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INTERIM REPORT ON ERB CI1*CT940059

For 1 January 1996 to 31 January 1997

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February 1997

Summary

During the second year of this project the following activities took place.

Visit to Mexico by Dr J B Stewart from 4 to 14 February 1996 to supervise the Project (installation of equipment and analysis of data).

Visit to UK by Dr H A R de Bruin to discuss analysis of first year's data.

Visit to Mexico by Dr H A R de Bruin from 13 to 23 September 1996 to supervise the Project (installation of equipment and analysis of data).

Acquisition of evaporation measurements over wheat and preliminary analysis of the data.

Acquisition of evaporation measurements over rangeland and preliminary analysis of the data.

The second interim report describes visits to Mexico and UK, the installation of equipment at the two sites and the measurement programmes.

Report of Visit to Mexico 4 to 14 February 1996

Visit to CIDESON in Hermosillo and rangeland site

by Dr John B Stewart

Met	Dr Chris J Watts	
	Julio Rodriguez	
	Hector M Arias	
	Oscar Hartogensis	(student under supervision of Dr HAR Bruin at Meteorology Department, Wageningen Agricultural University)

Drove to the rangeland site, 30 km on main road south from Hermosillo then 10 km on rough dirt track through farmland.

Hydra had been installed on tower at the rangeland site on 25 January. First two days of data had been affected by a rain storm, so the flux measurements were unreliable.

SITE

Site is very flat with only minor topographical features of a metre or so, due to small water courses and manmade banks to retain surface runoff. Nearest hills 4 km to east and 6 km to west.

Vegetation

Vegetation consists of approximately 50 percent grass, 10 to 20 percent bushes/trees and rest of area is compacted bare soil. Soil is sandy with little clay or organic content. Density and height of trees increases near the water courses which occur every 300 to 600 m. The particular farm where the tower is situated appears to have the correct stocking density, so that there are still considerable areas of dried-up grass even at this time of year; the last major rains having been in the previous summer. Surrounding farms, the nearest being about 300 m to the south, appear to be over-grazed with much more bare soil exposed.

Height of Vegetation

Grasses, which are all dried up at this time of year, had been blown over and are now 0.2 to 0.4 m high. When upright, they would have been 0.8 m high. There were also a number of species of herbs/forbes which had heights of 1.0 to 1.5 m, near the tower the highest were 1.35 m tall.

The results of an initial survey of heights of bushes/trees in an area around the tower at a distance of about 40 m radius are given in Table 1.

Table 1. Heights of 161 bushes/trees near the tower

Height range (m)	Number	Percentage	Cumulative Percentage
0.0 - 0.4	7	4.3	4.3
0.5 - 0.9	49	30.4	34.7
1.0 - 1.4	25	15.5	50.2
1.5 - 1.9	14	8.7	58.9
2.0 - 2.4	12	7.5	66.4
2.5 - 2.9	7	4.3	70.7
3.0 - 3.4	19	11.8	82.5
3.5 - 3.9	8	5.0	87.5
4.0 - 4.4	7	4.3	91.8
4.5 - 4.9	6	3.7	95.5
5.0 - 5.4	3	1.9	97.4
5.5 - 5.9	1	0.6	98.0
6.0 - 6.4	1	0.6	98.6
6.5 - 6.9	1	0.6	99.2
7.0 - 7.4	1	0.6	99.8

In a direction ENE towards the nearest hill, there was a tree somewhat higher than its neighbours. It was found to be a Mesquite with a height of 9.0 ± 0.5 m and was close to a water course about 200 m from the tower.

Species of Vegetation

One of the most common herbs/forbes was Estafiate (also spelt Nestafiate). In some areas the very poor inhabitants use the seeds of this plant to make flour.

The species of bushes/trees were, in order of frequency of occurrence: unknown prickly bush less than 1 m tall, Mesquite, Palo Verde and Palo Fierro (Ironwood). There were also a few cacti:- Pitahaya.

Bushes/trees: Mesquite - Prosopis juliflora
Palo verde - Cercidium microphyllum
Palo fierro (Ironwood) - Olneya tesota
Piojillo - Caesalpinia palmeri
Gobernadora (Creasote bush) - Larrea tridentata
Salicieso - Lysium *sp*

Cacti:	Pitahaya - Lemaireocereus thurberi Biznaga (Barrel cactus) - Ferocactus wislizenii Cinata o pitahaya barbona - Lophocereus shottii
Herbs/forbes:	Rama blanca - Encelia farinosa Estafiate (or Nestafiate) - Ambrosia cofertifolia

Tower

It is made up of rectangular sections 1.6 x 2.2 m by 1.55 m tall with a built-in staircase, each of which have a small horizontal area at the upper end of the stairs. The tower consists of 7 sections giving a height to the top platform of 10.85 m and stands on concrete bases 0.2 m above soil level. The handrail at the top is 1.1 m above the platform. There are only platforms at the middle and top of the tower. The long side of the tower is orientated east/west. The tower is positioned close to seven Mesquit trees 3.3 to 4.6 m tall on its south side.

Height of Instruments

The Hydra is mounted at 13.6 m on a pole fixed at the centre of the tower and guyed to each corner.

The relative humidity sensor is mounted at 1.34 m. The net radiometer is mounted at a height of 6.5 m on a boom extending 5 m from the tower. Half the radiation received by the net radiometer comes from an area consisting of 40 percent Mesquit trees and 60 percent grass and bare soil.

The infra-red thermometers were installed over representative surfaces in the southern hemicircle at distances of 10 to 15 m from the tower. Table 2 summarises the characteristics of the five sites.

Table 2. Characteristics of infra-red thermometer (IRT) sites

	Sensor Number	Direction from Tower from S	Surface	Height of Vegetation	Height of IRT(m)	Area seen by IRT(m^2)
4000AL	2254-5	70EW	Bare Soil	-	0.91	0.05
4000.2L	3280-2	10EW	Bare Soil	-	0.88	0.04
4000.2L	3280-4	30EE	Grass/Bare Soil	0.06-0.57	1.95	0.21
4000.2L	3280-3	40EW	Bush/Grass	0.78	1.99	0.19

4000.2L	3280-1	70EE	Tree (Palo verde)	3.36	3.81	0.79

The soil heat flux plates and soil temperatures will be installed under representative surfaces in the near future.

HYDRA Data

Four complete days of data were available for analysis. Net radiation was positive for 9 hours each day, from 0800/0900 to 1600/1700. Average fluxes and other data are given in Table 3.

Table 3. *Fluxes measured by the HYDRA averaged over the 9 hours each day when the net radiation was positive*

Date Variable	3/2/96	4/2/96	5/2/96	6/2/96
Net radiation (W m^{-2})	229	257	258	206
Sensible heat (W m^{-2})	124	142	137	92
Latent heat (W m^{-2})	50	59	50	35
Evaporation (mm)	0.65	0.77	0.65	0.46
Bowen ratio (-)	2.5	2.4	2.7	2.6
Minimum air temperature (EC)	8.7	11.5	11.4	11.5
Maximum air temperature (EC)	22.8	27.7	28.7	27.8
Specific humidity range (g m^{-3})	6.2-8.5	5.3-7.7	5.6-7.0	5.4-6.3

RECOMMENDATIONS

A second net radiometer should be mounted on an A-frame 1 m above grass/bare soil.

