THERMAL PROPERTIES OF AN UPPER TIDAL FLAT SEDIMENT ON THE TEXAS GULF COAST

A Thesis

by

NICHOLAS C. CRAMER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2006

Major Subject: Soil Science

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Approved by:

Chair of Committee,	J. L. Heilman
Committee Members,	K. J. McInnes
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ABSTRACT

Thermal Properties of an Upper Tidal Flat Sediment on
the Texas Gulf Coast. (December 2006)
Nicholas C. Cramer, B.S., Purdue University
Chair of Advisory Committee: Dr. James L. Heilman

Increased land use change near fragile ecosystems can affect the ecosystem energy balance leading to increased global warming. One component of surface energy balance is soil storage heat flux. In past work, a complex thermal behavior was noticed in the shrink-swell sediment of the upper Nueces Delta (upper Rincon) during summer months as it dried. Soil storage heat flux was found to first increase, then decrease, as the soil dried. It was suggested that the complex behavior was due to the relationship between thermal diffusivity and soil moisture, where thermal diffusivity increases to a local maximum before decreasing with respect to decreasing soil moisture. This study explores the observed phenomenon in a controlled laboratory environment by relating the sediment shrinkage curve to changing heat transfer properties.

Due to the complicated nature of the drying-shrinking sediment, it was necessary to measure the sediment shrinkage curve and heat transfer properties in separate experiments. The shrinkage curve was found by correlating measured sample volume with gravimetric moisture content. Heat transfer properties were found using a single needle heat pulse probe. A normalized gravimetric moisture content was used as a common variable to relate the shrinkage curve and heat transfer data.

Data suggests that the shrink-swell Rincon sediment portrays different behavior in drying than that which occurs for a non-shrink-swell soil. For the shrink-swell Rincon sediment, thermal conductivity is seen to increase with decreasing moisture, the suggested mechanism being increased surface area contact between particles as the shrinking sediment dries.

ACKNOWLEDGEMENTS

Appreciation goes to the chair of my committee, Dr. Heilman, and my committee members, Dr. McInnes and Dr. Roelke whose guidance and support allowed me to gain invaluable experience in diverse areas of research. I would like to extend special gratitude to Kathy Schmitt as well as the Faculty and Staff of the Soil and Crop Sciences Department for sharing their technical expertise and resources. Finally I cannot thank or show enough appreciation to my friends and family for being just that, my family and friends.

> "Sic vive tamquam cras moriturus, sic stude quasi semper victurus."
>
> Desiderius Erasmus of Rotterdam (1466-1536).

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INTRODUCTION

Land-use changes can have far-reaching effects on ecosystem processes. Alterations in surface cover can drastically affect surface energy balance partitioning, which in turn may cause shifts in ecosystem dynamics. Increased levels of radiation reflected or emitted by the surface may warm the atmosphere, affect meteorological patterns (Jin et al., 2005), and subsequently lead to increased global warming. Such radiation may be a greater contributor to global warming than are increased levels of greenhouse gasses (Pielke et al., 2002).

Increased human population diminishes both the amount of resources and the rate at which these resources are available to natural ecosystems. In coastal areas, increased anthropogenic need results in land-use change to support growth, and water may be appropriated from or diverted to downstream areas. This disruption of the natural hydrologic cycle alters freshwater influx upon which fragile estuarine ecosystems depend. Loss of freshwater can cause low-lying coastal areas to dry, which decreases overall productivity (Deegan et al., 1986; Porter et al., 1997; Sklar and Bruder, 1998; White et al., 2002) and increases the surface area of bare sediment exposed to the atmosphere. While it is true that diverted surface waters from multi-year storm events can inundate coastal areas, potentially restarting a coastal ecosystem through scouring, erosion and fresh deposition, it is also true that these events may only provide short-term relief. In many cases the ecosystem will eventually return to a fresh-water starved state.

This thesis follows the style of Soil Science Society of America Journal.

Temperature of bare and dry soil will increase more per unit solar irradiance than will soil which is submerged or covered by vegetation (Campbell and Norman, 1998). As the temperature of bare soil increases the rate at which evaporation occurs also increases. Increased loss of soil moisture means that peripheral vegetation is more stressed and likely to perish (Mitsch and Gosselink, 2000), exposing soil to erosion. Loss of this soil makes it increasingly more difficult for vegetation to regain a foothold on channel edges.

The Nueces River Estuary, near Corpus Christi, TX, covers approximately 120 square kilometers along the coastal bend of Southeast Texas, and is a richly diverse ecosystem that holds both economic and recreational importance for the State of Texas. The Nueces Delta acts as a haven for aquatic juveniles for both sport (Scates and Shook, 1999; Sikes, 2001) and industrial fishing (Riera et al., 2000), as well as for migrating waterfowl (Tyler, 1996). Over the past seventy years, the city of Corpus Christi has stored, diverted, or otherwise extracted freshwater from the Nueces watershed that would have supported the Nueces Delta ecosystem through the natural hydrologic cycle (Bureau of Reclamation, 2000). Such diversions have caused the system, particularly the upper Delta, to rely on numerous multi-year storm events to maintain itself. In this estuarine system, productivity is correlated with regulated release of freshwater inflow. Thus it is the goal of the city of Corpus Christi to develop a method by which planned release of upstream waters by the City of Corpus Christi would both maximize control of freshwater for the City while also maximizing productivity of the Nueces Estuarine system (Bureau of Reclamation, 2000; Riera et al., 2000).

In past work, Heilman et al. (2000) noticed a complex thermal behavior in the sediment of the upper Nueces Delta (upper Rincon) during summer months as it dried. They found soil storage heat flux first increased, then decreased, as the soil dried. With environmental conditions on each of the days being similar, it was suggested that the mitigating factor between each day was soil moisture, with moisture decreasing for days later in the summer. It was further suggested that the complex behavior was due to the relationship between thermal diffusivity and soil moisture (Jury et al., 1991), where thermal diffusivity increases to a local maximum before decreasing with respect to decreasing soil moisture.

Thermal diffusivity is the ratio of thermal conductivity to volumetric heat capacity. A soil with a high thermal conductivity will have a higher storage heat flux than a soil with a lower thermal conductivity. For a soil whose bulk density is relatively constant with diminishing soil moisture, thermal conductivity will decrease at a varying rate as air replaces water in the soil matrix (Hillel, 1998). Volumetric heat capacity, on the other hand, decreases linearly with decreasing moisture content. As a result, thermal diffusivity first increases and then decreases as a saturated soil dries (Jury et al., 1991).

Unlike the soils whose behavior have been described by Jury et al. (1991) and Hillel (1998), the soil of the Upper Rincon tidal flats is an unconsolidated alluvial sediment (Heilman et al., 2000) with a high shrink - swell potential. Collapsing pore space in an unconsolidated sediment may compensate for water volume lost (Brown et al., 1980) as the mixture dries, and minimize changes in thermal diffusivity.

