WATER RESOURCES RESEARCH, VOL. 36, NO. 10, PAGES 3107–3110, OCTOBER 2000

Reply

A. T. Cahill

Department of Civil Engineering, Texas A&M University, College Station

M. B. Parlange

Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, Maryland

We wish to thank *Or and Wraith* [this issue], (hereafter OW) for their thoughtful comments on the observations of soil moisture obtained with time domain reflectometry (TDR) which are presented in our paper, *Cahill and Parlange* [1998], (hereafter CP). We appreciate their interest and the time they took to formulate their comment. In this reply we point out where we agree and disagree with their comments and raise a question about the analysis they present in their comment and the general issue of how water vapor movement in soils is described.

The point of *Cahill and Parlange* [1998] was to demonstrate on the basis of field experiments that the theory of *Philip and de Vries* [1957], (hereafter PdV) was inadequate to describe vapor movement in soils near the land surface. This is important since the theory remains the basis for most simulation codes used today in hydrology and meteorology for the description of the soil-plant-atmosphere continuum. As we discussed in the CP work, the measurement of water in soils is not trivial, and hence we concluded our remarks with analysis based on the water vapor movement derived from the energy balance, since we know the temperature measurements in soil, in general, are more reliable.

We agree with OW that the effect of temperature on time domain reflectometry (TDR) readings of soil moisture content does exist and were glad to see the recent analysis published by *Or and Wraith* [1999] and *Wraith and Or* [1999] since further work was certainly needed. The work of *Or and Wraith* [1999] is a valuable contribution; it was, however, not available when our paper was published. As stated by CP, the neglect of temperature effects on the TDR readings on soil moisture was based on results presented in one of the few papers on this topic which was available at the time we wrote the paper [*Pepin et al*., 1995]. We deliberately presented all of our 'raw' data so that others could make use of them in that context, as OW have presented here.

We disagree, however, with OW's use of the figures in the papers that we cited in the CP paper. OW have presented figures from *Jackson* [1973] and *Rose* [1968] to bolster their claim that other researchers have not seen similar peaks in soil moisture at a depth of 2 cm shortly after noon.

OW selected a figure from *Jackson* [1973, Figure 2] that only plots soil moisture from 0 to 0.5 cm. The figure of *Jackson* [1973] that shows the data with moderate soil moisture at depths in the range of our TDR, which we discussed, is Jackson's Figure 3 (see Figure 1). Jackson does not plot days 3–8, but considering day 9 and depths 1–2 cm or 2–3 cm (closest to our 2 cm TDR probe), the pattern is clearly similar with moisture content peaking at or around noon. We agree the magnitude of the variation of our TDR measurements is accentuated because of temperature effects as discussed by OW, but the pattern in Jackson's measurements is certainly similar to our findings. Jackson noted "the water content increase(s) at these [1- to 2 cm] near midday." *Jackson* [1973] obtained the data gravimetrically in an intensive field campaign taking soil cores to 10 cm and sectioning into 1 cm increments at 1 hour intervals. The fact that Jackson's data are gravimetric means that they are free from temperature effects and hence an independent support of the pattern seen in the TDR measurements. In Figure 1 it can be seen that the soil moisture content from 1–2 cm can peak around noon, even while the soil moisture at 0–0.5 cm is decreasing following the sunrise.

The results from *Monji et al*. [1990] are shown in Figure 2. Their soil moisture data were obtained with yet another sensor, a thermal-conductivity-based moisture sensor. In Figure 2, *Monji et al*. [1990, Figure 4] have plotted the superposition of the diurnal changes for measurements obtained from December 1 to December 22, 1988, at an experimental farm of the University of Osaka Prefecture. The key observation, again, by Monji et al. is that the soil moisture at 1 cm only began to decrease at noon. As we concluded in the CP work, the physical phenomena driving the soil water content near the land surface is not included in the PdV theory, and *Monji et al*. [1990] commented that "no reliable relations [to explain the water content variation] have been formulated."