Visit to ITSON in Cd Obregon and field sites

by Dr John B Stewert

Met Dr Oscar Russo (Rector of ITSON)
Salvador Diaz-Maldonado
Oscar Camara-Duran
Jaime Garatuza-Payan
David Encinas
Amando Canales
Jose L Escajeda (a student who speaks English well and has telephoned IH on behalf of others at ITSON)

The Hydra has been set up in a field of irrigated wheat in the Yaqui Valley Irrigation Scheme.

SITE

In a block 2 x 1 km, 169 ha have been planted with wheat. 31 ha in NW corner of the block still contains maize which was planted last autumn. Wheat was planted on 16 December 1995.

Irrigation

First irrigation of the block of wheat began on 22 January and continued until 5 February. The surroundings of the Hydra were irrigated on 27 January - the field was still muddy on 9 February.

Location of the Hydra

The Hydra is positioned about 100 m west of channel running north-south and 100 m north of channel running east-west, giving a minimum fetch over wheat of 400 m (towards the north), 600 m to east and south and greater fetches in other directions.

Installation of the Hydra

The Hydra was installed on 3 January 1996. Hydra is orientated south-west at a height of 2.6 m. The wheat has now reached a height of 0.4m and will finally reach 0.6 m.

The site is normally visited twice a week, however after irrigation, the site cannot be reached for 10 days as the soil dries out.

Hydra Data

The data started at 1400 on 3 January 1996. Data was removed on 9, 13, 16, 23 and 27 January and 7 February. Generally the data looked very reasonable with daily totals of evaporation starting at about 1mm rising to 2mm as the wheat grew before irrigation and about 3 mm after irrigation.

Two problems were noted by D E and J G. Firstly, on 18 January σ_q was zero for hours from 0100 to 1200 and latent heat flux was zero. It was suggested that it was due to condensation on the infra-red hygrometer. JBS pointed out that the measurements of net radiation also indicated presence of condensation since the measurements rapidly increased from -60 to -11 W m^{-2} by midnight and then remained at -11 W m^{-2} until sunrise. Similar behaviour was observed after midnight on 21 January.

On the visit to the Hydra on 9 February, there was dew on the wheat and on the shaded side of the net radiometer domes at 11:10.

The temperature sensor failed at 0600 on 31 January so σ_T and sensible heat flux became zero and temperature was given as -12.6°C. This caused the values of specific humidity to reduce from 7 to 1 to 2 g m^{-3} and latent heat flux to reduce to half the values on the previous 3 days.

A new temperature sensor was installed on 7 February and the voltage on channel 4 indicated a realistic temperature.

AUTOMATIC WEATHER STATION DATA

The AWS at sites 910 and 1517 are still being operated as previously. An animal chewed through the main cable on the instrument in block 910 in May 1995. They have been able to repair most of the sensor cables except for the two solar radiation sensors. A new shielded cable will be used for the repair soon.

The AWS in block 910 has now been fitted with radio telemetry so that the data can be checked at ITSON without visiting the site. The site is visited every other week to take off the data.

RECOMMENDATIONS

The Hydra over the wheat should be raised to 3.45 m in the near future. The net radiometer should also be raised to about 1.6 m.

The data should be removed only once a week. During the other visit during each week the data should be checked but not removed.

To reduce the staff time and spares consumed, it is proposed to remove the net radiometer from site in block 1517 and maybe from block 910.

An Assmann psychrometer should be purchased urgently to check the humidity measurements since past experience has shown that the sensors tend to drift over time and they are now about 4 years old.

It is suggested that later in 1996, measurements should be made over spring planted maize after the measurements over wheat have been completed. No measurements over soybeans are planned, since the area being planted with soybeans is being greatly reduced. Since measurements over wheat should continue until it has reached sensence, the measurements over maize will start a month or so after planting/germination.

Since maize grows to a height of 2.5 m, it will be necessary to mount the Hydra at a height of 5 to 6 m using a triangular radio tower with dimensions of 0.3 to 0.4 m. To make access to the Hydra easier, it is proposed to mount it at a height of 0.5 m above the top of the triangular tower rather than 1.5 m. The tower should be installed soon after the crop has been planted/sown.

Report of visit to UK 19 - 21 February 1996

Visit to Institute of Hydrology

by Dr Henk A R de Bruin

Met Dr John B Stewart

A preliminary analysis of the measurements of actual evaporation from cotton in the Yaqui Valley irrigation scheme was carried out.

The first impression was that due to the fact that the sensible heat flux was positive on most days and only on a few days slightly negative, advection was negligible. As a result, evaporation will be close to the water equivalent of daily totals of net radiation. In its turn, net radiation is strongly correlated with incoming solar radiation. So finally we find that the incoming solar radiation is physically related to actual evaporation and therefore provides a good method of estimating it. It should be noted that in the first phase of the Project an operational system was developed and tested to estimate incoming solar radiation from satellite (GOES) data.

Report of Visit to Mexico 13 - 23 September 1996

Visit to Cideson in Hermosillo and rangeland site

by Dr Henk A R de Bruin & Bert Heusinkveld

Met Dr Chris J Watts
Julio Rodrigues
Oscar Hartogensis

The main purpose of this visit was to set up and run a scintillometer, which measures the average sensible heat flux over the distance between the transmitter and receiver. The scintillometer was to be run in the same area where the Institute of Hydrology's eddy correlation system, the Hydra, was measuring actual evaporation and sensible heat flux

This system is an addition to the Project and was not included in the budget estimates. However this additional intercomparison has been carried out within the existing budget.

Test of a Large Aperture Scintillometer (LAS)

INTRODUCTION

For various applications in meteorology, agriculture and hydrology, routine measurements of area-averaged surface fluxes of evaporation E and sensible heat H are required. Probably the best method to measure the area-averaged values of E and H is a network of eddy correlation stations. However, eddy-correlation equipment is still expensive and for maintenance and data handling well-trained staff is needed. So there are still a need for as a simpler approach.

Several studies carried out in the past decade have revealed that a remote-sensing technique, the scintillation method, is an attractive alternative for a routine observation of H (see e.g. Wesely, 1976; Champagne *et al.*, 1977, Kohsiek, 1982; Hill *et al.*, 1992; Green *et al.*, 1994, McAneney, 1995; De Bruin *et al.*, 1995, 1996). An important feature of this approach is that, because H is derived from the line-integral of the structure parameter of the refractive index of the air, an average value of H is obtained over an area bounded by the path length of the light beam of the scintillometer and a line in the upwind direction from the light beam. The meteorological Department of Wageningen Agricultural University (WAU) has investigated the applicability of a long-path scintillometer (LAS). Such a scintillometer has an aperture of about 15 cm. For more details the reader is referred to de Bruin *et al.* (1995, 1996).

BACKGROUND

A scintillometer is a device by which the turbulent intensity of the refraction index of air can be measured. To this purpose, a beam of light is transmitted over a (usually) horizontal path. At the receiver the fluctuation of the light intensity is analysed. These fluctuations are caused by inhomogeneities of the refraction index along the path of propagation.

The scintillometer used has been built at WAU. It has an aperture-size of 15 cm, and the light source is a light emitting diode (LED: TIES16, Texas Instruments, Texas, USA) operating at a wavelength of 0.94 micrometres. The electronics were built using the design

Ochs and Wilson (1993). Improvements were achieved for the signal-to-noise ratio and a reduction in sensitivity of electronics to temperature. The latter was tested in the field by comparing the analogue output with digital data processing carried out on a data logger (Campbell Scientific Ltd, Loughborough, UK). Note that this is a new application of the Campbell 21X data logger. It allows data processing using only the demodulated signal from the detector in the receiver of the scintillometer. The demodulation requires only simple and cheap electronics.