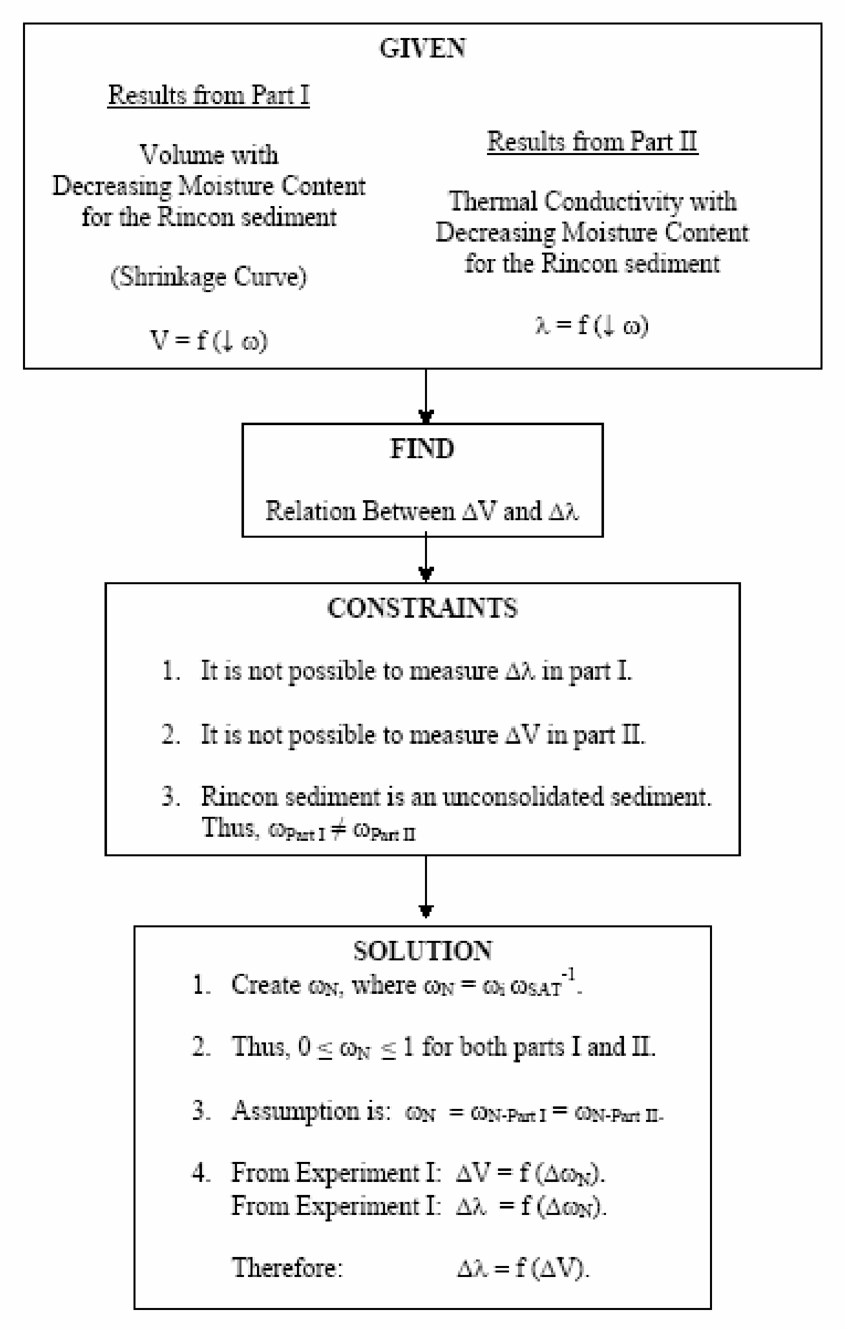
The objective of this research is to quantify the relationship between thermal diffusivity and water content of an upper tidal flat sediment in the Nueces River Delta.

MATERIALS AND METHODS

There were three parts to this study. Figure 1 outlines each part as well the relationships between them. In the first part a shrinkage curve of volume to moisture loss was created for the Rincon sediment. In the second part, thermal conductivity and changing sediment weight were measured while the Rincon sediment was oven-dried in a 600 ml beaker. In the third part, a normalized gravimetric moisture content was used to correlate volume data from part one with thermal conductivity data from part two. Part three was critical for this study because it was not possible to collect volume data during part two. Without the normalized gravimetric moisture content the author would have had no way to correlate shrinkage with changing thermal properties as the sediment dried. The three parts of this study are discussed independently in the following sections. All data reduction, processing, and portrayal was done using Matlab 6.5.1 (The Mathworks, Inc., Natick, MA)

Soil samples were taken from the acquisition footprint of the energy balance study performed by Heilman et al. (2000). Laboratory analyses were used to determine bulk density, particle density, and moisture content, according to methods described later in this section. Atterberg limits were determined according to ASTM standards. Salinity was determined according to methods discussed in Klute (1986) using a YSI Model 3100 Instrument (YSI Incorporated, Yellow Springs, Ohio).

Salinity of the soil is of interest due to its affect on both the thermal and shrinking behavior of the soil. It is expected that salinity is low in the flooded tidal flats, increases through evaporation, and potentially approaches a condition of hypersalinity at extremes



GIVEN

Results from Part I

Volume with Decreasing Moisture Content for the Rincon sediment

(Shrinkage Curve)

$V = f(\downarrow \omega)$

Results from Part II

Thermal Conductivity with Decreasing Moisture Content for the Rincon sediment

$\lambda = f(\downarrow \omega)$

FIND

Relation Between ΔV and $\Delta\lambda$

CONSTRAINTS

1. It is not possible to measure $\Delta\lambda$ in part I.
2. It is not possible to measure ΔV in part II.
3. Rincon sediment is an unconsolidated sediment. Thus, $\omega_{\text{Part I}} \neq \omega_{\text{Part II}}$

SOLUTION

1. Create ω_N, where $\omega_N = \omega_i\, \omega_{SAT}^{-1}$.
2. Thus, $0 \leq \omega_N \leq 1$ for both parts I and II.
3. Assumption is: $\omega_N = \omega_{N\text{-Part I}} = \omega_{N\text{-Part II}}$.
4. From Experiment I: $\Delta V = f(\Delta\omega_N)$.
   From Experiment I: $\Delta\lambda = f(\Delta\omega_N)$.

   Therefore: $\Delta\lambda = f(\Delta V)$.

Fig. 1. Study outline. V is volume, λ is thermal conductivity, and ω, ω_i, ω_{SAT}, and ω_N are the general, moisture specific, saturated, and normalized gravimetric moisture contents, respectively.

of the drying cycle. Salinity in the upper Nueces Delta is a function of the frequency and intensity of both upstream, freshwater, and downstream, seawater, flushing events that have occurred in ‘recent’ time.

Part One - The Rincon Sediment Shrinkage Curve

As water is lost from a soil with a shrinking/swelling potential, the volume of the soil will decrease and bulk density will increase. A relation between changing volume and sediment water content can be found from the sediment’s shrinkage curve where changing sediment density is plotted as a function of water content. This relation can be used to find the sediment density at a specific moisture content. The following process was used to determine the shrinkage curve of the Rincon sediment.

Pre-weighed and measured soil tins were coated with a thin layer of Vaseline, then filled with well-mixed and saturated Rincon sediment. Weight was measured using a Mettler PC 400 balance. The dimensions of each soil tin were determined by physical measurements using calipers (Series 505-675, Mitutoyo America Corporation, Westford, MA.). Initial volume of sediment in the soil tins was found using geometry where the diameter of the sediment column and tin were the same and the height of the sediment was the difference between the tin height and the distance from the tin top to the sediment top (Fig. 2).

The soil tins were dried in an oven at 100 °C for approximately 1 hour. Drying intervals depended on the amount of shrinkage observed. When a visibly significant

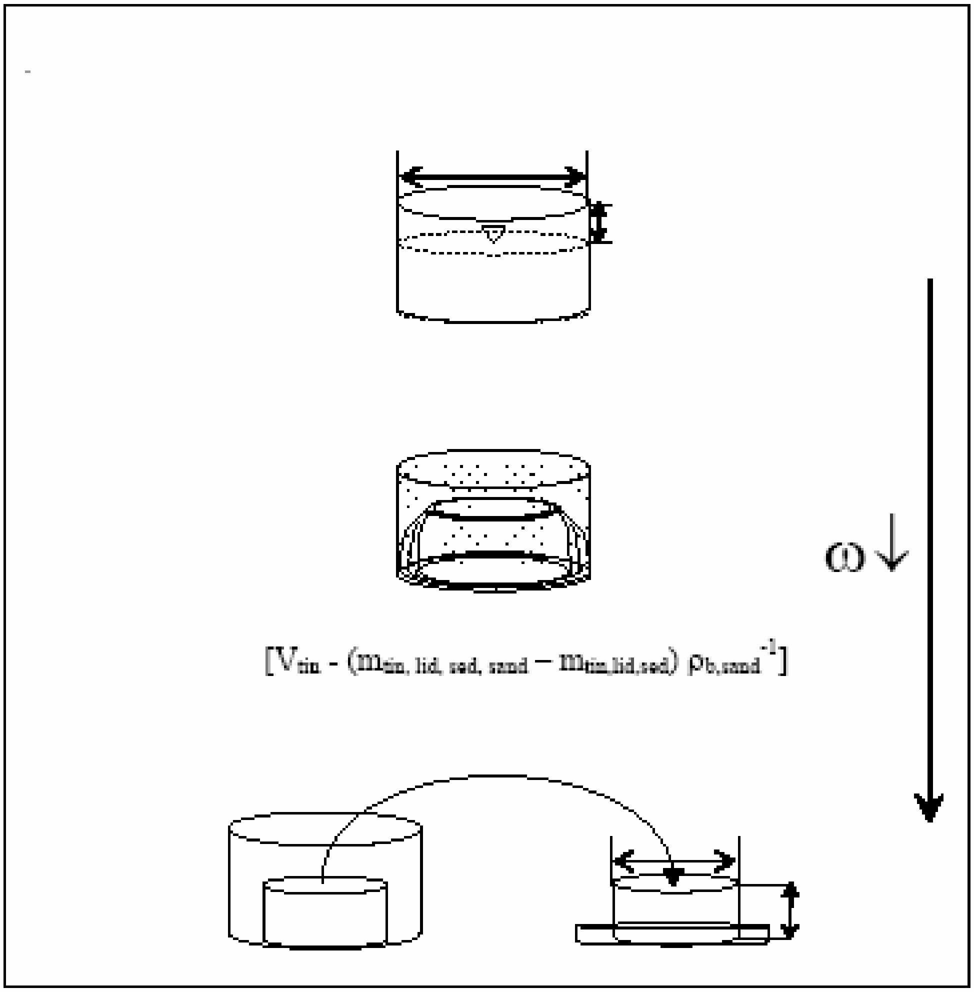


Fig. 2. Differing methods by which volume was measured along the sediment drying curve. Note that m is mass and ρ_b is bulk density.

amount of volume was lost, the soil tins were removed from the oven and allowed to cool to room temperature before being measured for weight and volume.