The results from *Rose* [1968] (Figure 2b of OW) support OW's assertion, but the soil is much drier, and in day one (wettest soil) it is not obvious as to the exact pattern. Note that the magnitude of the variation in moisture content in the Rose measurements (0–1.27 cm) is not dissimilar to what we observed in the Davis field experiment.

We also wish to comment on the assertion of OW that the TDR measurements of CP exhibit too much noise to be trusted. Some background on the instrumentation and analysis procedure used will help to shed light on this question. A Textronics 1502B cable tester was used to take the TDR measurements. The digitized waveform from the cable tester was transferred to a Campbell 21X data logger and then downloaded to a computer where it was stored. The analysis of the TDR waveform involves (1) finding the points of inflection in the waveform, (2) determining the distance between them using the distance represented by each pixel, (3) transforming this distance into an apparent dielectric constant for the medium, and (4) relating this apparent dielectric constant to a moisture content via a calibration curve. The cable tester digitized the waveform into 246 pixels or data points, and each of these data points represented 0.02 m (this distance can be set on the cable tester). Waveforms were not averaged, which may account for some of the increase in noise. As was stated by CP, the calibration curve of *Dasberg and Hopmans* [1992] for the

Paper number 2000WR900123.
0043-1397/00/2000WR900123$09.00

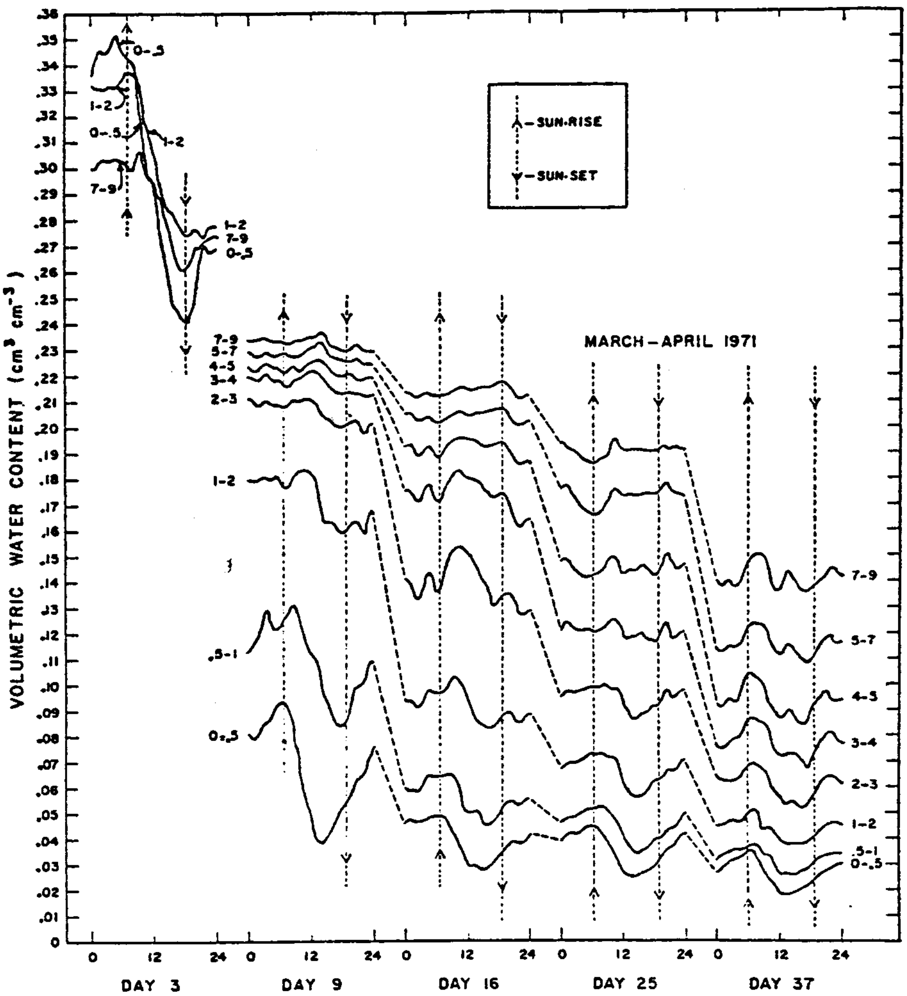

Figure 1. Time series of gravimetric measurements of near-surface soil water content (expressed on volume basis) during bare soil evaporation from *Jackson* [1973].

