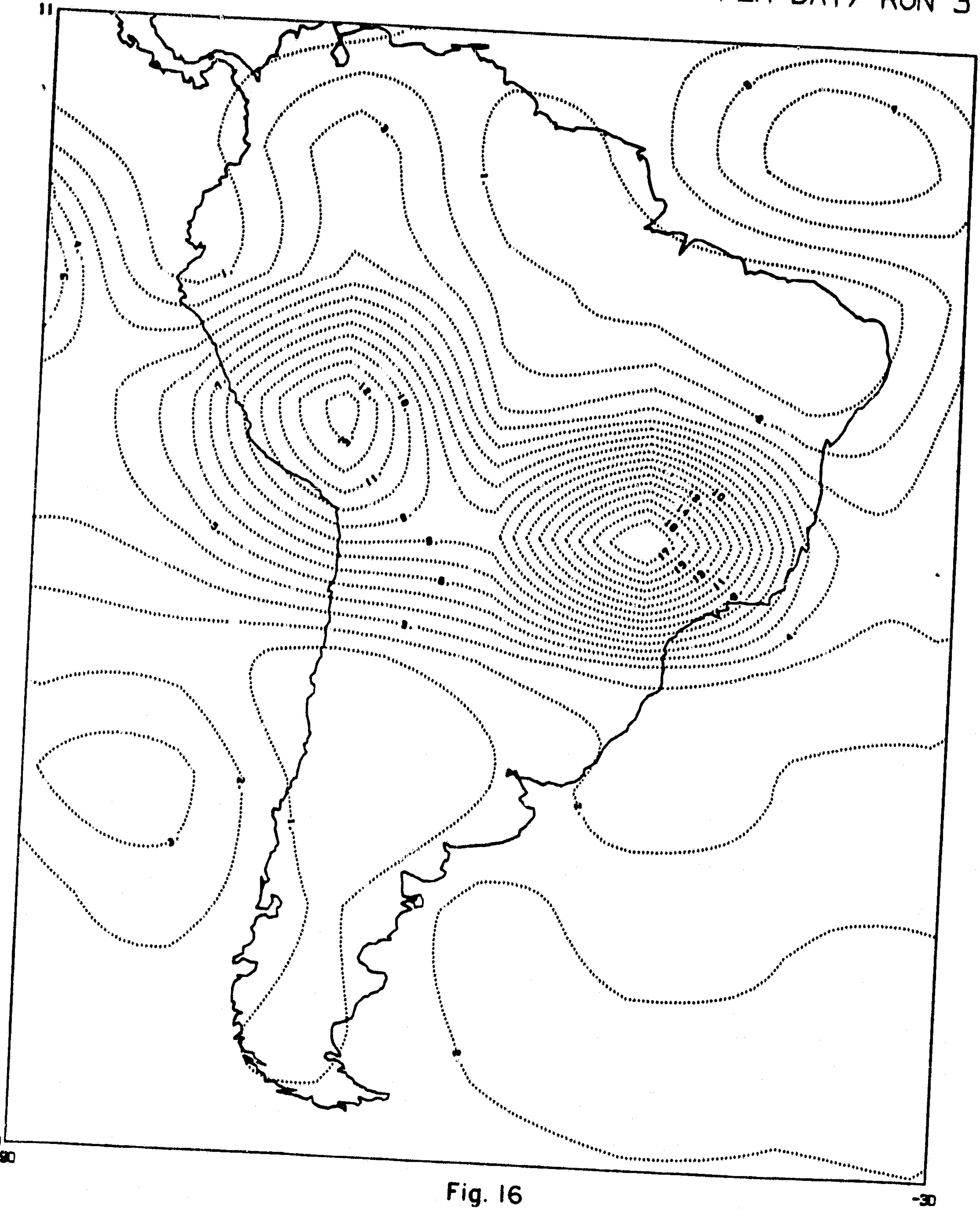


Fig. 16

PRECIPITATION (MILLIMETERS PER DAY) RUN 3 MINUS RUN 2

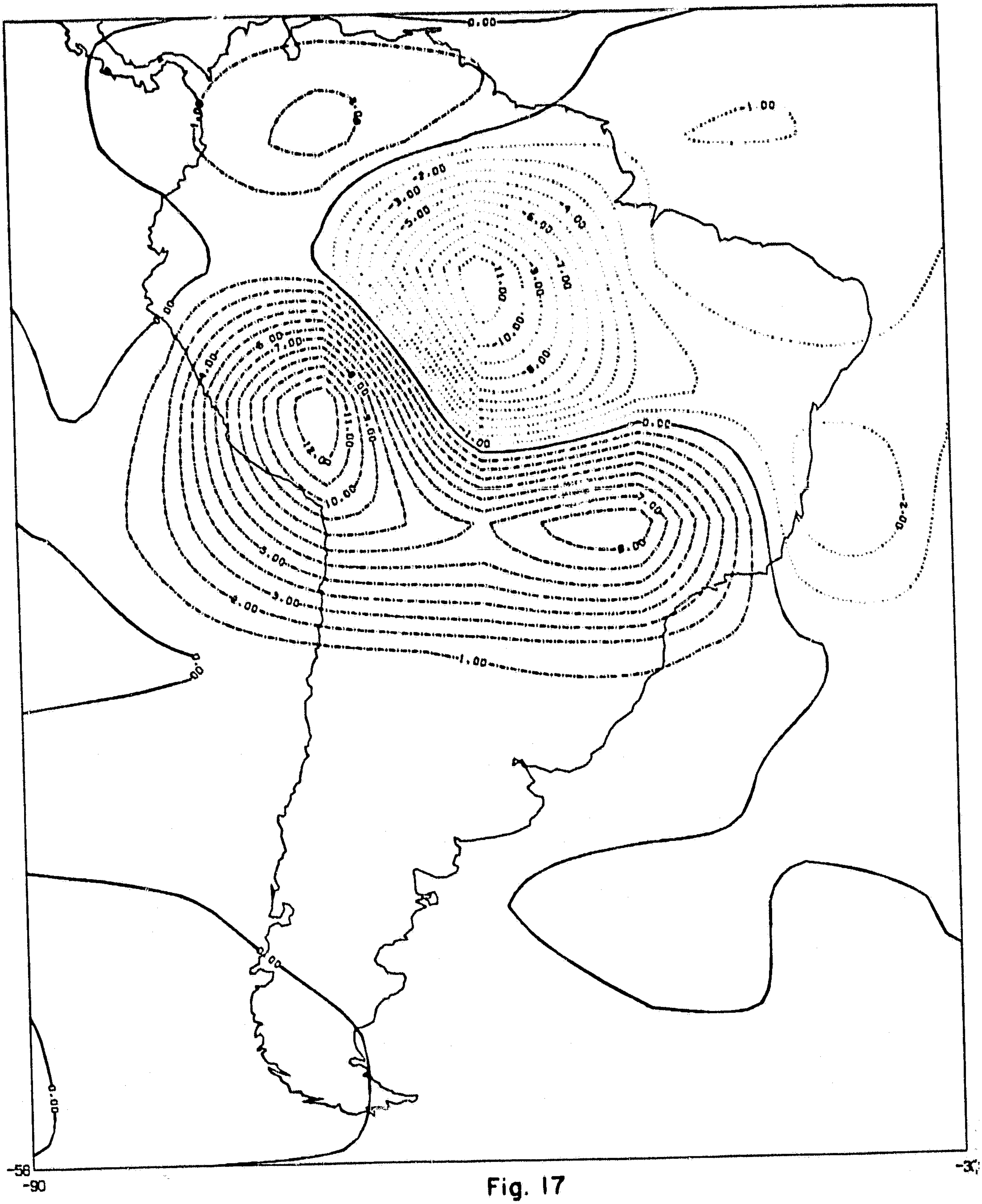


Fig. 17

PRECIPITATION (MILLIMETERS PER DAY) RUN 4

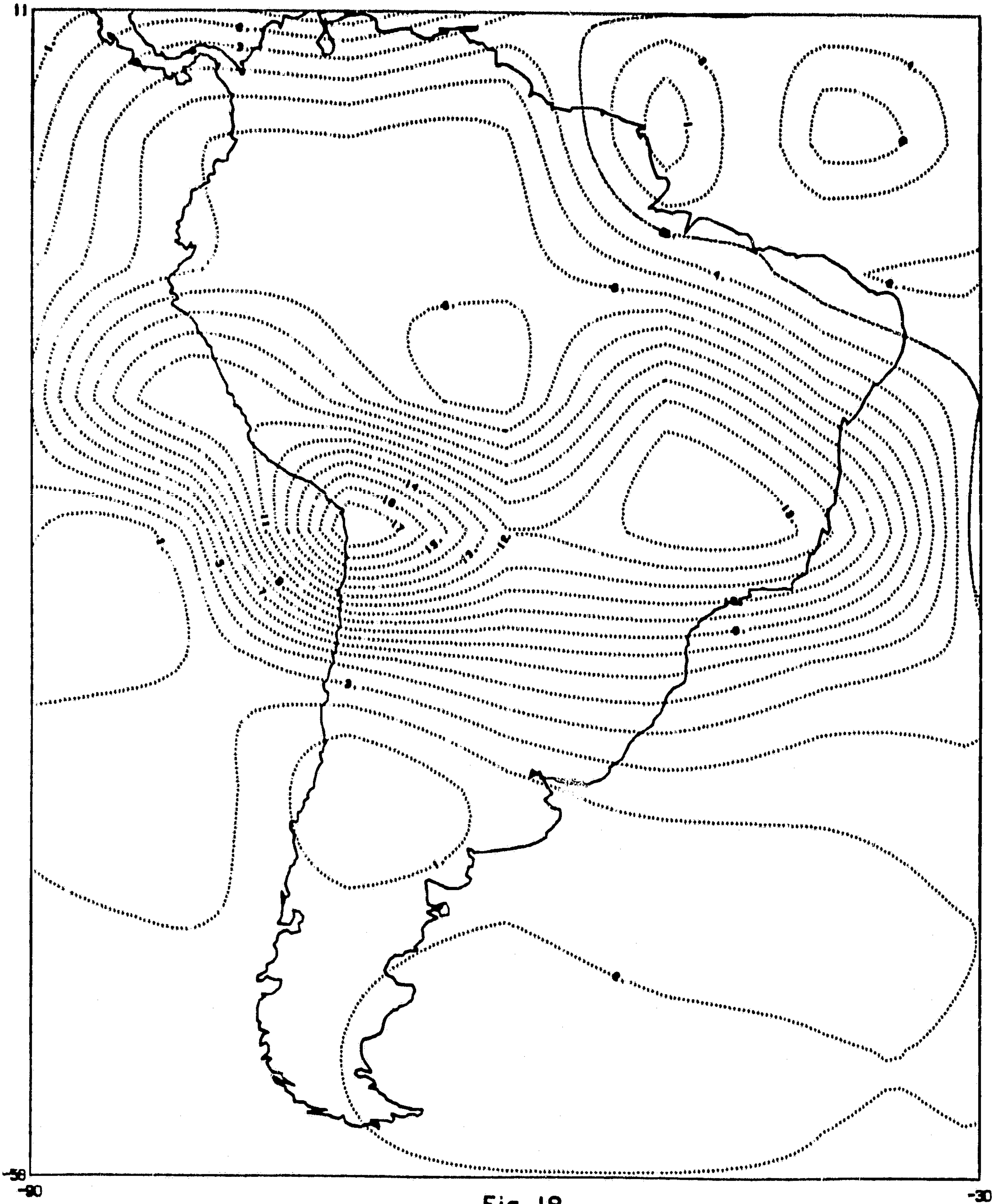


Fig. 18

PRECIPITATION (MILLIMETERS PER DAY) RUN 4 MINUS RUN 3

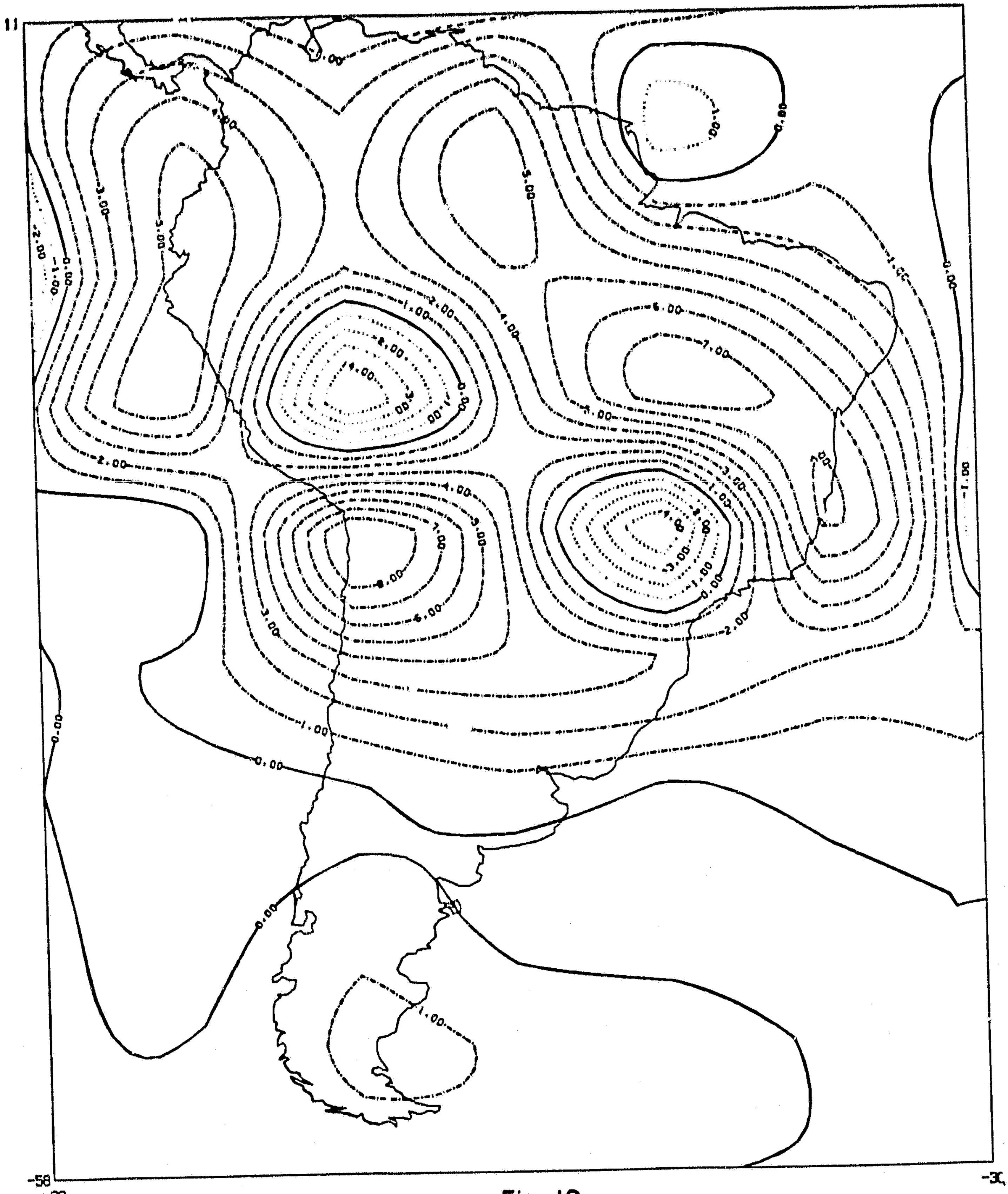


Fig. 19

PRECIPITATION (MILLIMETERS PER DAY) RUN 5

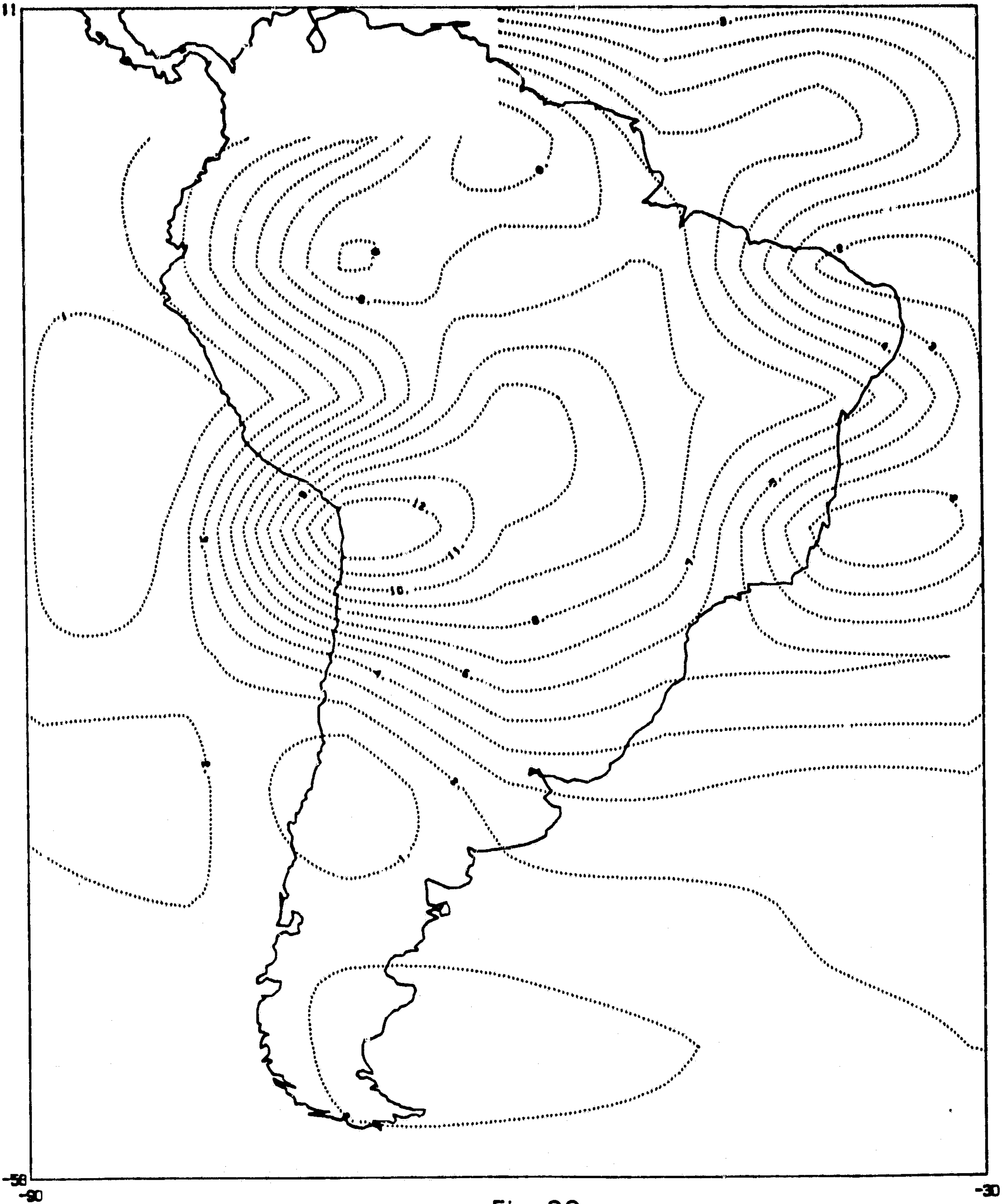


