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Remote Sensing of Soil Radionuclide Fluxes
in a Tropical Ecosystem

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SUMMARY

We are using a transponding geostationary satellite to collect surface environmental data to describe the fate of soil-borne radionuclides. The remote, former atomic testing grounds at the Enewetak and Bikini Atolls present a difficult environment in which to collect continuous field data. Our land-based, solar-powered microprocessor and environmental data systems remotely acquire measurements of net and total solar radiation, rain, humidity, temperature, and soil-water potentials. For the past year, our water flux model predicts wet season plant transpiration rates nearly equal to the 6-7 mm/d evaporation pan rate, which decreases to 2-3 mm/d for the dry season. Radioisotopic analysis confirms the microclimate-estimated 1:3 to 1:20 soil to plant ^{137}Cs dry matter concentration ratio. This ratio exacerbates the dose to man from intake of food plants. Nephelometer measurements of airborne particulates presently indicate a minimum respiratory radiological dose.

INTRODUCTION

The human food chain is the most significant component in the radiological dose-to-man received by the returning islanders at the old nuclear test sites on Bikini and Enewetak Atolls. The soil-water fluxes regulate the persistence of soil-borne radionuclides and are related to the tendency of the radionuclide to concentrate along the soil to the edible fruit pathway. Scarce equatorial climatological data exhibits

wide spatial and temporal variability¹ whilst the characteristics of the calcium-rich coral soil have no counterpart in the range of soil types found in temperate regions.

The temporal pattern of radionuclide movement and persistence in the soil will therefore contribute significantly to the understanding of the ecological phenomena that produce the radiological dose-to-man in populations of the returning islanders. The radionuclide movement in the soil depends in part on the fluxes of rainfall, soil-water through-flow and storage, evaporation and plant use; all of which are essentially the major terms of the water balance equation. Additional factors affecting the persistence of soil-complexed radionuclides are related to the chemical and physical properties of the highly calcareous soil². Transpiration (plant water use) and plant physiology measurements aid in estimating the important soil-to-plant and fruit concentration factors.

These atolls are presently uninhabited and are rarely visited. Microclimate and soil measurements require instrumentation that will take unsupervised, long-term data. Following non-productive experience with various cassette, printing, and EPROM recording instruments of our own or commercial design, we found

only occasional success with maintaining continuity of data collection. Short and sporadic visits to the field produced the opinion that the recorders were inadequate in memory capacity or in reliability for long recording periods. Worse yet, this equipment will not continuously endure the invasive and ever-present humidity and salt-air effects; nor can the investigator tolerate frequent voyages punctuated by moments of trauma on the trade-wind sea.

For these reasons we selected the National Weather Service (NWS) environmental satellite system³ as an appropriate means for remotely recording the microclimate and soil-water dynamics by a land-based station located on the atolls. The required on-site data storage is small and failures are alerted immediately by the regular land to satellite transmissions.

Established techniques of tropical micrometeorology⁴ estimate plant and soil evaporation (evapotranspiration, E) and soil through-flow (F). The continuous land surface satellite data and on-site soil and plant physiology measurements made by the investigators on site support these techniques. The satellite-reporting continuity has given us the opportunity to instrument a wind and solar powered nephelometer for documenting rare surface soil particle resuspension events that will bear on the respiratory pathway of the dose-to-man calculation.

LAND-BASED SATELLITE PLATFORM

The National Environmental Satellite System (NESS) operated by the NWS consists of 200 closely spaced UHF channels for relaying encoded weather data to a NWS data bank in Maryland³. Each channel is time-shared so that each user has one minute allocations to transmit his buffered data string (via the satellite) to a central or private data file.

