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Appendix 5

ESTIMATING PHOTOSYNTHETICALLY AVAILABLE RADIATION (PAR) AT THE EARTH'S SURFACE FROM SATELLITE OBSERVATIONS

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Estimating Photosynthetically Available Radiation (PAR) at the Earth's Surface from Satellite Observations

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Abstract

Current satellite algorithms to estimate photosynthetically available radiation (PAR) at the earth's surface are reviewed. PAR is deduced either from an insolation estimate or obtained directly from top-of-atmosphere solar radiances. The characteristics of both approaches are contrasted and typical results are presented. The inaccuracies reported, about 10% and 6% on daily and monthly time scales, respectively, are useful to model oceanic and terrestrial primary productivity. At those time scales variability due to clouds in the ratio of PAR and insolation is reduced, making it possible to deduce PAR directly from insolation climatologies (satellite or other) that are currently available or being produced. Improvements, however, are needed in conditions of broken cloudiness and over ice/snow. If not addressed properly, calibration/validation issues may prevent quantitative use of the PAR estimates in studies of climatic change. The prospects are good for an accurate, long-term climatology of PAR over the globe.

Introduction

Solar radiation reaching the earth's surface in the wavelength range 0.35-0.7 μm is used by aquatic and terrestrial plants in photosynthesis. Called photosynthetically available radiation (PAR), it governs primary production, the rate of carbon fixed by the plants. Knowing the geographical location and temporal variability of the fixed carbon and its forms of release is important in assessing the climatic impact of anthropogenic changes such as the destruction of major vegetation systems or the increase in atmospheric carbon dioxide. PAR is defined by

$$\mathrm{PAR}(\mathrm{Wm}^{-2}) = \int_{0.35}^{0.7} I(\lambda)d\lambda \qquad (1)$$

where $I(\lambda)$ is the downward spectral irradiance at wavelength λ. Since photosystem processes are quantum reactions, it is useful to consider the equation

$$\mathrm{PAR}(\mathrm{quanta\ m}^{-2}\mathrm{s}^{-1}) = \frac{1}{hc}\int_{0.35}^{0.7} \lambda I(\lambda)d\lambda \quad , \qquad (2)$$

where h is Plank's constant and c is the velocity of light in vacuum. Eqs. (1) and (2) indicate that PAR depends on the spectral interval considered which, for operational constraints, may sometimes differ from 0.35-0.7 μm.

Fig. 1 shows how primary production varies as a function of PAR over land (Fig. 1a) and ocean (Fig. 1b). The land case corresponds to typical, live, horizontal leaves (Sellers, 1985, Fig. 13a) and the ocean case to a 20°C, homogeneous water body (calculations were performed with the model of Morel, 1988). Over land, primary production increases rather linearly with PAR, the slope of variation depending on leaf area index (higher slope as leaf area index increases). The relationship, however, is affected little by leaf area index for leaf area indices above 4. Over the ocean, by contrast, the effect of PAR is highly non-linear in the range of PAR values generally encountered. As PAR increases, primary production becomes quickly insensitive to PAR. Saturation occurs at PAR values as low as 200 Wm^{-2} when phytoplankton concentration is as high as $1\mathrm{mgm}^{-3}$. Unlike over land, where primary production becomes independent of leaf area index at high values of the index, primary production over the ocean increases substantially even when phytoplankton concentration is high.

Fig. 1 provides some insight about the accuracy requirements for PAR. Owing to non-linearities in the relationship between primary production and PAR, the error permitted on PAR to achieve a reasonable 10% accuracy on primary production will depend on PAR as well as the biomass level. In the PAR region for which primary production can be considered directly proportional to PAR (i.e., 0-100 Wm^{-2} over land and 0-50 Wm^{-2} over the ocean), the 10% accuracy on primary production translates equally into a 10% accuracy on PAR, but 20% and 35% accuracies will be sufficient over land and ocean respectively, when PAR is above 300Wm^{-2}. Thus, a better relative accuracy on PAR is required at low PAR values, which occur either at low solar zenith angles or in the presence of clouds; under those conditions, unfortunately, satellite algorithms are less accurate. In view of available primary production models, however, the accuracy requirements on PAR may be relaxed. The models generally incorporate the fact that the growth rate of many plants is proportional to the rate of radiant solar energy absorption by chlorophyll pigments, but this rate (absorbed PAR) and the efficiency factors (functions of plant type, environmental conditions) are difficult to estimate with accuracies comparable to those mentioned above for PAR. In other words, useful estimates of primary production may still be obtained with larger errors on PAR.

If we are to understand truly the interactions between the biosphere and the atmosphere and their effects on climate, we need to know the geographic distribution and temporal variability of primary production and, thus, PAR over the globe. Until recently, our information was based on surface pyranometer networks (essentially over land) and a few PAR sensors deployed during research experiments. The networks are clearly insufficient for global change studies; the oceans and polar regions, in particular, are virtually not sampled, and long-term time series (from well-maintained, regularly-calibrated sensors) are only existent at a few locations. Furthermore, pyranometers measure insolation, or the solar radiation incident in the spectral range 0.4-4 μm, and the relationship between PAR and insolation depends on atmospheric conditions and radiation geometry (e.g., Baker and Frouin, 1987; Pinker and Laszlo, 1992). Clouds, which do not absorb at PAR wavelengths but do absorb substantially in the near-infrared, increase the ratio of PAR and insolation. Data from the pyranometer networks can be complemented by estimates based on empirical formulas and cloud observations made routinely at meteorological stations (e.g., cloud cover, cloud type). The formulas, unfortunately, have been established locally and are therefore difficult to apply confidently over large areas. Moreover, the dataset is uneven and too often of questionable quality. Because of these limitations, we do not yet have a clear picture of PAR's modes of variability over the globe. However the situation is being changed with existing earth-observing satellites, which provide regular coverage of the earth and observations of the basic cloud properties governing PAR variability.

Satellite Algorithms

While numerous studies have been devoted to estimating insolation from satellite data (e.g., Tarpley, 1979; Gautier et al., 1980; Möser and Rashke, 1984; Pinker and Ewing, 1985; Dedieu et al., 1987; Darnell et al., 1988), only a few satellite-based methods have been proposed for PAR, including the methods of Frouin and Gautier (1990), Eck and Dye (1991), and Pinker and Laszlo (1992). Part of the reason is that for many applications involving small space and time scales PAR can be measured directly. Furthermore, it has often proven satisfactory to take PAR as a more or less constant fraction of insolation. Deducing PAR from insolation, in fact, is the basis of Pinker and Laszlo's (1992) method, which can be qualified as indirect (requires an insolation estimate). Noting that meteorological satellites (except METEOSAT) carry instruments that measure in spectral channels resembling more the PAR wavelength range than the entire solar spectrum, Frouin and Gautier (1990) use the satellite radiances directly. Uncertainties in insolation are not propagated in that case, and the modeling of cloud effects is simplified (no narrow-band to broad-band transformation is necessary, and cloud absorption vanishes in the equations). This method, also used by Eck and Dye (1991), can be qualified as direct (does not require an insolation estimate). In what follows, we contrast the salient features of the indirect and direct methods, and we present typical results.

a Indirect approach

In Pinker and Laszlo's (1992) method, insolation (estimated using the model of Pinker and Ewing, 1985) is converted into PAR using a relationship established theoretically. This relationship depends on atmospheric conditions, which need to be specified. Under clear skies, the ratio of PAR to insolation varies little around 0.48, except at high solar zenith angles or extreme (low as well as high) water vapor amounts (Fig. 2), and the effect of aerosol turbidity is only significant when horizontal visibility is less than 10km. This suggests that the ratio of PAR to insolation can be considered constant to a good degree of approximation under clear skies. The situation is quite different under cloudy skies. Cloud optical thickness substantially changes the ratio of PAR and insolation, which can vary by more than 50% at low solar zenith angles (Fig. 3). This variability in the PAR-to-insolation ratio is corroborated by in-situ measurements (Fig. 4). Pinker and Laszlo's (1992) procedure is to therefore apply a variable conversion factor to insolation estimates. This factor depends on cloud optical thickness and fractional amount, parameters derived from the satellite measurements. Applying this method to hourly ISCCP C1 data at 250 km resolution, Pinker and Laszlo (1992) have produced the first global map of monthly PAR, effectively demonstrating that global satellite datasets produced within the frame of ISCCP will soon result in a global, long-term climatology of PAR. Owing to non-linearity, conversion factors are applied before averaging instantaneous insolation estimates over daily and longer time scales. It may be possible to apply conversion factors to daily or monthly insolation estimates without significant loss of accuracy. Fig. 5, established from surface data collected during the First ISLSCP Field Experiment (FIFE), shows that the PAR fraction of daily insolation remains fairly constant regardless of cloud conditions. The same finding was reported by Howell et al. (1983) and Rao (1984) on a monthly time scale. At those time scales the PAR fraction variability due to clouds is reduced because it strongly depends on sun zenith angle (Fig. 4). It may, therefore, prove useful to deduce PAR directly from the various insolation climatologies (satellite or other) currently available or being produced at daily or longer time scales (e.g., Bishop and Rossow, 1991). Fig. 6 shows a typical example obtained with METEOSAT data.