The physical state of the Rincon sediment was observed to pass through three shrinkage regimes as the sediment dried. Each state was defined by a distinct change in sediment consistency and shape. The first regime was defined by a differentiation period, where soil particles fell out of suspension, settled, and separated from the supernatant. The first regime ended when the supernatant evaporated, leaving the top of the sediment column exposed to the atmosphere. In the second regime, soil shrinkage was in the vertical dimension as loss of soil moisture only occurred through the top, exposed surface area. The third regime was differentiated from the second by simultaneous radial and vertical shrinkage. Radial shrinkage occurred as moisture was lost through newly exposed surface area on the sides of the sediment cylinder.

Such changes in the physical nature of the drying Rincon sediment necessitated the use of three different methods to measure volume. The first two regimes used the same method, while the third state required two additional methods. Throughout the first drying regime, it was possible to calculate sediment volume by measuring the height difference between the sediment surface and the top of the soil-tin (Fig. 2 - Top). In the second regime, the sediment was not solid enough to be removed from the soil tin, nor was it possible to measure radial shrinkage using calipers because radial shrinkage occurred heterogeneously along the upper part of the column sides. Volume was therefore measured in the following manner.

Firstly, the tin and sediment were weighed. Secondly, the tin was filled with dry-white sand and weighed again. Thirdly, weight of sand was found as the absolute value of the difference between these two measurements. Next, the sand volume was found as the quotient of this sand weight and the bulk density of the dry-white sand, calculated independently using standard methods (Klute, 1986). The volume of the sediment was then the absolute value of the difference between the tin and sand volumes (Fig. 2 - Middle).

In the third regime, the sediment column was dry enough to be physically removed from the tin. The column was then placed on a small open aluminum weighing tray and physically measured using calipers. After measuring volume, the sediment column was not returned to the soil-tin for drying but remained in the tray for the duration of the drying curve (Fig. 2 - Bottom). Bulk density and volumetric water content were calculated as the ratio of sample oven-dry weight to its volume and the product of gravimetric moisture content and bulk density over the density of water (Jury, et al., 1991), respectively.

Theoretical heat transfer properties for the sediment were calculated using the equation for thermal conductivity as described in Campbell (1985) by:

$$\lambda = A + B\theta - (A - D)\exp[-(C\theta)^{E}] \qquad [1]$$

and volumetric heat capacity for saturated material, modified from Campbell (1985), as:

$$C = C_s(1-\theta) + C_w\theta \qquad [2]$$

where λ is thermal conductivity, θ volumetric moisture content, coefficients A through D are curve fitting parameters, C_h is the volumetric heat capacity, C is the sediment volumetric specific heat, and C_s is the volumetric specific heat for the sediment solids.

Values for the curve fitting parameters in the model described by Campbell were found through iteration. The guidelines used in defining both the window for each parameter and the step values for the iterative method were based in Campbell's (1985) description of the parameters as well as initial work by this author, which defined a range and trend of thermal conductivity with decreasing soil moisture for the Rincon sediment. The parameter values were said to be reasonable for the purpose of this study when thermal conductivity as a function of decreasing moisture content was both within the range of values and followed the experimental trend found for the Rincon sediment.

Table 1 lists the parameters and how they defined the theoretical heat transfer parameters used in this adaptation of the model described by Campbell (1985).

Table 1. Definition of parameters for a shrink/swell soil for the model described by Campbell (1985) for the thermal conductivity of a non-shrink/swell soil.

Parameter	Definition
A	$(0.57 + 0.93\Phi_s)/(1-0.49\Phi_s)-2.8\Phi_s(1- \Phi_s)$
B	$2.8\Phi_s$
C	3.6
D	$0.03+2\Phi_s^2$
λ	$A + B\theta_w-(A-D)\exp(-(C\theta_w)^4)$

In Table 1, Φ_s is the ratio of the volume taken up by soil solids to the total soil volume and θ_w is the volumetric moisture content. Methods were applied before the start of each experiment to maintain a constant well-mixed and saturated initial drying state for the Rincon sediment at the wet end of its drying curve. Two intuitive assumptions were made in preparation of each sample for investigation. The first assumption stated that the sediment in each experiment would have the same moisture content. The second assumption stated that the starting mixtures would contain no air filled porespace. With respect to the second assumption, volume partitioning of the sediment was between the liquid and solid phases only, with no volume taken up by air. Following, the solid fraction was then unity minus the volumetric moisture content. Thermal diffusivity was calculated as the ratio of thermal conductivity to volumetric heat capacity.

Part Two – Experimental Heat Transfer Relations

The heat transfer study was conducted in a 600 milliliter Pyrex beaker, using a column composed of 600 milliliters of saturated Rincon sediment. A Mettler 4600 PM balance was used to weigh the sample and a web cam (WebCam Notebook, Creative Technology, Ltd, Milpitas, CA), connected to a Toshiba Satellite Pro 6100, was used to automate collection of water weight lost with time. The experimental apparatus was placed in a drying oven (Yamato DX-600) at 35 - 50°C. Temperature was increased from the low range during the experiment, to decrease drying time. For any single measurement period, the oven was maintained at a constant temperature.

Thermal conductivity was measured with a single needle heat pulse probe (Thermal Logic, Pullman, WA). A single needle, rather than a dual needle probe was used because shrinking of the drying sediment deformed the dual probe, altering the critical spacing between its pins. A CR7X (Campbell Scientific, Logan, UT) was used to control the single needle heat pulse probe and its data acquisition.

It was understood from initial work that the soil column would shrink along both the column height and radial dimensions. For this reason, the thermal conductivity probe was placed at a slightly oblique angle to the vertical, as an attempt to measure average heat transfer properties, disregarding whether shrinkage was in the vertical dimension, radial dimension, or both.

Thermal conductivity from the single needle probe was calculated from Jury et al. (1991) as:

$$T - T_0 = \frac{q}{4\pi\lambda}\ln(t - t_0) + d \qquad [3]$$

where T is temperature at time t, T_0 is temperature at initial time t_0, $T-T_0$ is the temperature rise, q is the heat flowing per unit time per unit wire length, and d is a constant. When $t >> t_0$, plotting temperature rise as a function of $\ln(t-t_0)$ yields a linear relation with slope, $m = q\,(4\,\pi\,\lambda)^{-1}$, and y-intercept, d. With all parameters known, the slope equation is solved for λ, thermal conductivity.

Volumetric heat capacity in each case was found as the sum of the heat capacities of the constituents weighted by their volume fractions (Jury et al., 1991). Thermal diffusivity was found as the ratio of thermal conductivity and volumetric heat capacity.

Part III – Correlation of Physical with Heat Transfer Data via Volumetric Relations

For many reasons it was not possible to acquire volume change data for the drying 600 ml sample in part two. Firstly, space in both the oven and 600 ml beaker radial surface area were limited which rendered physical or sonic measurements unrealistic. Secondly, it was decided to limit artificial fluctuations of scale measured weight by moving the sensor and beaker as little as possible. Thirdly, the changing sediment consistency and state through its drying curve made it impossible to have a singular representative surface for remote (sonic or laser distance ranging) measurements of volume change.

Parts one and two of this study give, respectively, the shrinkage curve and heat transfer properties of the Rincon sediment with decreasing moisture. To understand the mechanism by which heat transfer properties change with decreasing moisture, it was necessary to correlate the sediment shrinkage relations from part one with the heat transfer relations found in part two. With such a correlation heat transfer properties would be understood in terms of changing soil volume.

It should have been possible to relate volume based measurements (bulk density and volumetric moisture content) to the gravimetric heat transfer data using the gravimetric moisture content, by definition a normalized parameter. However the Rincon sediment is unconsolidated and has been shown to have gravimetric moisture contents not only greater than unity, but also not at a constant value at saturation. Preparation methods were consistently applied in attempts to maintain constant starting moisture contents for both parts one and two, however the complicated nature of the Rincon sediment made this state a very difficult goal to achieve. As a result the starting, saturated and well-mixed, moisture contents varied between the soil-tin/shrinkage-curve in Part One, and the beaker/heat transfer experiment, in Part Two. To relate bulk density and volumetric moisture content from the shrinkage curve in part one to the heat transfer data from part two it was necessary to further normalize the gravimetric moisture content.

