Evaluation of a Simple Soil Temperature Model on Root Zone Data
Agronomy 505 Spring 2007

Introduction

Soil temperature measurements are a key component in energy and flux budgets. For example, soil temperature is related to soil moisture flux, especially in the upper soil layer through the latent heat exchange which in turn affects the water and energy budgets (Lakshmi 2000). Additionally, soil temperature changes impact carbon and nitrogen budgets directly through changes in soil microbial processes (Davidson et al. 1998; Agehara and Warncke 2005) as well as changes in plant CO_2 assimilation rates caused by differences in soil moisture status (Verma et al. 1992). Accurate measurements of the soil temperature are therefore important to numerous fields including hydrology, micrometeorology, and ecology and many processes-based models in these disciplines utilize soil temperature models to aid in the calculation of fluxes and balances. Numerous models, of varying complexity, are available to calculate soil temperature fluctuations based on measured data (Andales et al. 2000; Casanova et al. 2005). The goal of this project is to evaluate whether a simple soil temperature model can be used to model diurnal soil temperature variations in the root zone (specifically $\leq$ 50 cm) for a short period of time (3-5 weeks).

Hypothesis

The simple soil temperature model,

$$T(z,t) = T_{ave} + A(0)\exp\left(-z/D\right)\sin\left[\omega(t-8) - z/D\right], \quad (1)$$

(Campbell and Norman 1998) can be used to model diurnal soil temperatures variations in the root zone for a relatively short period of time (3-5 weeks). Where T_{ave} is the average daily soil temperature (°C), $A(0)$ is the amplitude of the diurnal variation (°C), z is the depth of the soil (cm), and D is the damping depth (cm). The model determined to be adequate primarily on the basis of visual comparison between the times series of the modeled versus the observed data for each soil depth. A comparison on a modeled versus observed data on an x-y scatter plot may also be performed. These two methods were selected because they are commonly used methods of model assessment (Kirchner et al 1996), and while there are drawbacks, they do provide a reasonable first look at the data.

Site Description

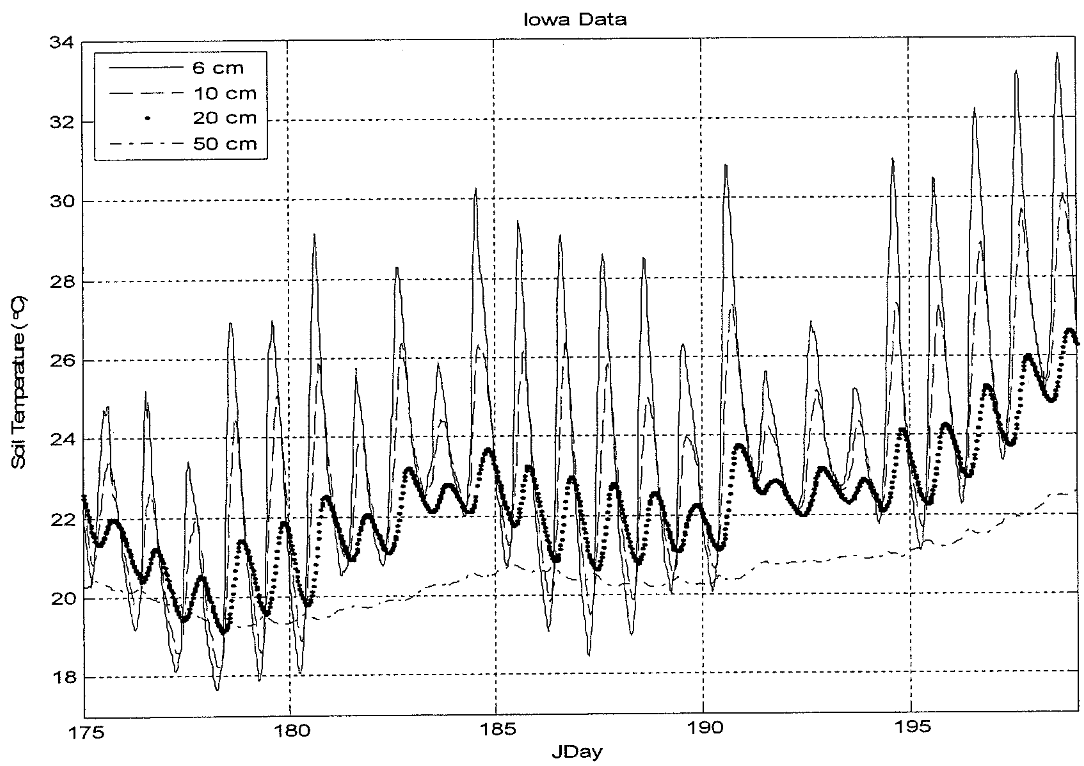

Figure 1. Soil temperature data from the Neal Smith site central Iowa during the summer of 2006. Readings are taken at 30 minute intervals.

