Forecasting Research Division
Technical Report No. 41

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Abstract

In June 1991 the Meteorological Office introduced a new operational suite. An archive of surface fluxes over the oceans was started during July 1991. This report investigates the fluxes between August 1991 and July 1992. Because many of the features of monthly means are also present in the annual mean, the report concentrates on the latter. Major systematic errors, in comparison with climatology, include: too much heat flux into the oceans in the Tropics and too little over the N Pacific; too weak wind stress over middle latitudes; and inadequate evaporation. Future studies should compare fields from different operational centres, because a major feature of the annual mean model fields is an anomalous circulation in the North Atlantic. Weather forecast models typically change their climatology during the forecast; the most significant spin up during the first 12 hours of the forecast in April 1992 was an increase in the precipitation, both convective and dynamical precipitation maxima almost doubled between the analyses and 12 hour forecasts.

1. Introduction

In June 1991 the Meteorological Office introduced a new operational forecast system (Cullen, 1991). This model has been derived independently of its predecessors, so there is no reason why the findings of Alves (1990 a, b) should be valid for the new model. This study investigates the surface fluxes over the ocean for the first 12 hours of the forecast.

Surface fluxes provide the mechanism for the atmosphere to interact with the ocean. The surface stress provides drag which is the eventual sink of the momentum generated in the atmosphere systems; evaporation provides the water to replace that lost by rainfall. Although accurate representations of these processes are important for climate simulations, the shorter length of weather forecasts allows less scope for errors in the surface fluxes to influence the evolution of the forecast (Chao, 1992). Surface fluxes are of prime importance for ocean models. Winds near the ocean surface govern the generation of surface waves (Holt, 1992), and ocean circulation is driven by the fluxes of heat, fresh water and momentum across the ocean surface. Although surface fluxes are of use as diagnostics of the accuracy of atmosphere simulations the main reason for investigating them is to assess their accuracy for oceanographic studies.

Surface fluxes were archived from operational forecasts from July 1991 onwards. This study covers the period August 1991 to July 1992 and considers only the global weather forecast model. Because the fluxes from the first 12 hours of the forecasts have been used by the Meteorological Office ocean circulation modellers in the past, the major part of this study involves the average of fluxes during the first 12 hours of the forecast. Differences between the analysed and forecast fields were examined for April 1992 to assess the magnitude of the "spin up".

The method of assessing the fluxes is to compare them with established climatologies. Although this can detect gross differences between the models and climatological fields, difficulties arise when comparing the circulation patterns for an individual year with a multi-year average. Future investigations should compare Meteorological Office fluxes with fields from models from different centres as well as climatology. Programs to extract ECMWF flux fields had not been completed in time to be used for this study.

The structure of this report is to discuss first the annual mean heat fluxes, then the precipitation, and then the wind stress. Analysed fields are compared with forecast fields for April 1992 to assess the main impact of spin-up.

2. <u>**Total Heat Flux**</u>

Of the climatologies of surface heat fluxes, that of Oberhuber (1988) is most widely used by oceanographers. The surface fluxes in that climatology were derived from the COADS dataset, and fluxes were not calculated when data were sparse, resulting in data gaps, mainly south of 30°S, but with some patches further north.

Figure 1 shows the total net surface heat flux into the oceans. Figure 1a shows the fluxes from the first year of the Unified Model, Figure 1b shows the Oberhuber estimates, and Figure 1c shows the difference between the two estimates of heat flux. The sign convention used in this and subsequent figures is that positive values denote fluxes into the ocean. The large scale characteristics of the Unified Model net heat flux agree with those of the climatology. In particular there is net heating in the tropics, and cooling in the extratropics. The greater resolution of the numerical weather prediction model can be seen where there are sharper gradients in the ocean sea surface temperature, for example the warming of the cold water to the west of the Gulf Stream on the eastern coast of the United States of America.

The general pattern is for the Unified Model to warm the oceans more than the climatology. The principal exceptions to this are the Pacific north of 30°N, where the cooling from the model exceeds that in climatology by more than 20 Wm^{-2} and in the eastern Atlantic, in both hemispheres, where again the cooling is greater than in the climatology the difference and reaches over 50 Wm^{-2}. Although the climatology contains few values in the south Pacific near the American coast, there are indications that a similar problem is found in that area.

In the dominant warming areas, the extra heat flux into the ocean is typically greater than 20 Wm^{-2}, and in places is more than 50 Wm^{-2} too high. As a result in the model the net surface heating of the oceans throughout the whole globe is equivalent to 17 Wm^{-2}.

It is necessary to look at the heat flux components to decide on possible causes of this imbalance. This paper will look at these in turn, starting with the solar heat flux, then the long wave radiation, the latent heat, and the sensible heat flux.

3. Solar Heat Flux

Figure 2 shows the annual average of net solar radiation entering the oceans. The immediate impression gained of the Unified Model solar heat flux is that it is a great improvement on the previous global model (Alves, 1990 b) (Figure 2). This is mainly because the Unified Model uses an interactive cloud scheme when calculating the solar radiation reaching the surface, whereas the previous global model used a cloud distribution which was essentially a zonally averaged climatology.

The patterns of the solar heat flux look realistic, when compared with Oberhuber, particularly when it is considered that the Unified Model fluxes sample a single year. Changing attention to the values, rather than the patterns, the solar heating field gives greater cause for concern. The most obvious feature is that equatorwards of 30° there is too much solar radiation by more than 50 Wm^{-2} over large areas.

In middle latitudes, over the central oceans, there is a tendency for too little solar radiation, by more than 25 Wm^{-2} in the North Pacific.

Although climatological fluxes are difficult to derive, it is unlikely that the errors would be as large as 50 Wm^{-2} for large areas of the globe. In particular, the area of the tropical oceans in the Unified Model with an annual mean heat flux of 200 Wm^{-2} implies a very large transmission through the atmosphere.

4. Long Wave Radiation

Figure 3 compares the long-wave radiation flux from the Unified Model with that from climatology. Although the regions of greatest heat loss by long wave radiation from the oceans are near the warm western boundary currents, it can be seen from Figure 3 that there must be other factors influencing the long wave radiation from the ocean surface, because the greatest heat flux does not coincide with the warmest water. Other factors which are of importance include the temperature of the atmosphere, the water content of the atmosphere and the cloudiness.

It might be expected that the largest differences in infrared radiation between the climatology and the Unified Model would be in the tropical Pacific, because 1991/92 was an El Nino period. Indeed, the difference between climatology and the model is consistent with the eastern Pacific sea surface temperatures being warmer during 1991/92 than the long term average, although this is by no means a dominant signal in the difference between the model and observed fluxes. The overall pattern of differences between the model and climatology of the middle latitude oceans is that there is too little heat lost from the ocean, while too much is lost along the western coast of North Africa and in the Arabian Sea and Bay of Bengal.

If there were too much cloud in middle latitudes, this would result in too little outgoing infrared radiation, and too little incoming solar radiation. Thus a consistent explanation for the errors in the solar heating and the infrared radiation would be excess cloud at middle latitudes.

The maximum difference between the model and the climatology is of the order of 10 to 20 Wm^{-2}. This may be compared with the requirements for the WOCE experiment of 10 Wm^{-2} for 5° grid boxes. Thus, for the net infrared radiation, the Unified Model comes close to achieving a goal of WOCE.

5. **Latent Heat (Evaporation)**

Figure 4 compares the latent heat flux from the model with that from climatology. As for the other fluxes the general pattern is good, with the higher resolution of the model showing up particularly in the western boundary currents. It is surprising, therefore, that when the difference between the model and the climatology fields is taken, over the western boundary currents there is less evaporation in the model than in the climatology. The expected pattern would be lower evaporation away from the core of the Gulf Stream in the model, while over the warmest water more evaporation in the model than the climatology might be expected. This is not the case, and evaporation is lower for much of the western Atlantic in the model than in the climatology. Similar patterns are found over the Kuroshio, and there is a hint of a similar error in the south Atlantic, although the climatology does not extend far enough south to confirm this. In the tropics, with the exception of the central Pacific, there is too much evaporation from the Unified Model. In the areas of both greater and less evaporation in the model than in the climatology, the extremes exceed 30 Wm^{-2}.

Evaporation, and thus latent heat flux, in the model depend on the wind speed and the difference between the saturated humidity mixing ratio at the sea surface temperature and the actual water content of the atmosphere. Errors in the latent heat flux could therefore arise either from errors in the wind speed, or from the water content of the atmosphere. If middle latitudes were too moist, it would be consistent with too much cloud, and one might expect too little evaporation in the model. Similarly if the tropics were too dry then there would be too much evaporation. Without looking at the structure of the atmosphere in the model in more detail this must remain speculation.

6. Sensible Heat Flux

Values of sensible heat flux, Figure 5, are in general much smaller than those for the other heat flux components. Only over the western boundary currents do the climatological heat fluxes exceed 20 Wm^{-2} in magnitude, and only over the cores of the currents are fluxes greater than 40 Wm^{-2}. In the model, however, filaments of sensible heat flux greater than 20 Wm^{-2} spread across the Atlantic and Pacific Oceans in the Northern Hemisphere; and in the Southern Hemisphere there are no noticeable regions of large sensible heat flux. Differences between the model and the climatology are, in general, such that the model loses more heat from the ocean than the observed estimates, by over 10 Wm^{-2} in many places. Although this is not a large heat flux in itself, it represents a very large percentage error for the basic field. Only in the North Atlantic and near the western boundary currents were model heat fluxes cooling less than in the climatology.

7. **Fresh Water Budget**

Evaporation, which is equivalent to latent heat, has already been discussed. Figure 6 shows the net fresh water budget over the oceans, that is the difference between precipitation and evaporation. Of all meteorological values to measure over the ocean, precipitation is perhaps the most difficult. Even more care should be taken when comparing the model to climatology for this field.

The dominant feature in the Unified Model annual mean is the south-west to north-east tilt of the division between net evaporation and net precipitation in the North Atlantic. Other features, such as the east-west orientation over the precipitation in the North Pacific, the ITCZ, and the convergence observed in the South Pacific, are perhaps more as expected from climatology. Without comparing the Unified Model fields to those from other models, for example ECMWF, it is not possible to determine whether the Atlantic feature is a real phenomenon of 1991/92, or whether it is an artifact of the model's climatology.

Looking at the difference between the model and climatology, it becomes apparent that the extremes in the model are greater than those in the climatology, so that the patterns in the climatology are exaggerated within the model. Middle latitudes are wetter, and the sub tropics drier; the pattern is very similar to that for the evaporation, so that evaporation, rather than precipitation, may be the cause of this. In the central Pacific, for example, precipitation exceeds evaporation by 3 millimetres per day more in the model than in the climatology.

Although in the north Pacific the pattern for the budget is feasible, there is over 3 millimetres per day too much flux of water into the ocean. This is also true under the ITCZ, although part of this may be due to the ITCZ being further north in the model than in the climatology.

8. **Wind Stress**

Wind stress in the model is compared with the climatology of Hellerman and Rosenstein (1983) in Figure 7. The patterns of westerlies at middle latitudes, and easterlies in the sub tropics and tropics, are captured by the model, but with more detail than in the climatology. The direction of the stresses is generally well represented, with a major exception of the North Atlantic. Instead of the westerly stress expected from climatology, the model has a south-westerly flow over the whole of the North Atlantic. ECMWF analyses of low level winds for August 1991 to December 1991 also showed a mean southwesterly flow over the North Atlantic.

Over almost all the oceans the wind stress is weaker in the model than in climatology. The main exceptions to this are in the southern oceans, where the climatological stress is now acknowledged to be too weak, and the NE Atlantic. Over the tropical oceans there is uncertainty over the extent to which the Hellerman and Rosenstein stresses are too strong (Harrison, 1989). Over the western tropical Pacific, the reduced wind stress associated with the El Nino phenomenon can be seen in the model.

The influence of the monsoon can be seen in the climatology from the strong wind stress over the Arabian Sea. This feature is almost absent from the Unified Model annual mean. Gyre-scale circulations in the ocean are driven by the curl of the wind stress, through the Sverdrup balance. This field is shown in Figure 8 for the North Atlantic.

Away from the Southern Ocean, for which the climatology is unreliable, there are no major differences between the wind stress curl of the model and climatology. There is, however, a systematic reduction in the magnitude of the curl over much of the north Atlantic and north Pacific Oceans, which would result in a reduction of strength in both the Gulf Stream and Kuroshio currents. This reduction in amplitude is consistent with wind stress itself being too small.

Independent verification of the low level winds from the Unified Model is possible using data from the ERS-1 radar altimeter. Figure 9 shows a histogram of weekly comparisons between the altimeter observations and the analyses from the Unified Model over the oceans to the north of 45°N. It is clear that during winter and early spring, observed winds were stronger than those in the model, while for the summer months the model winds tended to be slightly stronger than the observations. Because the strongest winds over the ocean were found during the winter months, it appears that the very strongest winds were being underestimated by the Unified Model, while lowest winds were being overestimated.