The normalized gravimetric moisture content was found as the ratio of the gravimetric moisture content throughout the drying curve to the homogeneous, saturated, and well mixed initial gravimetric moisture content.

$$\omega_N = \omega_i \omega_s^{-1} \qquad [4]$$

Where ω_N is the normalized gravimetric moisture content, ω_i is the gravimetric moisture content at a specific time interval and ω_s is the saturated gravimetric moisture content found as the gravimetric moisture content of the well-mixed and homogenous Rincon sediment at the beginning of its drying curve.

A polynomial fit was made between volumetric relations, bulk density and volumetric moisture content, and the normalized gravimetric moisture content for sediment shrinkage experiment. This fit was then applied to the normalized gravimetric moisture content from the heat transfer experiment in part two. The result was that sediment thermal properties could be related to volumetric water content and bulk density.

RESULTS AND DISCUSSION

The Rincon sediment was seen to undergo a 0.88:1 shrinkage ratio, rather than a 1:1 ratio (Fig. 3 – Upper Plot). This could be accounted for by gas bubble formation which would artificially increase the sediment total volume. The methods by which sediment volume was measured did not allow for differentiation between the volume taken up by gas bubble formation and sediment total volume.

Bulk density of the Rincon sediment increased as gravimetric moisture content decreased due to a reduction in soil volume (Fig. 3), similar to results reported by Abu-Hamdeh and Reeder (2000). The non-linear relations of bulk density and volumetric moisture content in both the middle and lower plots of Fig. 3 demonstrated that volume loss was not directly proportional to weight of moisture lost.

The bulk density and volumetric moisture content are plotted in Fig. 4 as functions of the normalized gravimetric moisture content, ω_n, and depict the relationship between soil volumetric properties and the normalized gravimetric moisture content. As the normalized gravimetric moisture content decreased from unity at saturation, volumetric moisture content also decreased while bulk density increased. It is expected that volume loss occurs with soil moisture loss in a shrink/swell soil and, as bulk density is defined as the weight of dry soil matter over its total volume, that bulk density would increase.

Figure 5 depicts the gravimetric and normalized gravimetric moisture contents as functions of time during the drying cycle for the heat transfer experiment. Fluctuations in this data were due to shrinking soil volume which necessitated that the single needle

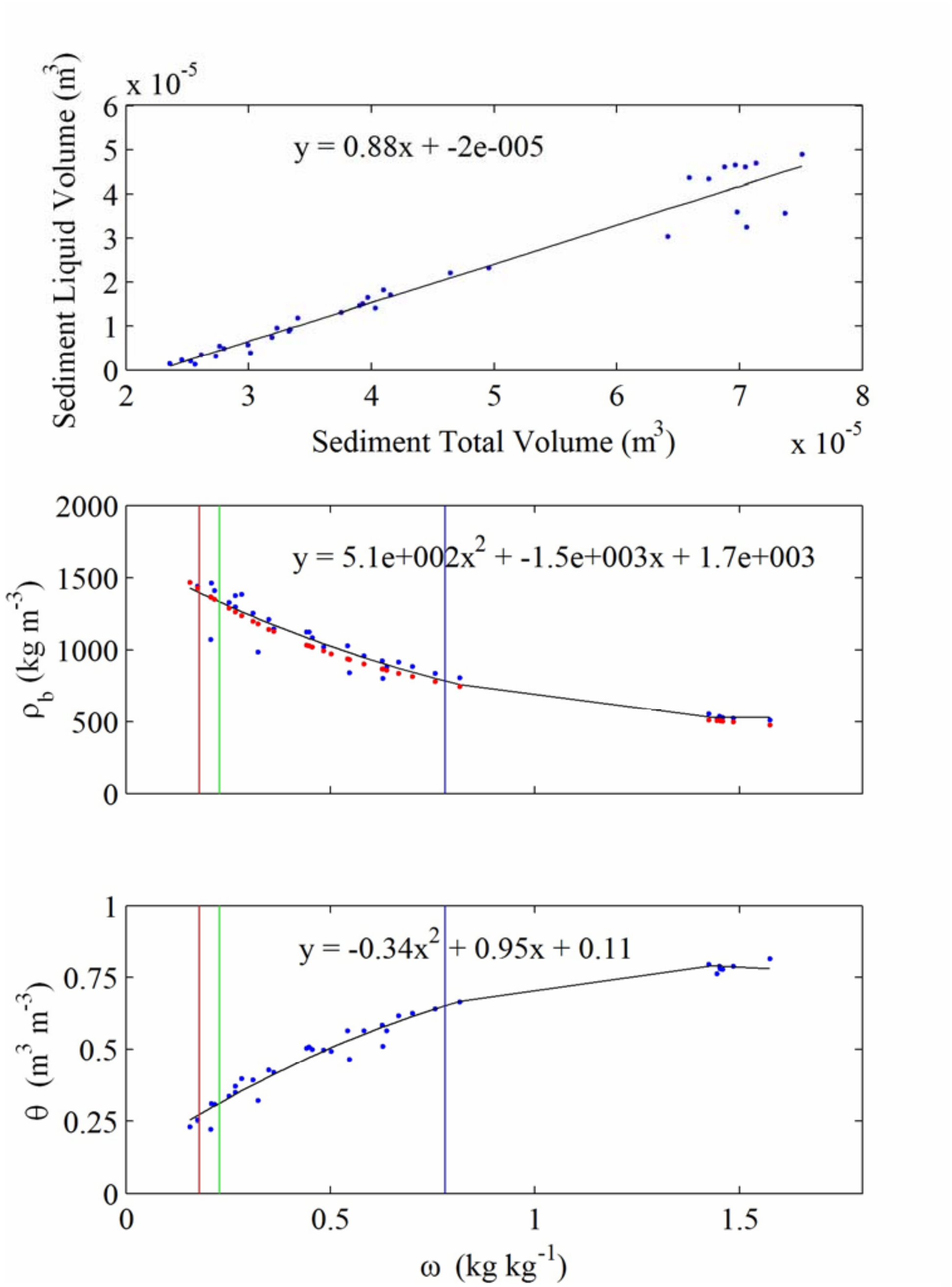


Fig. 3. Shrinkage indicators as functions of gravimetric moisture content. Top figure shows the shrinkage ratio. The bottom two figures show the physical properties as functions of the gravimetric moisture content. The blue and red points in the middle figure indicate experimental data and a theoretical 1:1 shrinkage ratio, respectively. Note that ρ_b is bulk density in kg m^{-3}, θ is volumetric moisture content in m^3 m^{-3}, and ω is gravimetric moisture content in kg kg^{-1}. Vertical lines in the bottom two figures from left to right are the: Shrinkage, plastic, and liquid limits, respectively.