b Direct approach

Frouin and Gautier's (1990) method is based on the formalism developed by Gautier et al. (1980) for insolation, that only requires slight modifications (in fact, simplifications) to be applicable to PAR. Cloud absorption vanishes in the cloudy sky model equations (clouds do not absorb at PAR wavelengths), and the clear sky model coefficients represent the PAR spectral interval instead of the total solar spectrum. Cloud albedo, the governing cloud parameter, is computed as in Gautier et al. (1980) from geostationary satellite observations in the visible and near-infrared. Since the solar channels of geostationary satellite instruments (except the METEOSAT radiometer) mostly capture radiation in the visible no narrow-band to broad-band conversion of cloud albedo is necessary. Because of these simplifications in the radiative transfer modeling, we expect, at least in principle, more accurate results for PAR than for insolation. Furthermore, by estimating PAR directly from the satellite radiances, uncertainties due to errors on insolation estimates and on the ratio of PAR and insolation, which are inherent to Pinker and Laszlo's (1992) method, are avoided. Fig. 7 shows, for selected days during the First ISLSCP Field Experiment (FIFE), the diurnal variation of measured PAR at the study site (Konza prairie, Kansas) and the corresponding satellite estimates at particular times during the day. In the figure, the in-situ values are half-hourly averages and the satellite estimates are spatial averages over the FIFE area (15x15km). Julian days 222, 223, 226, and 227 are mostly clear, whereas days 224 and 225 are cloudy. In general, the satellite estimates compare well with the measured values; they describe the diurnal cycle properly. The larger discrepancy observed during days 225 and 226 may be linked to spatial cloud variability, which is not accounted for in the modeling (see in the next section the discussion about effects of cloud heterogeneity). For daily averages, Fig. 8 shows the temporal variation of PAR at the site during intensive field campaigns 2 and 3. Satellite estimates correspond to measurements to within 10-15 Wm^{-2} (about 10%), and more than 85% of the observed variance is explained. These comparisons, although performed for a single geographical location, are strongly indicative of the method's ability to quantify PAR variability on daily or longer time scales.

Instead of using radiances in the visible and near-infrared, Eck and Dye (1991) use radiances (or, equivalently, reflectances) in the ultraviolet and test their method with Total Ozone Mapping Spectrometer (TOMS) data. Noting that cloud reflectivity is constant across ultraviolet and PAR wavelengths and that clouds do not absorb radiation at ultraviolet and PAR wavelengths, they parameterize the effect of clouds on PAR as a simple, linear function of TOMS ultraviolet reflectance. Cloud-screening is achieved by applying a threshold technique, and the authors argue that using data in the ultraviolet makes it easier to discriminate clouds from high-albedo background surfaces, except for ice and snow. The cloud-screening, however, may not be efficient because the TOMS data are in the form of monthly, 500x500km averages, and there is no way of assessing from the TOMS data alone whether the 500x500 km areas are partially contaminated by clouds or not. Furthermore, the radiative transfer modeling is rather crude (e.g., no correction is performed for molecular scattering above the clouds). Nevertheless, the effects do not appear significant on a monthly time scale (individual errors somewhat cancel out), as comparisons with surface measurements, which reveal less than 6% relative differences, demonstrate (Fig. 9).

Issues

The satellite algorithms so far proposed to monitor the variability of PAR over the globe utilize data from instruments (e.g., Advanced Very High Resolution Radiometer, Visible and Infrared Spin-Scan Radiometer) that are generally not calibrated after launch. These instruments have been shown to exhibit significant, even large changes in sensitivity. The resulting errors on PAR can be important, as Fig. 10 illustrates. For a cloud containing $100gm^{-2}$ of liquid water at 40^oN, for instance, a 10% loss of sensitivity translates into errors of up to $50Wm^{-2}$ on monthly averages. Degradation of that amplitude is quite common, as many studies have demonstrated (e.g., Frouin and Gautier, 1987; Staylor, 1990; Whitlock et al., 1990; Brest and Rossow, 1992). Therefore, unless a check-of-calibration is maintained on a regular schedule during the lifetime of the satellites, and instruments from various satellites cross-calibrated properly, it will be difficult to extract a meaningful signal for climate studies from observed changes.

Another issue deals with cloud spatial heterogeneity. The satellite estimates are generally less accurate in conditions of partial (broken) cloudiness (see for instance the results for days 224 and 225 in Fig. 6). This is not surprising as clouds are considered plane-parallel in the modeling, and top-of-atmosphere radiance is often assumed to be isotropic. Drastic assumptions of that sort are necessary, however, to close the system of equations and reduce the problem to one of estimating PAR from a single top-of-atmoshere radiance measurement. The drawback is that large errors on the PAR estimates may be introduced for some situations. Broken clouds, in particular, can significantly affect the spatial distribution of PAR, as the Monte Carlo simulations of Fig. 11 illustrate. For the cloud field considered, namely a regular network of cylinder clouds characterized by a radius of 0.5 km, a geometrical thickness of 0.2 km, an optical thickness of 12, and a distance between clouds of 2.5 km (typical conditions observed during the FIFE experiment on August 9, 1989), the cloud transmittance (flux transmittance) exhibits strong spatial variance, depending on whether the sun disk is obscured by the clouds or not, and reaches over 110% in areas directly illuminated by the sun. In other words, more sunlight that would be observed in clear sky conditions reaches the surface in those areas. This effect, observed by many investigators on pyranometer traces, cannot be reproduced by assuming plane-parallel clouds. Furthermore, depending on the cloud field, it may not cancel out on daily or monthly averages.

To assess the accuracy of the PAR estimates, one needs to compare them to other data, particularly surface measurements. The networks of well-calibrated PAR sensors, unfortunately, are generally inadequate, even over the continents. In fact, the networks of surface radiation instruments have been designed to monitor insolation not PAR –and deducing PAR from insolation is subject to uncertainty (see above). Furthermore, the satellite estimates are instantaneous whereas the surface measurements are local, making it difficult to compare the two types of data. When the method utilizes coarse resolution pixels (see Eck and Dye, 1991), validation by surface measurements becomes very difficult. One alternative is to compare low resolution PAR estimates to estimates obtained from higher resolution data using a validated satellite method; but the procedure is far from optimum. It is clear, however, that without proper validation strategy, satellite PAR estimates will not find quantitative use in global change studies of the carbon cycle.

Summary and Recommendations

Developing methods for estimating PAR from satellites is a recent activity that has strongly benefited from the work performed on insolation by many investigators. Satellite estimates of insolation can be converted accurately into PAR, which makes it possible to exploit already existing datasets (satellite and other). From the radiative transfer point of view, the problem of deriving PAR from top-of-atmosphere radiances in the visible is simpler for PAR than insolation because narrow-band to broad-band transformation is not necessary, and cloud absorption does not need to be parameterized (clouds do not absorb in the visible). In situations of partial cloudiness for which plane-parallel theory does not apply, the problem is as complex as for insolation. Although limited comparisons have been made, an inaccuracy smaller than 10% on a monthly time scale appears feasible by the methods reviewed. In view of the existing models of primary productivity, which involve terms other than PAR more difficult to estimate, a 10% inaccuracy is more than sufficient and should allow a correct description of the month-to-month PAR variability and reveal large scale seasonal and interannual phenomena.

Many of the recommendations of previous workshops on surface radiation budget (e.g., Suttles and Ohring, 1986; Sellers et al., 1990) are in order for PAR. Some effort particularly should be put to rigourously specifying the required accuracy on PAR. As suggested by Sellers et al. (1990), sensitivity studies are necessary, but it is unrealistic to expect that they will provide a complete, universal answer; the space and time scales of geophysical phenomena influenced by PAR are too varied. Whatever the phenomenon under study it will always be safe to define the required accuracy so that the variability of PAR over the phenomenon's characteristic space and time scales, generally observable, is described properly.

