Thermal and Hydrologic Signatures of Soil Controls on Evaporation: A Combined Energy and Water Balance Approach with Implications for Remote Sensing of Evaporation

**(NASA New Investigator Program, Part 1 of funds: *NAGW 5255* 7/1/96-12/31/97
Part 2 of funds: *NAG5-6716* 01/01/98 - 06/30/00)**

Final Technical Report

Guido D. Salvucci
Boston University
Department of Geography
675 Commonwealth Ave.
Boston MA 02215

phone: 617-353-8344
fax: 617-353-8399
email: gdsalvuc@bu.edu

I. Background

The overall goal of this research, as detailed in the original project description, is to examine the feasibility of applying a newly developed diagnostic model of soil water evaporation to large land areas using remotely sensed input parameters. The model, described in *Salvucci* [1997a], estimates the rate of soil evaporation during periods when it is limited by the net transport resulting from competing effects of capillary rise and drainage. The critical soil hydraulic properties are implicitly estimated via the intensity and duration of the first stage (energy limited) evaporation, removing a major obstacle in the remote estimation of evaporation over large areas. This duration, or "time to drying" (t_d), is revealed through three signatures detectable in time series of remote sensing variables. The first is a break in soil albedo that occurs as a small vapor transmission zone develops near the surface [*Idso et al.*, 1974]. The second is a break in either surface to air temperature differences or in the diurnal surface temperature range, both of which indicate increased sensible heat flux (and/or storage) required to balance the decrease in latent heat flux (e.g. *Diak and Whipple*, [1995]; *Shouse et al.* [1982]). The third is a break in the temporal pattern of near surface soil moisture. Soil moisture tends to decrease rapidly during stage I drying (as water is removed from storage), and then become more or less constant during soil limited, or "stage II" drying (as water is merely transmitted from deeper soil storage). The research tasks, as described in the initial proposal, address: 1) improvements in model structure, including extensions to transpiration and aggregation over spatially variable soil and topographic landscape attributes; and 2) applications of the model using remotely sensed input parameters.

II. Summary of Progress

Progress on this grant can be grouped into five related efforts: 1) Testing the diagnostic model and the ability to detect the time to drying (t_d) at the FIFE site; 2) Extending the basic structure of the model to explicitly address transpiration dynamics; 3) Incorporating soil and topographic induced heterogeneity into soil moisture and evaporation predictions. As part of this effort, we have conducted feasibility tests of using series of high resolution thermal (Landsat) imagery to estimate time averaged patterns t_d for mapping surface hydrologic fluxes and groundwater recharge. This effort has formed the core of a dissertation by John Levine, who will continue to work on the problem past the end of this grant; 4) Developments of statistical methods to infer the probability distribution of the time between storms (t_b) from monthly rainfall totals such that t_d and t_b can be compared and integrated over for mean estimation of evaporation from monthly climate data; and 5) Investigating rate-limiting processes in evaporation, specifically the role of vapor vs. liquid transport. Below our progress in each effort is discussed, along with a listing of publications and presentations of results. Parts of this report are directly reproduced from the earlier Progress Report covering 7/1/97-12/31/98.

1) FIFE Tests: The time series of evaporation from each eddy correlation and bowen ratio station were analyzed in detail for the period spanning 1987 to 1989. Four major dry-downs were identified during periods of measurement, and for those we analyzed the temporal patterns of albedo, surface temperature, soil moisture (where available), rainfall, and leaf area index. Most of the station data supported both the evaporation model, and the ability to estimate the critical input parameter t_d from the concurrent albedo, moisture and temperature measurements. In general the model worked best for long dry-downs.

To test the diagnostic model using satellite sensed t_d, the data were spatially aggregated. Albedo and daytime temperature differences measured by GOES gave the best estimates of time to drying. During the drydown spanning September 10 (day 255) to October 12 1987, for example, the best fit transition time based on the evaporation data was day 268, while surface measured temperature, moisture, and albedo indices estimated day 273, 270, and 267 respectively. GOES-7 estimated albedo and temperature difference index (thermal radiance at 1:30pm minus 7:30 am) each yielded and estimate of day 270. These evaporation, temperature, moisture and albedo series are illustrated in Figure 1. For this month long dry down, the error in estimation of t_d causes less than ten percent error in cumulative evaporation. Regarding remote sensing capabilities, we conclude that one strength of our approach is that it does not rely on absolute values of surface parameters, but rather on their relative variations in time.