Yolo silt loam (the field site in Davis, California) was tested and found to be accurate and hence was used in the analysis.

The analysis procedure can be inverted so that an ideal soil moisture content time series can be transformed into a time series of the ideal number of pixels between the two inflection points. We inverted the low-pass-filtered soil moisture content time series in this way and then compared the resulting time series of the ideal number of pixels between the inflection points to the actual measured number of pixels between the two inflection points for the different depths. The RMS difference between the ideal low-pass-filtered curve and the measured curve ranged from 1.9 pixels to 2.6 pixels for the three time series. This is an error of approximately 1% in a 246 pixel curve. In our opinion it is easy to see how variation of the order of 3 or 4 pixels could occur, which could translate into variation in the soil moisture content of 3% to 4%, depending where on the calibration curve the error occurs.

It may be pointed out that by comparing our low-pass-filtered curve to the measurements, we are only testing the effect of the low-pass filter on the separation distance between the two inflection points. This obscures the more important point that determining the inflection points on a nonsmooth digitized waveform is not exact. Minor noise that does not change the shape of the waveform appreciably can change the distance between the calculated inflection points by a few pixels. The few pixels difference leads to changes in moisture content of the order of variation seen in our waveforms. We grant that there maybe more noise than usual in our waveforms because of the high clay content of the Yolo silt loam, but some noise occurs simply because errors of a few pixels lead to errors in the calculated moisture content. Again, we plotted the original observations for completeness.

We wish to note a possible problem with the assumptions OW made to produce their Figure 1. Specifically, we question the use of "a linear reduction trend of mean daily values." We understand this to mean the "true" soil moisture content was a straight line decay on which the temperature-driven fluctuations of modeled TDR-measured moisture contents were imposed. If the "true" moisture content is taken to be a linear decay, with all moisture content variation measured by TDR due to temperature fluctuation, as OW seem to have done in Figure 1, the behavior of this "true" soil moisture content is at odds with all previous soil moisture measurements. *Rose* [1968] and *Jackson* [1973] show diurnal variation from gravimetrically measured soil moisture, while *Monji et al.*, [1990] observed their diurnal variation in soil moisture using a heat conduction sensor. To match the experimental results of soil moisture presented by CP by using the unrealistic assumption of a linear