9. Spin Up

Although the model used for assimilating data to produce analyses is almost the same as that used for forecasts, there are some differences. The most obvious is the code to add in "observation increments", but there is also a divergence damping scheme. Verification of the model winds against wave buoys, Figure 10, suggests that surface winds are lighter in the analyses than in the short range forecasts. This increase in wind speed is an example of spin up; the climatology of the analyses differs from that of the forecasts, and the model state undergoes a transition between them.

Ocean modellers need to be aware of the effect of spin up. Driving ocean models with fluxes from the assimilation cycle might give different results from running with fluxes from the short range forecasts. The aim of this section is to describe the differences between the surface fluxes from the assimilation and those from the first 12 hours of the forecast. Only one month has been investigated, April 1992, and only fields which are archived in the WGDOS archive could be compared (and only a subset of these was considered). The heat fluxes showed little difference between the monthly mean values from the forecast from the assimilation. Maximum differences were less than 12 Wm^{-2}, except for the solar heat flux for which there was a difference of about 30 Wm^{-2} in regions of total flux of 250 Wm^{-2}. Apart from the solar heat flux, the differences were insignificant compared with the total heating rate. Similarly, differences between the wind stress fields were negligible.

Looking at the precipitation rate shows a different story. Both dynamic and convective precipitation were greater in the 12 hour forecasts than the analyses, by as much as 50% of the analysed value (Figure 11). Two possible causes for this are the use of divergence damping during assimilation and a systematic reduction of relative humidity by the assimilation scheme in regions of rainfall.

Insufficient data are archived for a full investigation of the cause of the differences between analysed and forecast rainfall. Surface wind stress was used as a poor proxy for tropospheric winds. Figure 12 shows the divergence of the analysed wind stress and the difference between the forecast and analysed values. There are differences of about 20% in the region of enhanced North Atlantic rainfall, but it is at least consistent that there was more surface convergence in the forecasts than in the analyses.

10. Summary

This paper has compared surface fluxes from the Unified Model with climatology. Some of the features discovered, such as the excessive heating of the ocean in the tropics, and excessive cooling at middle and high latitudes, are likely to be features of the climatology of the Unified Model. Other aspects of the comparison, such as the difference in flow in the North Atlantic, may be due to 1991/92 being unrepresentative. Future studies should, therefore, compare fluxes from different weather forecast systems to distinguish between those aspects of the model intrinsic to the model and those which are a result of the particular synoptic situations being investigated.

The general pattern of the heat fluxes was one of too much heating in the tropics, and too little heating at middle latitudes. It was not the intention of this paper to attribute causes to this.

Wind stress in the model is generally lower than in the climatology, with the exception of the southern ocean. Southern Ocean wind strengths appear better in the model than in the climatology, and the weaker stress over tropical oceans is thought to be beneficial. There is, however, some evidence that strong winds in the model are too weak.

Looking at the spin up forecast from the analyses, most of the fluxes showed little difference between analyses and 12 hour forecasts. The major exception to this was precipitation, both convective and dynamic, which almost doubled their values during the first 12 hours of the forecast. There is a need to understand this process. The spin up continued well into the forecast periods, as was shown while verifying the winds.

The major problems that have to be tackled to improve the surface fluxes for use in oceanography are therefore: excess heating in the tropics; too little solar heating at middle latitudes; too much evaporation at low latitudes and too little over western boundary currents; weak winds during northern winter; and the spin up of precipitation during the first 12 hours of the forecast.

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Max-Planck Institute for Meteorology, Hamburg.
Report 15.

Figure Captions

Figure 1 Annual mean net heating of the ocean (a) Unified Model, (b) climatology, (c) difference (model-climatology). Units are Wm^{-2}.

(a) and (b) Contours: -150, -50, -20, 20, 50, 150

Shading: light: <-20, dark: >20

(c) Contours: -100, -50, -20, 20, 50, 100

Shading: light: <-20, dark: >20

Figure 2 Annual mean net solar radiation over the ocean. (a) Unified Model, (b) climatology, (c) difference (model-climatology). Units are Wm^{-2}.

(a) and (b) Contours: 50, 100, 150, 200, 250, 300

Shading: light: 100 to 200, dark: >200

(c) Contours: -50, -25, 0, 25, 50, 100, 150

Shading: light: <-25, dark: >25

Figure 3 Annual mean long wave radiation over the ocean. (a) Unified Model, (b) climatology, (c) difference (model-climatology). Units are Wm^{-2}.

(a) and (b) Contours: -100, -60, -50, -40, -30, -20

Shading: light: -50 to -40, dark: -100 to -50

(c) Contours: -50, -20, -10, 0, 10, 20, 50

Shading: light: <0, dark: >0

Figure 4 Annual mean latent heat flux over the ocean. (a) Unified Model, (b) climatology, (c) difference (model-climatology). Units are Wm^{-2}.

(a) and (b) Contours: -300, -150, -100, -50, -20

Shading: light: -150 to -100, dark: <-150

(c) Contours: -100, -30, -10, 10, 30, 100

Shading: light: <-10, dark: >10

Figure 5 Annual mean sensible heat flux over the ocean. (a) Unified Model, (b) climatology, (c) difference (model-climatology). Units are Wm^{-2}.

(a) and (b) Contours: -100, -40, -20, 20

Shading: light: -40 to -20, dark: <-40

(c) Contours: -20, -10, 10, 20

Shading: light: <-10, dark: >10

Figure 6 Annual mean fresh water budget (precipitation less evaporation) over the ocean. (a) Unified Model, (b) climatology, (c) difference (model-climatology). Units are mm day^{-1}.

(a) and (b) Contours: -25, -5, -2, 0, 2, 5, 25

Shading: light: <0, dark: >0

(c) Contours: -10, -3, 0, 3, 10

Shading: light: <0, dark >0

Figure 7 Annual mean wind stress over the ocean. Units are 10^{-1} Nm^{-2}.

(a) Unified Model, (b) climatology, (c) difference in magnitude (model-climatology)

(a) and (b) Contours: 0.5, 1, 1.5, 2

(c) Contours: -2, -1, -0.5, -0.2, 0.2, 0.5, 1, 2

Shading: light: <-0.2, dark: >0.2

Figure 8 Annual mean wind stress curl over the North Atlantic Ocean.

(a) Unified Model, (b) climatology, (c) difference (model-climatology) Units are 10^6 Nm $^{-3}$.

(a) and (b) Contours: -5, -1, -0.5, -0.2, 0, 0.2, 0.5, 1, 5

Shading: light: <-0.5, dark: >0.5

(c) Contours: -5, -1, -0.5, -0.2, 0, 0.2, 0.5, 1, 5

Shading: light: <-0.2, dark: >0.2

Figure 9 Time series of difference between Unified Model and ERS-1 altimeter observations of wind speed for oceans north of 45°N.

Figure 10 Histogram of Unified Model winds less those observed by wave buoys for different lengths of forecast.

Figure 11 Precipitation spin-up in the Unified Model.

(a) 12h dynamic rainfall accumulations during analyses for April 1992

(b) 12h dynamic rainfall accumulation during forecasts for April 1992

(c) 12h convective rainfall accumulations during analyses for April 1992

(d) 12h convective rainfall accumulations during forecasts for April 1992

Units are mm.

Contours: 0.2, 0.5, 1, 2, 10

Shading: light: 0.5 to 1, dark: >1

FIGURE 1a TOTAL HEAT FLUX
UNIFIED MODEL ANNUAL MEAN (AUGUST 91 TO JULY 92)
Contours: -150,-50,-20,20,50,150
Shading: light: < -20, dark: > 20

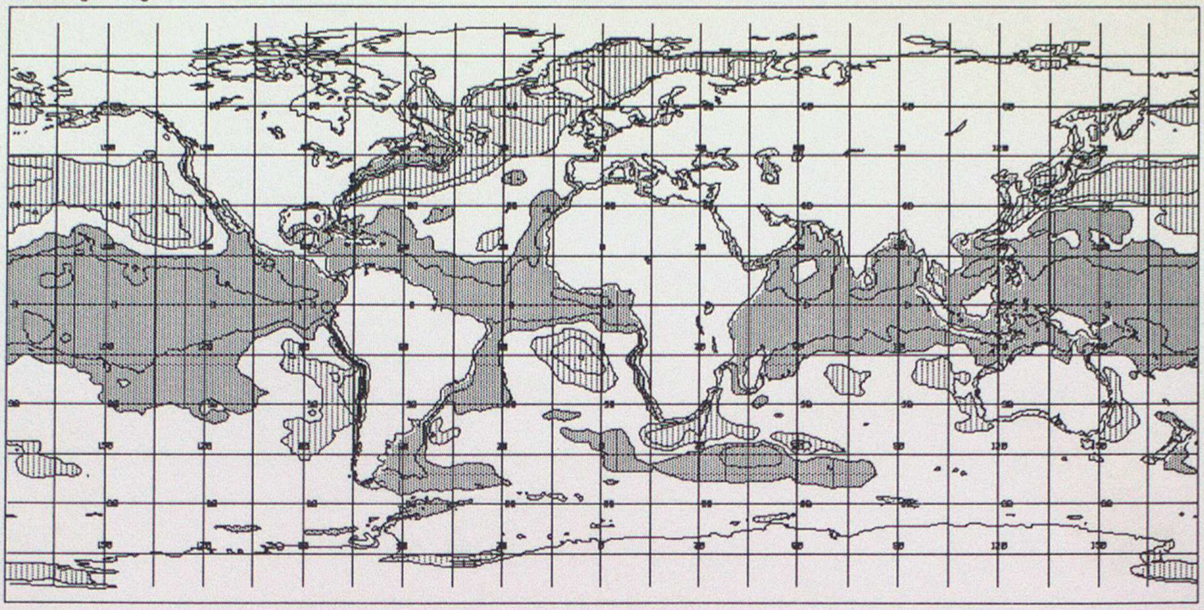


FIGURE 1b TOTAL HEAT FLUX
OBERHUBER ANNUAL MEAN
Contours: -150,-50,-20,20,50,150
Shading: light: < -20, dark: > 20

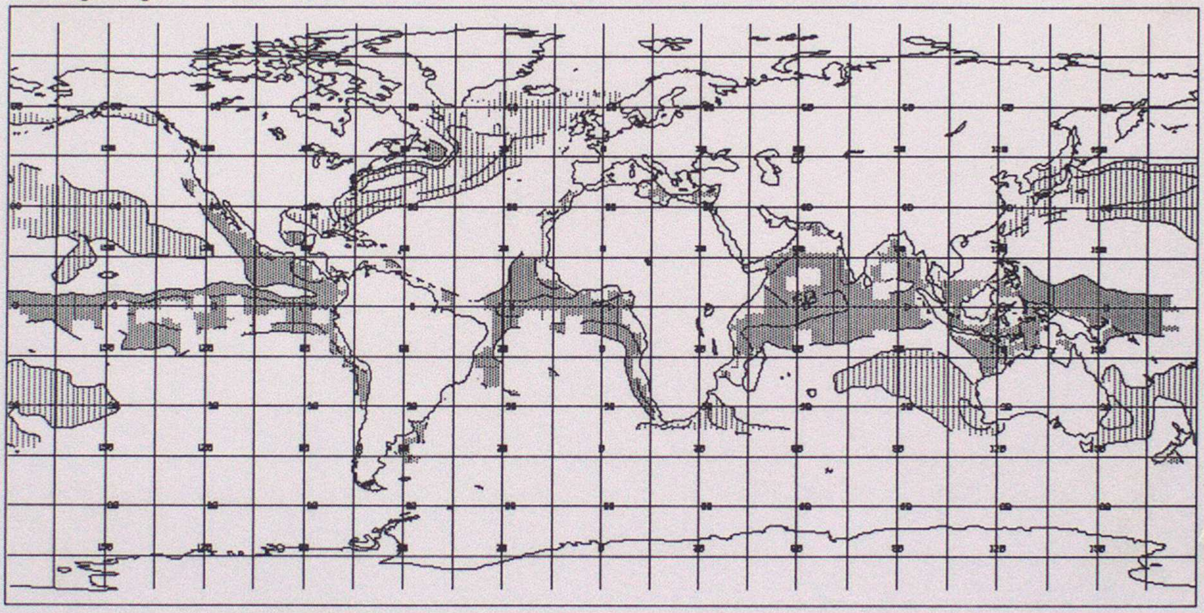


FIGURE 1c TOTAL HEAT FLUX
UNIFIED MODEL ANNUAL MEAN - OBERHUBER ANNUAL MEAN
Contours: -100,-50,-20,20,50,100
Shading: light: < -20, dark: > 20