We have two sites on the Pacific atolls (see Fig. 1) instrumented with micrometeorological and soil sensors. Each microprocessor controlled station (Handar Co., Santa Clara, Calif.), collects data every 20 minutes, which is then transmitted in assigned one minute intervals, three hours apart. Modest multi-use computer facilities, a HP9830A desk-top calculator (Hewlett-Packard, Santa Clara, Calif.) and a 201S modem (Prentice, Palo Alto, Calif.), retrieve and process the data in our laboratory (see Fig. 2). The line protocol uses vertical and longitudinal parity bits and a calculator-based algorithm that allows resending an erred data block. The data is stored, unmodified, on a floppy disc file for later conversion to engineering units. The calculator BASIC code includes interpolation and correction algorithms for errors or losses of the original transmitted messages. Numerical integrators are never reset so that the cumulative value is available in the event of interspersed transmission losses, while sufficiently high

Fig. 1. Meteorological and soil-water land platforms on the Bikini and Enewetak Atolls.

Fig. 2. A desk calculator fetches land-platform data from the satellite receiver.

collection frequency of analog data (every 20 min.) protects the temporal accuracy during these occasional interruptions.

The uninhabited, experimental sites require special procedures to ensure a reliable sensor system (see Fig. 3) which is without maintenance for three to six months. Sensor interface design must insure this also. Water-level thresholds on the Class A evaporation pan signal-conditioner activate a solar-powered pump which delivers a cistern water supply to the pan, thus replacing the evaporated water to the upper threshold of the evaporation-pan float. A coarse screen mounted over the pan prevents drinking by birds. Software compensates for the automatic refilling.

Temperatures are linearized and commutated for each of the eight thermistors. One calibrated port compensates for zero and gain drift while the remaining ports record various air and ground temperatures.

Plastic-coated Bouyoucos⁵ gypsum blocks (Beckman Instruments, N.J.) measure soil-water potential over a -0.5 to -10 bar range. Thirty-two blocks are commutated to a locally designed synchronous detector which reduces the capacitance effect of the conductivity

Fig. 3. Meteorological sensors include solar radiation (net and total), wind velocities (2), temperatures (7), soil-water potentials (31), evaporation pan, rain gauges (2), dew point, and nephelometer.

blocks and the 200 m connecting cables. A 100 bar pressure plate (Soil Moisture, Santa Barbara, Calif.) and dew-point thermocouple probes (Wescor Co., Logan, Utah) calibrate these blocks in the potential equivalent of pressure in bars. The function $\log(-\Psi) = 1.2 - 0.74 \log(Rk)$, (where Ψ = bars, and Rk = gypsum block resistance in $k\Omega$) is the empirical result of the pressure plate data. A three slope curve of $\log(Rk)$ and the synchronous detector output graphically derives the Rk from each measurement. Rk is temperature compensated by $\log(Rk) = \log(Rm) (1 + 0.0012 (T - 20))$, where Rm = measured resistance in $k\Omega$, and T = temperature of the block in $^{\circ}C$.

The most sensitive data (total solar energy and rain) are both stored in a cumulative register of sufficient size as to not overflow more than daily. As aforesaid, the long-term accuracy is not jeopardized by random transmission faults. Net insolation, wind speed, atmospheric visibility, and rainfall, although not so critical are recorded in the same way. Soil particle resuspension events are documented by a nephelometer which measures visibilities in terms of the atmospheric extinction coefficient. The commercially available instrument (Meteorology Research Inc., Model 1550B, Altadena, Calif.) was specially modified for a humid area and for low power use on solar cells. Since resuspension is thought to be an ephemeral event, or indeed rare, the visibility values are accumulated between each reading to the satellite. Visibilities are normally high (20-100 km) by temperate standards and accuracy near the limit of sensitivity demands an automatic calibration cycle (zero and gain). Every hour an alternate of two filtered-air (zero) cycles brackets a freon-calibrated gain cycle. Extinction coefficients are calculated by solving two equations,

$$aZ_{nm} + b = 0.23E-4 m^{-1}, \text{ and } aC_{nm} + b = 4.0E-4 m^{-1},$$

for a and b , where Z_{nm} = the m -th visibility reading on the n -th zero cycle, and C_{nm} = gain reading. The extinction coefficient is, $E_{xt} = aR_{nm} + b$, where R_{nm} = the m -th visibility reading on the n -th zero

calibration cycle. Calibration interpolations between successive zeros and gains are

$$C_{nm} = C_n + (C_n - C_{n+1})/6, \text{ and}$$

$$Z_{nm} = Z_n + (Z_n - Z_{n+1}) (m-1)/6.$$

Finally, the mass loading for the combination dust and salt-spray is $0.36 E_{xt} \mu\text{g}/\text{m}^3$.