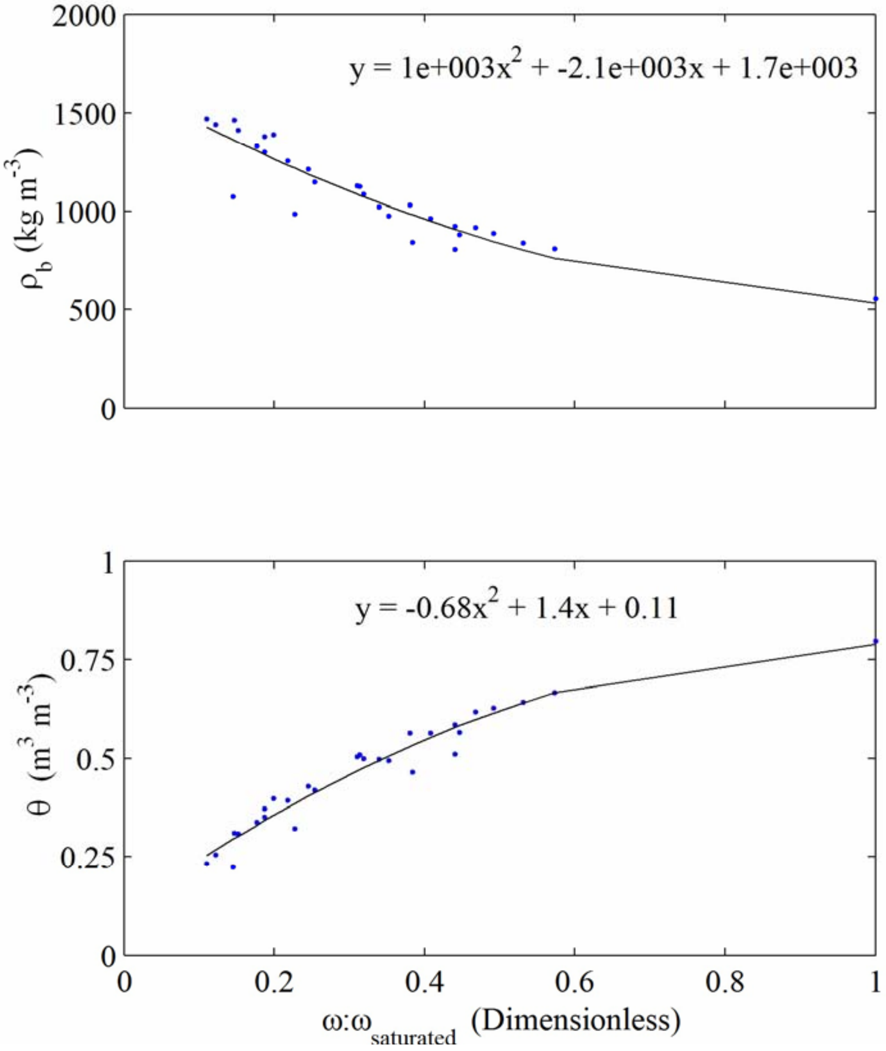


Fig. 4. Physical properties as functions of the normalized gravimetric moisture content. Note that ω_N is the normalized gravimetric moisture content defined as the normalized gravimetric moisture content ratio, $\omega_i : \omega_{SAT}$ (Dimensionless).

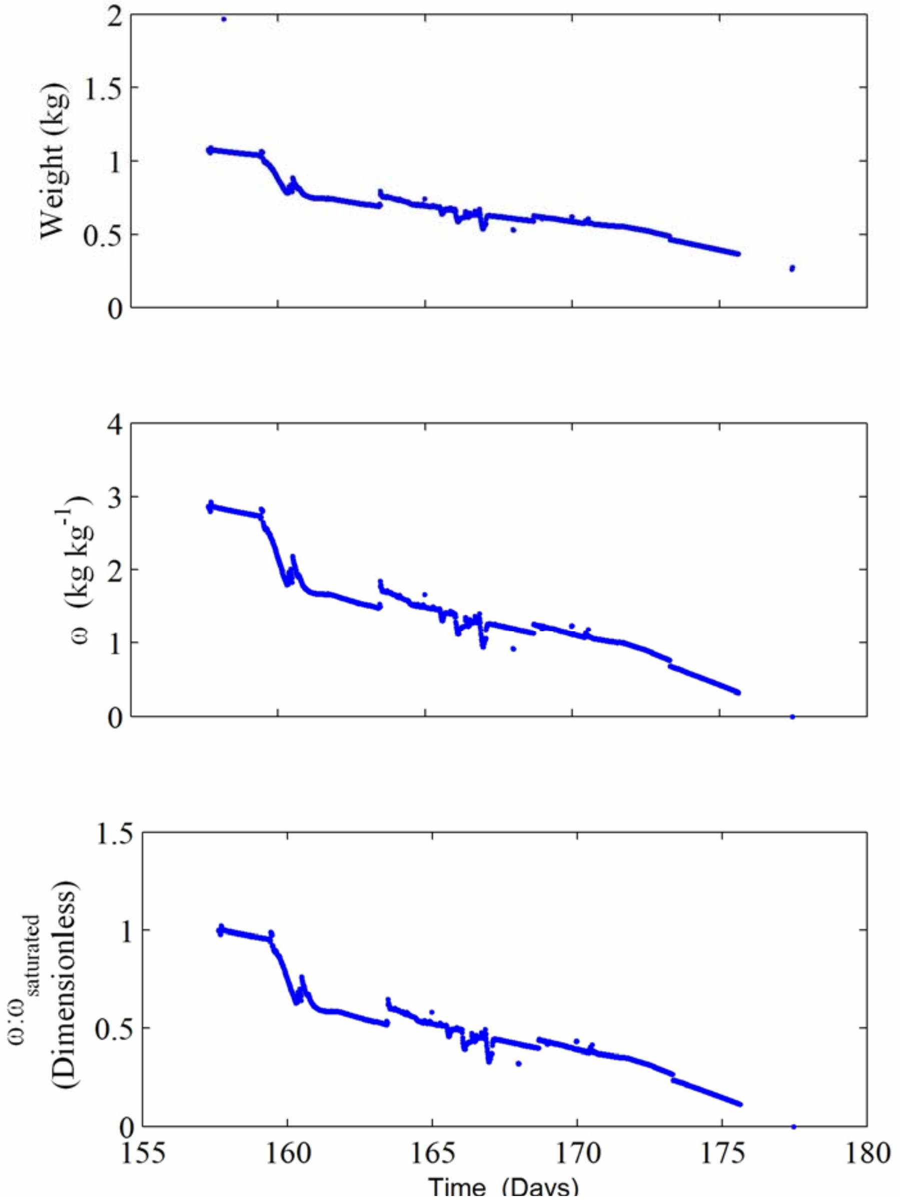


Fig. 5. Weight (kg), gravimetric moisture content and the normalized gravimetric moisture content as functions of Time (Days).

probe be repositioned. It is important to confirm from Fig. 5 that no trend was lost by use of the normalized gravimetric moisture content (ω_n) or by repositioning the probe.

Figure 6 shows the change in thermal conductivity as a function of the normalized gravimetric moisture content. Though the normalized gravimetric moisture content is unity at saturation and decreases as the soil dries, this figure provides no information with respect to changing sediment volume. From Fig. 6 it can only be concluded that thermal conductivity increases with a second order polynomial fit in relation to decreasing normalized gravimetric moisture content. The statement that thermal conductivity increases with soil moisture loss presents an incomplete conclusion. An understanding of the relationship between soil thermal conductivity, moisture loss, and change in volume is needed.

Figures 7 and 8 were created through correlations with the relations in Fig. 4 using the normalized gravimetric moisture content range in Fig. 6 as the independent variables in the Fig. 4 polynomials. Figures 6, 7 and 8 relate soil thermal conductivity, moisture loss, and change in volume.

Figure 7 shows that as bulk density increased, i.e. as soil volume decreased with soil moisture loss, thermal conductivity increased, volumetric heat capacity decreased, and thermal diffusivity increased. Figure 8 shows that as volumetric moisture content decreased with soil moisture loss, thermal conductivity increased, volumetric heat capacity decreased, and thermal diffusivity increased.

For a soil whose bulk density increases with diminishing soil moisture, Fig. 7 and 8 show that thermal conductivity increases as collapsing soil volume compensates for

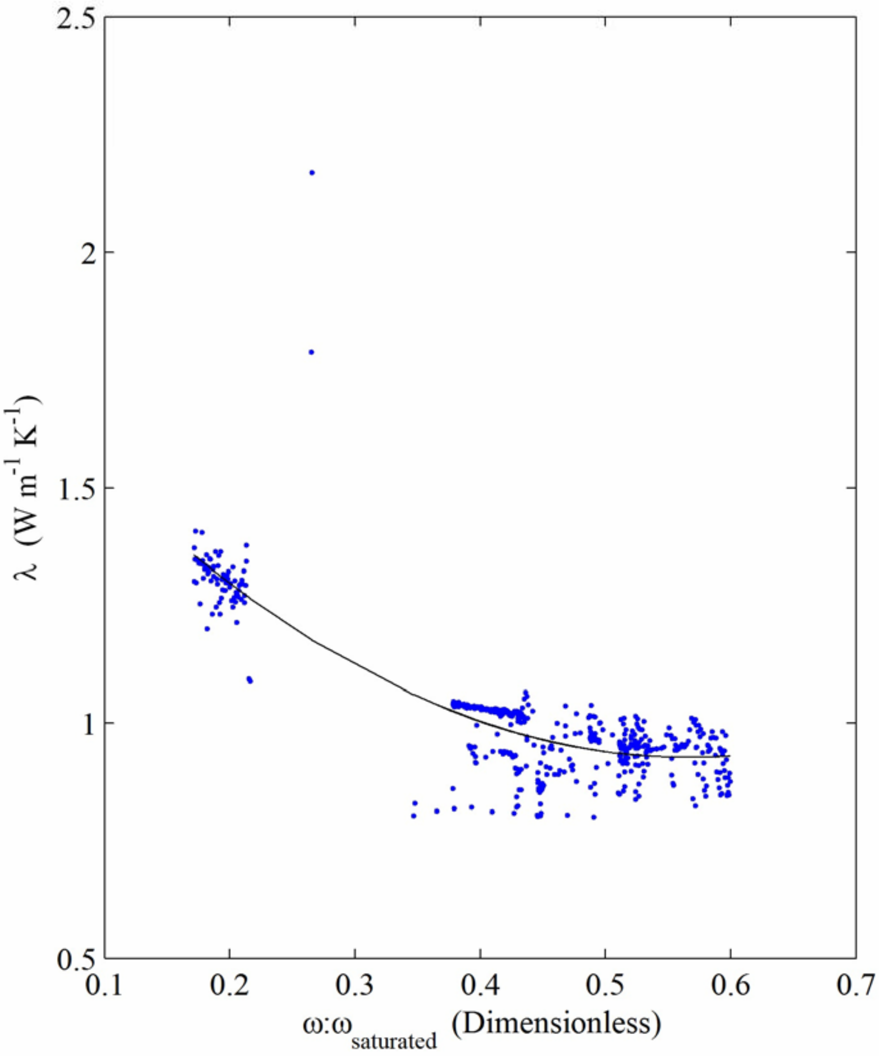


Fig. 6. Thermal conductivity as a function of the normalized gravimetric moisture content. Note λ is thermal conductivity in W m^{-1} K^{-1}.