Fig. 20

in figure 21 for the difference between runs 4 and 5. The principal difference between the two SST fields is the presence of colder water on the Pacific coasts of Ecuador, Peru, and Chile in run 5, which has the obvious (and beneficial) effect of reducing the precipitation in that region. However, as shown in figure 21, an equally large decrease in rainfall is found on the Atlantic coast of Brazil, despite the absence of any significant SST anomaly there, while increased precipitation is found over the north central region of the continent. Again, it is difficult to offer a simple explanation for this result.

As in the case of Australia, it appears that the flat, dry continent model best simulates the mean January precipitation pattern over South America, and that topography, surface physics, and zonal gradients of SST do not, in general, improve the climate simulation.

Summary and conclusions

The results of the perpetual January simulation with the GISS climate model are somewhat ambiguous regarding the computed continental precipitation. Over Australia and South America, the simplest form of the model, i.e., the flat, dry continents version, captures the main characteristics of the rainfall distribution in January, at least in a qualitative sense, and no improvement in the realism of the simulation is achieved with the introduction of topography, surface physics, and zonal variations of sea-surface temperature. On the other hand, the flat, dry continents model generates an unrealistic January rainfall climatology over Africa, where the simulation is markedly improved by the inclusion of surface physics (i.e., geographically variable surface albedo and soil moisture).