While the temperature and moisture indices appear to offer a clear signature of soil limited evaporation, there is some uncertainty at this point as to the relative contributions of soil and vegetation in the albedo measurements. While the dramatic increase in albedo could be attributed to senescence, we found that in general the ground based and satellite measured albedo *did not* follow the temporal pattern of surface measured green LAI, as one might expect. This could mean that the dramatic increase in albedo was indeed mostly caused by the brightening of the soil background, as found for example by *Idso et al.* [1974].

This work led to a masters thesis [*Amano*, 1997] and a paper in Remote Sensing Environment [*Amano and Salvucci*, 1999].

2) Scaling Transpiration Dynamics: As it currently exists, the model does not explicitly account for the effects of transpiration. To complement the analysis of the FIFE data (which, surprisingly, showed little relation between total evapotranspiration and LAI, further supporting the analysis of *Stewart and Verma* [1992]), we have coupled the unsaturated flow model developed by Chris Milly of GFDL [*Milly*, 1982] with the root sink model of *Cowan* [1965]. Our analyses indicate that a similar temporal scaling property exists for transpiration as for bare soil evaporation, i.e. stressed transpiration proceeds at a rate that may be scaled by "t_s", the time to stress, such that soil hydraulic properties need not be measured *in situ*. Essentially the same type of physical processes apply, except that transpiration becomes limited by competing capillary rise to and drainage from the root zone, as opposed to the soil surface.

Unlike the bare soil evaporation case which can be specified entirely in terms of time-to-drying and potential evaporation, the transpiration case requires one additional parameter group (initial moisture volume in the root zone) to be specified. If further modeling and data analysis support this method, the applicability of the model will be greatly enhanced (e.g. to grasslands and agricultural sites). An example of how well the simulated stressed transpiration drydowns collapse onto a common (scaled) curve is shown in figure 2. A large range of rooting depths, potential evaporation rates, and initial moisture contents were assumed to simulate each drydown, resulting in vastly different transpiration rates and times-to-stress ranging from 4 to 45 days. When time is scaled by t_s, and transpiration rate by a function of potential evaporation and root zone water storage, all of the transpiration traces collapse onto a more-or-less universal curve determined by the competing effects of capillary rise to and drainage from the root zone.

This work has been published in Water Resources Research [*Levine and Salvucci*, 1999].

3) Incorporating soil and topographic induced heterogeneity: One major effort over the past three years has been a modeling and field analysis of the role of soil texture and topography in determining the near surface moisture content after rainfall, and thus in determining the spatial variability and patterns in evaporation and time to drying. This work has included theoretical and field analysis of the relation between soil moisture and the so called scale factor (α) [*Warrick et al.*, 1977], and the modeling of coupled groundwater and surface water flows to explore the role of these couplings in spatial patterns of moisture, evaporation, and time to drying. The scale factor (α) is a parameter related to soil pore size distributions which has been widely used to simultaneously model random spatial variations in the Soil Water Retention Curve (SWRC) and hydraulic conductivity.

The groundwater-surface water modeling work, which is based on *Salvucci and Entekhabi* [1995], has lead us to a predictive description of *deterministic* spatial patterns of time to drying, which in the future will be applied to the Southern Great Plains 97 Soil Moisture Remote Sensing Project Sites. John Levine developed the model and participated in SGP97 while working as a research assistant on this grant, then applied the model to a related issue of groundwater-surface water interaction in the Canadian plains under an NSF supported grant, and then returned to this project to try to match predicted and remotely sensed areas undergoing changes of stage in drying (see below).

Regarding the field analysis of soil texture effects, we collected over 120 surface soil cores during rainstorms and drydowns, and performed laboratory analysis of their soil water retention to estimate the scale factor (α). The results have been very encouraging. We have found a simple power law relationship between the scale factor and the field moisture content of the form: $S_i = \langle s \rangle \left(\alpha_i / \langle \alpha \rangle\right)^n$ where the subscript i denotes the point-scale (i.e. soil core) value of saturation (S) and scale factor (α) and the angle brackets denote spatial averaging. The exponent of the power law (n) has been derived theoretically (from Richards equation of moisture flow) to be related in a simple fashion to the slope of the SWRC for the limiting cases of early time infiltration, long time infiltration, and long time transpiration, and long time bare soil evaporation. The analytical framework for this approach and comparisons with numerically simulated soil moisture fields have been summarized in a paper published in *Geophysical Research Letters* [Salvucci, 1998]. Figure 3a illustrates the temporal behavior of the exponent n under wetting and drying conditions as found in numerical simulations, along with the 4 analytically derived limits (solid lines). Figure 3b illustrates one example of of this relation for field measured soil moisture [*Ravella*, 1998]. This work has strong implications for scaling up the basic evaporation model because the derived power law implies a related power law relation between time to drying and α, from which we have derived a statistically spatially integrated dry down law [*Amano*, 1997]). This work also has strong implications for the interpretation and relation of in situ and remotely sensed soil moisture.