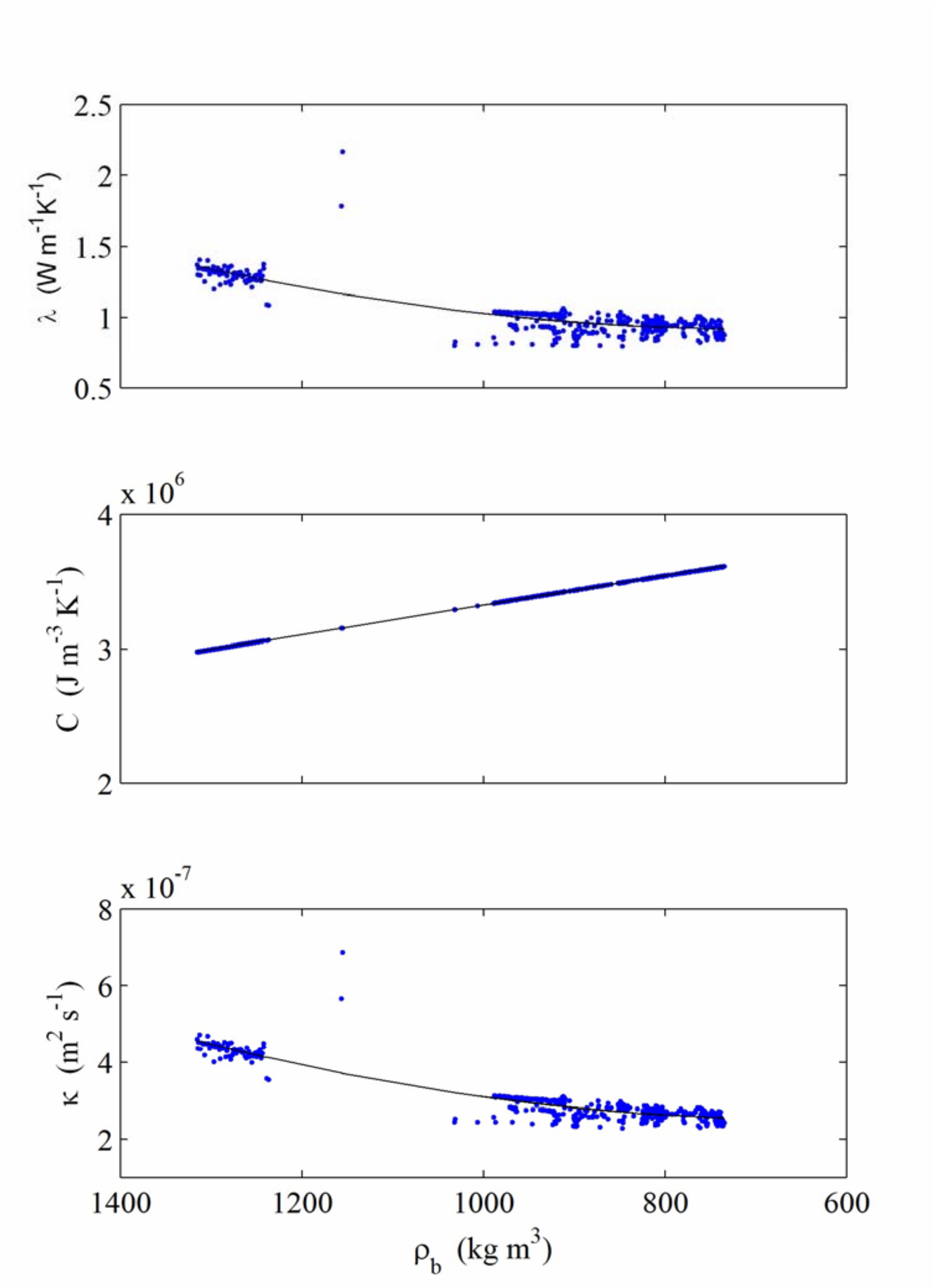


Fig. 7. Heat transfer properties as functions of bulk density. C is volumetric heat capacity in J m^{-3} K^{-1} and κ is thermal diffusivity in m^{2} s^{-1}.

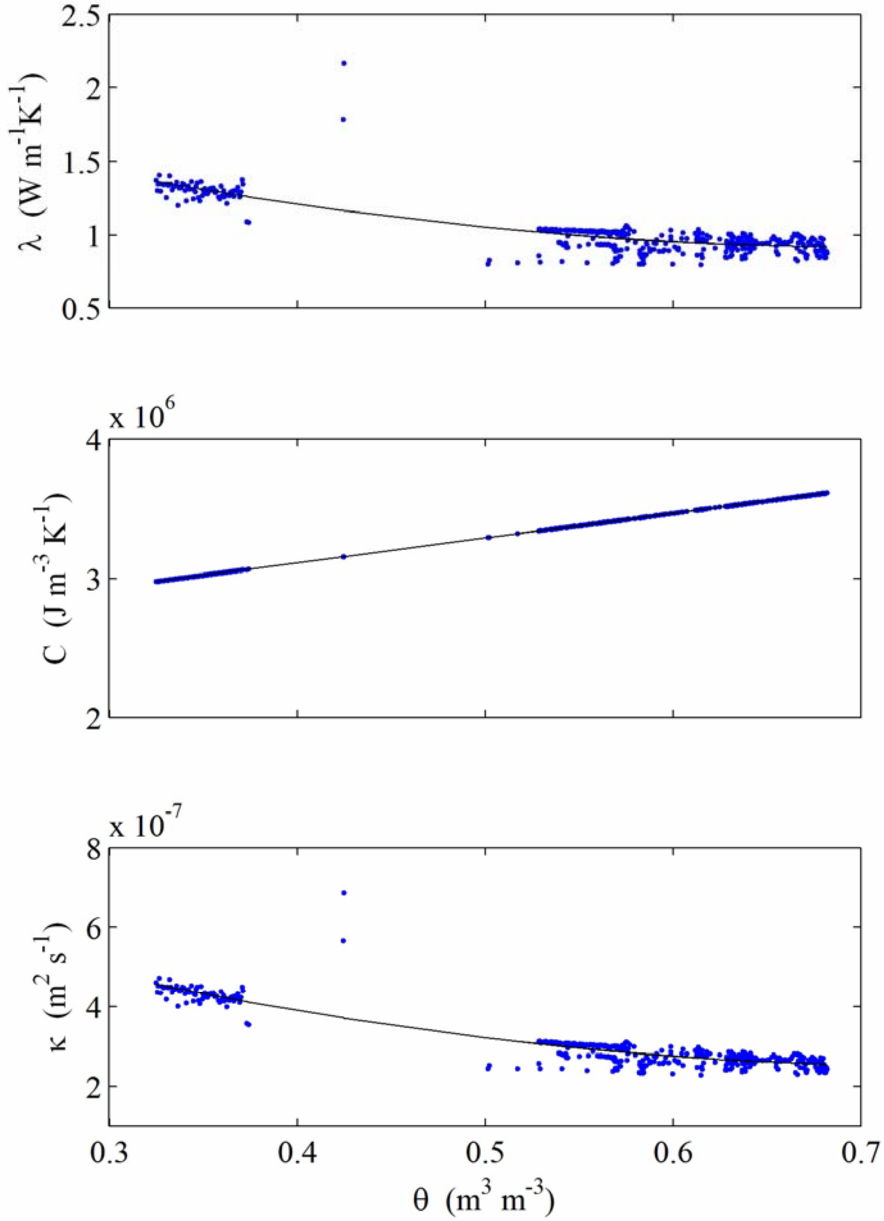


Fig. 8. Heat transfer properties as functions of volumetric moisture content.

water volume lost, as was found by Brown et al. (1980). The non-linear relationship for thermal conductivity was reported by Abu-Hamdeh and Reeder (2000) and is intuitive. A shrinking volume will increase surface area contact between sediment particles, increasing thermal conductivity. Figures 7 and 8 also show that volumetric heat capacity decreases linearly with decreasing moisture content. This occurs because water has a higher heat capacity than mineral or organic matter. Volumetric heat capacity is a multi-variant linear function of soil moisture, mineral, and organic matter.