The land platform must be frugal in consumption of the 5W solar-cell supplied power. The microprocessor and transmitter are powered by gel-cells only immediately prior and during the one-minute transmit intervals. Low-powered numerical-integrating circuits and the clock remain continuously powered. A prodigal 2a used for transmit, and the 80 ma, used momentarily once every 20 minutes for the sampling tasks sums to an average 20 ma budget supplied by the 12V gel-cells and solar-cells.

The soil-bound radionuclide fluxes are a sensitive function of the water-balance of the vegetated surface; we will review next the basic water relations that are measured by our satellite land platform.

WATER BALANCE

The rain-deposited water that flows through to the water table will elute the water-soluble fraction of the soil-bound radionuclides. The water balance equation defines the through-flow, (T) and is,

$$P - T - E + W = 0, \quad (1)$$

where P = precipitation,
E = evapotranspiration from the ground surface, and
W = soil-water storage.

The platform directly measures the rain (P) while micrometeorological methods estimate E. W is estimated by the profile of fractional soil-water saturation (measured by the platform soil-potential cells), and the laboratory-derived soil-water capacity. The remainder of Eqn. (1) is then the through-flow (T). Finally, we correlate the annual T with our laboratory soil-column leaching rates (3% - 4% for one soil-water turnover) to estimate the quantity of radionuclides that have left the soil inventory. The E term yields insight into the soil/ plant concentration ratio as we shall mention later.

EVAPOTRANSPIRATION

Evapotranspiration (E) cannot be directly measured in a remote region, however agricultural meteorology has developed an effective tool for making estimations of E. Aerodynamic diffusivity methods are frequent estimators where more direct methods are not practical. This method, combined with the surface energy balance, is the combination Penman function⁶ which uses a solar energy input term as a driving force for E and an aerodynamic term for eddy transport away from the evaporating surface. This function has been adapted⁷ to include the effective resistance to water-vapor flux through the transpiring leaf.

Intensive plant physiology measurements on the ubiquitous, small tree, *Argusia argentea*, has defined

the effective transpiration area surrounding the canopy shadow area. Our new steady-state porometer⁸ has measured the stomatal leaf resistance (range 10-300 s/m) as a function of insolation and soil-water potential. Destructive sampling of ten of these trees, ranging in weight by a factor of 5 yields a regression of trunk diameter to effective leaf area and standing water volume. This data permits us to estimate total island consumptive water use based on our assumed 60% canopy cover.

The soil-water potential sensors measure the current W and in the next section we shall describe the method used to estimate this soil water storage.

SOIL-WATER FLUX AND STORAGE

The soil-potential probes (conductivity blocks) estimate the soil-water flux by Darcy's equation,

$$F = -K(\theta) d\psi/dz, \quad (2)$$

where $K(\theta)$ = soil conductance, m/s,

θ = volumetric soil-water content, m^3/m^3 ,

ψ = soil-water potential, bars, and

z = vertical axis, measured downward, m.

Unfortunately $K(\theta)$ is a highly nonlinear function of soil-water content (θ). Pressure-plate techniques⁹ yield the form of the $K(\theta)$ function; however, this curve will exhibit a displacement along the ordinate axis that must be calibrated by an independent saturated soil conductivity measurement. In face of the difficulty of extracting intact soil cores, we have chosen the approximate infiltration method¹⁰ for $K(\theta)$ at saturation water capacity.