I evaluated the model using two sets of data, one in Oklahoma and the other in Iowa. The dataset for the Iowa site was obtained through Dr. Tom Sauer at the USDA-ARS Soil Tilth Lab.

The data analyzed here cover approximately 3 ½ weeks in the summer period, June 24th through July 17th (doy: 175-198) in 2006. Soil temperature was selected from 4 depths for the study, namely: 6, 10, 20, and 50 cm, and readings were taken every 30 minutes. Data assurance indicated that all data measurements from this time interval were valid, so there is no missing data in this data set.

The dataset for the Oklahoma site was obtained through the Codiac data archive and contains data from one station (A130) that is part of the Little Washita Watershed Micronet. The data analyzed here cover approximately 3 weeks in the spring period, April 15th through May 5th (doy: 106-126) in 2004. Soil temperature was measured at 4 depths: 5, 10, 15, and 30 cm, and readings were taken every 15 minutes. Data assurance indicated that all data measurements from this time interval were valid, so there is no missing data in this data set.

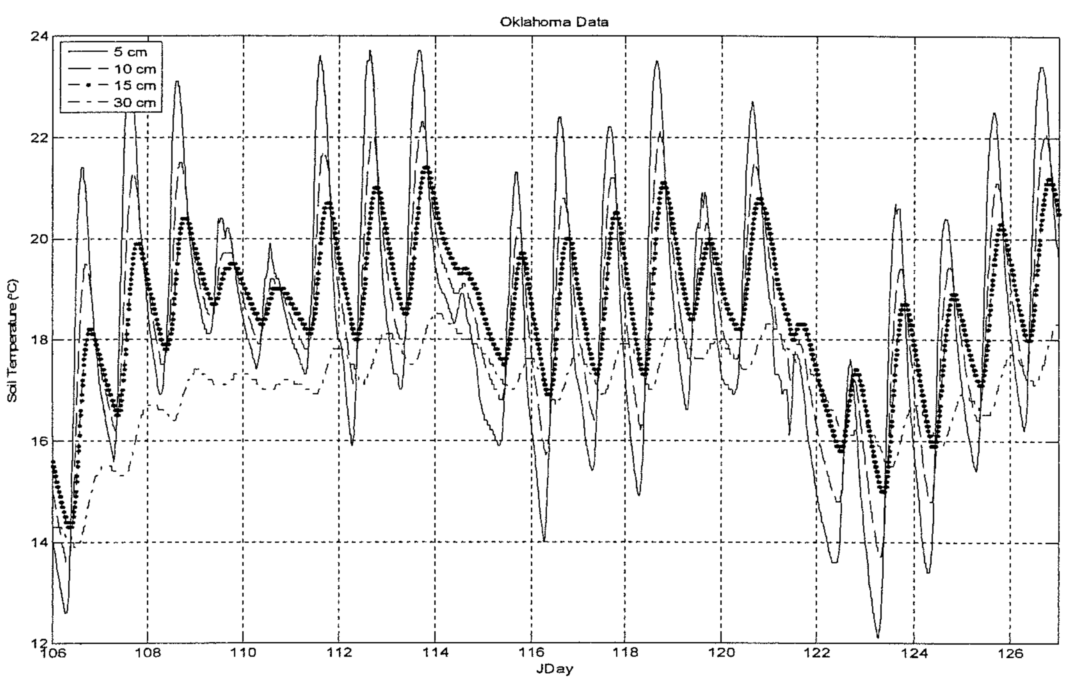

Figure 2. Soil temperature data from the A130 site in the Little Washita Watershed during the spring of 2004. Readings are taken at 15 minute intervals.