COMPARISON BETWEEN SCINTILLOMETER AND HYDRA MEASUREMENTS

LAS data have been collected at La Posa over rangeland about 30 km south of Hermosillo near the micrometeorological mast, where sensible and latent heat fluxes were measured using the Hydra - the Institute of Hydrology's eddy-correlation system. This allows a comparison between the LAS and the eddy-correlation fluxes.

LAS and Hydra data were gathered from 18 September to 24 November. In the first two weeks of September a number of rain showers occurred producing more than 100 mm of rainfall. So the surface was saturated at the start of the measuring campaign.

From 18 September - 7 October the receiver of the LAS was installed at about 12 m on top of the tower. The transmitter was located on the slope of a hill at 50 m. The path length of the light beam was 3.2 km. So, in this period the light beam was not parallel to the surface. This non-ideal set-up was chosen to avoid saturation of the signal; according to our calculations at 12 m it could be possible that saturation of the signal could occur around noon.

A theoretical analysis showed that it was possible to use an effective height of about 26m (i.e. different from the average height) in the free convection formula (de Bruin *et al*, 1996) to calculate the sensible heat flux from the scintillometer data. The results are shown in Figure 1. There is a lot of scatter but agreement seems reasonable considering that Hydra and scintillometer are sampling rather different areas. There appears to be a tendency for the scintillometer to overestimate at low H and underestimate at high H. Similar effects were observed previously in quiet different conditions (de Bruin *et al*, 1996). Another inherent difference is introduced by the fact that the Hydra uses an averaging period of one hour whereas the scintillometer uses a ten minute period.

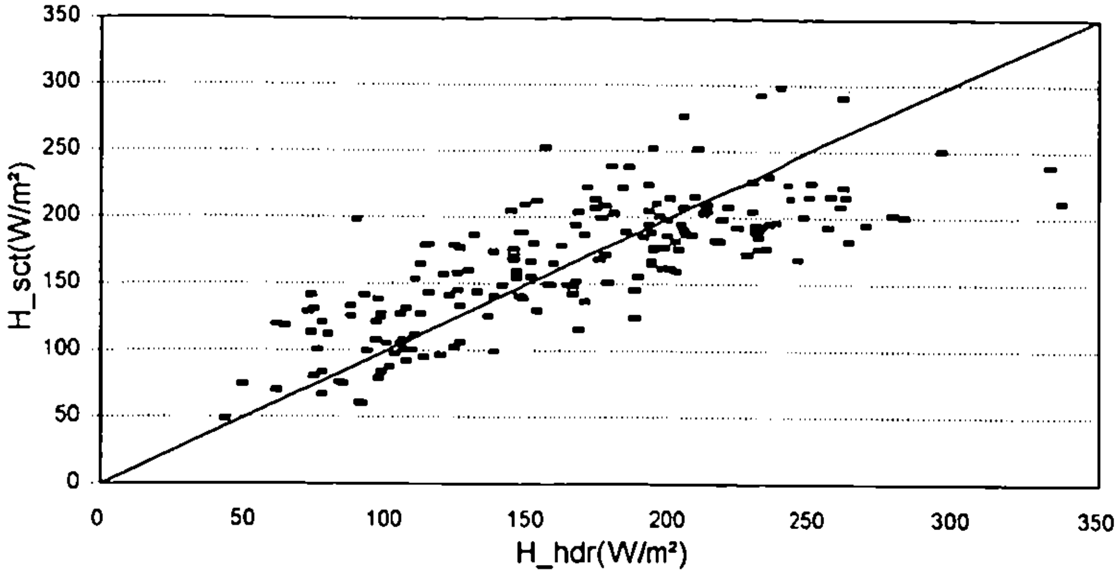

Figure 1 *Comparison of scintillometer against Hydra measurements of sensible heat flux for the period 18 September to 7 October 1996 at La Posa.*

From 10 October - 24 November the LAS was installed to operate between two hills which were 1.1 km apart. The heights of the transmitter and receiver were both at 30 ASL, so that the light beam was parallel to the ground surface. At 30 m there should be no problem with saturation of the signal. These two hills were several kilometres from the Hydra mast; but over similar terrain and vegetation. In total data were collected for 13 days. This data has yet to be analysed.

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Preliminary report of measurements over wheat in 1996, in Yaqui Valley, Sonora, Mexico

INTRODUCTION

Knowledge of evaporation is required for estimating irrigation water requirements for design and running of irrigation schemes. It is also required for estimating water resources and for hydrological studies particularly for semi-arid regions.

Measurement of evaporation requires sophisticated equipment, which is costly to purchase and run. Evaporation is spatially very variable when there are differences in vegetation or soil water availability as occurs particularly in semi-arid regions. To obtain reliable values for these regions it would be necessary to replicate the measurements of evaporation, which would be prohibitively expensive. As an alternative evaporation can be estimated from mathematical formulae. These formulae vary in their data requirements and physical realism - the fewer assumptions needed in their derivation the more data they require to run. Evaporation from vegetation plentifully supplied with soil moisture - potential evaporation - is much less variable and primarily depends on the meteorological conditions, rather than on the vegetation and soil characteristics. Therefore potential evaporation can be estimated from simpler formulae.

Traditionally the necessary data to run the formulae to estimate evaporation were collected from ground-based meteorological stations. With the development of remote sensing using satellite-bourne sensors, it is possible to obtain the data to run some of the simpler evaporation formulae with data collected by satellites.

One of the major objectives of this Project was to assess the accuracy of these evaporation formulae that could run on data derived from satellite measurements. To remove the problems and errors caused by using satellite data it was decided to use ground-based data equivalent to that available from a satellite to run the formulae. To compare the estimates from the various formulae, measurements of actual evaporation were made over different crops, which were experiencing little or no lack of soil moisture.

In 1995 measurements were made over irrigated cotton within the Yaqui Valley Irrigation Scheme, and were reported in the first Interim Report on this Project. In 1996 measurements were made over another major irrigated crop - wheat - within the Scheme and compared to estimates of potential evaporation by a number of formulae.

METHODOLOGY

Four different models (two combination types: Penman and Shuttleworth and two radiation based types: Priestley-Taylor and Makkink) were used to estimate Reference Evapotranspiration (λE_r) over wheat in the Yaqui Valley, Mexico during the growing season. The main parameters needed for each method are summarized in Table 5. For an in depth description of these methods, see Shuttleworth (1993), except for Makkink which is described in Garatuza (1992).

All these four models were tested for their performance in predicting measured evapotranspiration. Evapotranspiration was measured using a Mark II Hydra instrument as described by Shuttleworth *et al.* (1988). Continuous measurements of sensible, latent and soil heat flux density and net radiation were carried out from January 4 to April 28, 1996, over wheat.

Site Description

The Yaqui Valley (27° N, 110° W) is situated in the state of Sonora in the northwest of Mexico. The coastal plain, with a width of approximately 60 km, is bordered to the west by the Gulf of California and to the east by the foothills (up to about 1500 m) of the Sierra Madre Occidental. A considerable part of the Yaqui Valley is occupied by an irrigation district, fed by the Alvaro Obregon Reservoir (on the Yaqui river), north of the Valley.

This reservoir has a capacity of 3 million cubic meters. The area of irrigated land is about 225,000 ha.