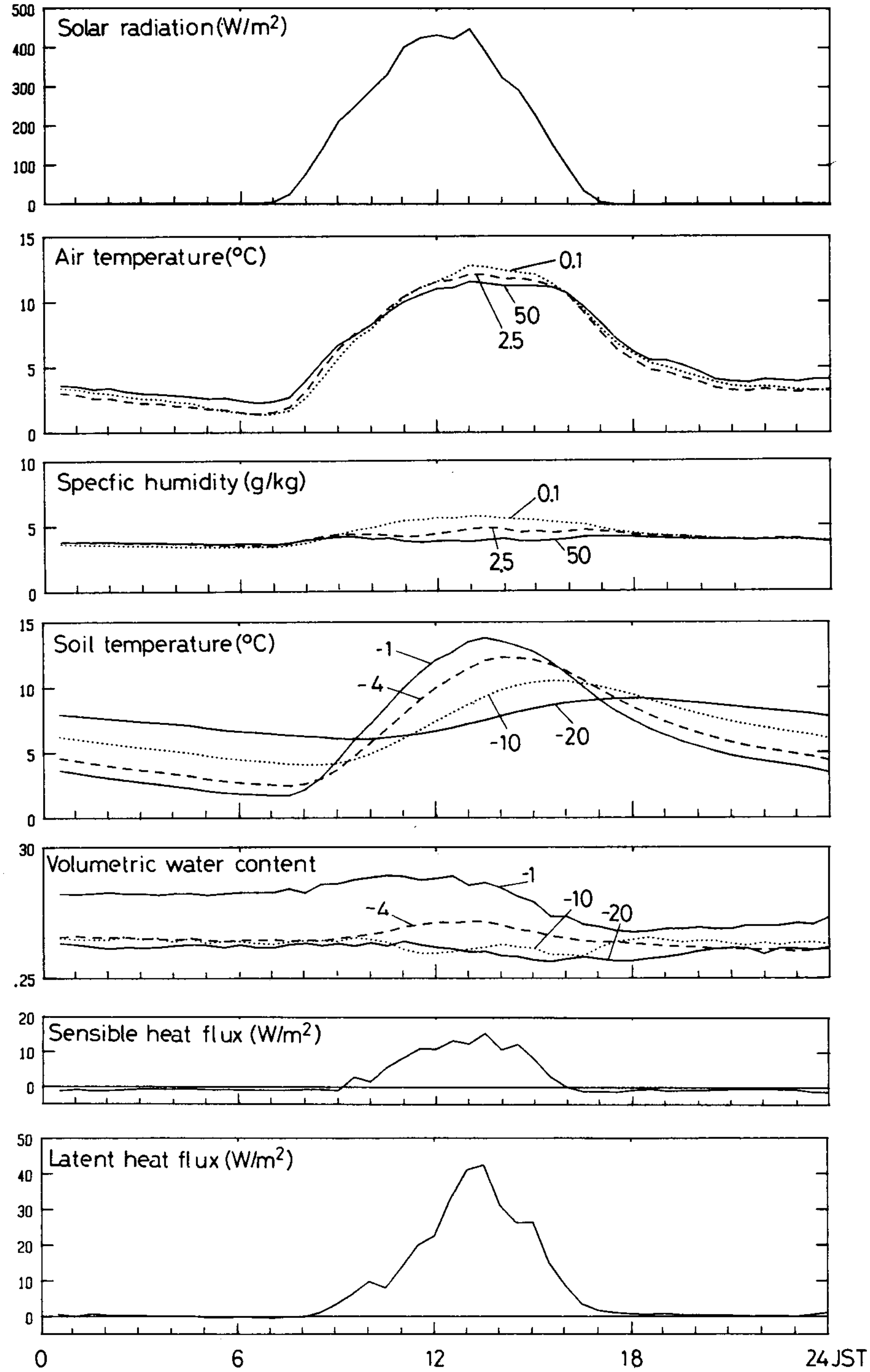

Figure 2. Superpositions (18 days) of the diurnal variations of solar radiation, air temperature, specific humidity, soil temperature, volumetric water content, sensible heat, and latent heat, where the numbers indicating the curves are the distance from the soil surface in centimeters, [from *Monji et al.*, 1990].

decay in "true" soil moisture content does not engender complete confidence in the model results.

Finally, we agree wholeheartedly that the matter of describing coupled heat and moisture transport in soils remains unresolved. The problem of reconciling downward thermally driven diffusion of water vapor in soils in the daytime, as predicted by PdV, with the upward movement of water vapor indicated by evaporation measurements in the atmospheric boundary layer needs to be resolved to understand the land-atmosphere interaction. Clearly, the PdV theory that has formed the basis for most soil-atmosphere continuum models in use today gives paradoxical results when compared to field measurements. To the best of our knowledge, there has not been a satisfactory comparison of water vapor flux measured in field soils with theory for moderate soil moisture contents [e.g., *Jackson et al*., 1974]. Note that we carried out the energy balance to calculate the effect of vapor flux on soil moisture content using soil temperature measurements. We note that the temperature measurements are, of course, more trustworthy than the soil moisture measurements. Our experimental observations on the magnitude of heat or moisture change due to vapor flow are similar to other field experimental studies [*Westcot and Wierenga*, 1974; *Cary*, 1965; *Rose* 1968; *Jackson et al*., 1974]. It is interesting that somehow this issue of the breakdown of PdV theory for water vapor movement under diurnal solar forcing has not been explored critically until recently [e.g., CP; *Parlange et al*., 1998; *Webb*, 1999; A. T. Cahill et al., Convectively enhanced water vapor movement at the Earth's surface, unpublished manuscript, 1998]. We agree with OW that further experimental work in the area of soil hydrology is needed; since TDR seems to be the field measurement of choice, the temperature effect on TDR measurements described by *Or and Wraith* [1999] needs to be taken into account in the future.