As discussed above, John Levine, who also participated in effort number 2 *Scaling Transpiration Dynamics*, is continuing work on using time series of high resolution thermal (Landsat) imagery to estimate time averaged patterns t_d for mapping surface hydrologic fluxes and groundwater recharge. Early results are promising, but final methods and publications will not be completed for another 12 months. This effort, which John will perform without funding, will form the final part of his Ph.D. Dissertation.

4) Temporal Disaggregation: The original proposal detailed the need to estimate the probability distribution of the time between storms such that the fraction of time in stage-one vs. stage-two could be determined from monthly climate data. While many models exist for describing rainfall intermittency, none determined how this distribution changes from month to month given rainfall totals. The proposed method should be useful for those situations in which knowledge of storm or interstorm characteristics are required (e.g. for driving the evaporation model derived herein, or more generally for other hydro-ecological and rainfall-runoff models), but for which precipitation data is only available, or only of sufficient quality, as a monthly aggregate. This condition exists in many historical, satellite derived, and model assimilated/generated precipitation data sets.

To address this need, we derived analytical probability distributions, using Bayes' theorem, for the conditional arrival rate and conditional depth distribution for a given realization of monthly total precipitation. The conditioning procedure yields answers to questions of the following nature: If the precipitation in a given month is twice the mean, what is the likelihood that it rained more frequently and/or with larger storm depths ? The derived frequency can then be compared with estimates of the time to drying so that the percent of time in stage-one vs. stage-two evaporation (or transpiration) can be determined. From these percentages and the analytical expression of drydown rates, monthly ET estimates can be formed. Two examples of the conditional storm distribution are provided in Figures 4a and b.

This work led to a paper in the Journal of Hydrometeorology [*Salvucci and Song*, 2000].

5) Rate Limiting Processes in Soil Evaporation: The methods derived in this proposal rest heavily on an assumption [*Salvucci*, 1997] that liquid transport to the drying front at which vaporization takes place is the rate-limiting process in evaporation, and not vapor transport between the drying front and atmosphere. A set of numerical experiments were conducted to test this hypothesis, and a simple two-region analytical model (one liquid dominated and one vapor dominated) with a moving boundary was derived. The results of both the numerical and analytical integrations indicate that indeed liquid transport is the rate-limiting process under most conditions, and thus this critical assumption in the derived methods holds up.

This work had further implications for land surface modeling of heat and moisture transport and has been published in Advances in Water Resources [*Saravanapavan and Salvucci*, 2000].

III. Statement of Inventions and Patents

No inventions have been produced.

IV. References

Cowan, I.R., Transport of water in the soil-plant-atmosphere system, *Journal of Applied Ecology*, 2, 1965.

Diak, G.R., and M.S. Whipple, Note on estimating surface sensible heat fluxes using surface temperatures measured from a geostationary satellite during FIFE 1989, *Journal of Geophysical Research, 100* (D12), 25453-25461, 1995.

Idso, S.B., R.J. Reginato, R.D. Jackson, B.A. Kimball, and F.S. Nakamaya, The three stages of drying in a field soil, *Soil Science Society of America Proceeding*, 38, 831-836, 1974.

Milly, P.C.D., Moisture and heat transport in hysteretic, inhomogeneous porous media: a matric head based formulation and a numerical model, *Water Resources Research*, 18(6), 489-498, 1982.

Shouse, P., W.A. Jury, and L.H. Stolzy, Field measurement and modeling of cowpea water use and yield under stressed and well watered growth conditions, *Hilgardia*, 50, 1-25, 1982.

Stewart, J.B., and S.B. Verma, Comparison of surface fluxes and conductances at two contrasting sites within the FIFE area, *Journal of Geophysical Research, 97*, 18623-18628, 1992.

Warrick, A.W., G.J. Mullen, and D.R. Nielsen, Scaling field measured soil hydraulic properties using a similar media concept, *Water Resources Research*, 13(2), 355-362, 1977.

V. Published Work, Work in Progress, and Conference Contributions supported by NAGW-5255 and NAG5-6716

Student Theses (4)

Amano, E., Estimation of interstorm soil limited evaporation over bare and sparsely vegetated surfaces using remote sensing, Masters Thesis, Boston University, 1997.

Ravella, M.R. Field observations of the relation between near surface soil moisture and the similar media parameter alpha, Masters Thesis, Boston University, 1998.

Thambirajah Saravanapavan, MA, 1999. Analysis of rate-limiting processes in soil evaporation with implications for soil resista nce Models, Masters Thesis, Boston University, 1999.