The climate of the region can be characterized as very dry. The main determining factor for the climate is a high pressure belt associated with the Bermuda High pressure cell. In winter the high pressure belt lies south, whereas in summer it lies north of Mexico. This implies a westerly air flow in winter and an easterly current in summer. Due to the continuous proximity of the high pressure belt and the associated subsidence, the weather is characterized by relatively sparse cloud cover and little rain. In late spring, when the center of the high pressure belt is approximately situated at the latitude of the Yaqui Valley, these effects are most pronounced.

During the winter months, November to February, the region is, from time to time, influenced by polar disturbances, resulting in increased cloudiness and, in some cases, rainfall. From March to June cloudiness decreases and May and June are usually characterized by the absence of rainfall. In July, August and September, local storms and tropical disturbances, either in the form of cyclones or mesoscale convective complexes, bring rain and increased cloudiness. Rainfall is usually in the form of intense convective storms. Temperature as well as humidity are at their maximums in July.

Average yearly precipitation is of the order of 350 mm, ranging from less than 200 mm at the coast to approximately 400 mm at the foot of the mountains. Average daily temperatures range from 18°C in January to 31°C in July. The daily range in temperature is typically 10-15°C. Average daily values of relative humidity range from 70% in the two wet seasons to 50% in May and June. In these months relative humidity of less than 25% can occur during daytime (Stewart *et al.*, 1994).

Measurement of evapotranspiration and energy balance

The Mark II Hydra instrument measures evaporation using an *eddy correlation* technique, which involves many practical problems. Notwithstanding the technical difficulties involved in applying it properly, the eddy correlation technique is the preferred micro-meteorological method on the grounds that is a direct measurement with minimum theoretical assumptions. Good present-day eddy correlation systems can provide routine evaporation measurements with an accuracy of 10 to 20 percent.

Installation of the instruments was done in the northwest side of an 1000x1500 m irrigated commercial agricultural plot, leaving, at least, 500 m of fetch to the closest side of the plot.

The greatest fetch was oriented towards the predominant winds. Taking the roughness length and zero plane displacement as, respectively, 10 and 63% of the maximum crop height (1.2 m), Gash's (1986) predicts that 90% of the measured flux will emanate from a fetch of 400 m, meaning that in the worst conditions, more than 90% of the fluxes might be expected to flow out from the field of experimental interest.

The crops were managed according to the recommendations of the local agricultural research center. Dates of planting, emergence, irrigations and harvesting are shown in Table 4. Irrigation was done by surface flooding and it took 6 days to complete it over the 1000 x 1500 m field.

Table 4. *Significant dates for the wheat crop*

Stage/Irrigation	Dates in 1996
Planting	Dec. 15
Emergence	Dec. 21
1st Irrigation	Jan. 27
2nd Irrigation	Feb. 16
3rd Irrigation	Mar. 8
4th Irrigation	Mar. 27

During the first growing season (April-July, 1995), two Hydra instruments were installed side by side, 20 m apart, to intercompare them. The agreement between both instruments was quite good, when both were working properly. Because there were some periods when one instrument failed to work, the data was combined to have a complete record, as follows: when both of the instruments were working adequately, the data from both was averaged; when only one instrument was working rightly, its data was used alone.

Daily means were computed from the hourly data for all the components of the energy balance. A daily energy balance was carried out with these data. It was found that the energy balance did not close. Further analysis showed evidence of a possible temperature dependency in the calibration done by the instrument when computing the latent heat flux. This problem made us decide to use the evapotranspiration as the residual from the energy balance equation, because the measurement of the other components in the energy balance is more reliable:

$$\lambda E = R_n - G - H$$

Weather data

Weather data, measured by the Mark II Hydra instrument and an automatic weather station, were used to run the reference evapotranspiration models. The automatic weather station was located approximately 10 km SW of the Hydra and provided continuous measurements of:

- air temperature (T) and relative humidity using a temperature/relative humidity probe (Vaisala, Sweden),

- horizontal wind speed (U) and wind direction with and anemometer and wind vane (R.M. Young, Michigan),

- solar radiation (R_s) using a solar pyranometer (Eppley, Research Laboratories, New Jersey, USA)

- soil heat flux (G) using three soil flux plates (REBS, Washington, USA)

These variables were recorded on a CR10 datalogger (Campbell Scientific, Utah) as hourly average values (mean of 60 readings per hour), for both crops.

In addition, net radiation (R_n), also on an hourly basis (mean of 3600 readings per hour), was measured by the Hydra using a net radiometer (REBS, Washington, USA). The net radiometer was located at a height of 2.35 m for cotton and 2.75 m for wheat.

The hourly average weather data was first converted into daily means. Mean monthly weather variables were computed from the daily means over the period of observations for the two crops (Table 3).

Vapour pressure deficit (D) was computed hourly using the saturated vapour pressure at air temperature (e_{sat}) and the relative humidity (R_H), as follows:

$$D = e_{sat} - e$$

$$e_{sat} = 0.6108 \exp\left(\frac{17.27\,T}{237.3 + T}\right)$$

$$e = R_H \, e_{sat} / 100$$

where T is the air temperature in °C and R_H is the relative humidity in per cent. Daily and monthly averages of vapour pressure deficit were computed from these hourly values.

Estimation of reference evapotranspiration

A program was developed to calculate the reference evapotranspiration λE_r for all models on a daily basis using the daily averaged data from the two crops. The mean monthly λE_r was computed as the average from the daily results. The theoretical background of the methods used here have been discussed in Shuttleworth (1993) and Garatuza (1992) and have been used for several years (ASCE, 1989). The procedures for estimating λE_r are briefly listed here for clarity.

The Penman equation, which gives a physically sound description of the process of potential evaporation (λE_P) is:

$$\lambda E_P = \frac{\Delta (R_n - G) + \rho c_p D / r_a}{\Delta + \gamma}$$

with: λE = Latent heat flux density (W m^{-2}),
R_n = Net all wave radiative flux density (W m^{-2}),
G = Soil heat flux density (W m^{-2}),
D = Slope of the saturation water vapour-temperature curve (Pa K^{-1}),
g = Psychrometric constant (Pa K^{-1}),
r = Density of air (kg m^{-3}), and
c_p = Heat capacity of air at constant pressure (J kg K^{-1})

Shuttleworth (1993) has developed the Reference Crop Equation (λE_S) given by:

$$\lambda E_S = \frac{\Delta}{\Delta + \gamma^*}(R_n - G) + \frac{\gamma}{\Delta + \gamma^*}\frac{900}{T + 275} U_2 D$$

$$\gamma^* = \gamma(1 + 0.33 U_2)$$

where U_2 is the wind speed at 2 m in m s^{-1}.

Priestley-Taylor equation (Priestley and Taylor, 1972) exploits the factor that potential evaporation depends strongly on net radiation and that the second term (aerodynamic term) on the right-hand side of the Penman and Shuttleworth equations is typically one-fourth the size of the first term (the energy term) for low vegetaton well supplied with water. It is given by:

$$\lambda E_{PT} = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G)$$

where α = 1.26

This equation describes the evapotranspiration loss from "saturated land" surfaces surprisingly well (Brutsaert, 1982). Much research has been conducted on the properties of α. It has been shown that it is not a universal constant, being dependent on (among others) the surface resistance, and the entrainment of dry air into the atmospheric boundary layer (de Bruin, 1983). Besides, seasonal and daily fluctuations in the value of α occur (Brutsaert, 1982). However, for many wet or well watered surface types (implying potential evaporation), a value of 1.26 has been found.