Parameter Estimation

In order to run the model, parameter values for $A(0)$, D, and T_{ave} must be estimated. Because the model utilized here suggests that $A(0)$, D, T_{ave} remain constant across all dates and depths, it should theoretically be possible to use a sample of selected dates and depths to calculate these parameters.

For each site two depths were chosen for two different dates and these values were used to determine the parameters. Initially, dates and depths were chosen at random for parameter estimation of $A(0)$, D, and A_i, where $A_i = T_{\max}(z_i) - T_{ave}$, and $T_{\max}(z_i)$ is the maximum daily temperature at a soil depth of z_i. Additionally, average daily soil temperature was chosen from a different set of randomly selected dates and depths and used in the estimation of T_{ave}. However, because the average daily soil temperature fluctuations varied from day to day (discussed below) and because the average soil temperatures were not the same at varying depths (see Figures 3 and 4), it was not possible to obtain valid parameters from the randomly chosen datasets, as the date and depth combinations selected resulted in negative values of A_i, and therefore made it impossible to solve for D. Because of this dates and depths were picked by inspection for use in estimating the parameters. Average mean daily soil temperature was determined by calculating the maximum and minimum values over a number of days. This was done at multiple soil levels for each site.

The damping depth was calculated from

$$D = \frac{z_1 - z_2}{\ln(A_2) - \ln(A_1)}. \tag{2}$$

Because data from the surface was either not available or not appropriate for use in determining model parameters it was also necessary to estimate $A(0)$, where

$$A(0) = A_i * \exp\left(-z_i/D\right) \qquad (3)$$

Calculations were made to the same degree of precision as the data available (1/100th for Iowa , 1/10th for Oklahoma), then averaged and rounded 3 significant figures (1 decimal place). good consideration of significant figures

Table 1. Dates and data used to estimate model parameters for the Iowa dataset.

Day	Depth (cm)	T_{min} (°C)	T_{max} (°C)	T_{ave} (°C)	A_i (°C)
177	10	18.57	22.01	20.29	1.72
177	20	19.41	20.55	19.98	0.57
189	10	20.51	23.97	22.24	1.73
189	20	21.09	22.26	21.675	0.59

Table 2. Estimated Parameters used in the Iowa soil temperature model.

Parameter	Description	Estimate	
A(0)	Amplitude temperature fluctuations	5.2	°C
T_{ave}	Mean daily soil surface temperature	21.1	°C
D	Damping Depth	9.1	cm

The data in Tables 1 and 3 were used to determine the model parameters for Iowa and Oklahoma, respectively. Parameters values were obtained by averaging the values across the depths and plugging into (2) and (3). The resulting parameter values can be found in Tables 2 and 4.

Table 3. Dates and data used to estimate model parameters for the Oklahoma dataset.

Day	Depth (cm)	T_{min} (°C)	T_{max} (°C)	T_{ave} (°C)	A_i (°C)
108	10	17.5	21.5	19.5	2.0
108	15	17.8	20.4	19.1	1.3
117	10	16.4	21.2	18.8	2.4
117	15	17.3	20.5	18.9	1.6

Table 4. Estimated Parameters used in the Oklahoma soil temperature model.

Parameter	Description	Estimate	
A(0)	Amplitude temperature fluctuations	5.1	°C

T_{ave}	Mean daily soil surface temperature	19.1	°C
D	Damping Depth	11.6	cm

Results

In the Iowa dataset, temperature values range from approximately 17-33 °C, with the most variation seen in the shallowest depth (5 cm). The data generally follows a simple diurnal oscillation, but it can be seen trending upward beginning on day 194 across all soil depths. In the Oklahoma dataset soil temperature values in the root zone range from approximately 13 °C to just over 24 °C. This dataset shows more variation from the average daily temperature values, with the upper three soil depths frequently trending upwards and then reverting back down to the mean. The lowest depth shows similar patterns but with very pronounced damping.