Levine, J.B. Modeling and monitoring of coupled saturated-unsaturated zone hydrologic processes. Doctoral Dissertation in Progress.

Published Peer-Reviewed Journal Articles (6)

Salvucci, G.D., Soil and moisture independent estimation of stage-two evaporation from potential evaporation and albedo or surface temperature, *Water Resources Research*, 33(1), 111-122, 1997.

Salvucci, G.D., 1998: Limiting relations between soil moisture and texture with implications for measured, modeled and remotely sensed estimates, *Geophysical Research Letters, 25* (10), 1757-1760.

Amano, E., and G.D. Salvucci, 1999: Detection and use of three signatures of soil limited evaporation at FIFE, *Remote Sensing of Environment, 67*(1), 108-122.

Levine, J.B., G.D. Salvucci, 1999: Characteristic rate and time scales of supply-limited transpiration under a Richards/Cowan framework, *Water Resources Research*, *35*(12), 3947-3954.

Saravanapavan, T., and G. D. Salvucci, 2000: Analysis of rate-limiting processes in soil evaporation with implications for soil resistance models, *Advances in Water Resources*, *23*, 493-502.

Salvucci, G.D., and **C. Song, 2000: Derived distributions of storm depth and frequency conditioned on monthly total precipitation: Adding value to historical and satellite-derived estimates of monthly precipitation, *Journal of Hydrometeorology*, *1*(2), 113-120.

In Review/in Progress Peer-Reviewed Journal Articles (1)

Ravella, M.R., and G.D. Salvucci, Field observations of the influence of similar-media heterogeneity on near surface soil moisture during wetting and drying events.

Abstracts and Presentations (10)

Salvucci, G.D., Surface and subsurface moisture dynamics during transitions between atmosphere and soil limited evaporation, Feb. 1997 *American Meteorological Society*

Amano, E., and G.D. Salvucci, Estimation of soil limited evaporation over semiarid areas using remote sensing, Spring meeting of *American Geophysical Union*, 1997.

Salvucci, G.D. and E. Amano, Surface and satellite estimates of the transition between soil and atmosphere limits on evaporation, (Invited), Spring meeting of *American Geophysical Union*, 1997.

Salvucci, G.D. and M. Ravella, Limiting relations between soil moisture and soil texture based on similar media theory, Fall 1997 *American Geophysical Union*

Ravella, M. and G.D. Salvucci, Field observations of the relation between near surface soil moisture and the similar media parameter alpha, Fall 1997 *American Geophysical Union*

Salvucci, G. D, Empirical estimation of evaporation efficiency from monthly moisture and precipitation statistics, Fall 1998 *American Geophysical Union*

Saravanapavan, T., and G.D. Salvucci, Limiting processes in soil evaporation, Fall 1998 *American Geophysical Union*

Ravella, M. and G.D. Salvucci, Spatial variability of near surface soil moisture during field drydown conditions, Spring 1998 *American Geophysical Union*

Salvucci, G. D, and C. Song, Derived distributions of storm depth and frequency conditioned on monthly total precipitation: Adding value to historical and satellite-derived estimates of monthly precipitation, Spring 1999 *American Geophysical Union.*

Levine, J. B. and G.D. Salvucci, Characteristic rate and time scales of supply limited transpiration under a Richards-Cowan framework, Spring 1999 *American Geophysical Union*

Invited Seminars (5)

Salvucci, G.D., Characterization of Hydrologic Processes for Modeling and Remote Sensing Retrieval, Harvard University, Division of Engineering and Applied Sciences, Cambridge, Massachusetts, May 11, 1998.

Salvucci, G.D., Characterization of Hydrologic Processes for Modeling and Remote Sensing Retrieval, Massachusetts Institute of Technology, Department of Civil and Environmental Engineering, Cambridge, Massachusetts, May 18, 1998.

Salvucci, G.D., Characterization of Hydrologic Processes for Modeling and Remote Sensing Retrieval, Cornell University, Department of Agricultural and Biological Engineering, Ithaca, New York, June 5, 1998.

Salvucci, G.D., Estimation and Prediction of Hydrologic Processes through Simple Models,Measurable Parameters, and Statistical Aggregation, Boston College Department of Geology and Geophysics, Boston, Massachusetts, December 4, 1997.