PRECIPITATION (MILLIMETERS PER DAY) RUN 5 MINUS RUN 4

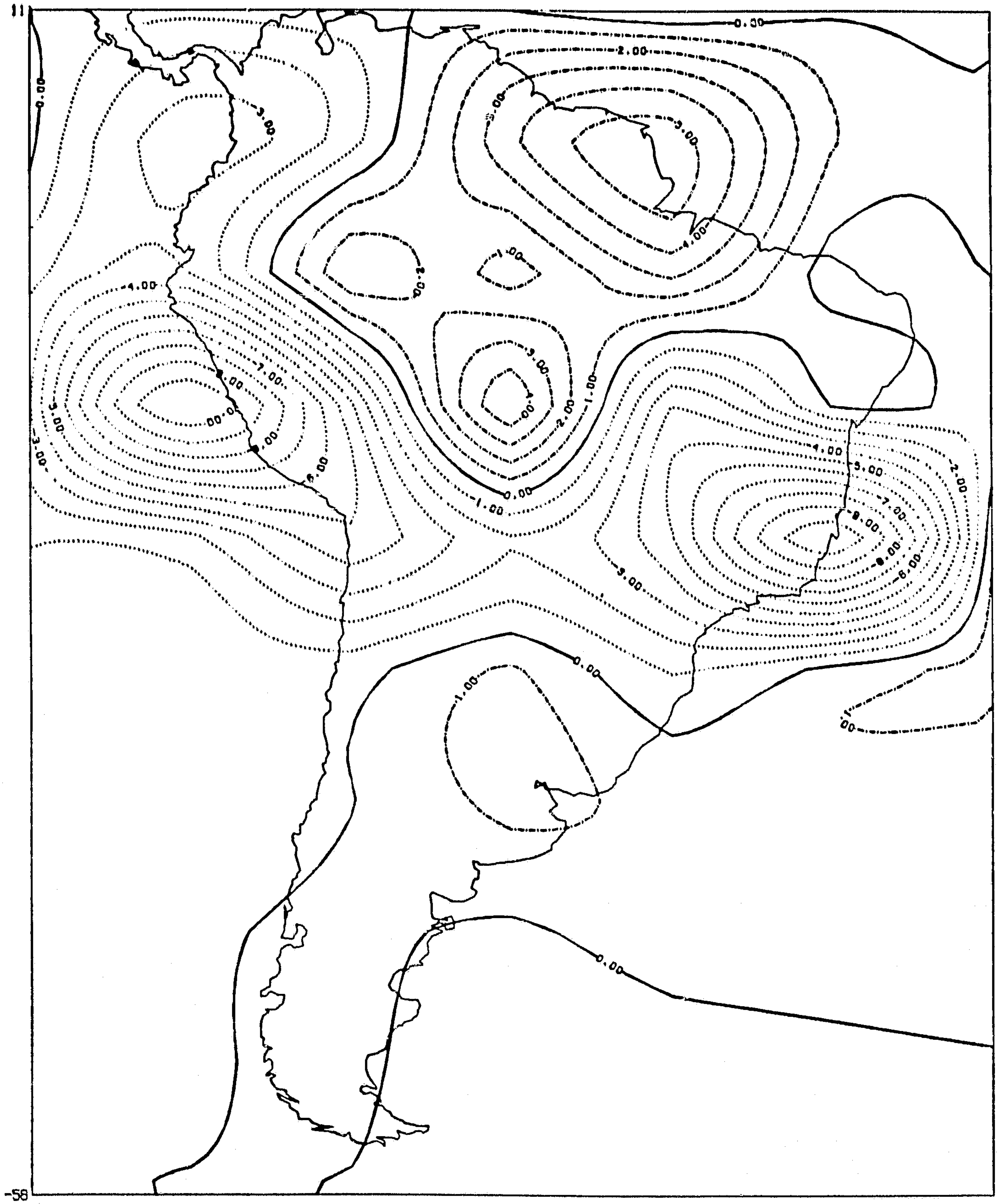


Fig. 21

The calculation of precipitation over the continents is found to be very sensitive to topography, SST variations, and surface physics. As soil moisture and surface albedo variations were both introduced simultaneously in run 4, it is not possible, from this experiment, to separate the influence of each of these two factors. However, the complex interaction of albedo and soil moisture is indicated by the fact that over Australia (and, to a large extent, over South America) the general effect of surface physics was to increase the precipitation, while over Africa the reverse was true in the model simulation. This suggests that the albedo may determine whether the influence of soil moisture on precipitation will be positive, due to increased humidity from evaporation of rainwater, or negative, due to the stabilizing effect of evaporative cooling of surface air. Further studies, now in progress, may help to clarify this problem.

Acknowledgements

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