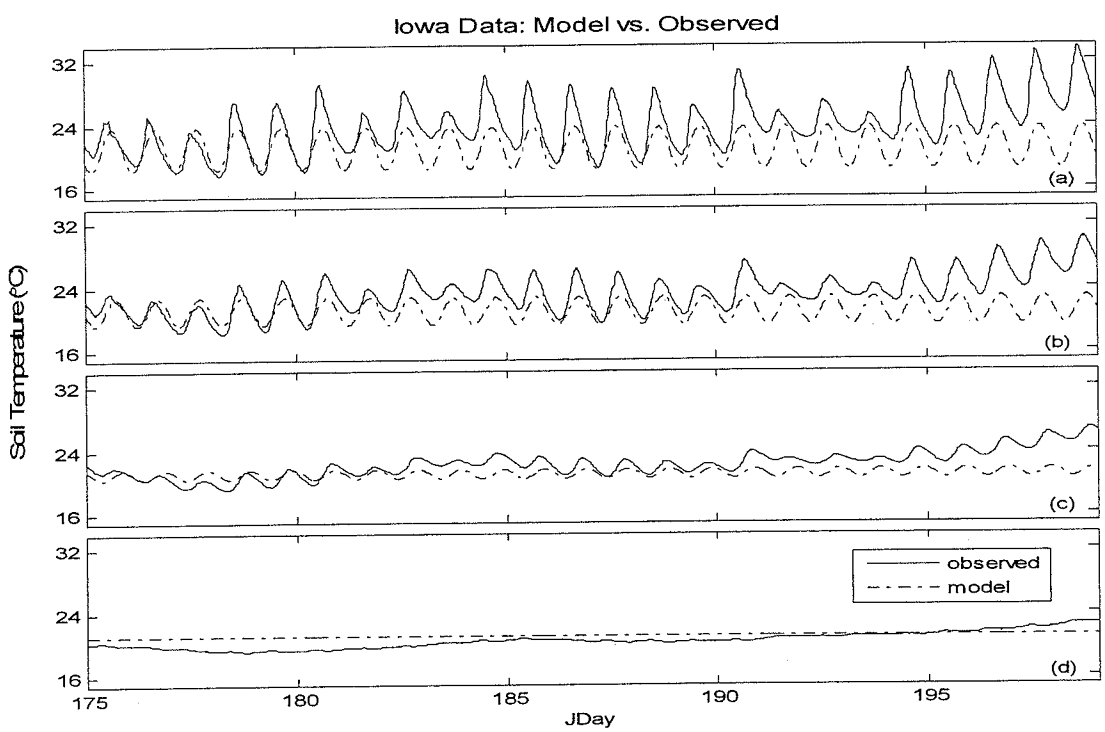

Figure 3. Modeled versus observed data for the root zone for the Iowa dataset. (a) 6 cm, (b) 10 cm, (c) 20 cm, (d) 50 cm

Scatter plots of the data (not shown) did not show a good agreement between the modeled and observed data, for any of the depths observed. However, given nature of the data, a scatter plot does not seem the most appropriate choice of model evaluation (number of unique model observations for entire dataset limited to the maximum number of daily observations) so this analysis method is not further considered. The hypothesis that a simple soil temperature model is adequate to be used for short time periods within the root zone does not hold true for these datasets. While the model did work fairly well for very shallow depths, it does not adequately describe the soil temperature patterns found below 20 cm, specifically the model and data do not have the same phase for diurnal oscillations and the average daily temperatures of the data and model are dissimilar. In the case of the Oklahoma dataset there is no intersection of the model and the observed data at the 30 cm level.