As thermal conductivity increases at a faster rate than volumetric heat capacity decreases, thermal diffusivity, the ratio of thermal conductivity to volumetric heat capacity, increases as soil volume decreases with moisture loss.

Calculations using the model described by Campbell (1985) showed that λ and κ increased as the sediment dried (Fig. 5). Figure 9 shows theoretical and experimental results as functions of decreasing volumetric moisture content for the Rincon sediment. The theoretical results underestimate thermal conductivity and diffusivity towards saturation perhaps because the model does not describe the dynamic processes of sediment separation and particle rearrangement from settling and supernatant evaporation which define this portion of the shrinkage curve.

At the drier end of the moisture curve, the model overestimates thermal conductivity and diffusivity. In the dry regime, sediment shrinkage occurs as coupled with the processes of expanding gas-filled pore-space from organic matter decay and spatial variation of salt concentration and migration. Thermal conductivity is lower for soils with gas filled pore space relative to highly dense, closely packed, soils. This is

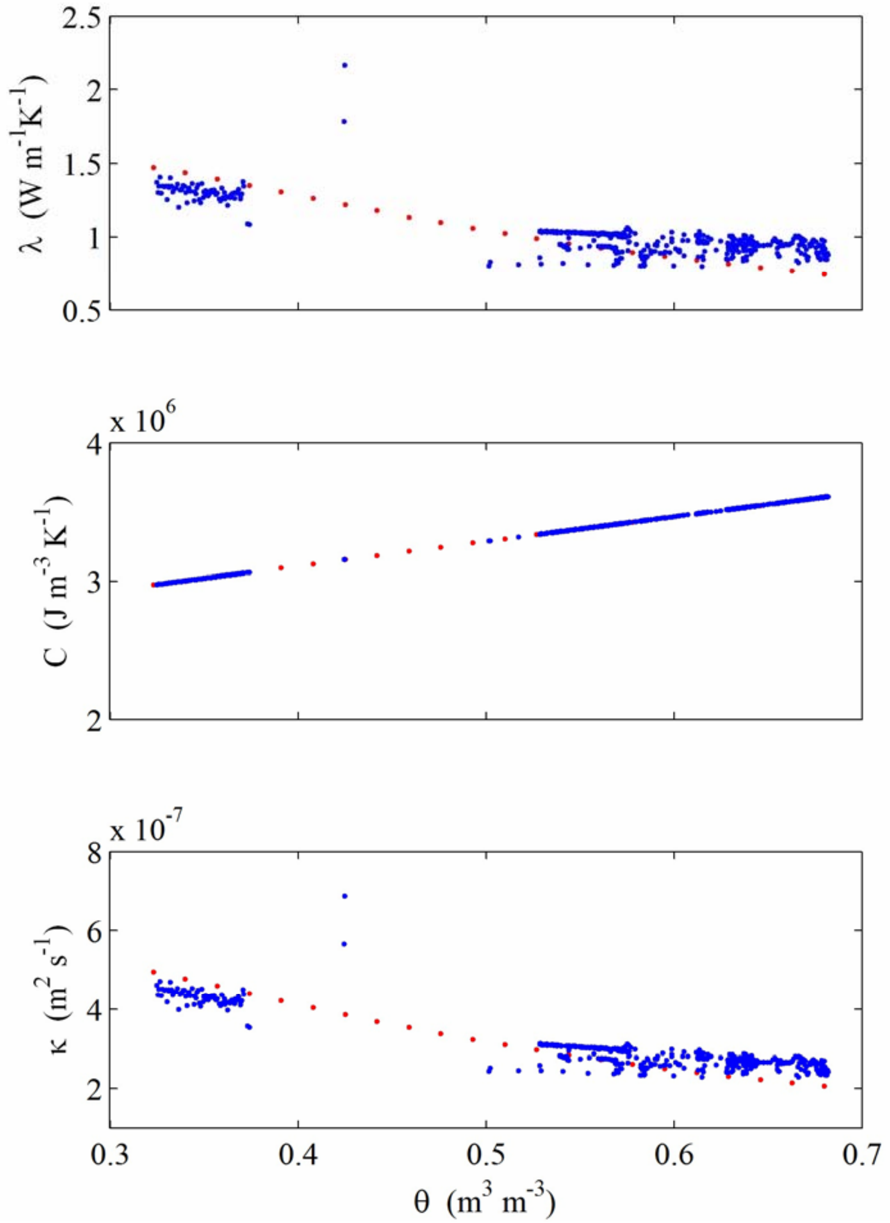


Fig. 9. Theoretical (red) and experimental (blue) heat transfer properties as functions of volumetric moisture content.

because gas is a poorer conductor of heat than is solid matter. Furthermore, Noborio and McInnes (1993) showed soils with higher salt concentrations are poorer thermal conductors than soils with lower concentrations of salt. Abu-Hamdeh and Reder (2000) have shown that soils with a higher organic matter content have a lower thermal conductivity than soils with lower concentrations of organic matter.

Figure 10 shows an R-squared value of 0.72 and 0.85, respectively for experimental thermal conductivity and diffusivity, each plotted against their theoretical values. With the understanding that the physics of a drying shrink-swell soil are not scenarios discussed by Campbell (1985) in his suggestions for parameter values for the thermal conductivity equation, it is reasonable to expect some variation between experimental and theoretical results.

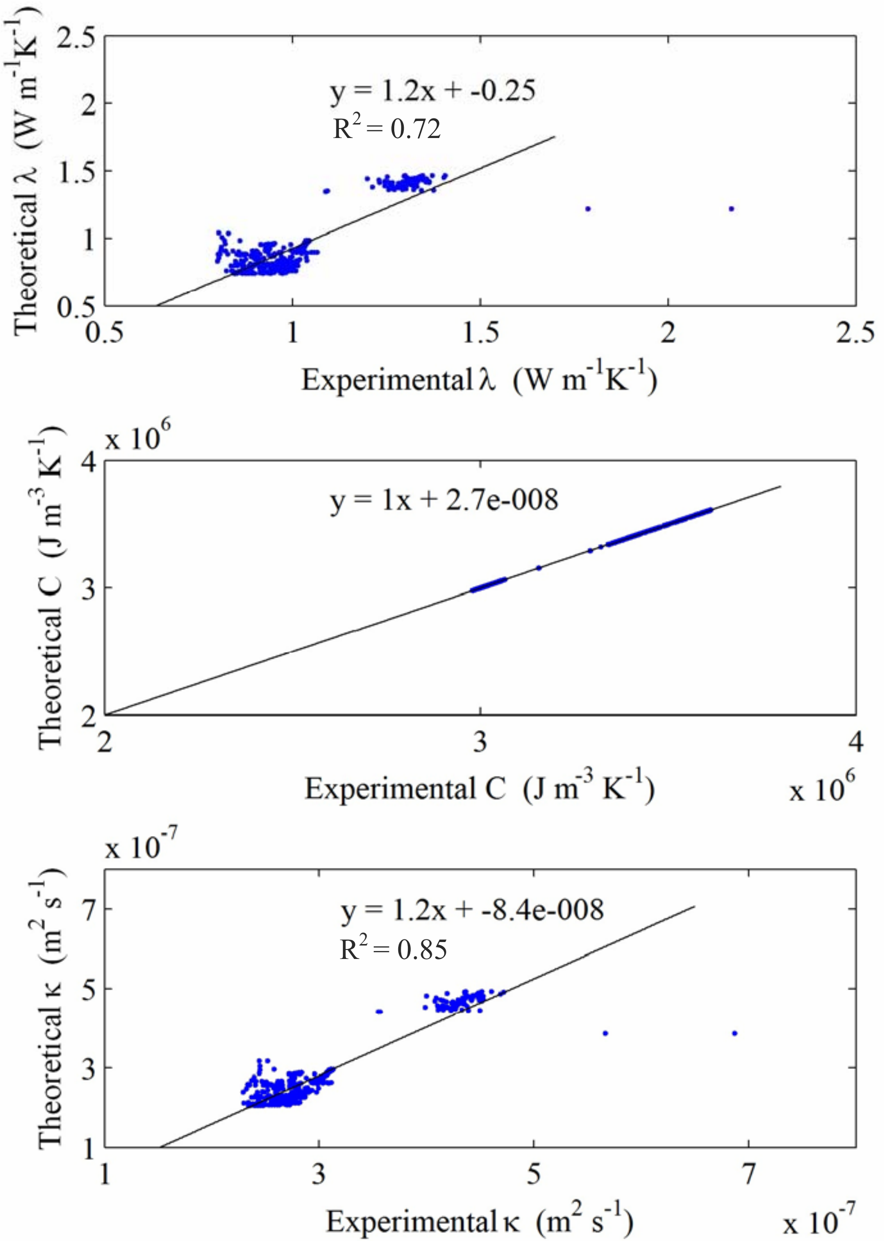


Fig. 10. Theoretical as functions of experimental heat transfer properties.