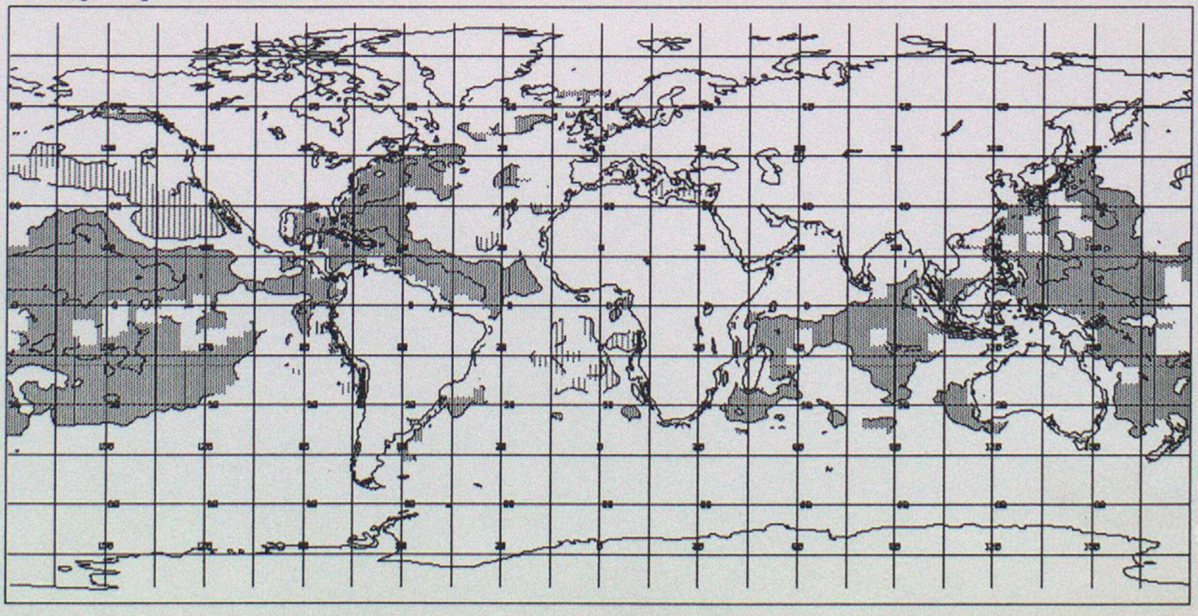


FIGURE 2a SURFACE NET SOLAR RADIATION
UNIFIED MODEL ANNUAL MEAN (AUGUST 91 TO JULY 92)
Contours: 50,100,150,200,250,300
Shading: light: 100 - 200, dark: > 200

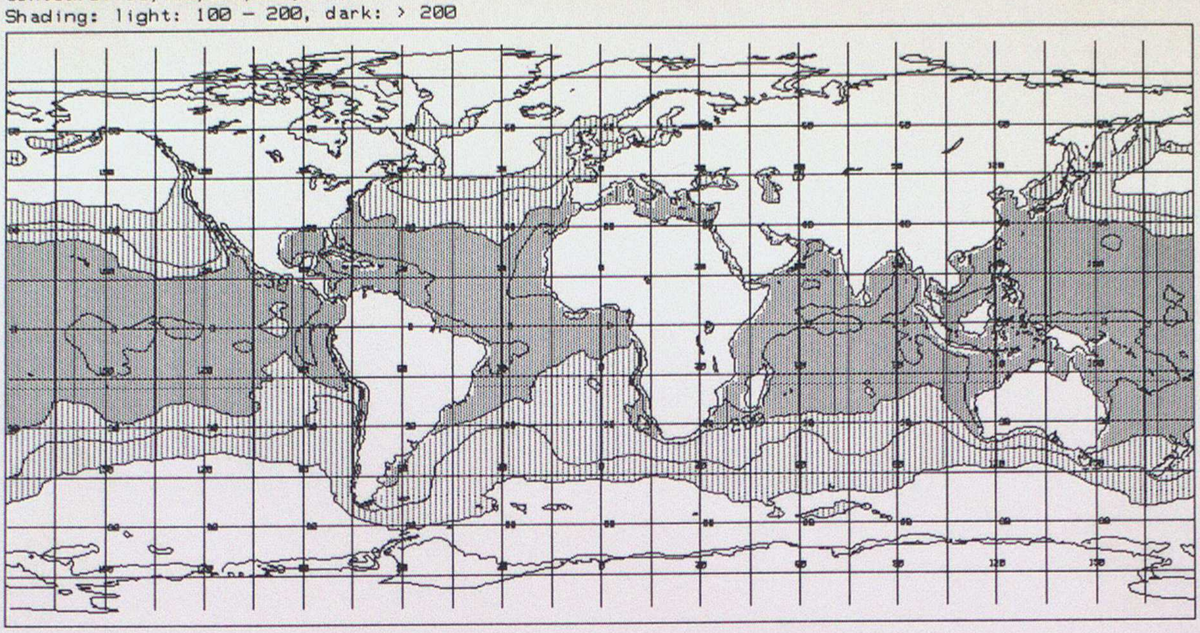


FIGURE 2b SURFACE NET SOLAR RADIATION
OBERHUBER ANNUAL MEAN
Contours: 50,100,150,200,250,300
Shading: light: 100 - 200, dark: > 200

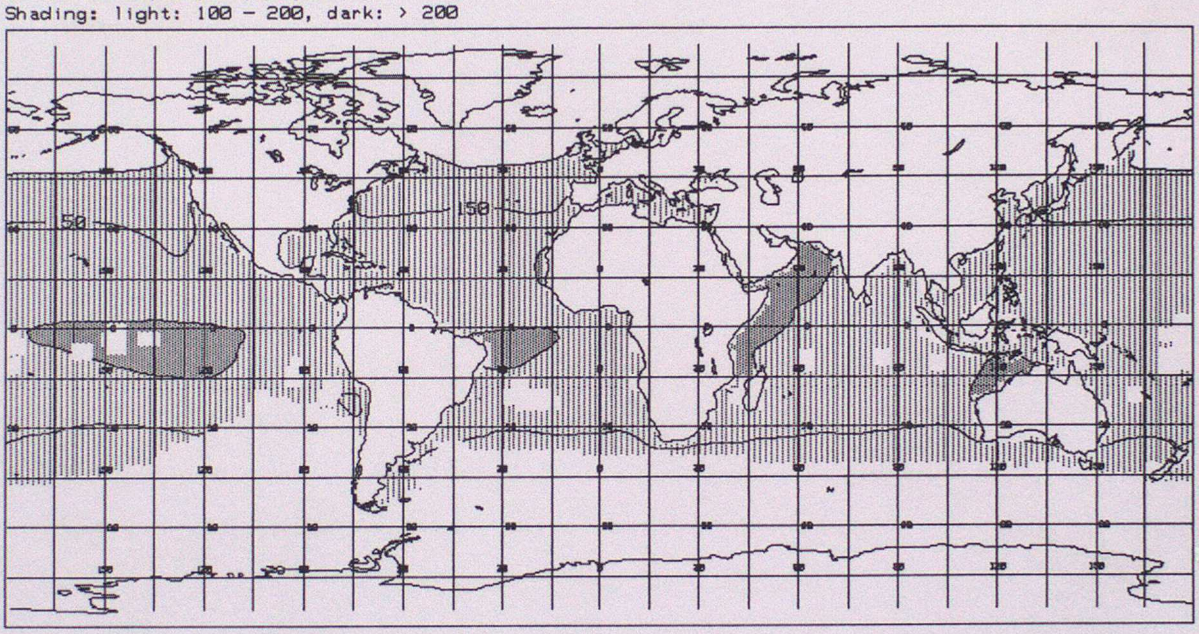


FIGURE 2c SURFACE NET SOLAR RADIATION
UNIFIED MODEL ANNUAL MEAN - OBERHUBER ANNUAL MEAN
Contours: -50,-25,0,25,50,100,150
Shading: light: < -25, dark : > 25

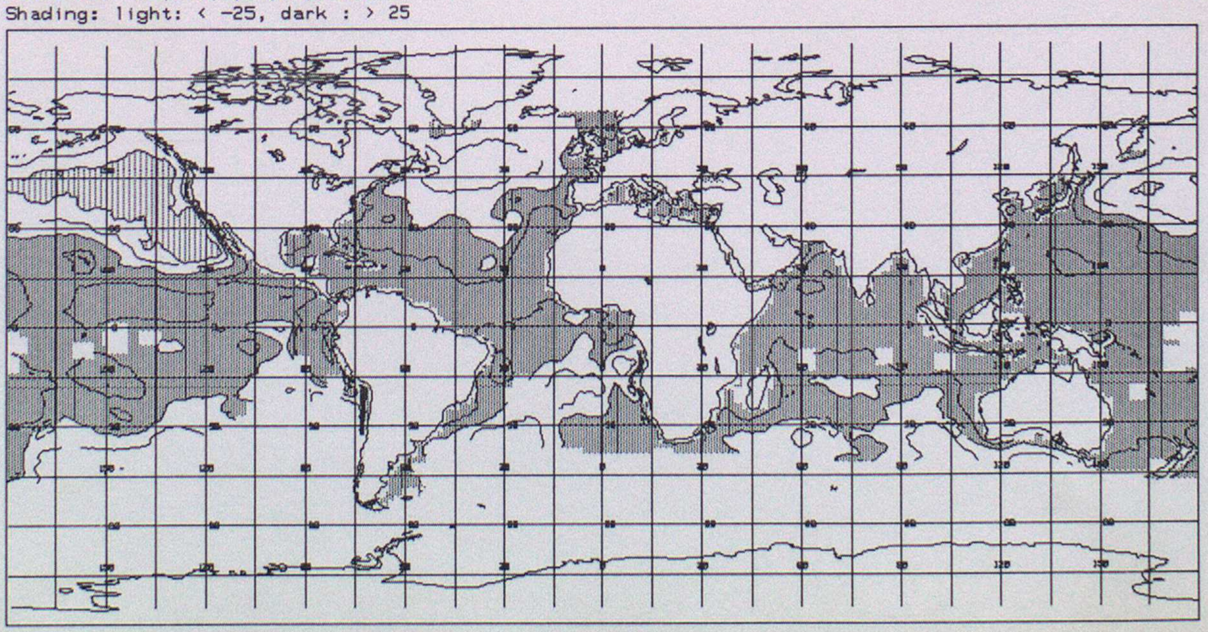


FIGURE 3a INFRA RED RADIATION
UNIFIED MODEL ANNUAL MEAN (AUGUST 91 TO JULY 92)
Contours: -100,-60,-50,-40,-30,-20
Shading: light: -50 to -40, dark: -100 to -50

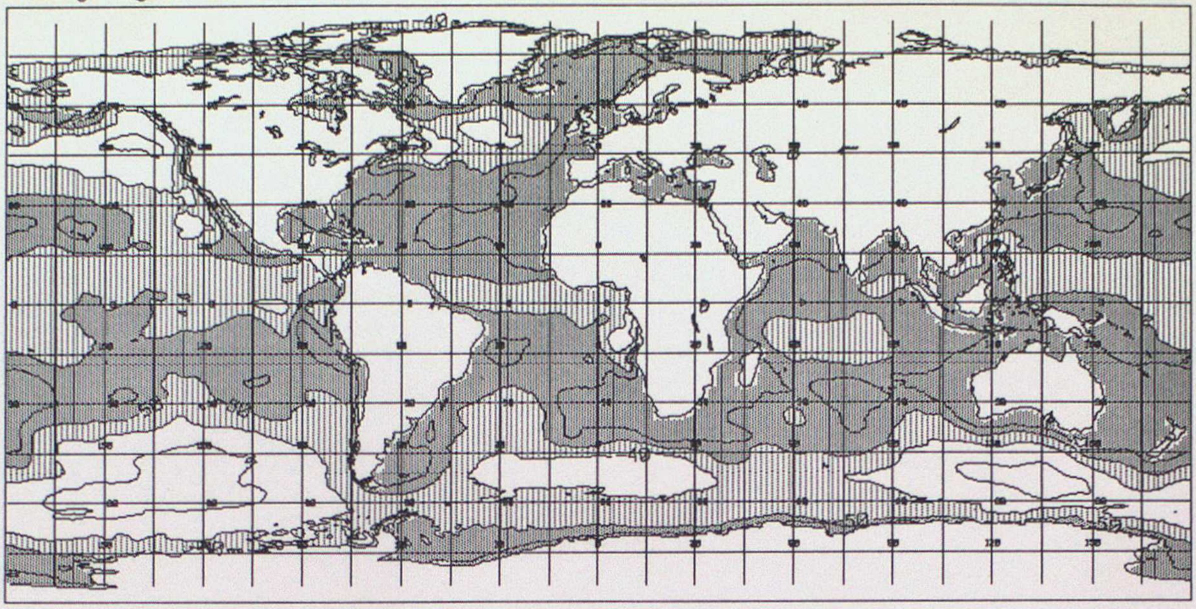


FIGURE 3b INFRA RED RADIATION
OBERHUBER ANNUAL MEAN
Contours: -100,-60,-50,-40,-30,-20
Shading: light: -50 to -40, dark: -100 to -50