Regarding the calibration issue, a lot of progress has been made during the last 2-3 years to monitor sensor degradation of meteorological satellites, those used for PAR, after launch (e.g., within the frame of ISCCP, NOAA and GOES pathfinder activities). Despite the numerous studies a consensus sometimes has been difficult to reach on the calibration coefficients to use for some sensors. This underscores the need for instruments that possess on-board calibration capabilities and for detailed, realistic calibration plans prior to launch. In view of the potential of radiometers carried by meteorological satellites for PAR monitoring, it appears in order to equip future versions with a proper calibrator for their solar channels. In the long run, the strategy might prove more economical and rewarding, since costly aircraft calibrations would be downsized, and scientists would be relieved from tedious, time-consuming calibration tasks they too often have to perform themselves at the expense of other work.

Regarding validation activities, care should be exercised when satellite-derived estimates are compared with in-situ measurements. In general, the two quantities are not the same. On the one hand, satellite-derived values are instantaneous and averaged spatially; on the other hand, surface measurements are local and averaged temporally. The space and time scales at which the comparisons should be made need therefore to be selected rationally, and instrument networks designed accordingly. Using a single instrument is not optimum; dense networks are more appropriate. Such networks were installed during various ISLSCP experiments but covered a limited time period. They should be operated continuously at sites representing world-wide conditions and include measurements of other parameters (e.g., cloud properties) to test individual parameterizations in the models. PAR sensors, which are inexpensive, should also be deployed to complement the networks of pyranometers already in place, at least in representative areas of the globe. Effort should also be made to create a database of PAR measurements from various research experiments and make it available for validation studies. Comparisons of algorithms such as those for insolation should be made (e.g., Whitlock et al., 1990), but with the purpose of understanding the advantages and drawbacks of each algorithm instead of selecting one.

One of the major limitations of the methods is their inability to provide reasonable estimates when plane-parallel theory is not applicable (case of broken clouds, liquid water spatial heterogeneity). Efforts to improve the techniques should therefore focus on situations of cloud heterogeneity. One approach is to perform radiative transfer calculations for realistic cloud fields, determine the cloud parameters that govern departures to plane-parallel theory, and investigate relationships between the governing cloud parameters and observable cloud characteristics (texture, moments, etc.). If this approach proves suitable, current strategies to create long-term, large-scale satellite datasets might have to be reviewed to include those cloud characteristics.

Two other aspects of the methods should also be addressed, namely the presence of snow or ice at the surface and diurnal sampling. Over snow and ice it is not easy to distinguish clouds, and the methods proposed would likely fail. Efforts should be made to improve the methods in those situations, all the more as the polar oceans cannot be neglected in studies of the global carbon cycle because of their high primary productivity. Regarding diurnal sampling, the success of the satellite methods generally resides in their ability to sample diurnal cloud variability properly. Polar-orbiting satellites do not provide adequate sampling at middle and low latitudes. Statistically obtained correction factors may be used, but they do not offer the solution. The problem may be obviated, however, by complementing data from polar-orbiting and geostationary satellites, as is currently being done to generate ISCCP datasets.

The sensors adapted to PAR monitoring from space are not limited to those used in the algorithms so far proposed. Other instruments, scanners as well as wide-field-of-view radiometers, have not yet been exploited, in particular those of the Earth Radiation Budget Experiment. In fact the current algorithms can be easily modified to become applicable to those sensors. Furthermore, their longevity, careful calibration and characterization, as well as the continuity of the mission well beyond the end of the century (Clouds and Earth's Radiant Energy System, CERES, investigation), make them an ideal tool for studying PAR's inter-annual modes of variability and related questions of climate change. Looking ahead, apart from the future versions of meteorological satellites and the CERES scanner a battery of instruments will be available for PAR monitoring during the Eos era, in particular the MODerate resolution Imaging Spectrometer (MODIS) and the MEdium Resolution Imaging Spectrometer (MERIS). Our prospects are good for an accurate, long-term climatology of PAR over the globe.

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Figure Captions

Fig. 1. Primary production as a function of photosynthetically available radiation, PAR. (a) Case of a green canopy with horizontal leaves and a leaf area index ranging from 0.1 to 6 (after Sellers, 1985). (b) Case of a homogeneous, 20^{o}C ocean containing 0.3, 1, 3, and 10 mgm^{-3} of chlorophyll pigments.

Fig. 2. Ratio of photosynthetically available radiation, PAR, and insolation as a function of water vapor amount (top), ozone amount (middle), and aerosol type and visibility (bottom). (After Baker and Frouin, 1987.)

Fig. 3. Ratio of photosynthetically available radiation, PAR, and insolation as a function of cloud optical thickness and sun zenith angle. (After Pinker and Laszlo, 1992.)

Fig. 4. Surface-measured ratio of half-hourly photosynthetically available radiation, PAR, and insolation as a function of satellite-derived instantaneous cloud liquid water content during the First ISLSCP Field Experiment. The ratio varies between 0.25 and 0.75, corroborating theoretical calculations.

Fig. 5. Surface-measured ratio of daily photosynthetically available radiation, PAR, and insolation as a function of satellite-derived daily cloud cover during the First ISLSCP Field Experiment. At this time scale the PAR fraction variability is small, with values ranging between 0.43 and 0.52.

Fig. 6. Monthly photosynthetically available radiation, PAR, derived from METEOSAT data for June 1990. Monthly insolation was first obtained using the method of Dedieu et al. (1987) and PAR was then deduced by taking the ratio of PAR and insolation equal to 0.45.

Fig. 7. Surface-measured and satellite-derived photosynthetically available radiation, PAR, for selected days during the First ISLSCP Field Experiment. Satellite estimates are instantaneous whereas measured values are half-hourly averaged.

Fig. 8. Surface-measured and satellite-derived daily photosynthetically available radiation, PAR, during the second and fourth intensive field campaigns of the First ISLSCP Field Experiment.

Fig. 9. Satellite estimates of monthly photosynthetically available radiation, PAR, versus surface estimates from pyranometer measurements adjusted to PAR. (After Eck and Dye, 1991.)

Fig. 10. Typical error on satellite-derived monthly photosynthetically available radiation, PAR, due to a 10% increase in the calibration gain, g, of the sensor's solar channel. Clouds contain $100 gm^{-2}$ of liquid water, and the clear atmosphere contains 0.3 atm-cm of ozone and aerosols of continental type and optical thickness of 0.22 at 550 nm. Latitude is 39^{o}N. As fractional cloud coverage, N, increases, the error increases in magnitude, reaching -50 Wm^{-2} in June and July.

Fig. 11. Monte Carlo simulations of the spatial distribution of cloud transmittance (in percent) on August 8, 1989 at 13:30 local time over the Konza prairie, Kansas. The clouds are cylindrical of radius 500m, separated by 2,500m, and located between 2,000 and 2,200m (geometrical thickness of 200m). The cloud optical thickness is 12. When the sun disk is not obscured by clouds, cloud transmittance reaches 113%, indicating that the surface receives more photosynthetically available radiation than in clear sky conditions.