Practicality confines the satellite system to monitoring only three soil profiles, despite widely ranging, log-normally distributed $K(\theta)$ ¹¹. These profiles are effectively calibrated by 32 more manually measured profiles. During thrice yearly field trips, we use the *in situ* neutron moisture method¹² (Campbell Instruments, Pacheco, Calif.) for measuring the θ of these soil profiles. Pressure-plate derived ψ vs. θ function, equivalence the neutron measured θ and satellite measured ψ .

SOIL-PLANT RADIONUCLIDE CONCENTRATION RATIOS

Trace minerals (e.g., radionuclides) in soil are often stored and concentrated in organic matter, particularly if they follow the same translocation pathways of chemically similar essential minerals.

In the potassium deficient atoll soil, ¹³⁷ Cs is concentrated by plants over the soil values by a factor between 3 and 20. The radionuclide concentration ratio is clearly crucial to estimating the low level radio-biological dose to man from his food chain over several decades, which is required by regulatory agencies.

Direct soil and plant measurements most commonly assess the concentration ratio at the study area. This procedure, unfortunately, ignores the changing temporal state of the microclimate and hydrology, the plants, and the soil. van Dorp, et al¹³ have considered some approximations to the real process of estimating concentration ratios for species, taking

* transpiration coefficient. The van Dorp, et al equation was modified to a dry weight concentration ratio and is,

$$CR = FSP \frac{E_c}{E_t} / (\theta/\rho + K_d) pCi g^{-1} \text{ plant} / pCi g^{-1} \text{ soil}, (3)$$

where F = fraction of absorbed nuclide transported to sampled organ,

S = root selectivity,

P_t = production of plant organ/total production, g/g dry weight

E_c = transpiration coefficient, ml H₂O/g of dry production,

θ = root zone soil water capacity, ml/cm³,

ρ = soil density, g/cm³, and

K_d = pCi (2.2 disintegrations/min.) adsorbed per g soil/pCi in ml of soil solution.

Field work and the satellite platform easily evaluate ρ and θ ; transpiration estimates and allometry measurements of the indicator plant, Argusia argentea, estimate E_c ranging from 500 to 1500 ml

H₂O/g dry weight. Growth marker data indicates the canopy growth fraction, $P_t \sim 0.8$; F and S are not so

easily inferred so we have boldly used the van Dorp et al¹³ fruit/plant ratio F = 1, and the selectivity, S = 1.

RESULTS AND DISCUSSION

Climatology

Eight months of continuous application of the satellite land based platforms has given us the first basis of intensive climatology. Enewetak Atoll has had only very sporadic meteorological recording during the atomic testing period, while 200 miles to the east, Bikini Atoll has had none. Our Bikini platform has been the longer in service and those results to date are exhibited in Table 1, and compared to the only available, conventionally collected Enewetak weather data.

The uniformity of the weather is the salient feature of the data, with the daily variation being more extreme than the seasonal. The rainfall is conspicuous among the other variables by being more capricious in season, amount, and rate. This year we witnessed a wet season superimposed on a normally dry time of the year. Our soil-water potential probes indicated the root zone to be constantly at field capacity (except, occasionally, in the top 10 cm). Sparse earlier data indicates that this water saturation is unusual and amounts to a four times dilution of the standing soil-water capacity in the soil column. Constancy of the other weather variables, in particular, insolation, eases our task of long term surface water balance estimates. Allowing sufficient time to establish the climatology of the two atolls, solar radiation and rainfall may be the only crucial data to accurately predict soil-water fluxes.

Evapotranspiration

Table 2 illustrates examples of a calculation of wet and dry Penman evapotranspiration rates (using wet and dry season stomatal resistance, r_v , of 250 and 700

Table 1. Recent bikini data compared to available climatology.