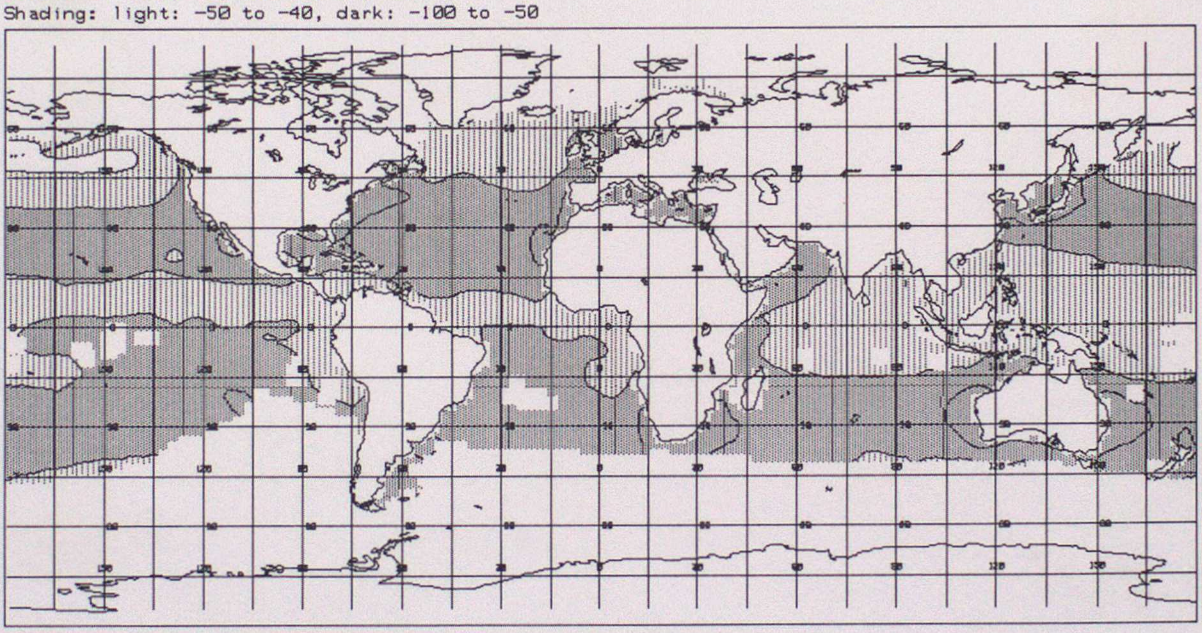


FIGURE 3c INFRA RED RADIATION
UNIFIED MODEL ANNUAL MEAN - OBERHUBER ANNUAL MEAN
Contours: -50,-20,-10,0,10,20,50
Shading: light: < 0, dark: > 0

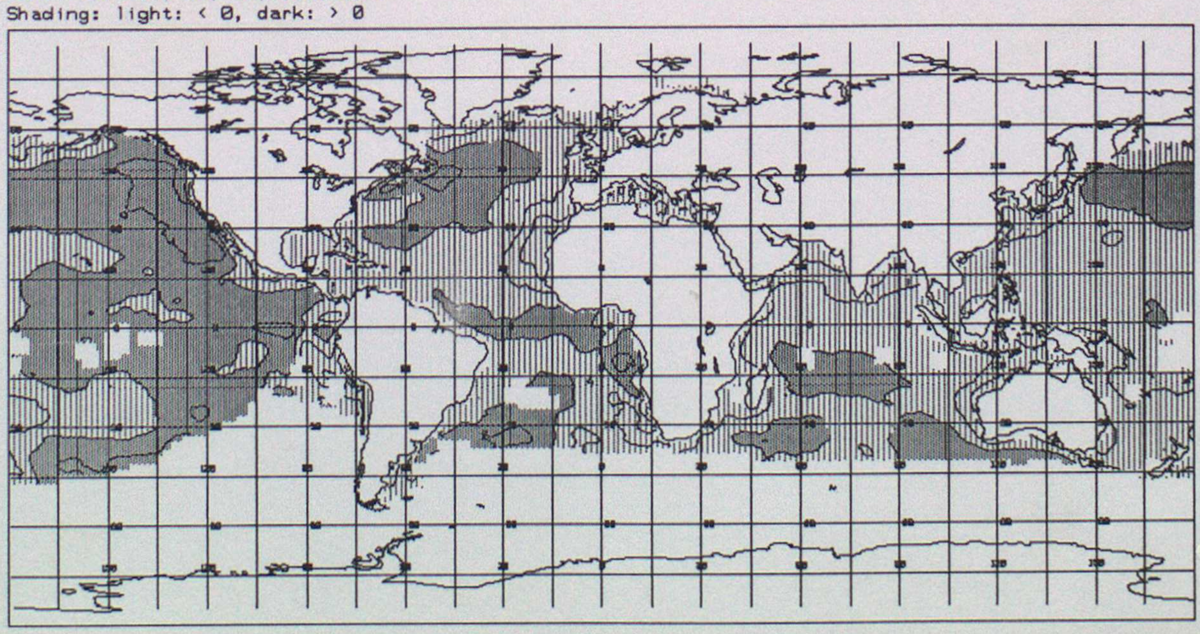


FIGURE 4a LATENT HEAT
UNIFIED MODEL ANNUAL MEAN (AUGUST 91 TO JULY 92)
Contours: -300,-150,-100,-50,-20
Shading: light: -150 to -100, dark: < -150

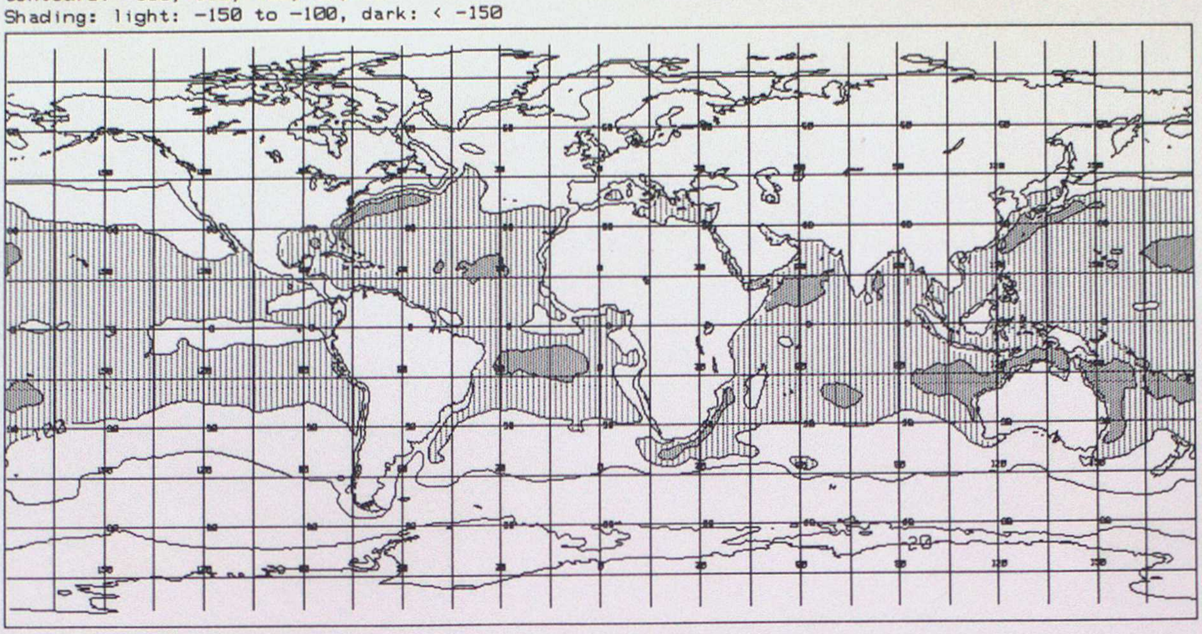


FIGURE 4b LATENT HEAT
OBERHUBER ANNUAL MEAN
Contours: -300,-150,-100,-50,-20
Shading: light: -150 to -100, dark: < -150

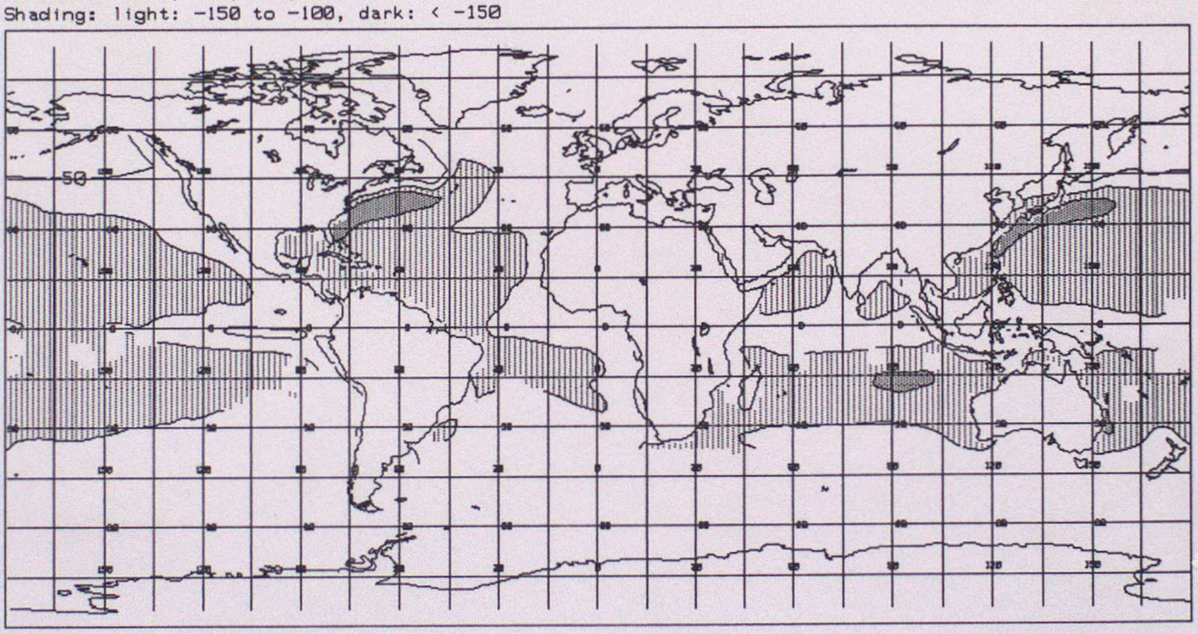


FIGURE 4c LATENT HEAT
UNIFIED MODEL ANNUAL MEAN - OBERHUBER ANNUAL MEAN
Contours: -100,-30,-10,10,30,100
Shading: light: < -10, dark: > 10

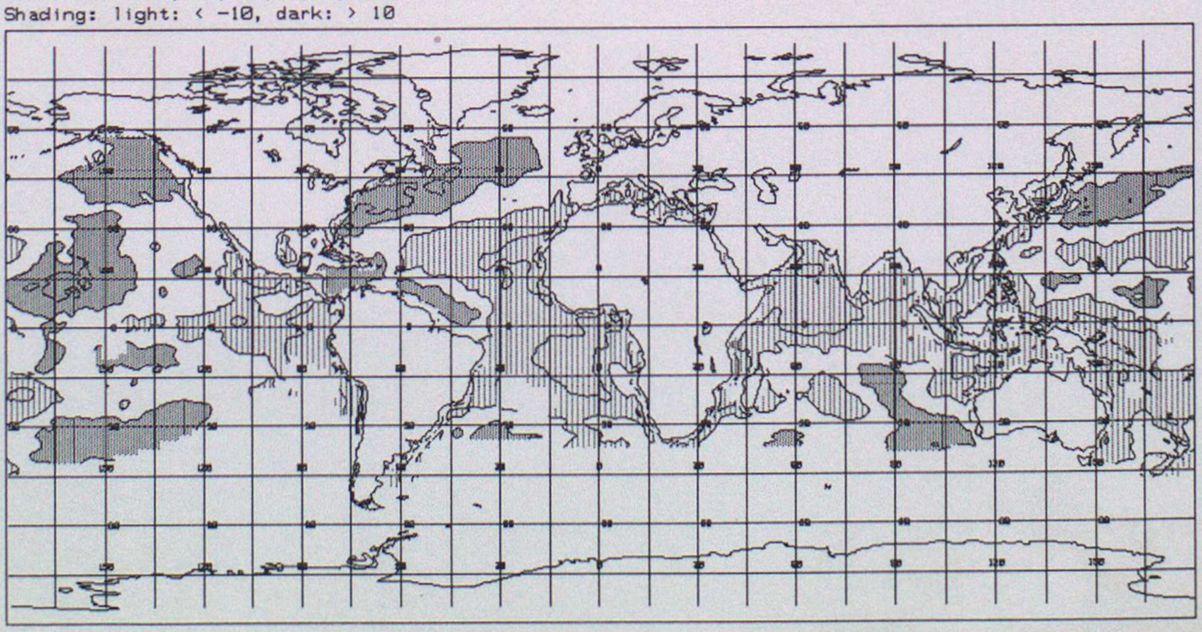


FIGURE 5a SENSIBLE HEAT
UNIFIED MODEL ANNUAL MEAN (AUGUST 91 TO JULY 92)
Contours: -100,-40,-20,20
Shading: light: -40 to -20, dark: < -40