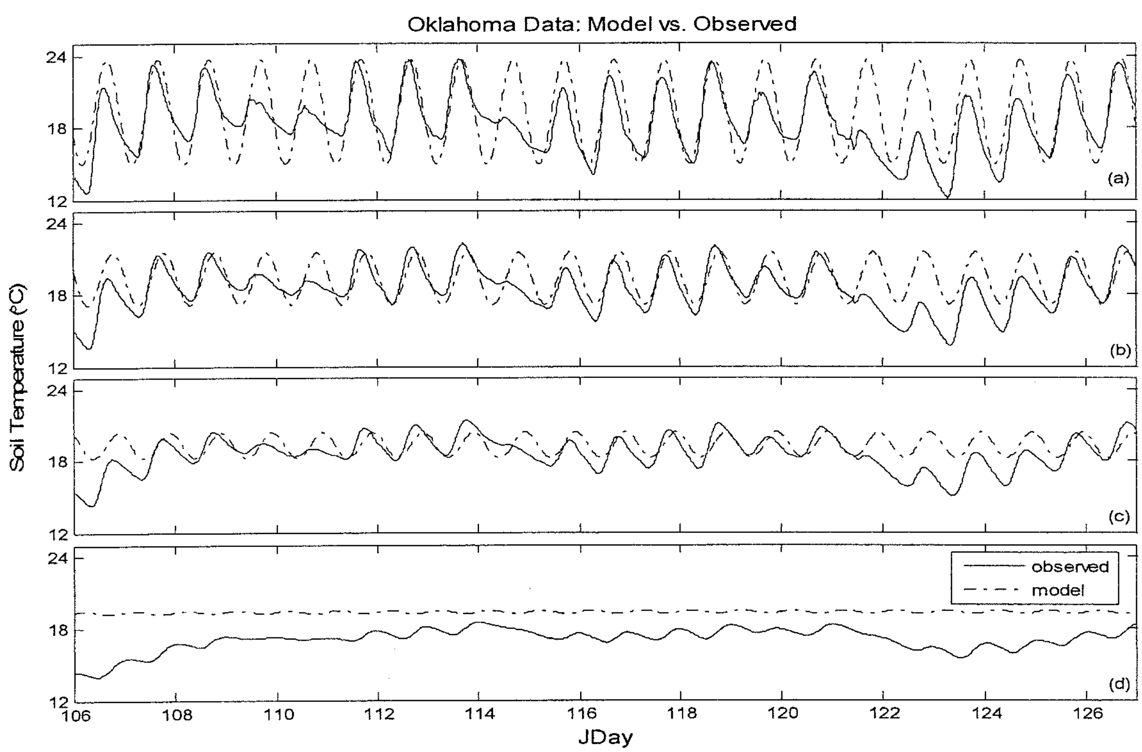

Figure 4. Modeled versus observed data in the root zone for the Oklahoma dataset. (a) 5 cm, (b) 10 cm, (c) 15 cm, (d) 30 cm.

In both datasets, depths up to 20 cm followed the basic pattern of the model, with average daily soil temperature roughly centered around the same value. Peak (and minimum) temperatures seem to show agreement between the model and the data. While the actual magnitude is not always the same, the timing is very close. In the case of the 50 cm depth of the Iowa data and the 30 cm depth of the Oklahoma data, the model is clearly not an appropriate representation of the data (see Figure 3d, 4d). For example, the average soil temperature of the 30 cm depth (Oklahoma) calculated for use in the model is much higher than both the actual average soil temperature and the minimum daily temperature of the data.

Discussion

One of the challenges of the data estimation process is determining what method to use in selecting parameters. As mentioned previously, it was not possible to use randomly selected parameters with these datasets because the estimation procedures used required certain assumptions to be true about the data that were not (i.e. the average daily temperature selected from one day will always be lower than the maximum daily temperature on a different day). In choosing data points by inspection it is possible to avoid these problems by choosing multiple days that have smooth diurnal. However, given the amount of fluctuation in the data on even a relatively small time scale, it can be seen that two different sets of data points picked with these criteria could yield much differ results. For example in the Iowa data, using dates 179 and 186 yields, $A(0)$ = 8.4 °C, D = 9.5 cm, and T_{ave} = 21.9 °C (model data from days 177 and 189: $A(0)$ = 5.2 °C, D = 9.1 cm, T_{ave} = 21.1 °C).

The model assumes that daily temperatures at all soil levels will fluctuate around a common average temperature (T_{ave}), with the amplitude varying based on depth, which is represented by the $A(0)\exp\left(-z/_D\right)\sin\left[\omega(t-8)-z/_D\right]$ term in (1). However, the model being examined is based on the assumption that there is a uniform soil profile. It is possible that the reason the average soil temperature (which was calculated from the upper soil layers), does not apply to the lower depths (30 cm Oklahoma, 50 cm Iowa) is that there was a change in one of more soil properties that contributes to heat transport. Additionally, the amplitude of the diurnal temperature variations of these depths are higher than that calculated in the model, which would indicate that in addition to the parameter T_{ave} being incorrect, the damping depth, D, might also incorrect as well (this further supports the notion of a change in soil properties, since the soil properties are reflected in this parameter). The timing of the peaks in the lowest depths also varies between the models and the data. timing (phase) also dependent on D

Estimates of the model parameters used in calculating D were obtained from directly picking points on the graph. In general however, there seems to be close agreement with the phases of the modeled versus actual data curves with the exception of 30 and 50 cm depths (which are discussed above). This would indicate that in this case a reasonable value of D could be obtained (that would work throughout the year) even when there is a limited dataset.