Since the daily average of soil heat flux is negligible small and the daily net radiation is proportional to the daily incoming short wave radiation, the Priestley-Taylor equation can be simplified even further (de Bruin, 1982) to yield the Makkink equation:

$$\lambda E_m = C \frac{\Delta}{\Delta + \gamma} K^{\downarrow}$$

where C is a calibration constant and $K^{\downarrow}$ is the short wave radiation (W m^{-2}) The value of C is dependent on the ratio $R_n / K^{\downarrow}$. It may vary from climatic region to climatic region, and has to be determined experimentally. For the Yaqui Valley, it has been found that C is approximately equal to 0.65 on a yearly basis (Moenne and Garatuza, 1992).

Table 5 lists the main variables required for each formulae.

Table 5. *Main variables required to run these four models used to estimate potential evaporation*

Model	**Main parameters required**
Penman	T, q, U, R_n, G
Shuttleworth	T, q, U, R_n, G
Priestley-Taylor	T, R_n, G
Makkink	T, R_s

RESULTS

Crop conditions

Table 4 gives the dates of planting and emergence of the wheat in this field and the dates of the four irrigations during its growth. Table 6 gives the monthly average weather conditions experienced by the wheat.

Table 6. *Monthly average variables measured at the eastern site within the Yaqui alley irrigation scheme. T temperature, D vapour pressure deficit, U wind speed, H sensible heat flux, λE latent heat flux, R_n net all wave radiation, G soil heat flux and R_s incoming shortwave radiation.*

	T (°C)	**D** (kPa)	**U** ($W m^{-2}$)	**H** ($W m^{-2}$)	**λE** ($W m^{-2}$)	**R_n** ($W m^{-2}$)	**G** ($W m^{-2}$)	**R_s** ($W m^{-2}$)
Wheat, 1996								
January	15.23	1.05	1.50	22.2	50.4	70.4	-2.2	164.1
February	17.90	1.38	1.78	-0.7	112.3	107.9	-3.6	195.6
March	18.74	1.20	2.42	15.0	135.7	148.0	-2.6	254.8
April	21.74	1.25	2.27	70.4	91.2	165.9	4.3	285.6

Measurements of evaporation

Figure 1 shows the fluxes measured over wheat for two sample days - one before and one after irrigation on 25th and 30th January 1996. After irrigation, evaporation markedly increased, due to greater soil moisture availability, and a consequential decrease in the sensible heat flux.

The ratio of the integrated daily available energy (R_n - G) to the integrated daily values of sensible plus latent heat flux is plotted on Figure 2, as a function of daily mean air temperature, for the 107 days of uninterrupted complete data. The average recovery ratio was 1.00009 and is within expected experimental error.

Reference crop evaporation

The mean daily reference crop evaporation for each month and the whole growing season was obtained by averaging the daily values (Table 7) together with the measured evaporation. Over the growing season two of the methods - Penman and Makkink - agreed within 1% of the measured value, whereas the other two methods - Preistley-Taylor and Shuttleworth - over-estimated the evaporation by 8% and 28% respectively. This compares with the similar results found in the previous year for cotton where Preistley-Taylor and Shuttleworth over-estimated by 15% and 28% respectively and Makkink under-estimated by 3%.

On a month by month basis all the methods over-estimated the measured evaporation during January, when the crop was still developing and during April, when the crop was senescing. A similar trend had been found the previous year for cotton.

Table 7. *Monthly averages of measured evaporation, from irrigated wheat, λE, and estimates of potential by Penman, λE_P, Priestley-Taylor, λE_{PT}, Shuttleworth λE_S and Makkink, λE_M, formulae*

	λE (W m^{-2})	λE_P (W m^{-2})	λE_{PT} (W m^{-2})	λE_S (W m^{-2})	λE_M (W m^{-2})
Wheat, 1996					
January	50.4	66.3	57.9	81.7	66.1
February	112.3	91.9	88.7	118.2	83.5
March	135.7	111.6	124.8	145.6	110.6
April	94.4	130.4	149.2	157.3	130.1
Season	100.3	100.0	107.8	128.2	99.4
		-0.3	+7.8	+28.2	-0.9
RMSE		38.0	41.0	46.5	44.6

FUTURE ANALYSIS

To overcome the systematic bias found in the estimates of evaporation early and late in the growing season, the introduction of a crop factor has been proposed. In previous studies crop factors were made dependent on the physiological stage of the crop. This could then account for initial crop development and senescence. This analysis will be presented in the Final Report of this Project.

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Preliminary Report on Measurements over Rangeland at the Posa Site Sonora, Mexico

INTRODUCTION

To assess the water resources of semi-arid rangeland areas the evaporation must be measured or estimated. The evaporation from vegetation in semi-arid areas exhibits extreme variation, due to the highly variable availability of soil moisture and the high degree of evaporation control exerted by the many different spices of plants that have adapted to the conditions in the Sonoran desert. Therefore it is very difficult to estimate evaporation in these situations and measurements are generally relevant to a small surrounding area, less than 1 km^2. A possible method of measurement surface fluxes at a larger scale comes from the use of satellite data. Satellite data is available over large areas; but cannot be used to determine evaporation directly. However other terms of the energy budget can be determined from satellite data, then the evaporation can be determined as the residual of the energy budget.

One of the main objectives of this project is to assess the accuracy of the methods of determining one of the major components of the energy budget, the sensible heat flux, which can be derived from remotely sensed measurements of the surface temperature. To eliminate the problems and additional errors involved in the use of satellite measurements of surface temperature, this project uses similar sensors to those carried on satellites; but mounted on tripods at heights of a few metres above the ground.

DESCRIPTION OF THE SITE

The site is located 30 km South of Hermosillo on federal highway 15, inside of Cruz Galvez communal lands. The characteristics around of tower are as follows:

Vegetation: The natural vegetation is a mixture of grasses, bushes and trees. The more common species are:

Trees mesquite, palo verde, brea and palo fierro;

Bushes salicieso and cosahui;

Grass zacate liebrero. Vegetation cover is around 25%, having as dominant species mesquite (Prosopis juliflora) and palo verde (Cercidum microphyla), with higher cover close to ephemirial water courses and bare soil between them. The height of the plants is variable: some mesquite are around 8 m high, but the average of all species is close to 2 m.

Soil: deep and sandy close to the surface, with little clay or organic material, but below this stratum it is clayey and without stones. The area is flat (slope between 1 to 2%) in direction southeast to northwest, crossed by small streams.

Climatology: La Posa is located in the Sonoran desert, where the climate is marked by extreme heat and low rainfall, with the principal rainy season in summer and a mean annual rainfall of 340 mm. The maximum temperature in summer is close to 50°C and minimum in winter near to 5°C.

MICROMETEOROLOGICAL MEASUREMENTS

Continuous measurement of latent, sensible and net radiation flux density were carried out using a Mark II Hydra located on a tower of 10.8 m. The exact height of the sensors were: thermocouple at 13.5m with source and detector for the sonic anemometer and infra-red hygrometer respectively 10 cm above and below the thermocouple, horizontal cup anemometer at 14 m, relative humidity sensor 12.2 m and net radiometer 6.5 m (Plate 1). Additional measurements were made using 6 soil heat flux plates (SHFP), 3 soil thermometers, 2 pyranometers, 1 rain gauge, 1 wind direction sensor, 2 wind speed sensors, 1 net radiometer, 4 infra-red thermometers(IRT) and 1 thermocouple (Table 8).

Table 8. Characteristics of additional instruments located at La Posa site.