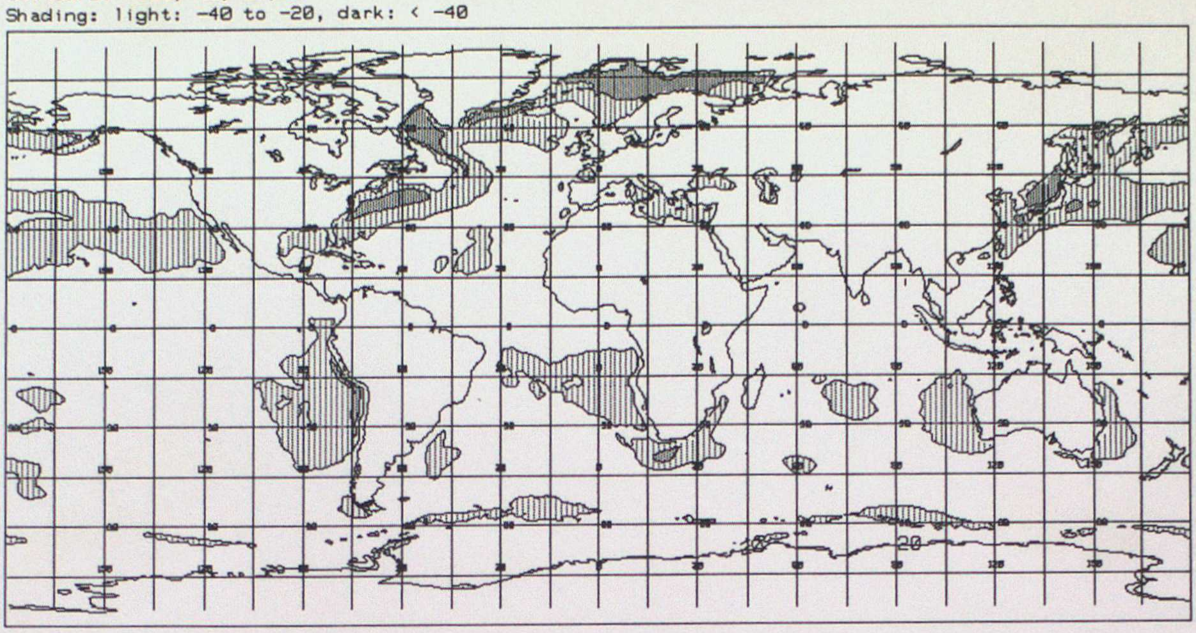


FIGURE 5b SENSIBLE HEAT
OBERHUBER ANNUAL MEAN
Contours: -100,-40,-20,20
Shading: light: -40 to -20, dark: < -40

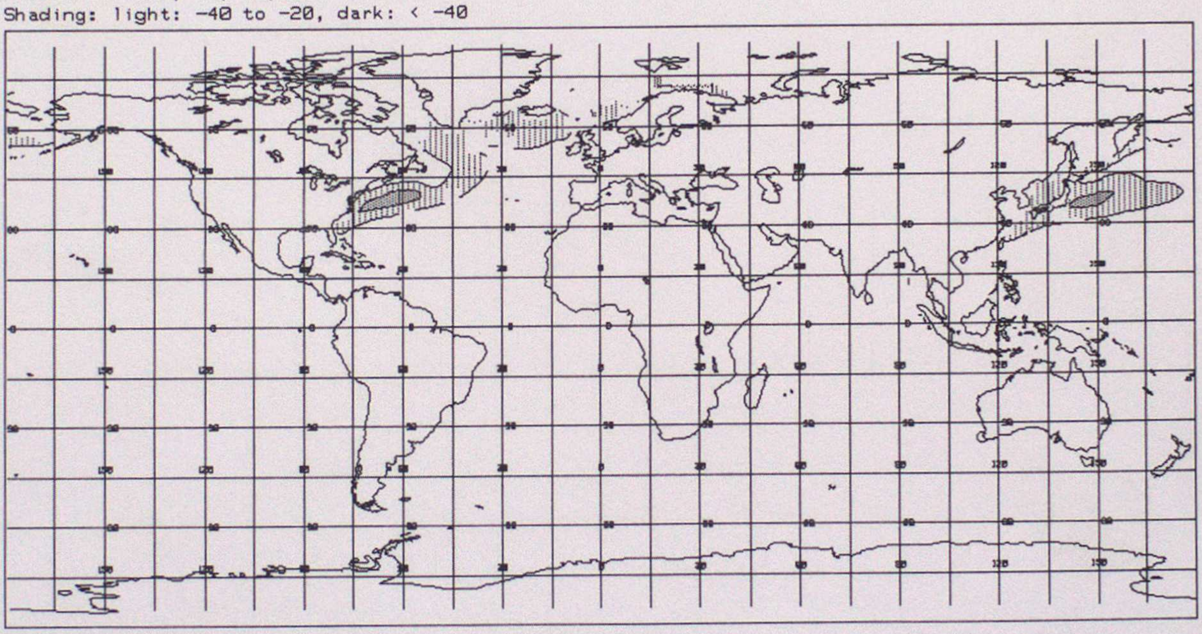


FIGURE 5c SENSIBLE HEAT
UNIFIED MODEL ANNUAL MEAN - OBERHUBER ANNUAL MEAN
Contours: -20,-10,10,20
Shading: light: < -10, dark: > 10

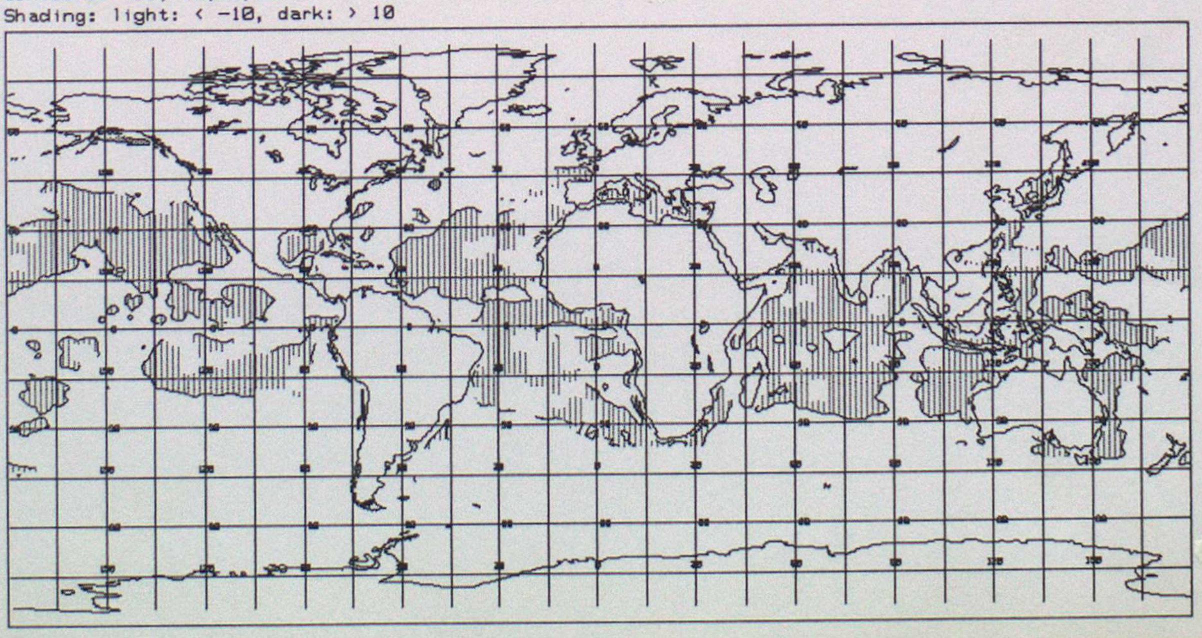


FIGURE 6a PRECIPITATION MINUS EVAPORATION
UNIFIED MODEL ANNUAL MEAN (AUGUST 91 TO JULY 92)
Contours: -25,-5,-2,0,2,5,25
Shading: light: < 0, dark: > 0

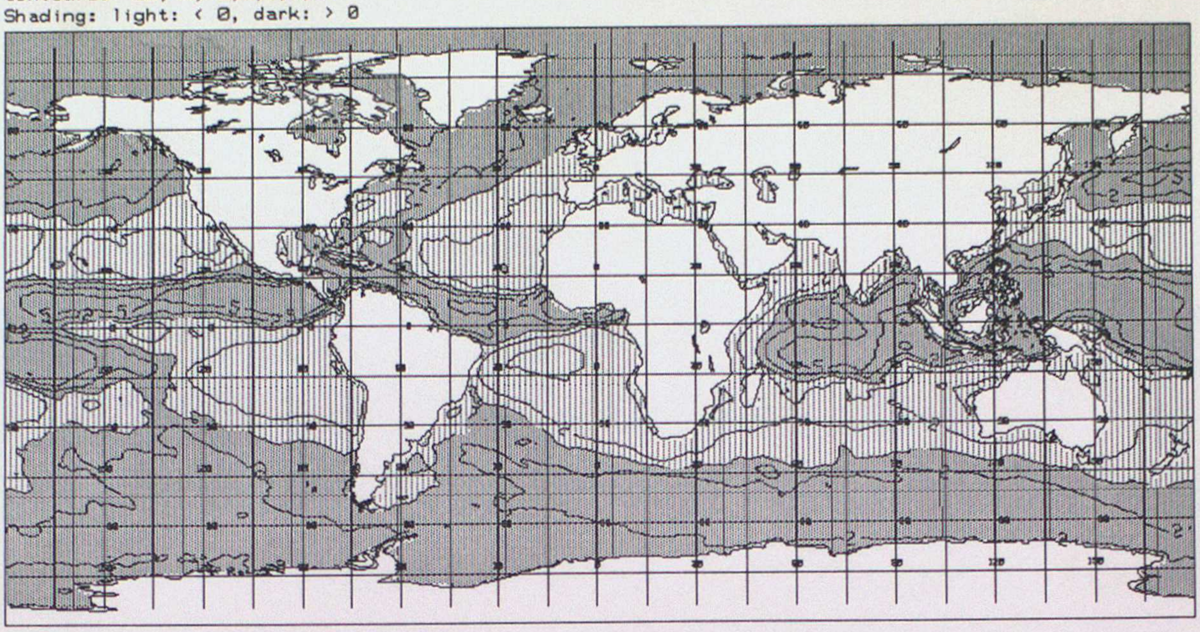


FIGURE 6b PRECIPITATION MINUS EVAPORATION
OBERHUBER ANNUAL MEAN
Contours: -25,-5,-2,0,2,5,25
Shading: light: < 0, dark: > 0

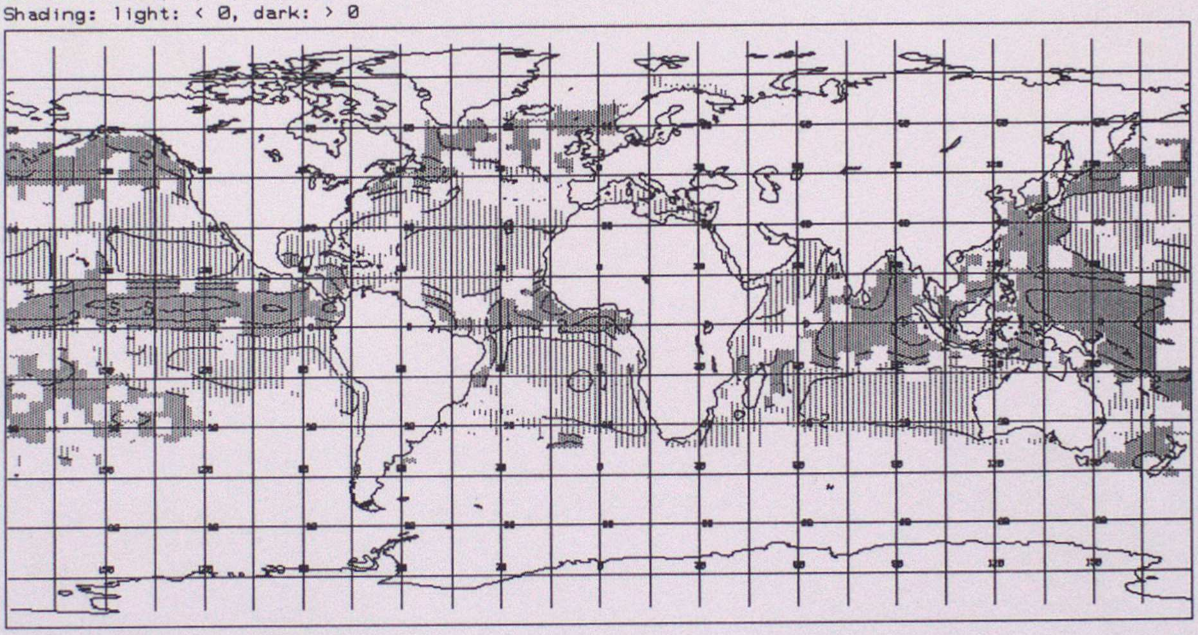


FIGURE 6c PRECIPITATION MINUS EVAPORATION
UNIFIED MODEL ANNUAL MEAN - OBERHUBER ANNUAL MEAN
Contours: -10,-3,0,3,10
Shading: light: < 0, dark: > 0