	Bikini land platform		Enewetak climatology ¹
Rain	March-Sept.	1100 mm	1346 mm/y
	March	23	(167-2160) ²
	Sept.	463	
Solar ³	March-Sept.	7.7 ± 1.3 mm/d (2.3-10.0) ²	
	March	8.2 ± 1.3	
	Sept.	6.4 ± 2.6	
Evaporation pan	March	6.1 ± 1.1 mm/d	
	Sept.	4.7 ± 1.3	
Wind	March	5.2 m/s (3.5-6.4)	3-12 m/s
		ENE, ESE, 99%	NE, ENE, 99%
	Sept.	2.7 m/s (0.6-5.8)	1-6 m/s
		NNE, 13% ENE, ESE, 68%	NE, ENE, E, 87%
Temperature	March	27.9 ± 0.8°C (25-31)	25.4-30.6°C 1% seasonal variation
	Sept.	27.9 ± 1.7 (24-33)	
Relative humidity	March-Sept.	69-84%	70-89%
Typhoons			1 per 5-25 y

¹6 years of Enewetak Atoll observations, sporadically collected between 1945 and 1955¹.

²98 percentile range.

³Daily insolation in equivalent heat-of-vaporization of water, mm/d.

Table 2. Wet and dry season evapotranspiration.

	E_{wet}^1	E_{dry}^2	E_{pot}^3	E_{pan}^4 mm/d
25 Feb.	5.2	2.1	5.5	5.3
26 Feb.	6.3	2.5	7.2	6.6
27 Feb.	6.3	2.5	7.0	9.6
28 Feb.	6.2	2.4	6.9	7.4
1 March	5.9	2.3	6.5	6.1
2 March	6.4	2.5	7.2	7.3
3 March	6.2	2.4	6.9	7.8
4 March	6.3	2.5	7.1	6.8
2 April	5.1	2.0	5.0	6.2
3 April	5.7	2.3	6.2	6.1
4 April	6.6	2.6	7.4	6.3
Plant-water time const.	1.8 d	4.3 d		
Tritium tracer	2.6 d	6.9 d		

¹ $r_v = 200 \text{ sm}^{-1}$

² $r_v = 700 \text{ sm}^{-1}$

³ $r_v = 0 \text{ sm}^{-1}$

⁴Class A evaporation pan

s/m). These r_v values are derived from a composite of data taken over the last two years on the indicator species, Argusia argentea. This pioneer dry tropics tree is ubiquitous on these islands and the measure-

ments on these trees represent an initial approximation to transpirational water use. Potential evapotranspiration assumes the maximum possible ($r_v = 0$) while pan evaporation, times the "pan factor", presents an equivalent free water surface⁴ and will therefore approximate the fully hydrated transpiration of a plant leaf. The instrumented Class A evaporation pan evaluates the efficacy of the Penman function⁷ for estimates during the wet season where soil-water is not limiting.

These simple pans are used throughout the world to evaluate agricultural water use. Accuracy is highest in humid areas free of advective energy imports.

Chan⁴ has found the daily evapotranspiration use in tropical regions to be equal to $K_{pan} E_{pan}$ mm/d, where K_{pan} is the "pan-factor" and averages 1.1 for a mature crop (range, 0.6-1.3) and E_{pan} is the measured evaporation. Our February-September data yields a K_{pan} value of 0.9780.07 for a 60% vegetative cover. Table 2 compares our wet season E with the values predicted by the evaporation pan.

The dry season values cannot be confirmed by the evaporation pan as the actual evapotranspiration is substantially less than the potential free water value. The annual water balance is sensitive to the wet/dry season E ratio which is almost equal to 2.5. *In situ* leaf resistance measurements have defined the season; however, we will use the satellite data on soil potential to indicate the wet/dry physiological state¹⁴ during the next year.