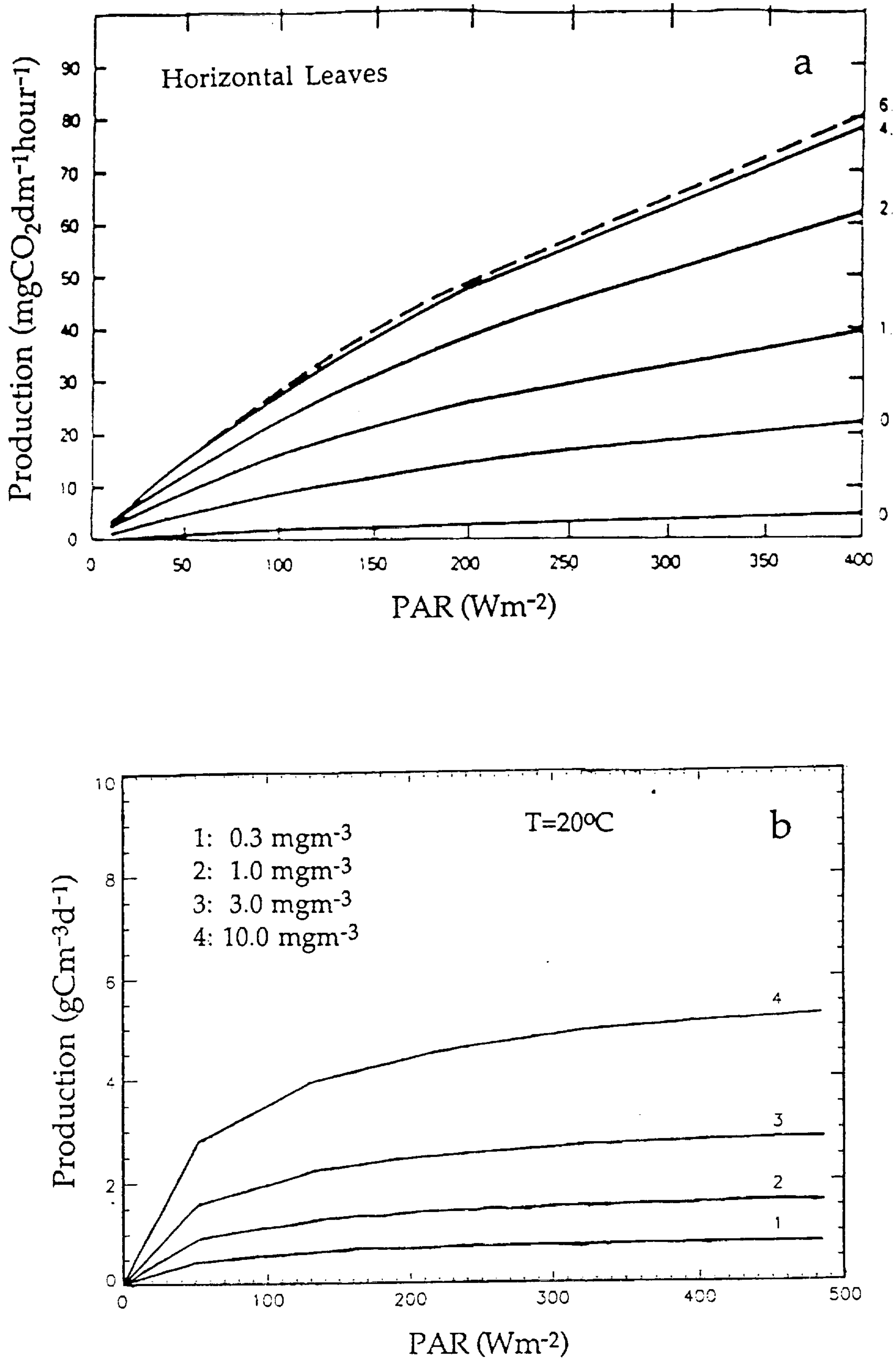

Fig. 1. Primary production as a function of photosynthetically available radiation, PAR. (a) Case of a green canopy with horizontal leaves and a leaf area index ranging from 0.1 to 6 (after Sellers, 1985). (b) Case of a homogeneous, 20°C ocean containing 0.3, 1, 3, and 10 mgm^{-3} of chlorophyll pigments.

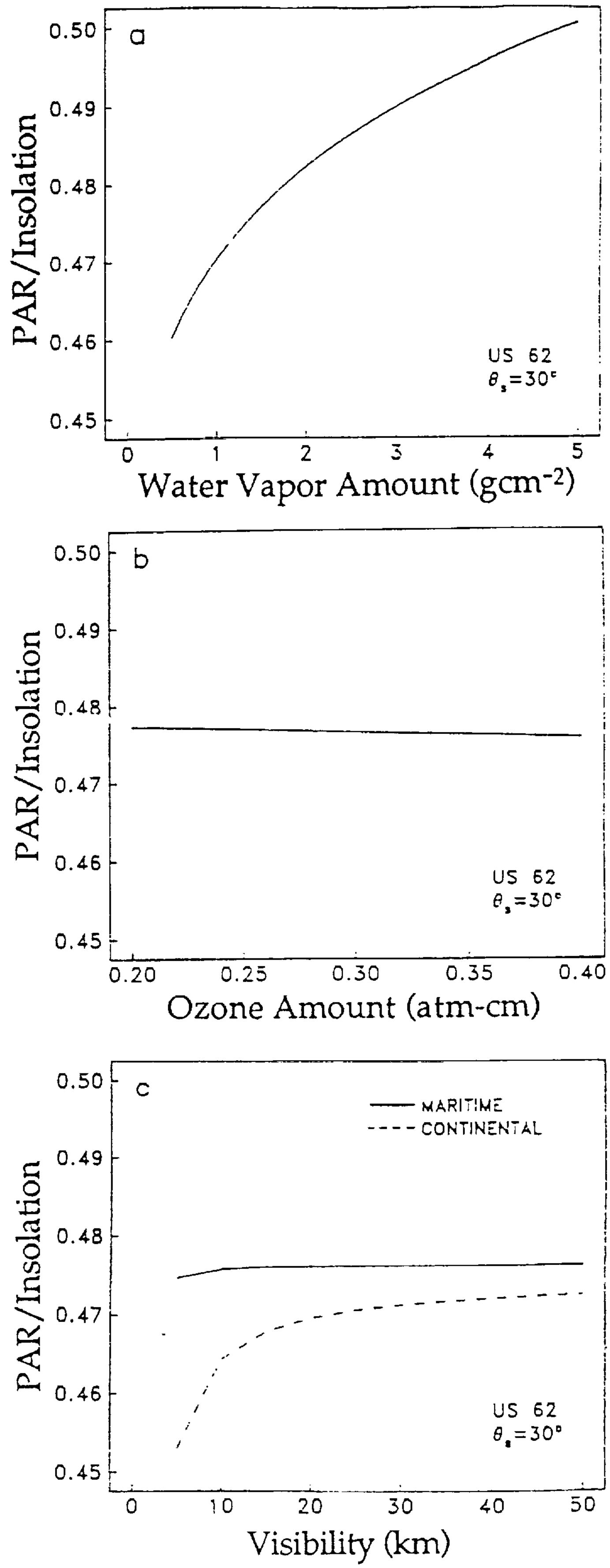

Fig. 2. Ratio of photosynthetically available radiation, PAR, and insolation as a function of water vapor amount (top), ozone amount (middle), and aerosol type and visibility (bottom). (After Baker and Frouin, 1987.)

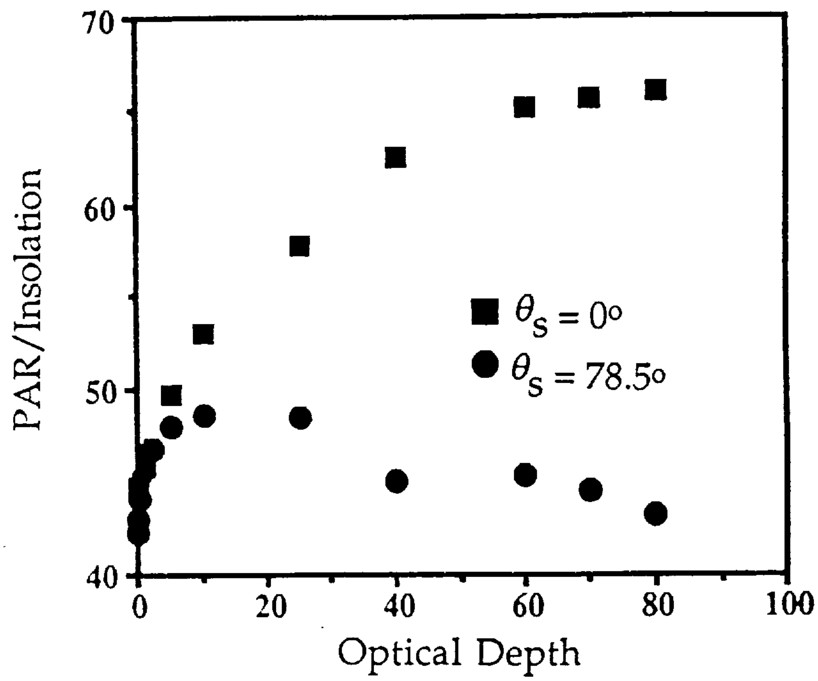

Fig. 3. Ratio of photosynthetically available radiation, PAR, and insolation as a function of cloud optical thickness and sun zenith angle. (After Pinker and Laszlo, 1992.)