Salvucci, G.D., Estimation of soil limited evaporation from surface observations, Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, Maryland, December 10, 1996

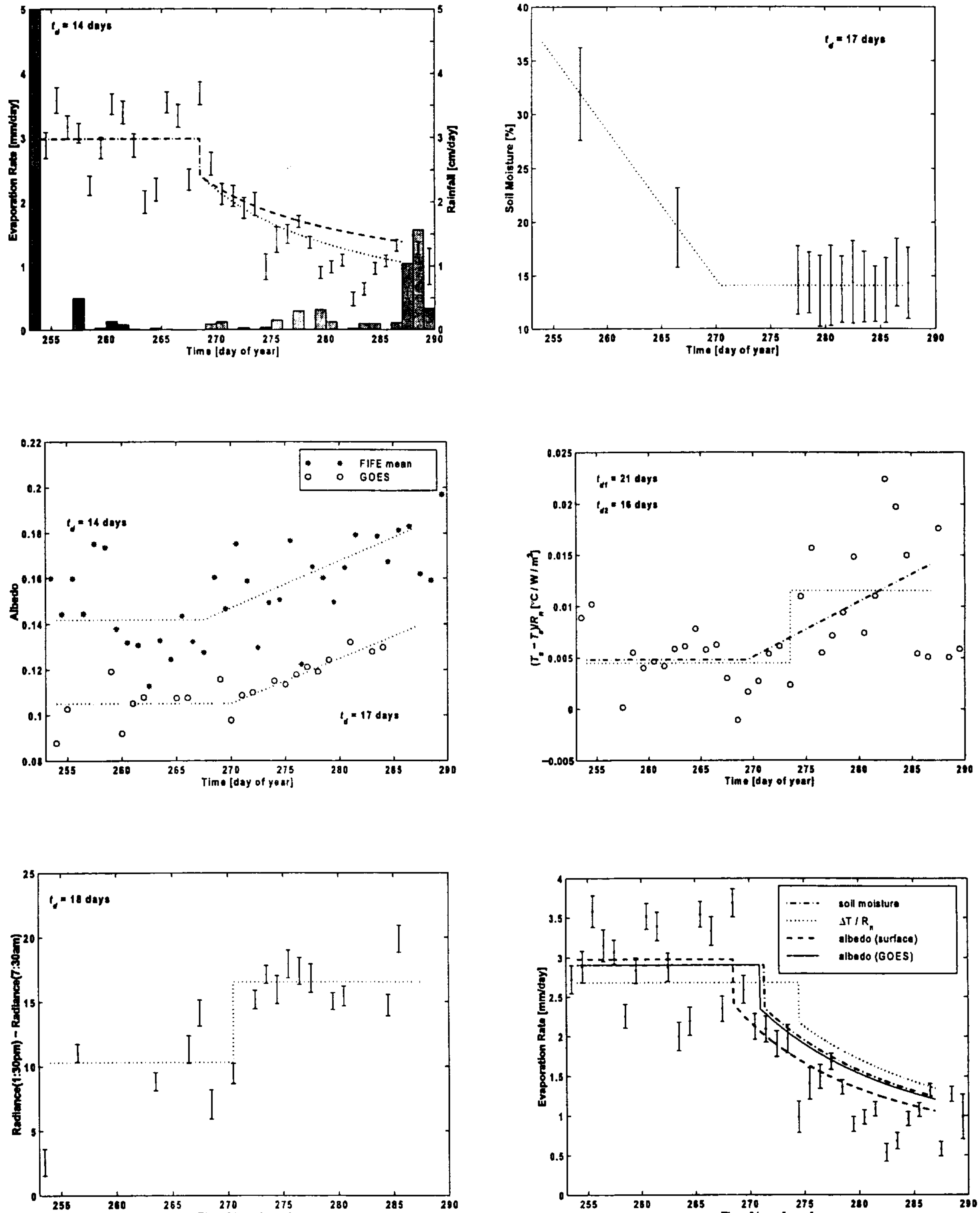


Figure 1: Stages of drying at FIFE revealed in series of evaporation, albedo, temperature, and moisture.