Sensor	**location**
Soil heat flux plates	1, 1.5 and 10 cm under bare soil. 10, 10 cm under grass and 10 cm under bush.
Pyranometers	one at 12 m for incoming radiation one at 6.5m for albedo
Soil thermometers	10 cm under bare soil, 3 and 8 cm under bush.
Infra-red thermometers	1 over bare soil at 0.91m; 1 over bush 1.99 m; 1 over grass/bare soil at 1.95 m and 1 over a palo verde tree at 3.40 m.
Net radiometer	1.1 m over bare soil.
Thermocouple	Campbell thermocouple at 12 m above ground (on tower)
Cup anemometers	12.4 m and 10.6 m (on tower).
Rain gauge	0.63 m over ground

Period of measurement

The devices were installed at various times during the experiment and we had problems with several instruments. The Hydra was taken down recently, but the other sensors continue working correctly (Table 9).

Table 9. Instruments, sensor and duration of installation at La Posa site

	Period		
Instrument/Sensor	Began	End	Failure
Mark II Hydra	Jan, 31 1996	Nov. 1 1996	Mar, Apr, Sep.
IRT	Feb, 14 1996		Jul 13 to Sep 30 1996
SHFP	Feb. 12 1996		
Pyranometer($K^{\downarrow}$)	Feb. 2 1996		
Pyranometer($K^{\uparrow}$)	Feb. 20 1996		
Net Radiometer(Q7)	Feb. 5 1996		Oct 11 to Oct 17 1996
Anemometer	Feb. 2 1996		
Wind direction	Feb. 5 1996		
Campbell thermocouple	Oct 12 1996		

Results

VEGETATION

Measurements were made in La Posa site around of tower, using a combination method (line-area). 10 samples of 113 m^2 were taken, separated from each one by 50m in each direction (N, E, S and W), giving a total of 40 samples. In each sample, measurements were made of height, length and width for each plant and its species was identified. The height of the trees was very variable, as shown in Table 10.

The dominant cover species are P*rosopis sp* and *Cercidium sp* and the Figure 2 show the difference in height for both plants. This difference is possibly due to over-grazing by cattle of Mesquite since this species is the main food for animals in the rangelands of Northwestern of Mexico. The bushes here are abundant, but very little is eaten by animals and they have attained their maximum height. During the field measurements the grasses were dry, and we have not been able to make measurements of the ground cover.

Table 10. Species in La Posa and some parameters of the vegetation community.

	Length	Width	Height	Area	Number	Cover(%)
Prosopis sp	1.42	1.45	1.51	383.87	129	8.49
Krameria sp	1.21	1.25	0.67	29.52	19	0.65
Cercidum sonorae	1.90	2.26	2.16	128.71	19	2.85
Lysium	1.10	1.07	0.92	61.77	53	1.37
Encelia farinosa	0.43	0.43	0.52	2.74	16	0.06
Lophoceresus Shottii	2.10	2.15	2.00	7.12	2	0.16
Acacia constricta	1.35	1.33	1.55	57.16	14	1.26
Cercidium microphyla	2.93	3.24	3.35	279.06	28	6.17
Olneya tesota	5.47	5.37	5.30	155.13	6	3.43
Caesalpinia palmeri	0.76	0.81	1.03	39.00	49	0.86
Hyptis sp	0.47	0.49	0.52	4.45	15	0.10
Average	1.74	1.80	1.77			
Total				1148.52	350	25.41

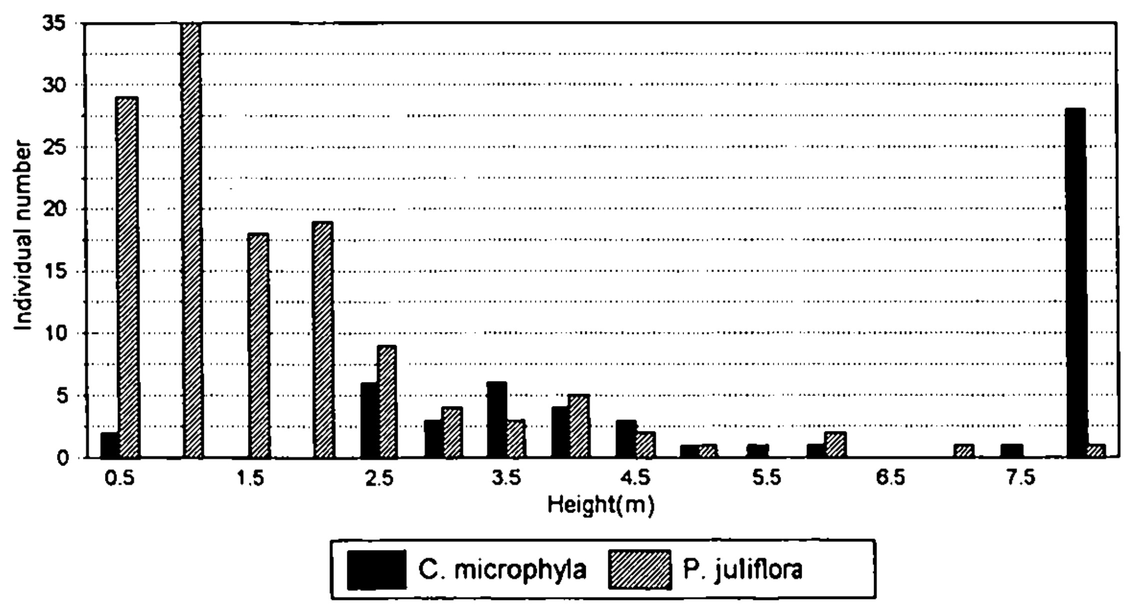

Figure 2. Comparison of height of dominant species in La Posa site.

AERIAL AND VIDEO PHOTOGRAPHY

In June of 1996 video and pictures were taken the over site, using a conventional photographic camera (35 mm) and a video camera on an aircraft at a height of 4000 to 5000 ft. The objective of the survey was the evaluation of the vegetation in La Posa and to gain a better idea of the distribution of trees and bushes (Plate 2). This showed that the vegetation distribution is heterogeneous and determined by micro-topography: the density is higher close to the emphemiral water courses with more bare soil in between.

ABOVE CANOPY FLUXES

In order to compute only values of the fluxes measured by the Hydra when net radiation is positive,data from 9 to 17 hours was used to compute daily averages. Data was also removed when λE, H or R_n gave negative values during the day, when rainfall occurred or when the Hydra failed. Figure 3, shows all the data screened in this way for the entire experiment from 3rd February to 1st November,1996. The sensible heat flux H reaches its maximum in the dry season (March to June) and minimum during the rainy season (July to September); the difference between air temperature and surface temperature is a maximum during the dry season and a minimum during the rainy season. The latent heat flux λE and the net radiation R_n reach their maximum in the rainy season, since the rainfall increases the above-ground, green biomass (annual and perennial species), so increasing evaporation, decreasing reflected solar radiation and increasing the net radiation R_n. In Figure 4, the Bowen ratio B and rainfall are shown. It can be observed that B starts decreasing in spring, before the first rains, corresponding to the production of leaves, flowers and seeds by the scrubland, which increases evaporation. The lowest values for B occur in the rainy season, as a result of transpiration from the plants and evaporation from the wet soil surface. After the rainy season, B begins to increase again as the soil dries out and plants have less available soil moisture.