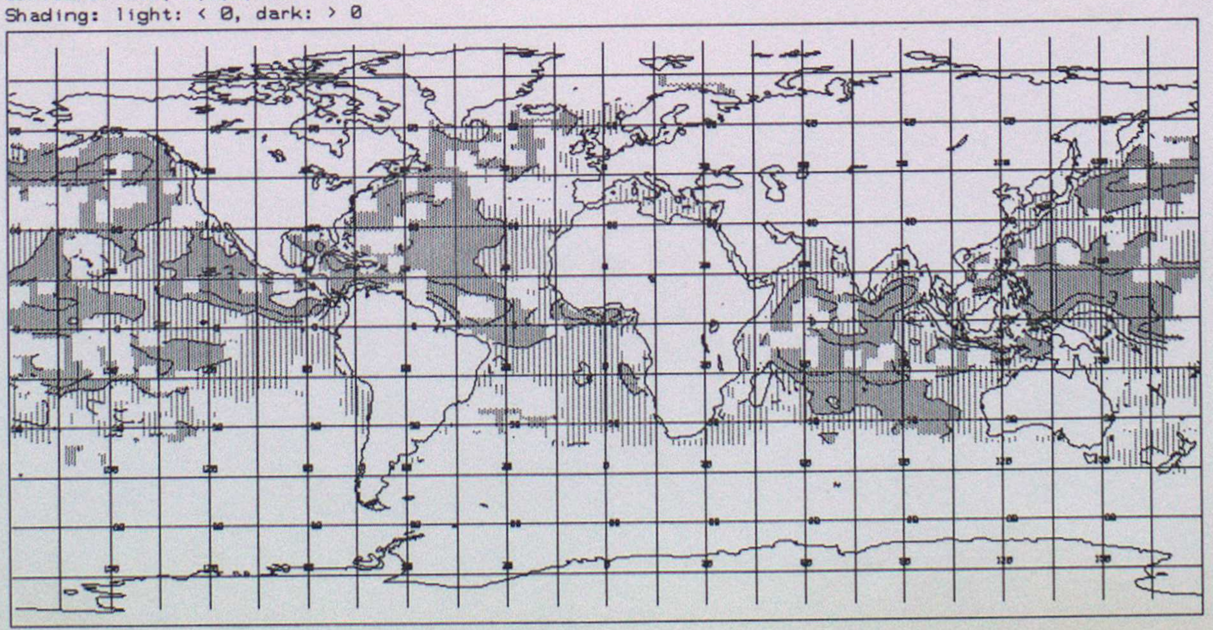
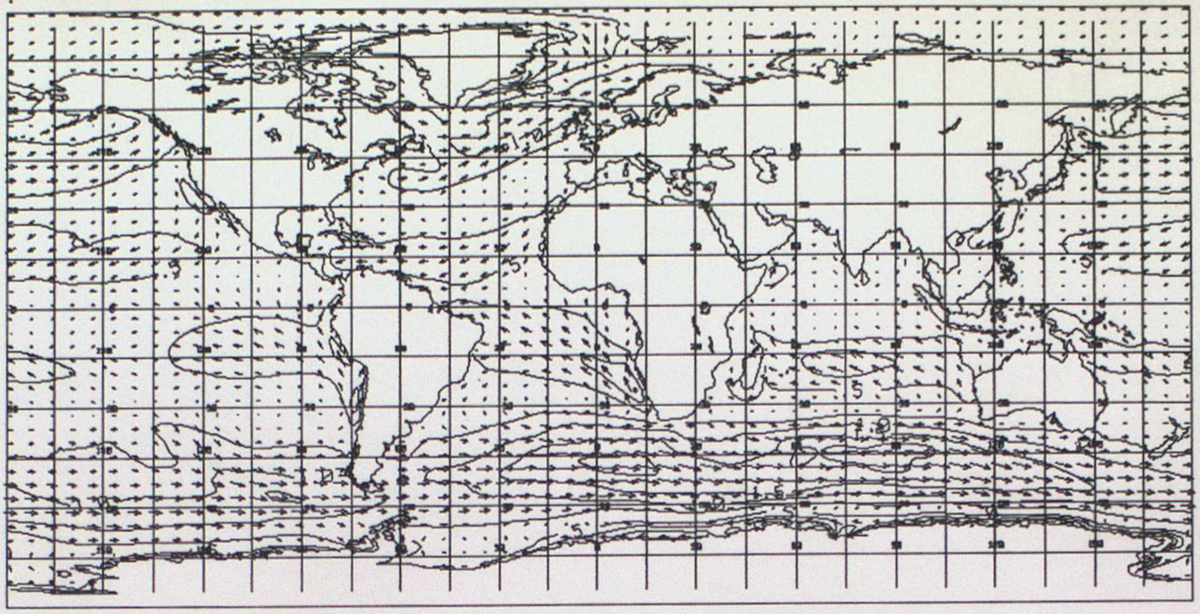
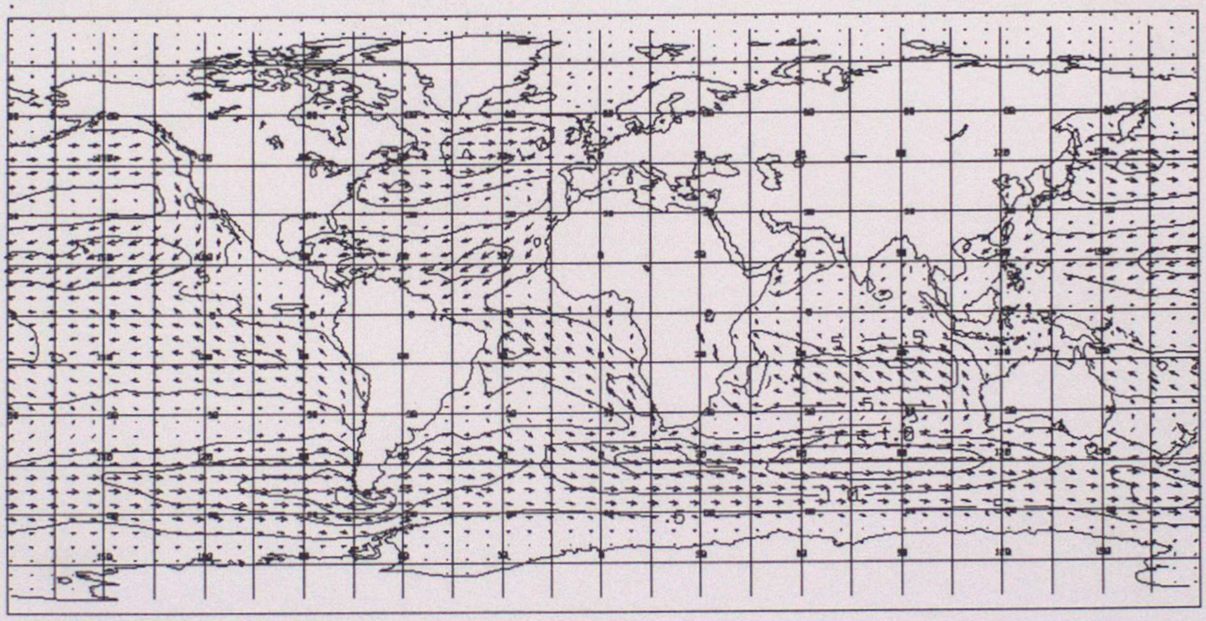


FIGURE 7a WIND STRESS
UNIFIED MODEL ANNUAL MEAN (AUGUST 91 TO JULY 92)
Contours: 0.5,1,1.5,2



→ REPRESENTS 2.5 MKS UNITS

FIGURE 7b WIND STRESS
HELLERMAN/ROSENSTEIN ANNUAL MEAN
Contours: 0.5,1,1.5,2



→ REPRESENTS 2.5 MKS UNITS

FIGURE 7c WIND STRESS (DIFFERENCE IN MAGNITUDE)
UNIFIED MODEL ANNUAL MEAN - HELLERMAN/ROSENSTEIN ANNUAL MEAN
Contours: -2,-1,-0.5,-0.2,0.2,0.5,1,2
Shading: light: < -0.2, dark: > 0.2

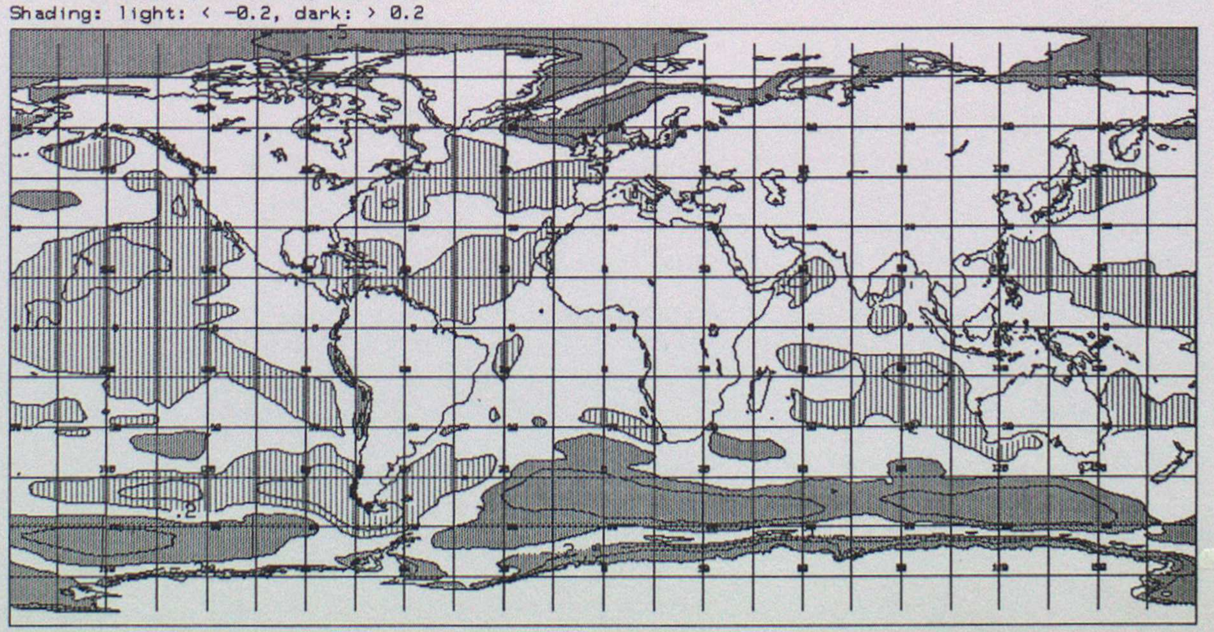


FIGURE 8a WIND STRESS VORTICITY - VERTICAL COMPONENT (INTERPOLATED)
UNIFIED MODEL ANNUAL MEAN (AUGUST 91 TO JULY 92)
Contours: -5,-1,-0.5,-0.2,0,0.2,0.5,1,5
Shading: light: < -0.5, dark: > 0.5