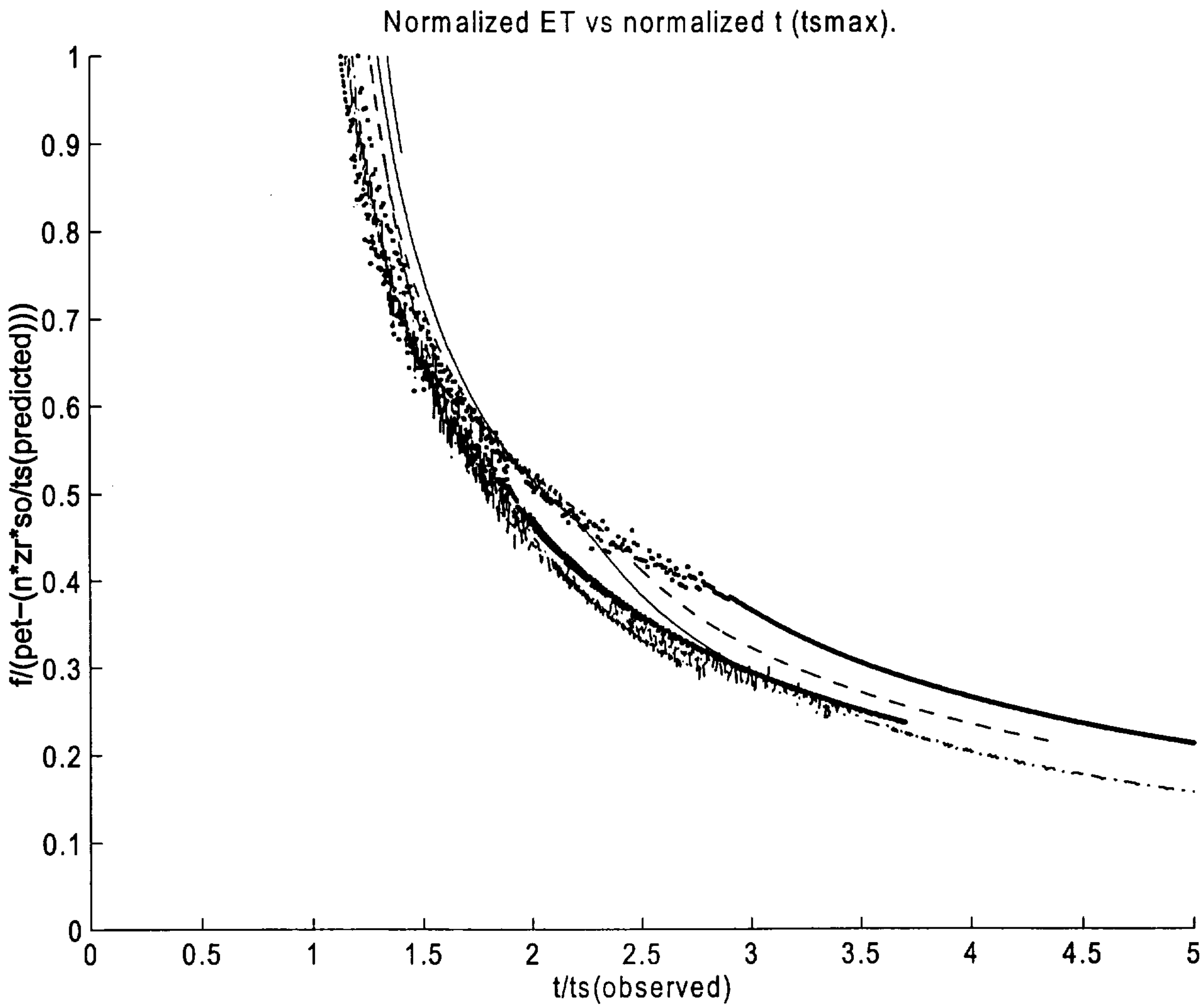
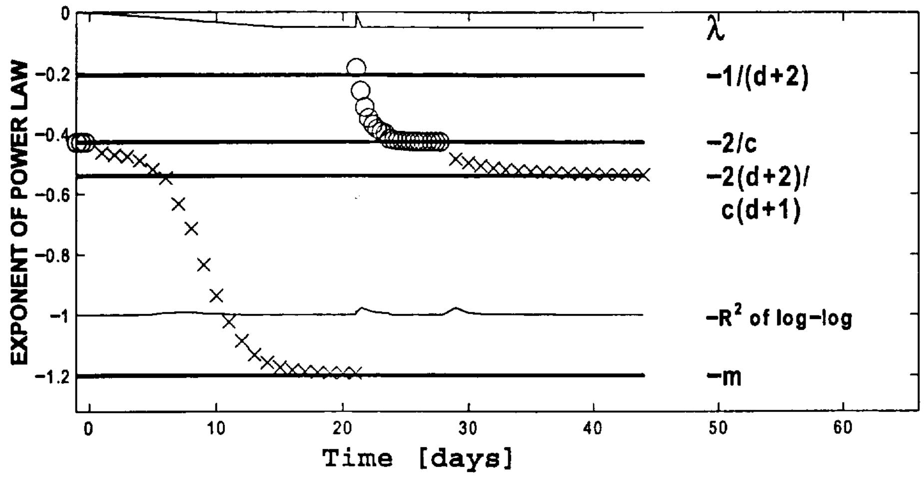


Figure 2: Traces of simulated stressed transpiration under vastly different initial moisture content, potential evaporation rates, and rooting depths. Time is scaled by "ts", the time from rainfall until the onset of stress. Transpiration is scaled by the difference between potential evapotranspiration and a function of root zone water storage. All traces collapse onto a common curve determined by competing effects of gravity drainage from and capillary rise to the root zone. As for the bare soil case [*Salvucci*, 1997a], detailed soil hydraulic characterization need not be specified because it is reflected in the time-to-stress.