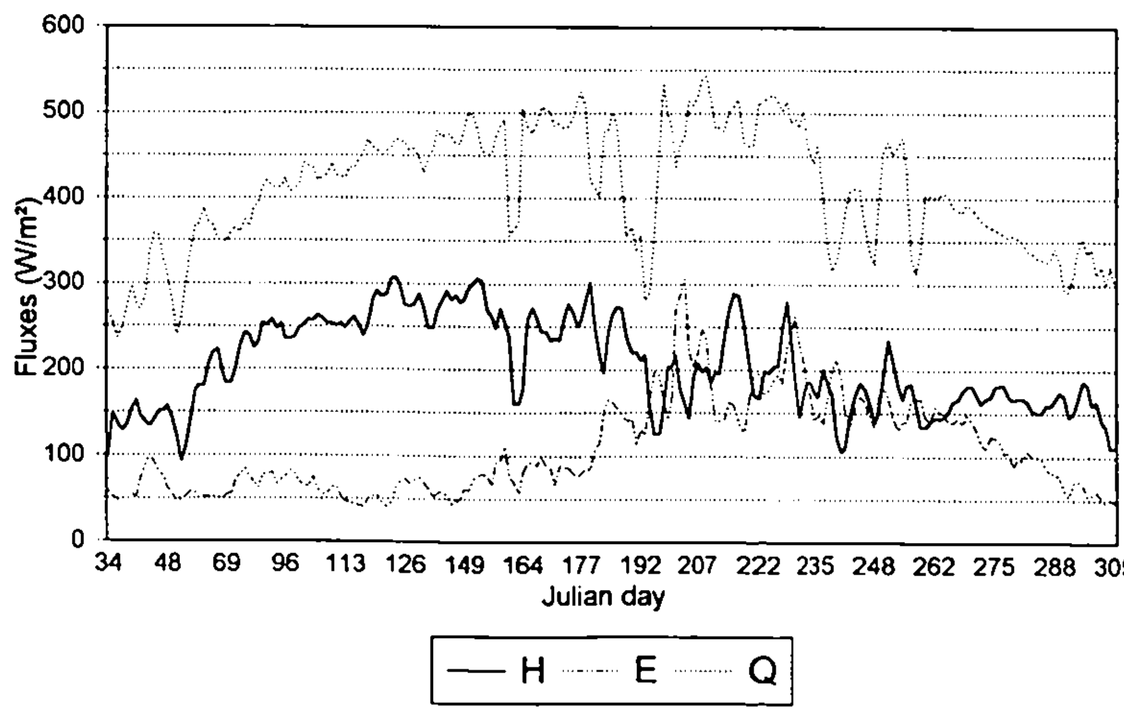

Figure 3. *Energy fluxes above canopy in La Posa site from 3rd February to 1st November 1996.*

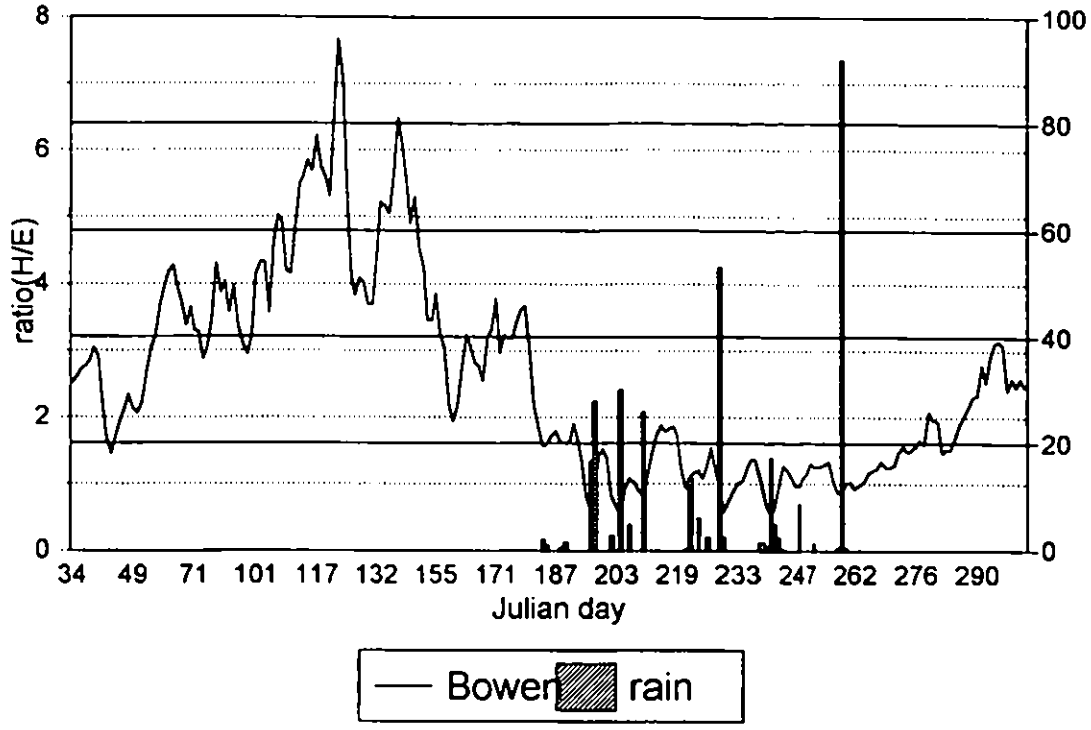

Figure 4. *Bowen ratio and rainfall in La Posa site from 3rd February to 1st November 1996.*

The Figure 5 shows the behaviour of the global radiation, reflected radiation and net radiation at height of 1.1 m. As before, only hours with positive net radiation were selected (9 to 17) for producing daily averages. Global radiation reaches its maximum in spring, similar to the Yaqui valley in previous years. Net radiation shows its maximum in summer, when the grass is green and the soil moist, after this it decreases due to lower solar insolation and senescence of the vegetation. There is little change in the reflected radiation in this period, but decreases at the end of the spring and summer, Figure 6 shows this decrease of albedo, having a minimum when the surface was covered by the maximum biomass and there was maximum soil moisture.

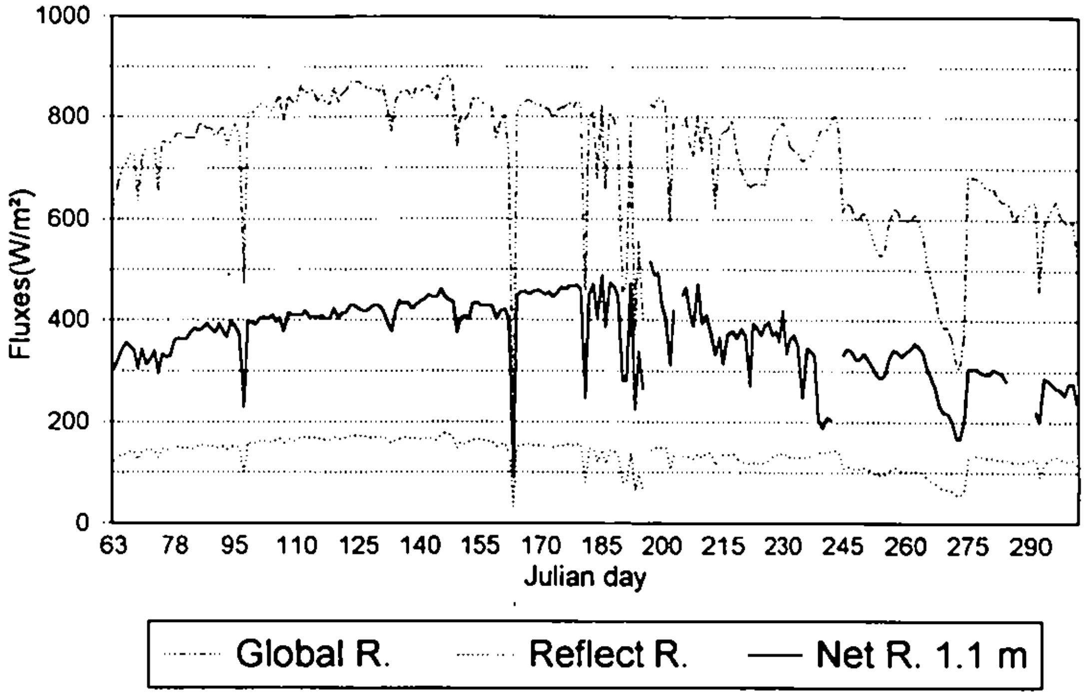

Figure 5. *Fluxes of global radiation, reflected radiation and net radiation at a height of 1.1m, at La Posa from 3rd March to 1st November 1996.*