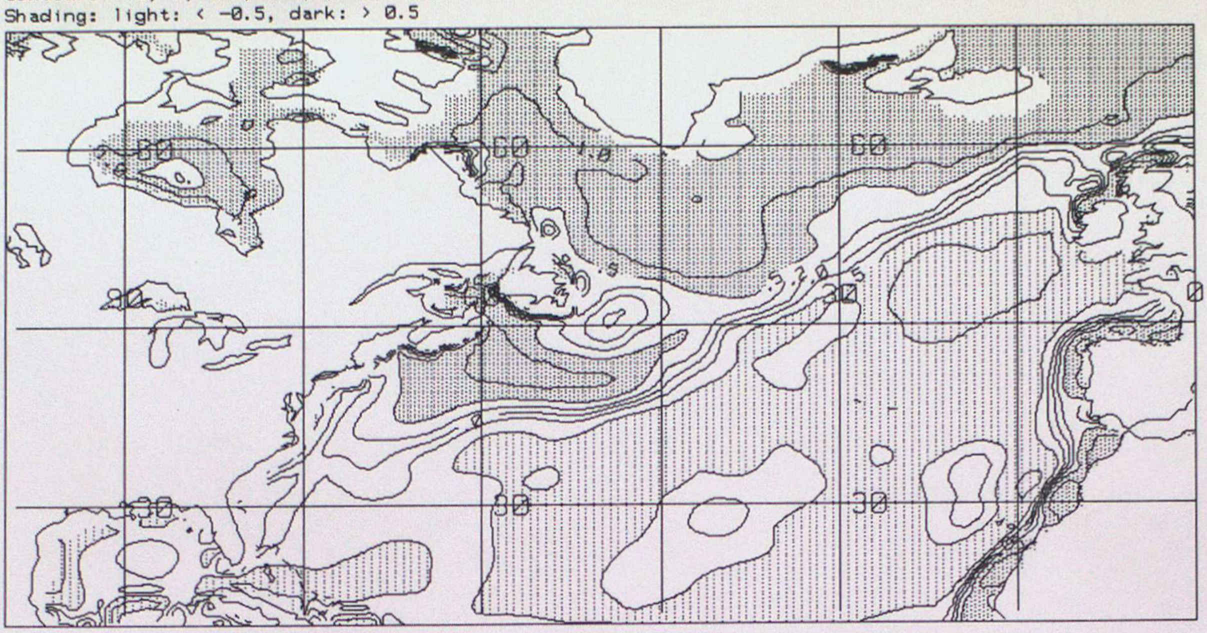


FIGURE 8b WIND STRESS VORTICITY - VERTICAL COMPONENT (INTERPOLATED)
HELLERMAN/ROSENSTEIN ANNUAL MEAN
Contours: -5,-1,-0.5,-0.2,0,0.2,0.5,1,5
Shading: light: < -0.5, dark: > 0.5

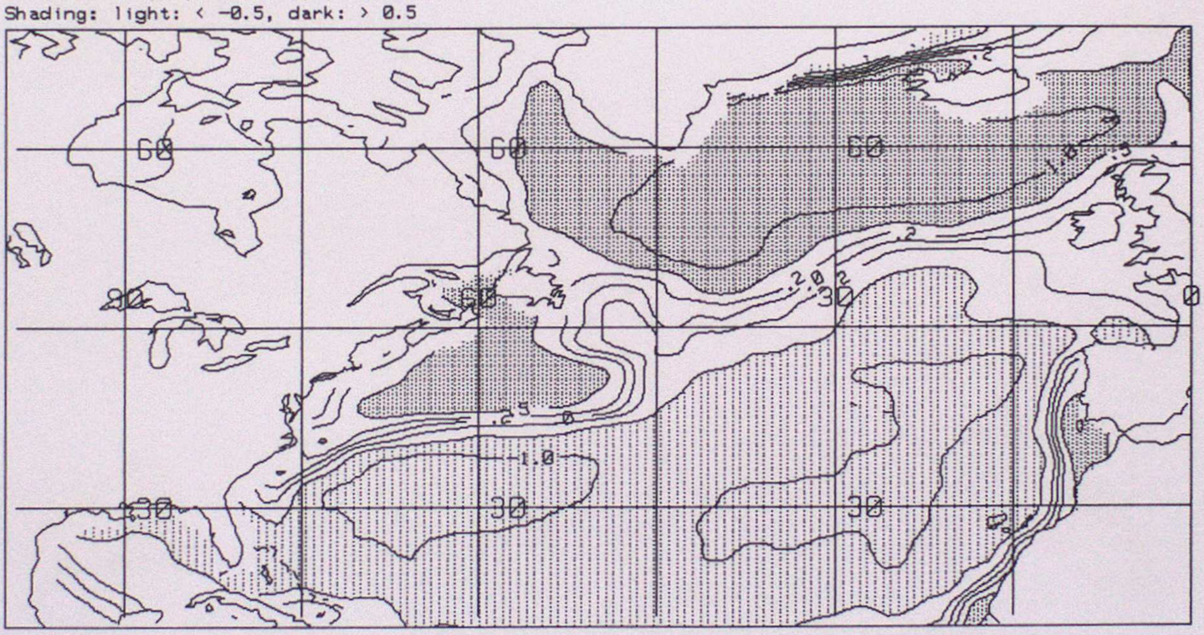


FIGURE 8c WIND STRESS VORTICITY - VERTICAL COMPONENT (INTERPOLATED)
UNIFIED MODEL ANNUAL MEAN - HELLERMAN/ROSENSTEIN ANNUAL MEAN
Contours: -5,-1,-0.5,-0.2,0,0.2,0.5,1,5
Shading: light: < -0.2, dark: > 0.2

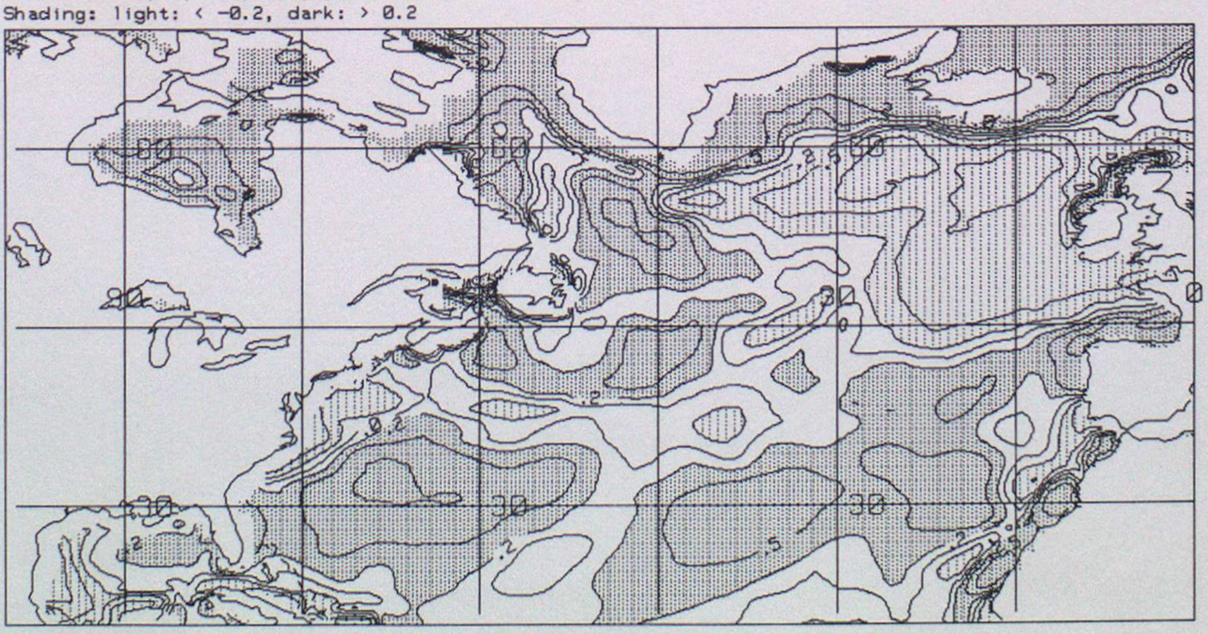
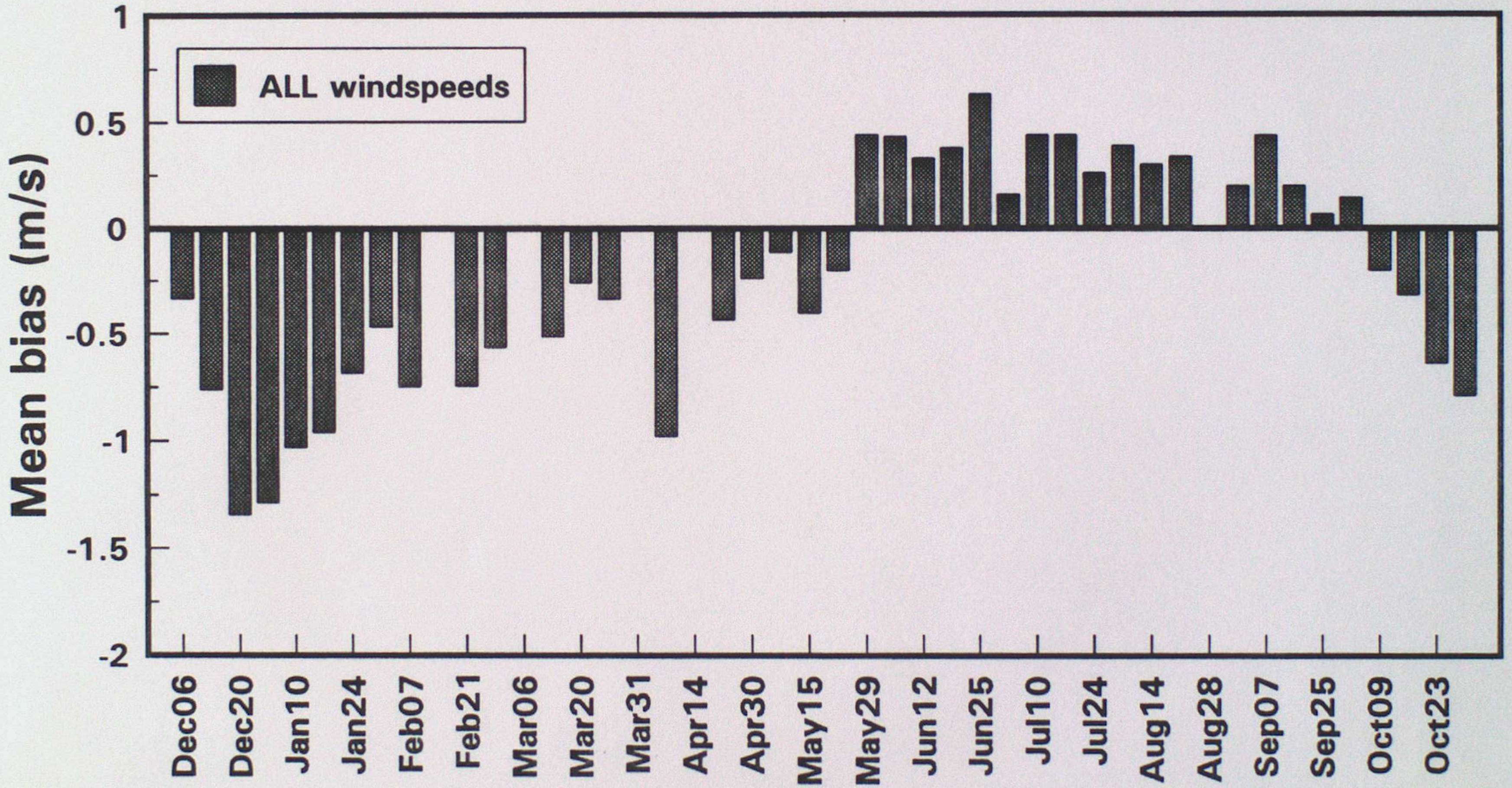