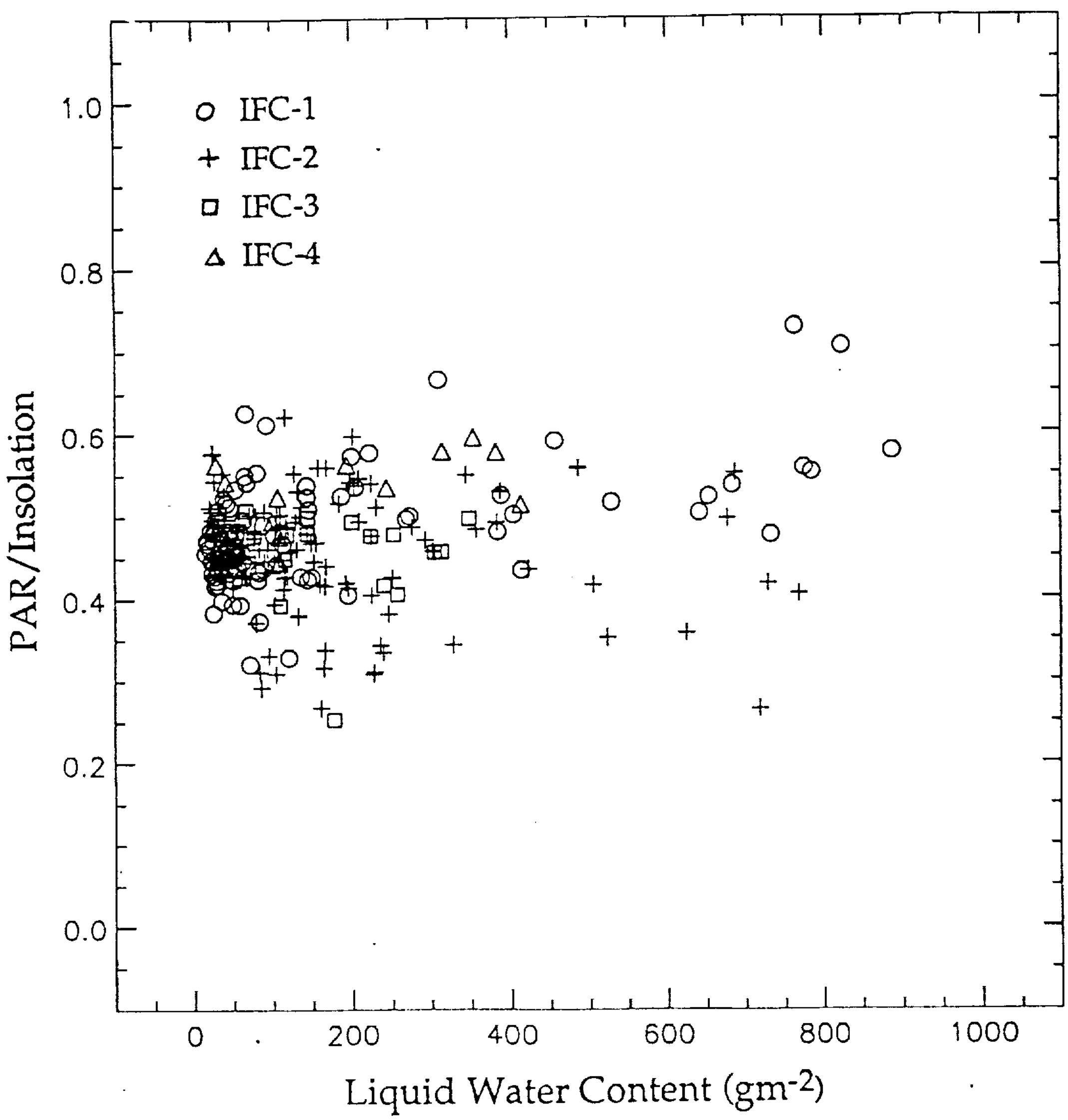

Fig. 4. Surface-measured ratio of half-hourly photosynthetically available radiation, PAR, and insolation as a function of satellite-derived instantaneous cloud liquid water content during the First ISLSCP Field Experiment. The ratio varies between 0.25 and 0.75, corroborating theoretical calculations.

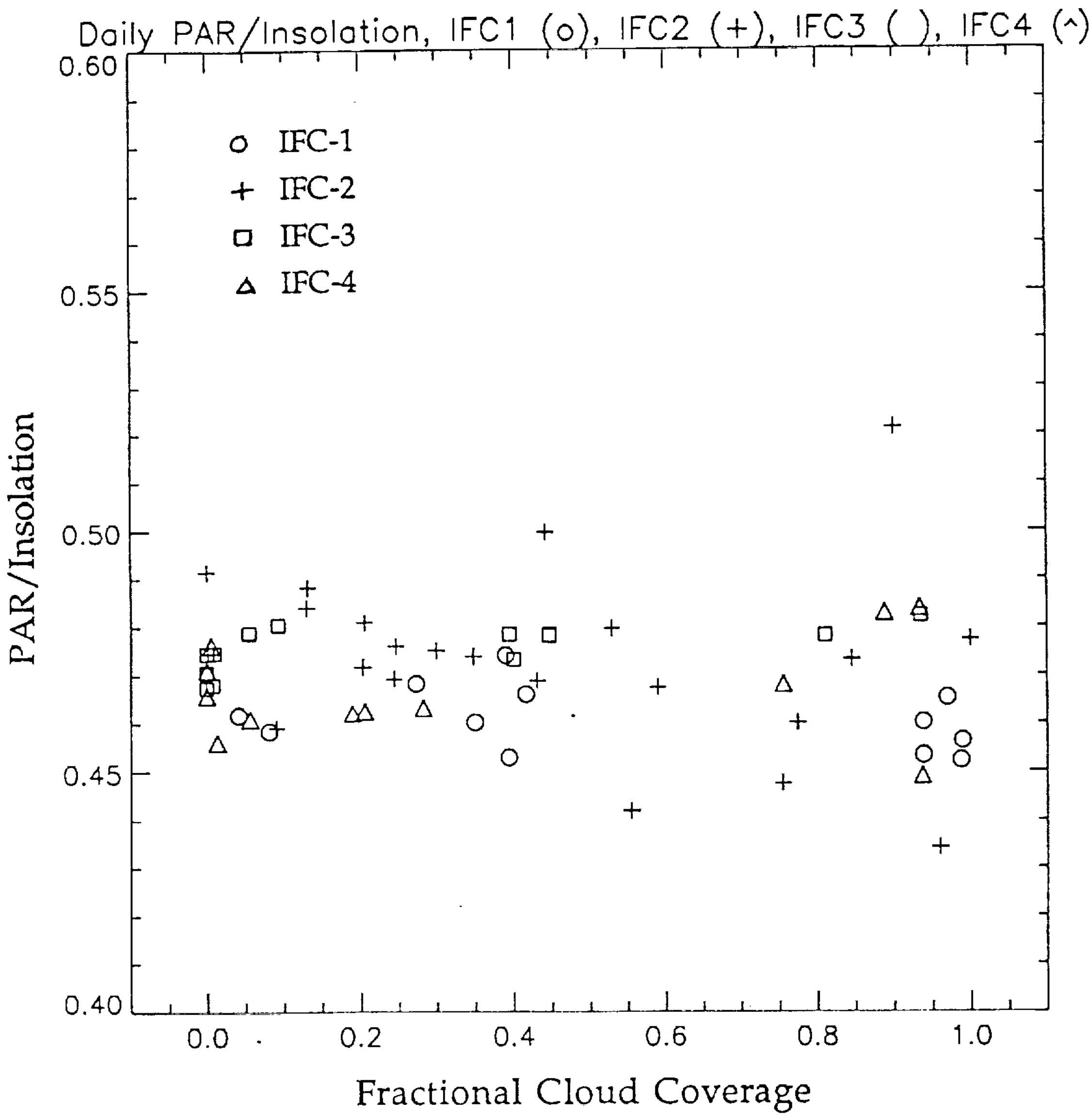

Fig. 5. Surface-measured ratio of daily photosynthetically available radiation, PAR, and insolation as a function of satellite-derived daily cloud cover during the First ISLSCP Field Experiment. At this time scale the PAR fraction variability is small, with values ranging between 0.43 and 0.52.