SOURCES OF ERROR

The ranges of the gravimetric moisture content differed between parts one and two in this study. It is acknowledged that the use of a normalized gravimetric moisture content despite differences in the range of gravimetric moisture content ranges in Parts One and Two introduce experimental error to this analysis. However, another method to relate volume based parameters to heat transfer data was not available

The Rincon sediment is a highly organic soil mixture. Heating of the Rincon sediment, caused out-gassing from organic matter decay which encouraged crack formation, growth, and in some cases sediment column separation. An example of a crack which opened along the probe needle length occurred around day 166 and caused the rapid decline in thermal conductivity seen in Fig. 6.

Salinity of the saturated and oven dry sediment was 17 and 34 parts per thousand, respectively. Noborio and McInnes (1993) showed thermal conductivity decreases as salt concentration increases. In this experiment, salt concentration was not taken into account in the calculations of theoretical heat transfer properties. Furthermore, as the Rincon sediment moved further from the liquid state, salt migration was observed. This migration of salts would have caused heterogeneity in the thermal properties of the column. Error could be introduced if heterogeneous distribution of salts occurred in the acquisition footprint of the single needle probe.

CONCLUSIONS AND FUTURE WORK

From this study it is possible to see the general trend of increasing thermal conductivity with decreasing soil moisture in a shrink-swell soil. This differs from results portrayed by Jury et al. (1991) for a non-shrink-swell soil. The mechanism is understood to be that shrinking pore volume compensates for pore water loss by increasing the amount of surface area contact between particles. It is not possible however, to portray subtleties in the shape of this curve due to noise generated from heterogeneous conditions which occurred in the sediment mixture during drying. Nor was it possible to see the trend of heat transfer properties in the Rincon sediment at lower volumetric moisture contents which are described by Jury et al. (1991).

At the ecosystem level it is necessary to know how sediment moisture content, albedo, sensor placement and salinity all change, to better understand how sediment heat transfer relates to changing ecosystem physical properties. This is especially true in the heterogeneous soils found in the Rincon Upper Tidal Flats. If the relation noticed by Heilman et al. (2000) was a local maximum in the drying thermal diffusivity curve, volumetric moisture contents taken by Heilman et al. (2000) show this observed local maximum would have occurred in the wetter regions of the curve than that described by Jury et al. (1991).

Rincon sediment is a dynamic media which moves, cracks, and shrinks as it dries. Sensor error could account for differences as shifting soil heat flux plates record artificial changes in storage heat flux. Soil heat flux plates are known to tilt, shift, or find their acquisition footprint compromised by crack or gas cavity formation when left over time in the Rincon Upper Tidal Flats.

Under conditions of hyper-salinity at extremes of the drying cycle, salt crusts have been recorded by this author in the system acquisition footprint. Covering the sediment with a low-conducting / highly reflective barrier of salts would insulate it from meteorological forcings, storing heat in the soil and causing phase shifts between what is recorded beneath and above the salt barrier. Such an effect could possibly underestimate fluxes during the day and overestimate fluxes at night.

The use of a shorter single needle probe, perhaps of 0.03 m rather than 0.06 m, would simplify measurements. In both ecosystem and laboratory studies, shorter single needle probes would decrease the sensor footprint, similarly decreasing the possibility of media/sensor decoupling or shifting in the sediment. Specifically in the laboratory, a thermal conductivity probe of shorter length would allow a smaller volume of soil to be used, decreasing errors due to gas void and fissure development.

Additionally, to support experimental with analytical methods, numerical solutions of the heat diffusion equation, using thermocouple field data as boundary conditions, could be compared with both the laboratory thermal conductivity probe data and an ecosystem energy balance system to better understand how media spatial variability affects the single needle probe. Finally, at the ecosystem level, mapping sediment cracks, and noting how albedo changes in the acquisition footprint would also facilitate a better understanding of the observed phenomenon.

REFERENCES

Abu-Hamdeh, N. and R. C. Reeder. 2000. Soil Thermal Conductivity: Effects of Density, Moisture, Salt Concentration, and Organic Matter. Soil Sci. Am. J. 64:1285-1290.

Brown, K. W., K. W. Launius, and L. E. Deuel, Jr. 1980. Physical Properties of Confined Dredged Materials. Soil Science. 129:95-106.

Bureau of Reclamation. 2000. Concluding Report: Rincon Bayou Demonstration Project. Volume II: Findings. United States Department of the Interior, Bureau of Reclamation, Oklahoma-Texas Area Office, Austin, Texas.

Campbell, G. S. 1985. Soil Physics with Basic Transport Models for Soil-Plant Systems. Elsevier Science Publishing Company, Inc, New York.

Campbell, G. S. and J. M. Norman. 1998. An Introduction to Environmental Biophysics. Second Edition. Springer-Verlag, New York.

Deegan, L. A. 1986. Relationships Among Physical Characteristics, Vegetation Distribution and Fisheries Yield in Gulf of Mexico Estuaries. Estuarine Variability. 83-100.

Heilman J. L., F. A. Heinsch, D. R. Cobos, and K. J. McInnes. 2000. Energy Balance of a High Marsh on the Texas Gulf Coast: Effect of Water Availability. J. Geophys. Res., 105:22371 – 22377.

Hillel D. 1998. Soil Temperature and Heat Flow p. 309 – 339. *In* Environmental Soil Physics. Academic Press, San Diego.

Jin, M., Shepherd, J., Marshall, J. 2005. Inclusion of Urban Landscape in a Climate Model: How Can Satellite Data Help? Bulletin of American Meteorological Society. 86:681-689.

Jury, W. A., Gardner, W. R., Gardner, W. H. 1991. Soil Physics. Fifth Edition. John Wiley & Sons, Inc. New York.

Klute, A. (ed.) 1986. Methods of Soil Analysis. Part 1, 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Mitsch, W. J., Grosselink, J. G., 2000. Wetland, 3rd ed. John Wiley & Sons, Inc, New York.

Noborio, K. and K. J. McInnes. 1993. Thermal Conductivity of Salt-Affected Soils. Soil Sci. Soc. Am J. 57:329-334.

Pielke Sr, R. A., G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. S. Niyogi, S. W. Running. 2002. The Influence of Land-Use Change and Landscape Dynamics on the Climate System: Relevance to Climate-Change Policy Beyond the Radiative Effect of Greenhouse Gases. Phil. Trans.: Math., Phys. & Eng. Sci. 360:1705 – 1719.

Porter, D. E., D. Edwards, G. Scott, B. Jones, W. S. Street 1997. Assessing the Impacts of Anthropogenic and Physiographic Influences on Grass Shrimp in Localized Salt-Marsh Estuaries. Aquatic Biology 58:289-306.

Riera, P, P.A. Montagna, R. D. Kalke, P. Richard. 2000. Utilization of Estuarine Organic Matter During Growth and Migration by Juvenile Brown Shrimp Penaeus Aztecus in a South Texas Estuary. Marine Ecology Progress Series. 199:205-216.

Scates, C. and P. H. Shook. 1999. Fly Fishing the Texas Coast. Pruett Pub. Co. Boulder, CO.

Sikes, D. Sunday, March 25, 2001. A day of non-fiction fishing in Nueces Bay. *In* Debra Fisher (Ed.) Corpus Christi Caller-Times. Caller-Times Publishing Co, Corpus Christi, TX.

Sklar, F. H., and J. A. Bruder. 1998. Coastal Environmental Impacts Brought About by Alterations to Freshwater Flow in the Gulf of Mexico. Env. Man. 22:547-562.

Tyler, R. (ed.) 1996. The New Handbook of Texas. Texas State Historical Association, Austin, TX.

White, W. A., R. A. Morton, C. W. Holmes. 2002. A Comparison of Factors Controlling Sedimentation Rates and Wetland Loss in Fluvial-Deltaic Systems, Texas Gulf Coast. Geomorphology. 44:47-66.

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