FIGURE 9

ERS-1 altimeter

Windspeed comparison at UKMO model SEA points

WINDSPEED Mean Bias MODEL - OBS 45N - 90N



Binned by mean (Obs + Model)
Gaps are missing data

FIGURE 10

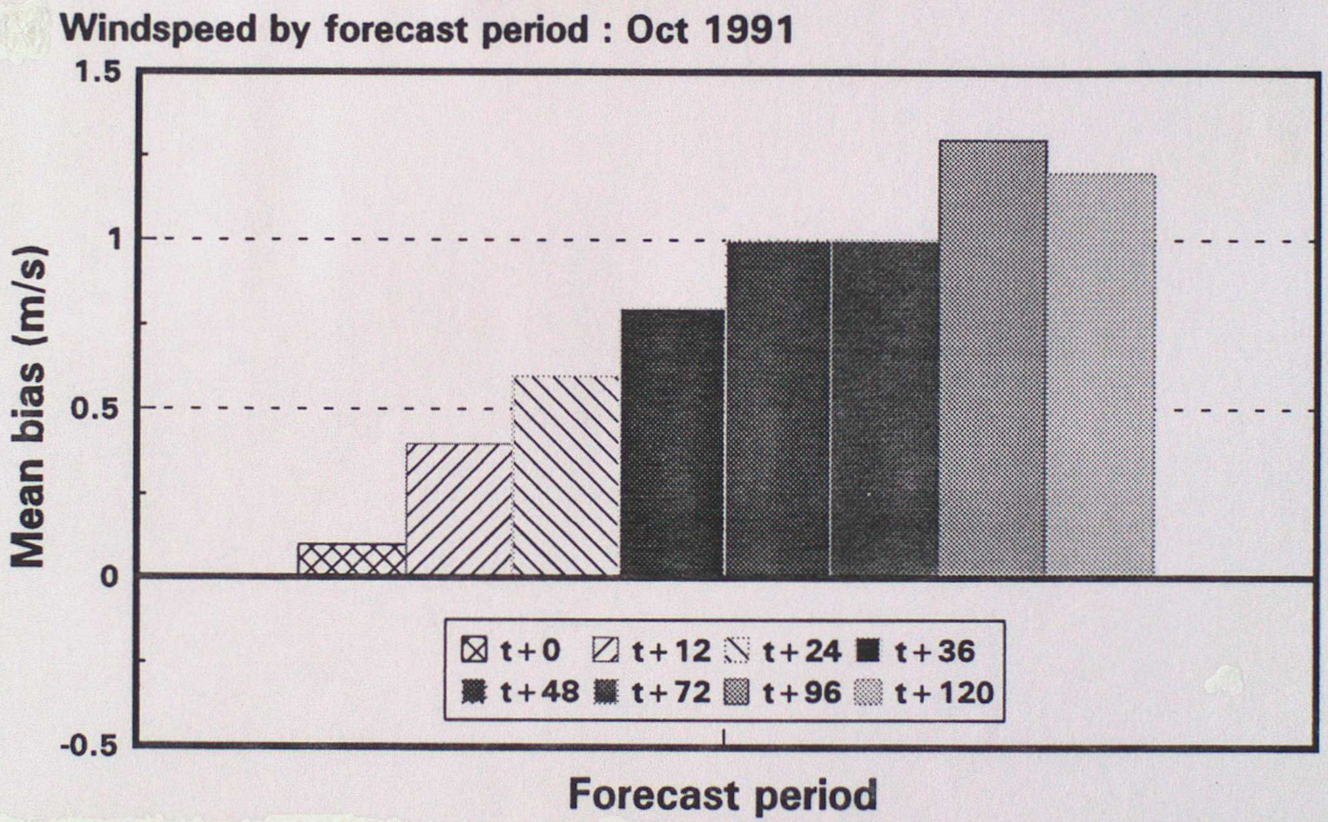

Windspeed by forecast period : Oct 1991
1.5
1
0.5
0
-0.5
Mean bias (m/s)
t+0
t+12
t+24
t+36
t+48
t+72
t+96
t+120
Forecast period

FIGURE 11a 12-HOUR DYNAMIC RAINFALL ACCUMULATIONS
ANALYSIS FIELD (APRIL 92)
Contours: 0.2,0.5,1,2,10
Shading: light: 0.5 to 1, dark: > 1

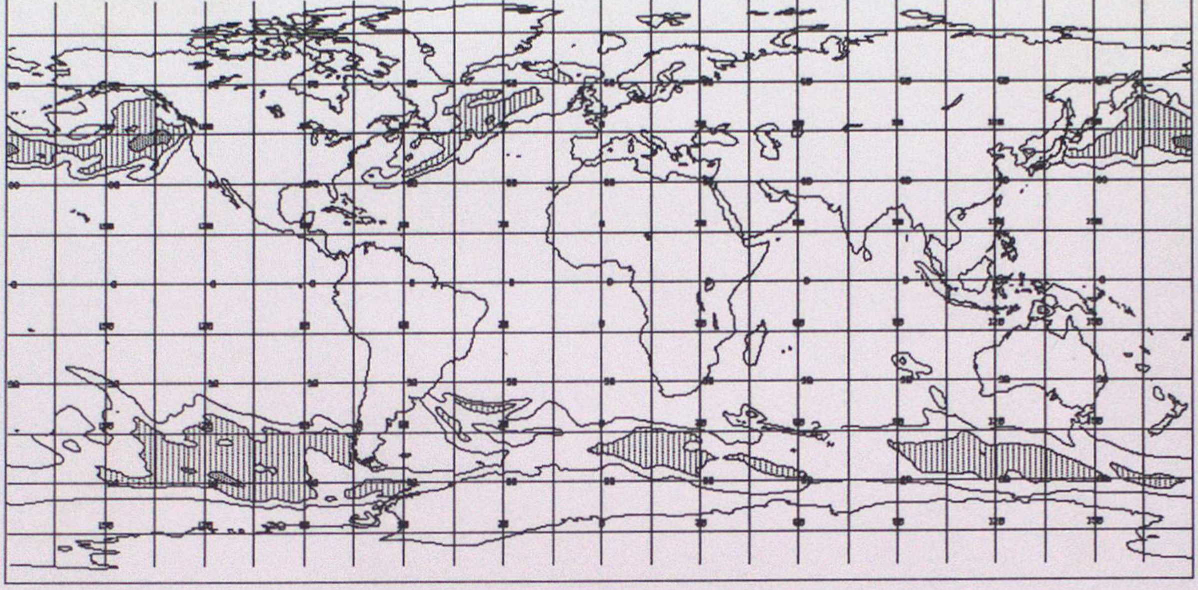


FIGURE 11b 12-HOUR DYNAMIC RAINFALL ACCUMULATIONS
FORECAST FIELD (APRIL 92)
Contours: 0.2,0.5,1,2,10
Shading: light: 0.5 to 1, dark: > 1

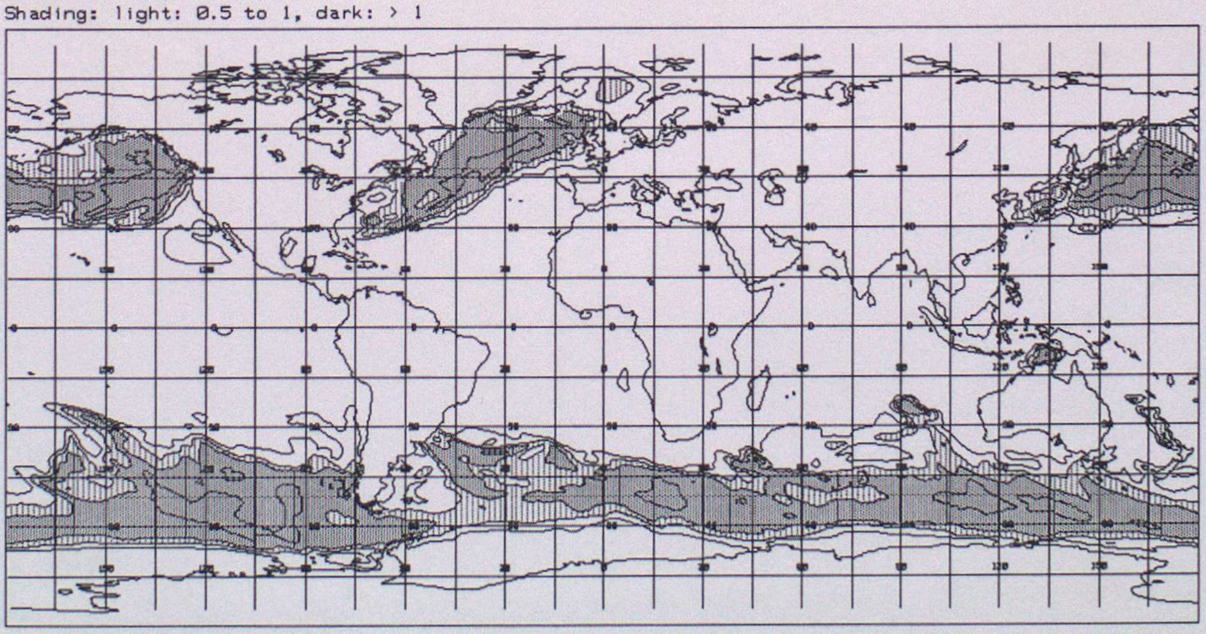


FIGURE 11c 12-HOUR CONVECTIVE RAINFALL ACCUMULATIONS
ANALYSIS FIELD (APRIL 92)
Contours: 0.2,0.5,1,2,10
Shading: light: 0.5 to 1, dark: > 1

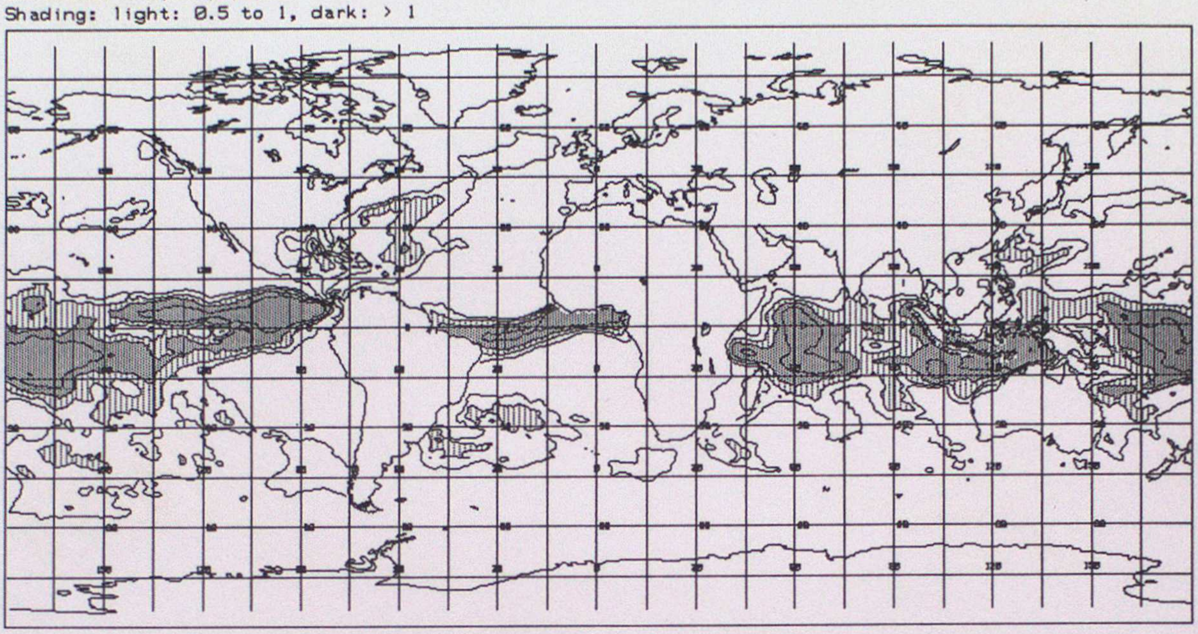
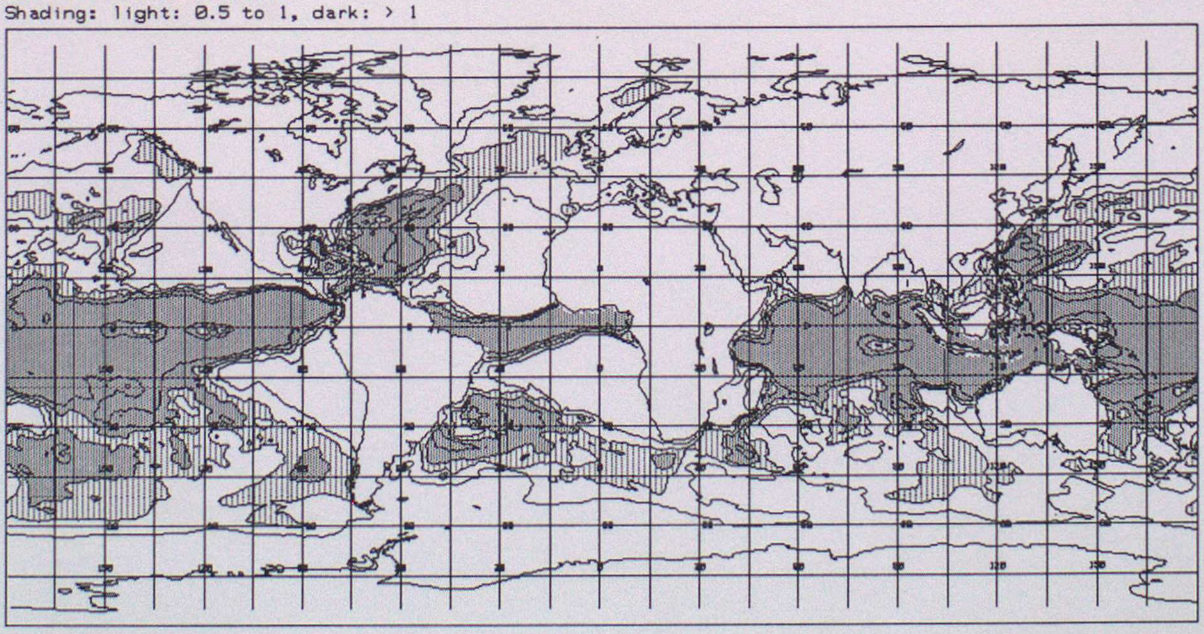


FIGURE 11d 12-HOUR CONVECTIVE RAINFALL ACCUMULATIONS
FORECAST FIELD (APRIL 92)
Contours: 0.2,0.5,1,2,10
Shading: light: 0.5 to 1, dark: > 1



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