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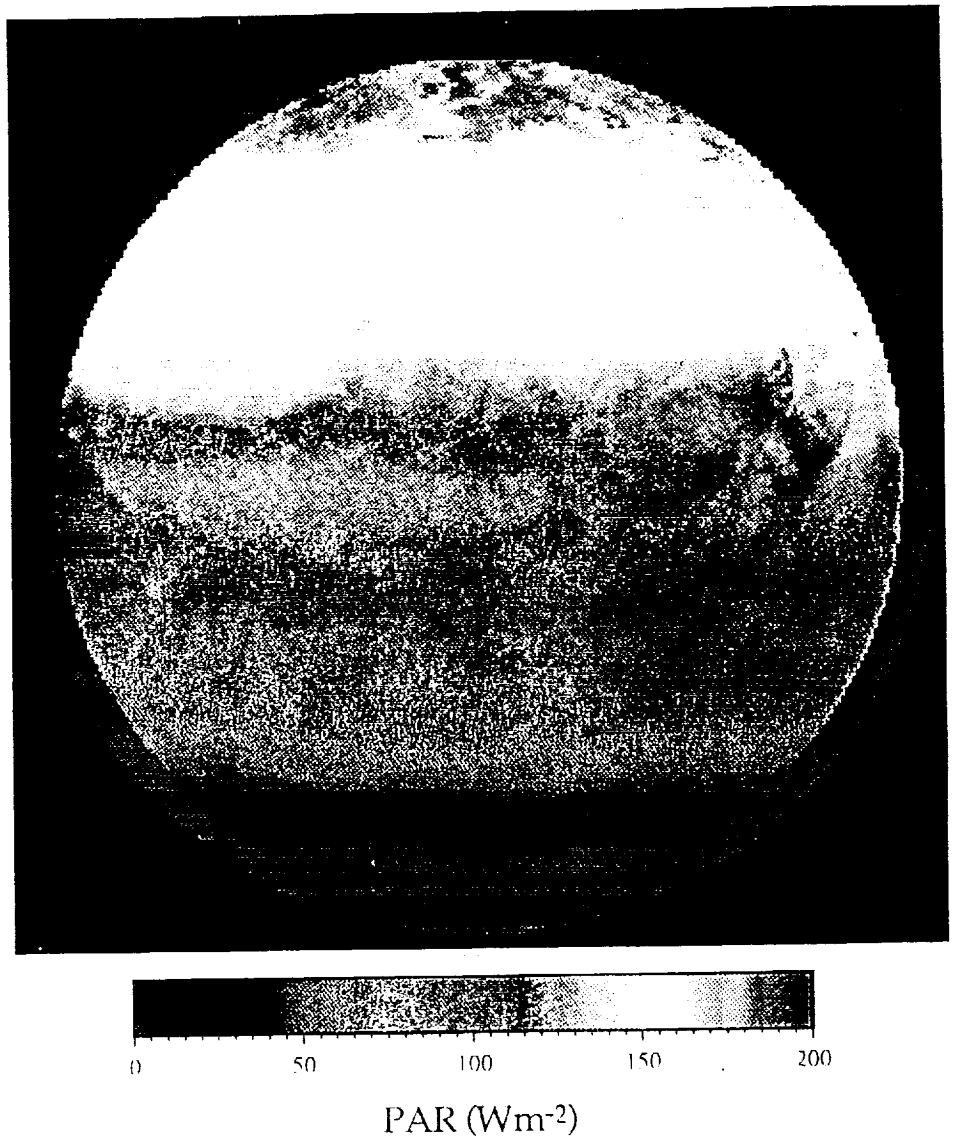


Fig. 6. Monthly photosynthetically available radiation, PAR, derived from Meteosat data for June 1990. Monthly insolation was first obtained using the method of Dedieu et al. (1987) and PAR was then deduced by taking the ratio of PAR and insolation equal to 0.45.

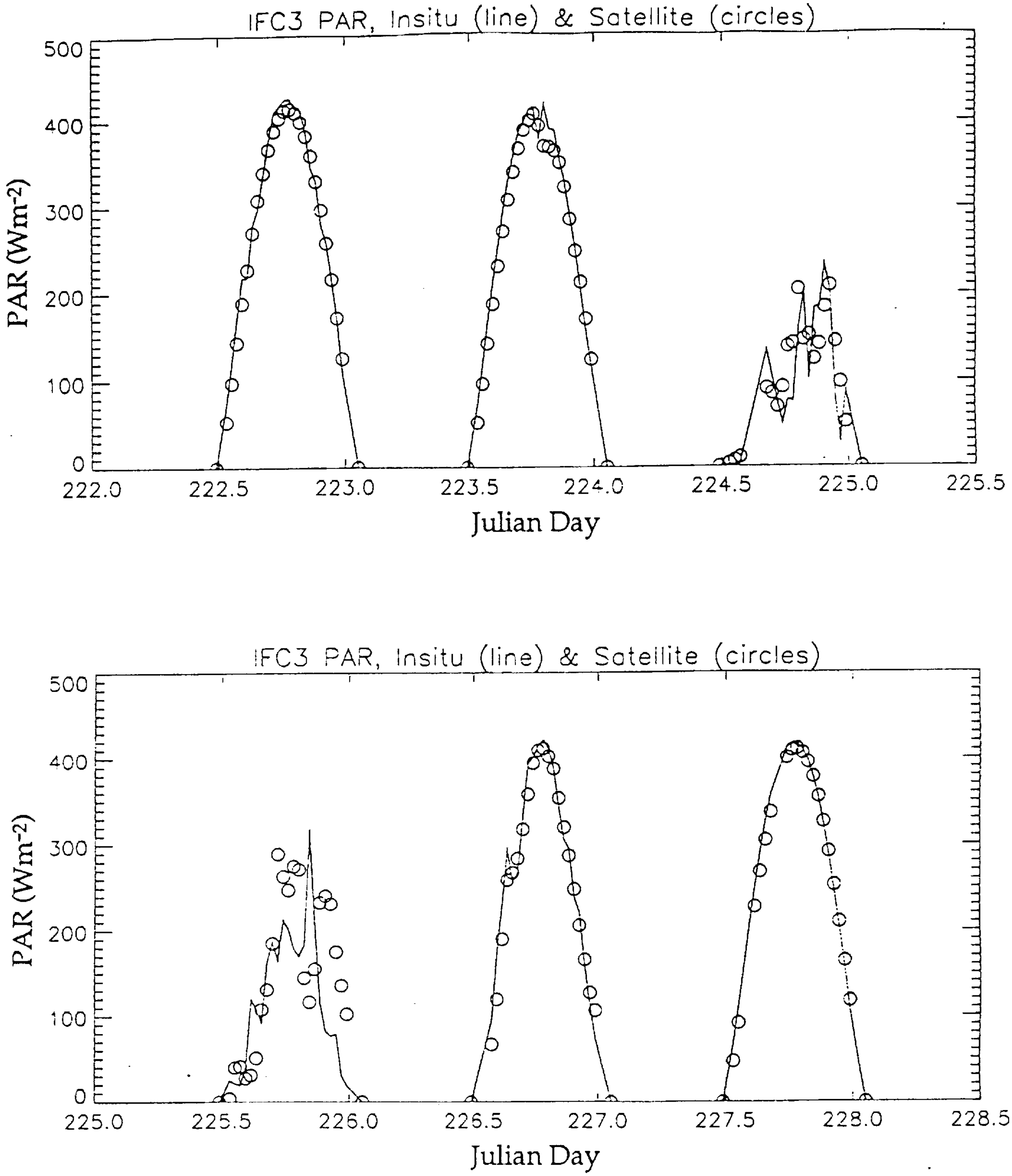
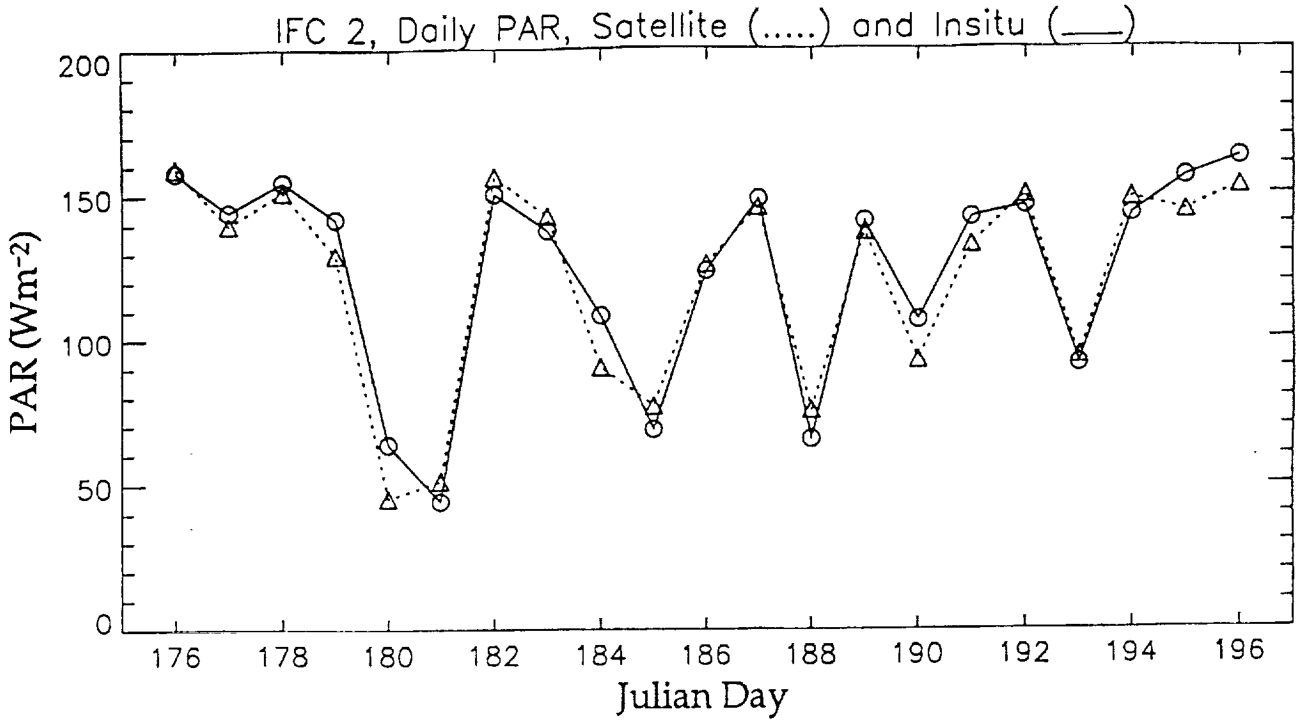