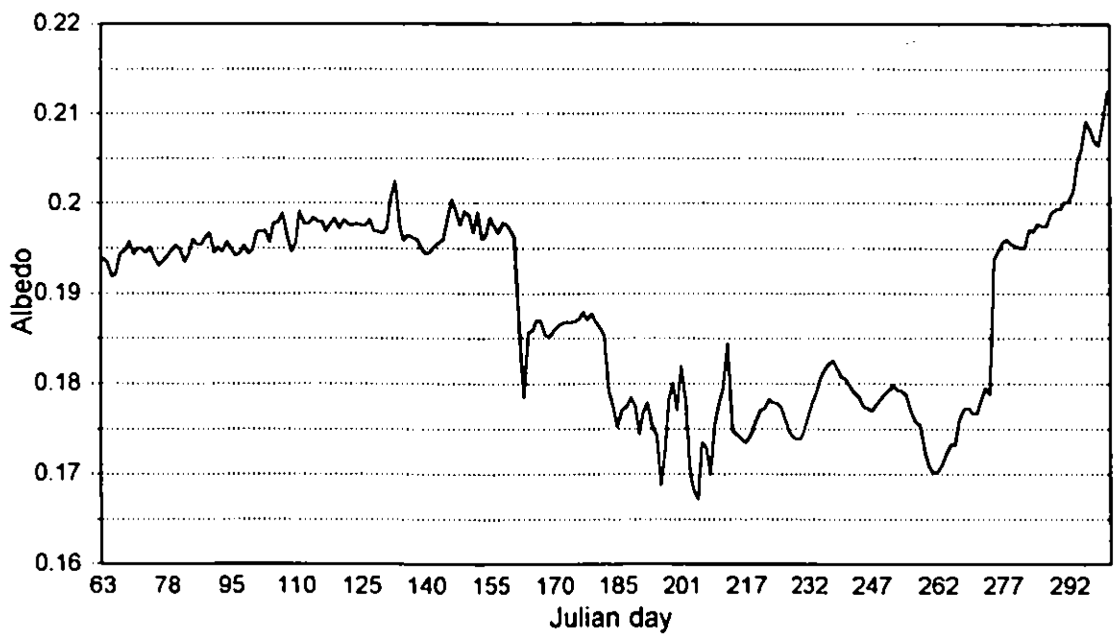

Figure 6. *Albedo for the same period, using a pyranometer at a height of 6.5 m at La Posa.*

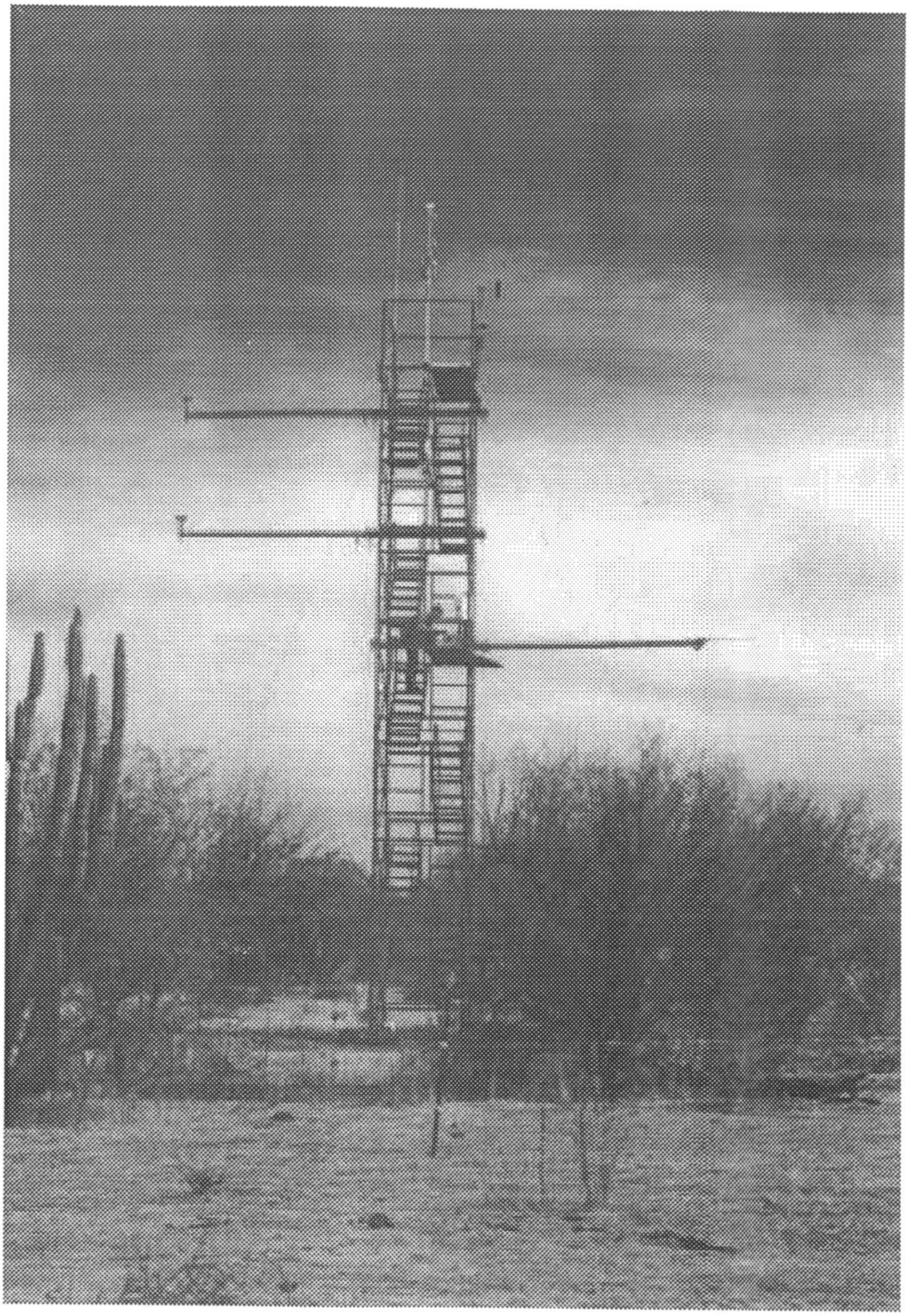

Plate 1. *Tower installed at the La Posa site, with anemometers and radiometer to left and right of the tower respectively. Other instruments and the Hydra are mounted at the top of the tower.*

***Plate 2**. Aerial photographs of the La Posa site surrounding the tower.*

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