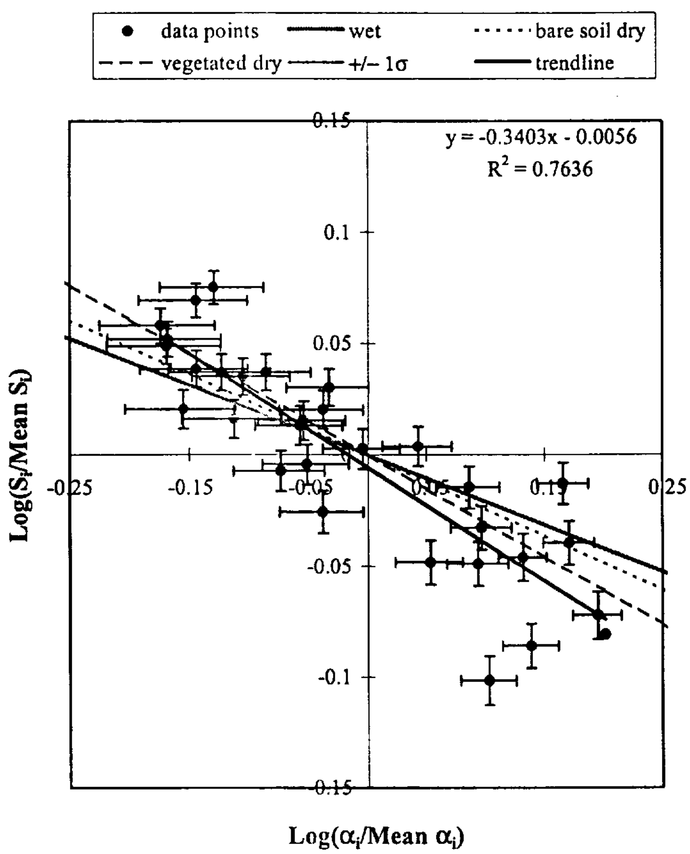


Figure 3a: (top) Behavior of simulated exponents of power law relation between soil saturation and the Miller and Miller scaling parameter alpha [*Salvucci*, 1998].

Figure 3b: (bottom) Example field test of power law relation between soil moisture and alpha [*Ravella*, 1998].