Fig. 7. Surface-measured and satellite-derived photosynthetically available radiation, PAR, for selected days during the First ISLSCP Field Experiment. Satellite estimates are instantaneous whereas measured values are half-hourly averaged.



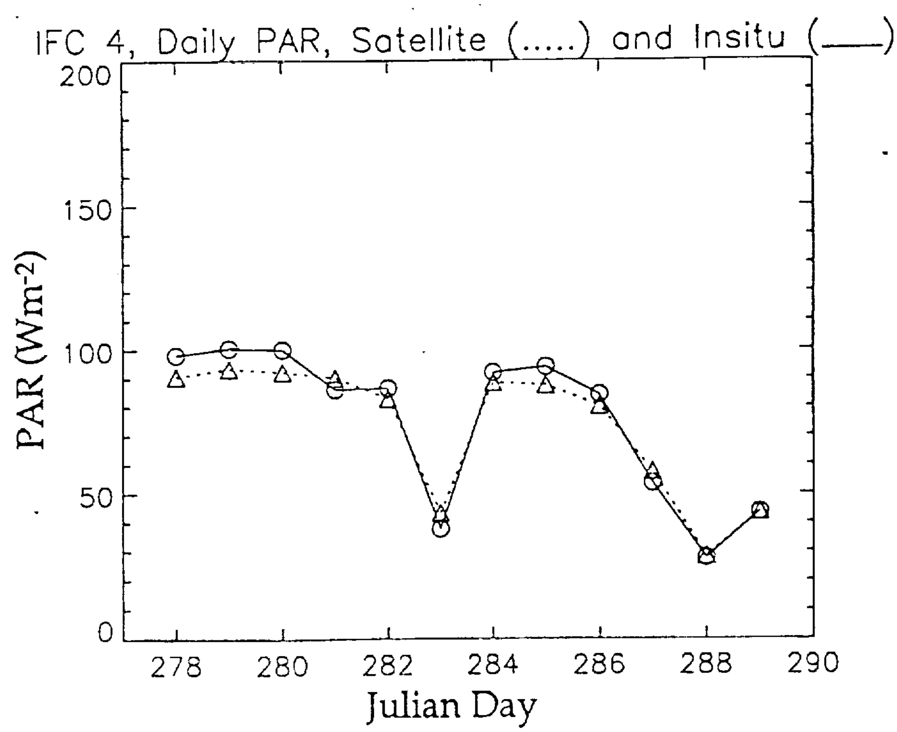


Fig. 8. Surface-measured and satellite-derived daily photosynthetically available radiation, PAR, during the second and fourth intensive field campaigns of the First ISLSCP Field Experiment.

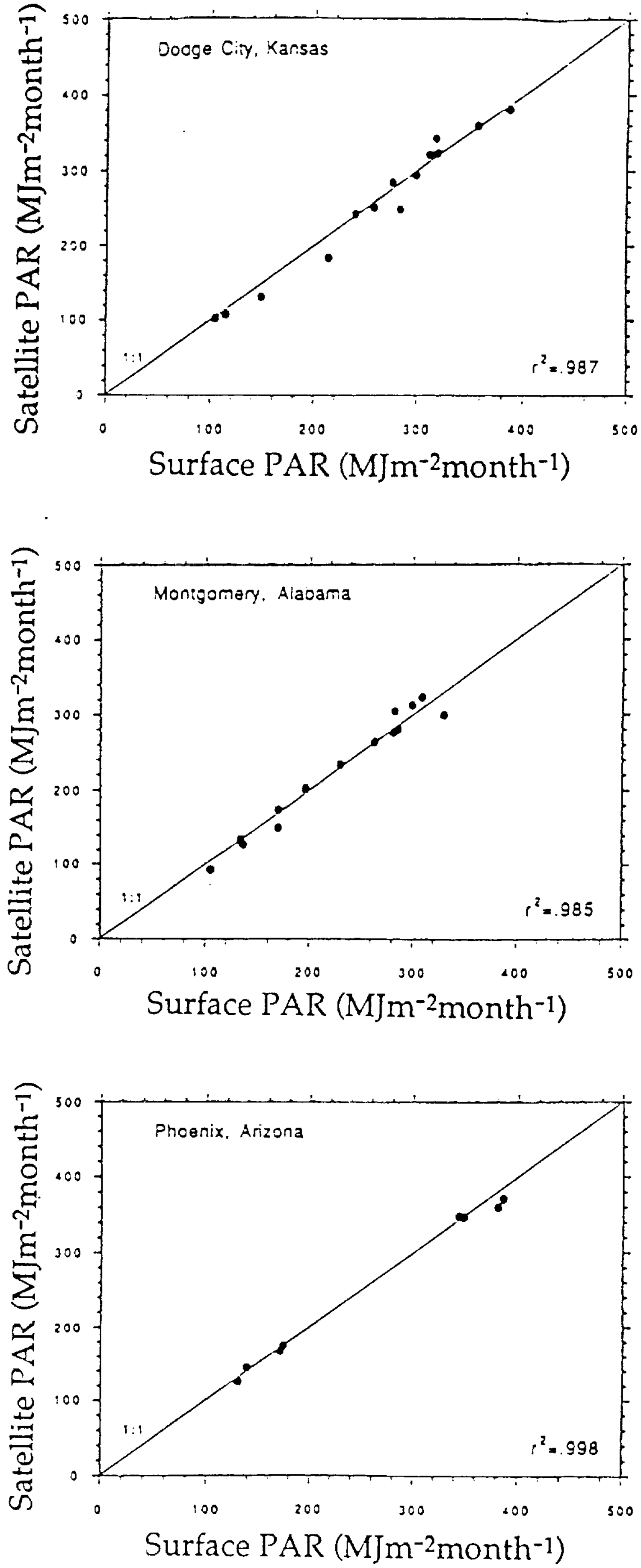


Fig. 9. Satellite estimates of monthly photosynthetically available radiation, PAR, versus surface estimates from pyranometer measurements adjusted to PAR. (After Eck and Dye, 1991.)