The synoptic March to September water balance exhibited a 325 mm excess (see Fig. 4) at the end of

Fig. 4. Rain, evapotranspiration, and soil storage components of surface water balance.

the present data base. The evapotranspiration rates were always characteristic of the wet season regime. Extensive root sampling indicates the root zone extends to 450 mm. Field water-capacity, θ , (average, 0.28 ml/cm³; range, 0.20-0.32) results in an equivalent 126 mm soil-water column; and that is diluted 2.5 times by the 325 mm of excess water. Our laboratory soil-column studies indicate 11% of the ¹³⁷Cs leaches to the water table during a triple elution of the water in the soil column. Subsequent soil sampling may confirm this loss of ¹³⁷Cs.

The constantly saturated soil prevented us from using Eqn. (2). However, during high fluxes of rainfall, we did estimate saturated soil conductivity $K(\theta)$ ranging from 200 to 2700 cm/d; both are profligate rates by temperate standards. The earlier shallow well infiltration measurement yielded values ranging from 400 to 1500 cm/d. Any distorting of Eqn. (1) by lateral runoff during heavy rains is nearly precluded by these conductive, loose sandy soils.

¹³⁷Cs Concentration Ratio

The plant/soil concentration ratio (CR) substantially effects the radiological dose-to-man calculation. Despite our assiduous vegetation and soil sampling effort, CR's vary over a decade of value. Table 3 exhibits an application of Eqn. (3) in a quest to use environmental and physiological factors for estimating CR's.

Table 3. Measured and estimated ¹³⁷Cs Plant/Soil Concentration Ratio¹.

Plant	Measured ²	E_c^4	Calculated Eqn. (3)
Argusia (wet season)	4 ± 4 (1-20) ³	1500	12
Argusia (dry season)	(1-20)	500	4
Pandanus	(4-40)	400	3
Breadfruit	(4-20)	1500	12

¹ $F = S = P_t = 1$, $K_d = 100$, $\theta = 0.29$, $\rho = 1.2$, $P_t = 0.5$.

² $pCig^{-1}$ plant/ $pCig^{-1}$ soil, dry weight.

³ Range.

⁴ Transpiration, ml/g dry productivity.

The widely ranging measured values enclose our Eqn. (3) calculation based on a preliminary assumption of many of its parameters. The result remains, however, that our calculated CR's do indeed express a difference in coral soil properties when compared to temperate CR's, which are usually less than one.

Airborne Resuspension

The nephelometer data (99%) falls near the limit of lower sensitivity (see Table 4). Occasional readings above 100 $\mu g/m^3$ coincided with rain squalls, irrespective of gustiness. These data confirm our suspicion that visibilities are uniformly high and resuspension seldom occurs on this damp soil surface during the wet season; in contrast, we do find resuspended material on rooftops, but the source may be different. We have yet to record characteristic

	Average $\mu\text{g}/\text{m}^3$	Highest 1% $\mu\text{g}/\text{m}^3$	Visibility lowest 1%
March	25 $\pm$ 30	70-150	12-33 km
April	24 $\pm$ 10	250-300	8-13
May	40 $\pm$ 15	70-240	7-33
June	40 $\pm$ 25	160-250	7-10
August	30 $\pm$ 23	70-150	12-33
September	25 $\pm$ 25	70-150	12-33

dry season data that may include rare resuspension of local radioactive soil particles from a dry surface.

CONCLUSIONS

We are faced with an intensive radiological assessment to be done in a remote and nearly inaccessible region. The usual manual sampling measurements are difficult, and the corrosive, salt-air environment is inimical to elaborate electronic and mechanical equipment in the usual unsupervised experiments.

The land-based satellite experiments have kept field complexity to a minimum while meeting the demands of a continuous environmental experiment. The data continuity enables us to estimate the coral atoll hydrology (and biometeorological parameters) with an accuracy not before attained even in continuously manned-experiments. The described satellite land-platform method has a greater economy of recording than most conventional data collection systems. This may be important from a data management standpoint as well as to fiscal constraints of a program.

An active interest in the use of a geostationary satellite "party-line" to record data received from remote land platforms has been manifested by many potential users. Meteorologists in the Southwest Equatorial Pacific have found the data recorded and made available in this program very useful in forecasting synoptic weather patterns in this previously unstudied region.

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