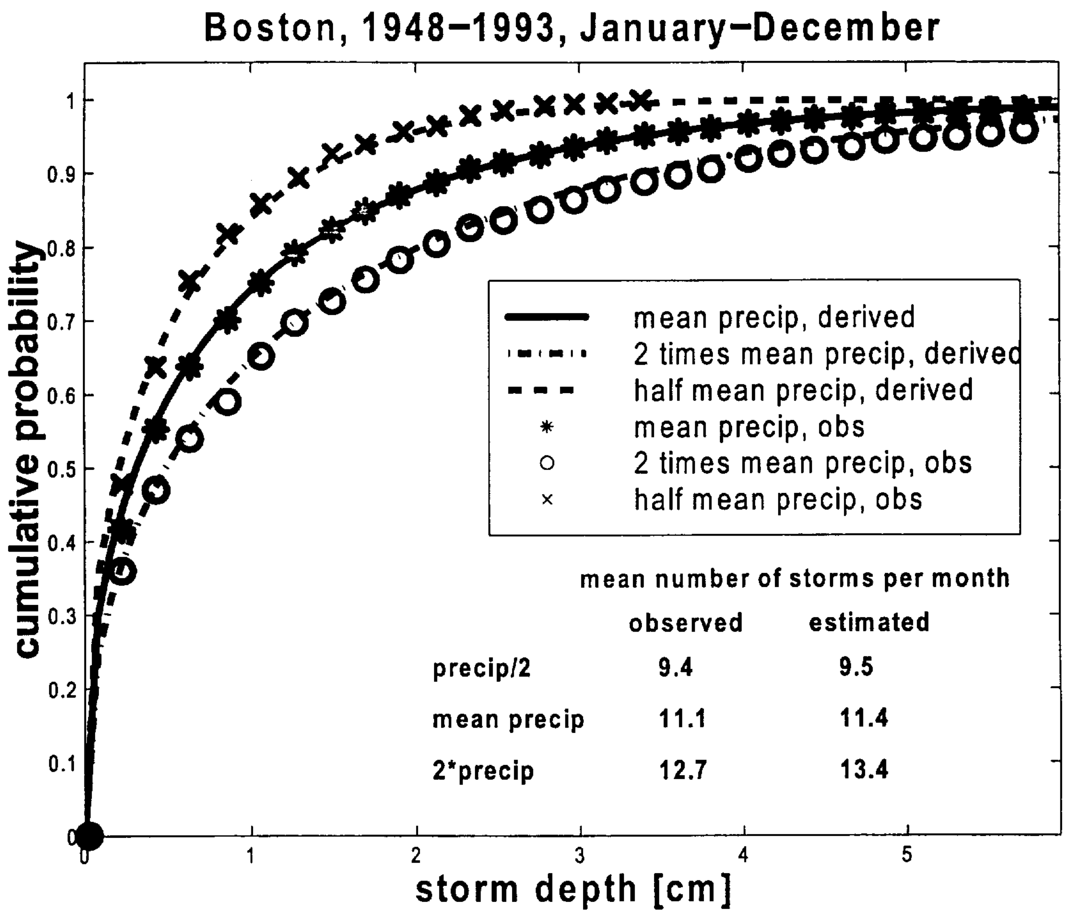


Figure 4a: Comparison of empirical and derived distributions of storm depth and frequency conditioned on monthly aggregated precipitation for storm climate of Boston, Massachusetts.

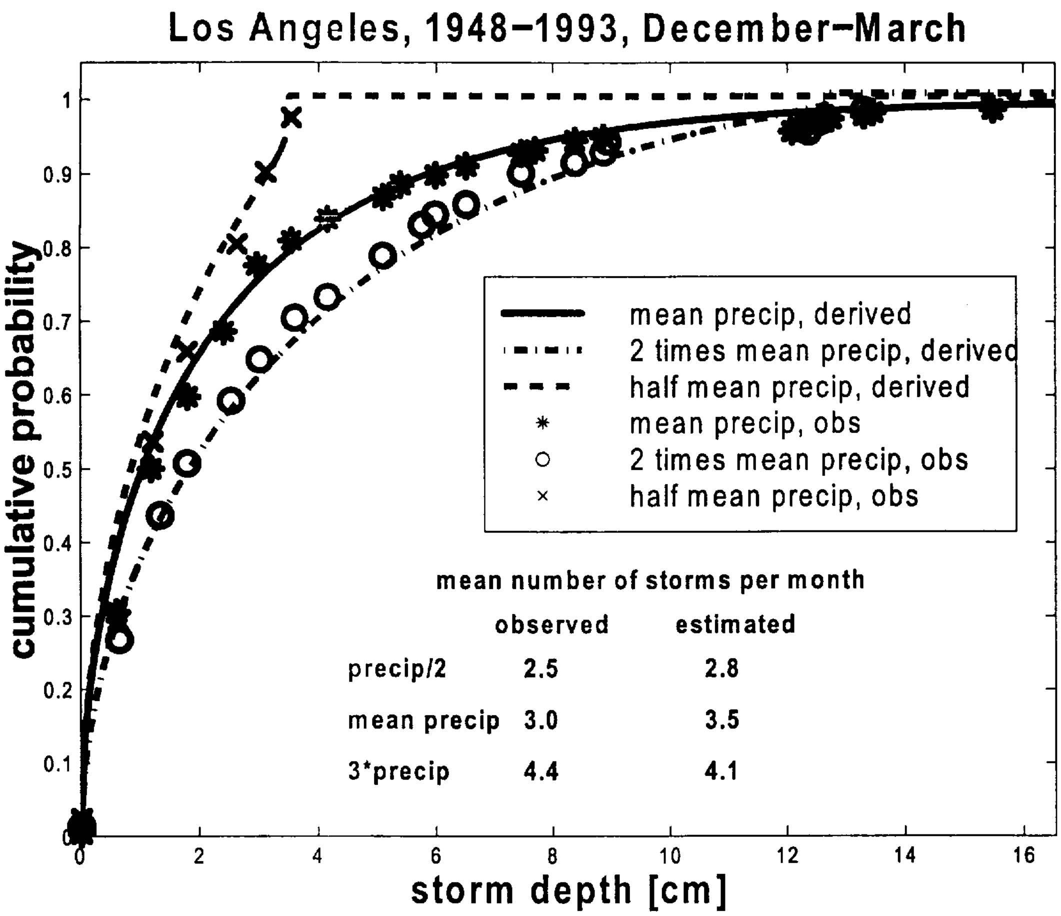


Figure 4b: Comparison of empirical and derived distributions of storm depth and frequency conditioned on monthly aggregated precipitation for storm climate of Los Angeles, California.