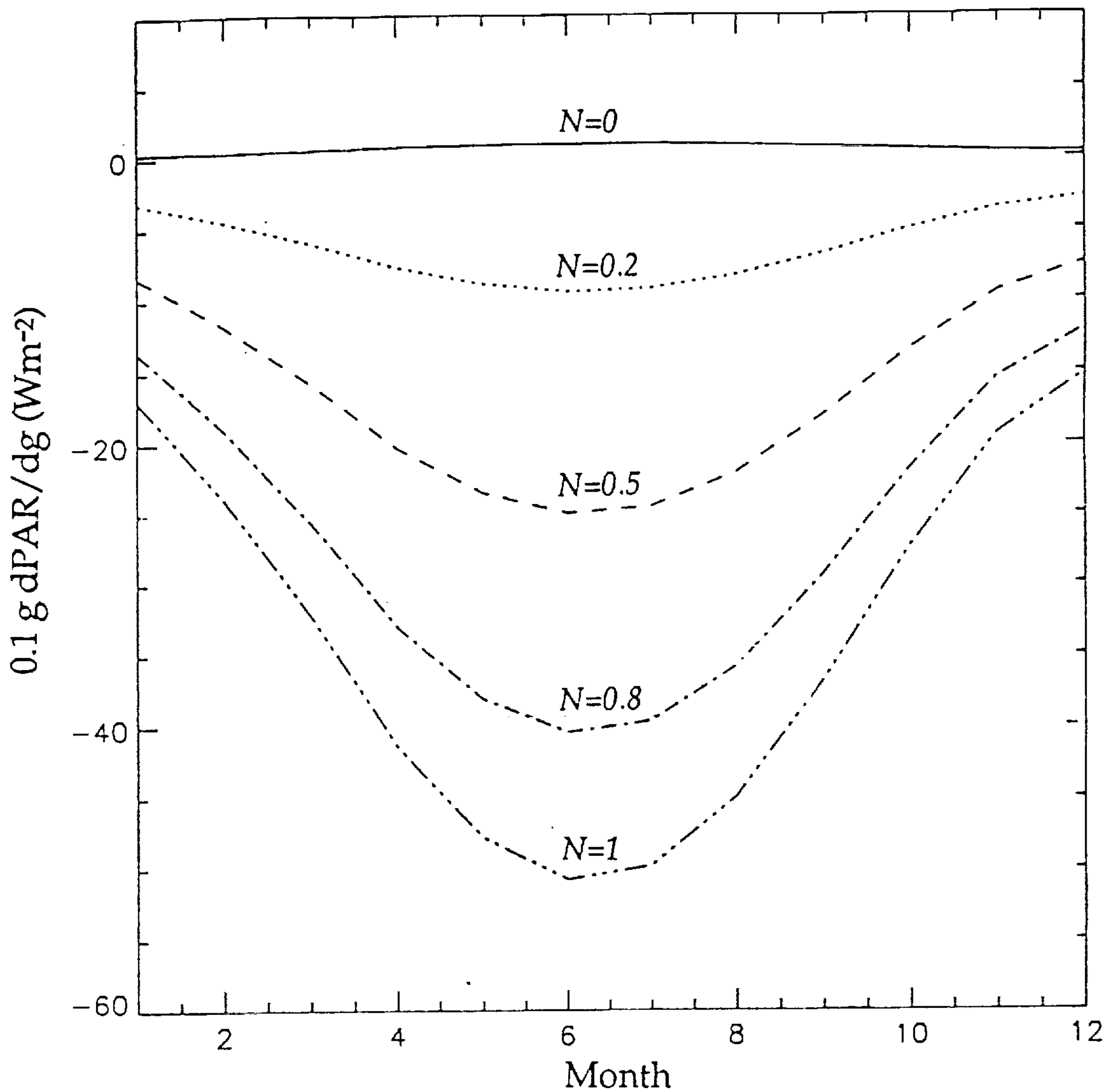


Fig. 10. Typical error on satellite-derived monthly photosynthetically available radiation, PAR, due to a 10% increase in the calibration gain, g, of the sensor's solar channel. Clouds contain 100gm^{-2} of liquid water, and the clear atmosphere contains 0.3 atm-cm of ozone and aerosols of continental type and optical thickness of 0.22 at 550 nm. Latitude is 39°N. As fractional cloud coverage, N, increases, the error increases in magnitude, reaching -50 Wm^{-2} in June and July.

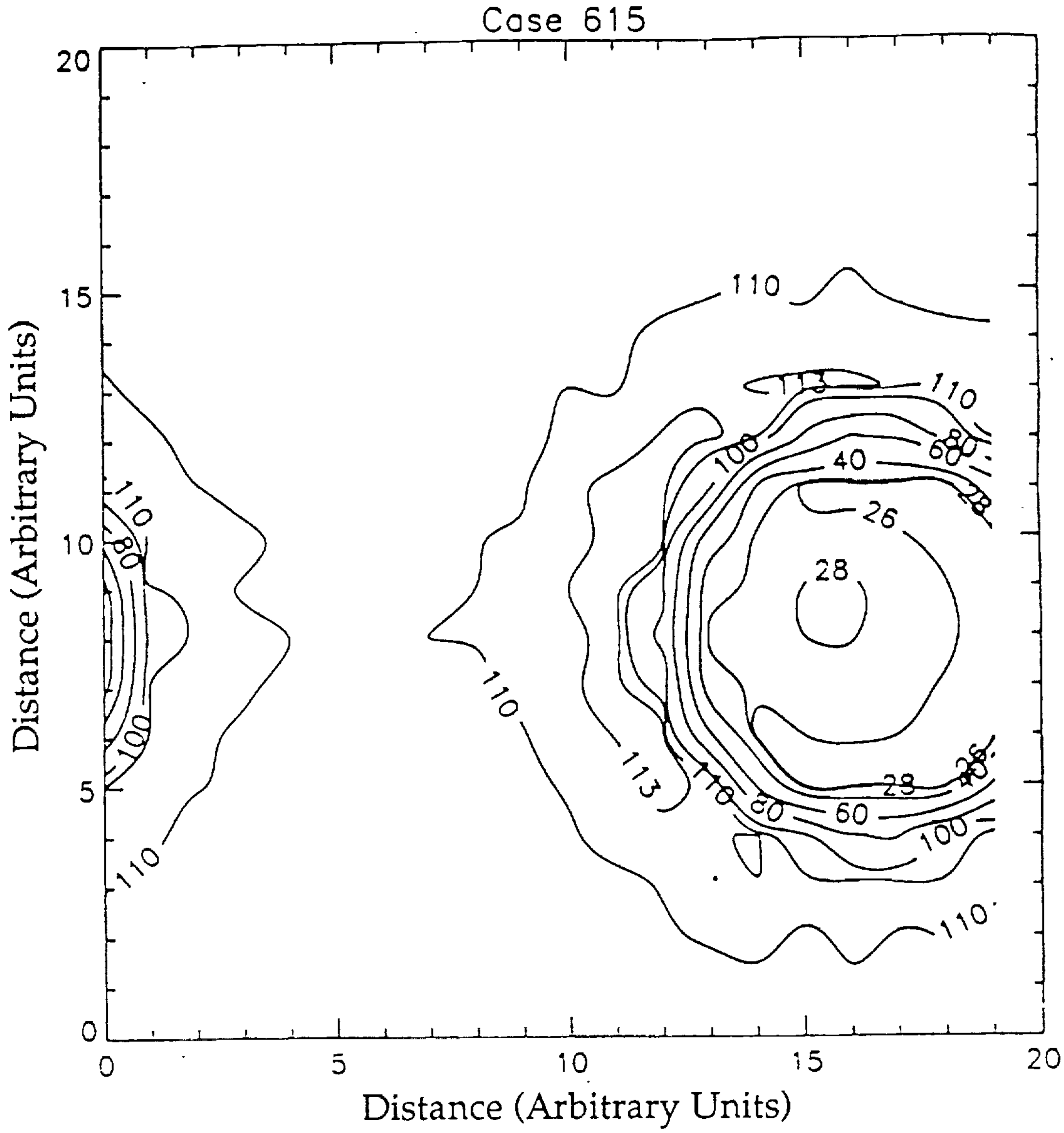


Fig. 11. Monte Carlo simulations of the spatial distribution of cloud transmittance (in percent) on August 8, 1989 at 13:30 local time over the Konza prairie, Kansas. The clouds are cylindrical of radius 500m, separated by 2,500m, and located between 2,000 and 2,200m (geometrical thickness of 200m). The cloud optical thickness is 12. When the sun disk is not obscured by clouds, cloud transmittance reaches 113%, indicating that the surface receives more photosynthetically available radiation than in clear sky conditions.