Acknowledgments. Partial funding for this work was provided from the NRI Competitive Grants Program/USDA.

References

Cahill, A. T. and M. B. Parlange, On water vapor transport in field soils, *Water Resour. Res*., *34*, 731–739, 1998.

Cary, J. W., Water flux in moist soils: Thermal versus suction gradients, *Soil Sci*., *100*, 168–175, 1965.

Dasberg, S., and J. W. Hopmans, Time domain reflectometry calibration for uniformly and nonuniformly wetted sandy and clayey loam soils, *Soil Sci. Soc. Am. J*., *56*, 1341–1345, 1992.

Jackson, R. D., Diurnal changes in soil water content during drying, in *Field Soil Water Regime*, edited by R. R. Bruce et al., *SSSA Spec. Publ*., *5*, 37–55, 1973.

Jackson, R. D., R. J. Reginato, B. A. Kimbell, and F. S. Nakayama, Diurnal soil-water evaporation: Comparison of measured and calculated soil-water fluxes. *Soil Sci. Soc. Am. J*., *38*, 861–866, 1974.

Monji, N., K. Hamotani, and Y. Omoto, Dynamic behavior of the moisture near the soil-atmosphere boundary, *Bull. Univ. Osaka Prefect., Ser. B*, *42*, 61–69, 1990.

Or, D., and J. M. Wraith, Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: A physical model, *Water Resour. Res.*, *35*, 371–383, 1999.

Or, D., and J. M. Wraith, Comment on "On water vapor transport in field soils" by A. T. Cahill and M. B. Parlange, *Water Resour. Res*., this issue.

Parlange, M. B., A. T. Cahill, D. R. Nielsen, J. W. Hopmans, and O. Wendroth, Review of heat and water movement in field soils, *Soil Tillage Res*., *47*, 5–10, 1998.

Pepin, S., N. J. Livingston, and W. R. Hook, Temperature-dependent measurement errors in time domain reflectometry determinations of soil water, *Soil Sci. Soc. Am. J*., *59*, 38–43, 1995.

Philip, J. R., and D. A. de Vries, Moisture movement in porous materials under temperature gradients, *Eos Trans. AGU*, *38*, 222–232, 1957.

Rose, C. W., Water transport in soil with a daily temperature wave, I, Theory and experiment, *Aust. J. Soil Res*., *6*, 31–44, 1968.

Webb, S. W., Temperature gradient effects on vapor diffusion in partially-saturated porous media, paper presented at 5th ASME/JSME Thermal Engineering Conference, Am. Soc of Mech. Eng., San Diego, Calif., March 15–19, 1999.

Westcot, D. W., and P. J. Wierenga, Transfer of heat by conduction and vapor movement in a closed soil system, *Soil Sci. Soc. Am. Proc*., *38*, 9–14, 1974.

Wraith, J. M., and D. Or, Temperature effects on soil bulk dielectic permittivity measured by time domain reflectometry: experimental evidence and hypothesis development, *Water Resour. Res*., *35*, 361–369, 1999.

A. T. Cahill, Department of Civil Engineering, Texas A & M University, College Station, Texas 77843-3136.

M. B. Parlange, Department of Geography and Environmental Engineering, Johns Hopkins University, 313 Ames Hall, Baltimore, MD 21218. (mbparlange@jhu.edu)

(Received December 22, 1998; revised April 19, 2000; accepted April 20, 2000.)