Recommendations

While the model could be applied over a longer time period (for example a year), these examples show that even over a short period of time, significant deviations can occur. Using the model on a longer time period would likely result in seasonal trending of the overall curve (i.e. on average higher temperatures in the warmer months and cooler temperatures in the colder months), which would mean that there would be significant deviations from the curve if an average yearly temperature was used. Given the results of the data analyzed here, this model would be ideally applied in an area and time period over which there was average air temperature is constant and the soil conditions are uniform. For example a situation for this might be in a large controlled environment experiment where air temperature is fairly controlled and the soil properties are known.

One factor to consider in the applicability of this model for year-round use is how the soil conditions may change and the effect that this would have on the model. For example, frozen soils (i.e. frozen soil water) can have different thermal characteristics than that of the same soil when there is no freezing (Fuchs et al. 1978). Additionally the presence of snow on the soil surface has been shown to affect the underlying soil temperatures because snow can act as an insulating layer (Mellander et al. 2005).

One improvement that could be made to this model is one in which T_{ave} is adjusted based on air temperature. While there are other models which make adjustments in T_{ave} based on the time of year (Casanova et al. 2005), the data in Figures 3 and 4 show that changes in the average daily temperature do not show a linear increase. The soil temperature patterns are very similar to the air temperature oscillations (not shown). A recent model (Elias et al. 2004) attempts to address these issues by having an adjustment factor for daily soil temperature based on air temperature but still keeping the model relatively simple. While the model presented here is not always appropriate to use in determining soil patterns (even rough approximations), it can be a useful first step as it allows for rather simple analysis using data that can be fairly easily obtained or estimated. Furthermore, this analysis process can provide information about the potential processes or conditions affecting the soil through its failure to conform to model predictions.

Nice discussion

References

Agehara, S, Warncke, DD (2005) Soil Moisture and Temperature Effects on Nitrogen Release from Organic Nitrogen Sources. *Soil Science Society of America Journal*, **69**(6), 1844-1855.

Andales, AA, Batchelor, WD, Anderson, CE (2000) Modification of a Soybean Model to Improve Soil Temperature and Emergence Date Prediction. *Transactions of the ASAE*, **43**(1), 121-129.

Campbell, GS, Norman, JM (1998) *An Introduction to Environmental Biophysics*, Springer–Verlag, New York.

Casanova, JJ, Judge, J, Jones, JW (2005) Calibration of the CERES-Maize Model for Linkage with a Microwave Remote Sensing Model. *ASAE Annual International Meeting.* Tampa, FL. Paper #053027.

Davidson, EA, Belk, E, Boone, RD (1998) Soil Water Content and Temperature as Independent or Confounded Factors Controlling Soil Respiration in a Temperate Mixed Hardwood Forest. *Global Change Biology*, **4**, 217-227.

Elias, EA, Cichota, R, Torriani, HH, van Lier, Q (2004) Analytical Soil Temperature Model: Correction for Temporal Variation of Daily Amplitude. *Soil Science Society of America Journal*, **68**(3), 784-788.

Fuchs, M, Campbell, GS, Papendick, RI (1978) An Analysis of Sensible and Latent Heat Flow in a Partially Frozen Unsaturated Soil. *Soil Science Society of America Journal*, **42**(3), 379-385.

Kirchner, JW, Hooper, RP, Kendall, C, Neal, C, Leavesley, G (1996) Testing and Validating Environmental Models. *The Science of the Total Environment*, **183**, 33-47.

Lakshmi, V (2000) A Simple Surface Temperature Assimilation Scheme for Use in Land Surface Models. Water Resources Research, **36**(12), 3687-3700.

Mellander, P, Laudon, H Bishop, K (2005) Modelling Variability of Snow Depths and Soil Temperatures in Scots Pine Stands. *Agricultural and Forest Meteorology*, **133**, 109-118.

Verma, S, Kim, J, Clement, R (1992) Momentum, water vapor, and carbon dioxide exchange from a centrally located prairie site. *Journal of Geophysical Research*, **97**, 18629-18639.

You stated the problem,
formulated a hypothesis,
tested the hypothesis,
and revised the hypothesis.

You did a good job of presenting in class.

The only weakness in this report is the unclear discussion at the top of the second page.

95