Modeling Frost Line Soil Penetration: Using Freezing Degree-Day Rates, Day-Length, and Sun-Angle

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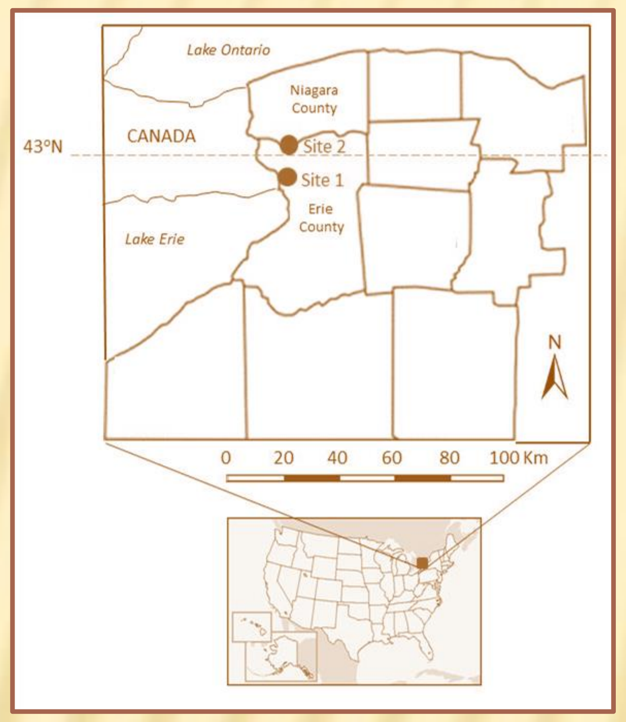
INTRODUCTION

Seasonally frozen ground undergoes a freeze-thaw cycle every year. Much of the contiguous United States, with the exception of the most southern states and western California, experiences some level of seasonal soil freezing. There exist a number of direct approaches to determine frost depth, but each of these approaches requires in-situ observations through the soil column. The simplest approach is the use of the Air Freezing Index (AFI), where freezing-degree days are accumulated and used as a surrogate for frost depth. While the AFI provides a rough estimate of frost depth, it is not the best indicator as it tends to over-predict frost penetration. The objective of this study is to develop a simple-to-use climate-only model which calculates the progression and depth of the frost line in saturated or near-saturated soil using a FDD/day rate approach, with solar adjustments.

METHODOLOGY

Measuring Soil Frost Depth

CRREL-Gandahl frost tubes were used to measure soil freezing depth. The tubes were constructed to a length of one meter, and filled with a solution of methylene blue (0.5 g/L). Freezing depth was indicated by a color change in the dye from blue (thawed) to clear (frozen). The length of the color change from the ground level downward was measured as the freezing depth. The tubes were slide within a capped PVC pipe which was placed into the ground. The ground level was marked on the frost tube. The area around the frost tube was kept clear of snow. The frost tubes were installed at two locations within Western New York, United States.



Site locations in Western New York, United States.

Frost tube measurement showing a frost depth of 8.8 cm (3.5 inches)

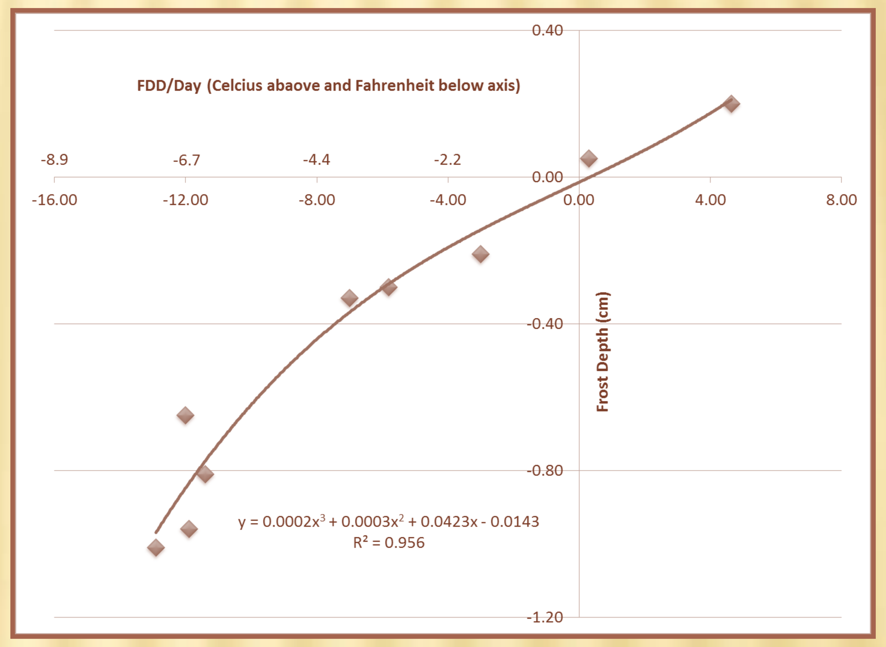
A frost tube (with outer PVC casing) in a snow cleared area .

Calculating Degree Days

Freezing degree days were calculated by subtracting mean daily temperatures from 32°F. A negative value was recorded as a freezing degree-day (FDD), while a positive value was recorded as a thawing degree-day (TDD). A running total of Degree-days was maintained through the winter season – November through March.

MODEL DEVELOPMENT

The model begins with an assumption that the dominant control on the progression and depth of the frost line is air temperature. The FDD/day rate was correlated with FDD/depth. For the years 2008-10 the paired rates were plotted on a rating curve and a best-fit line was applied. A polynomial best-fit equation was derived, where [$y = 0.0002(x^3) + 0.0003(x^2) + 0.0423(x) – 0.0143$], giving an R^2 value of 0.96. The resulting best-fit equation was multiplied by the daily degree-days (either freezing degree days or thawing degree days), and the accumulated values were used to calculate the progression of the frost line over time (Initial Model). Modeled accumulated freezing depths that showed a positive value (soil not frozen) were truncated at zero.



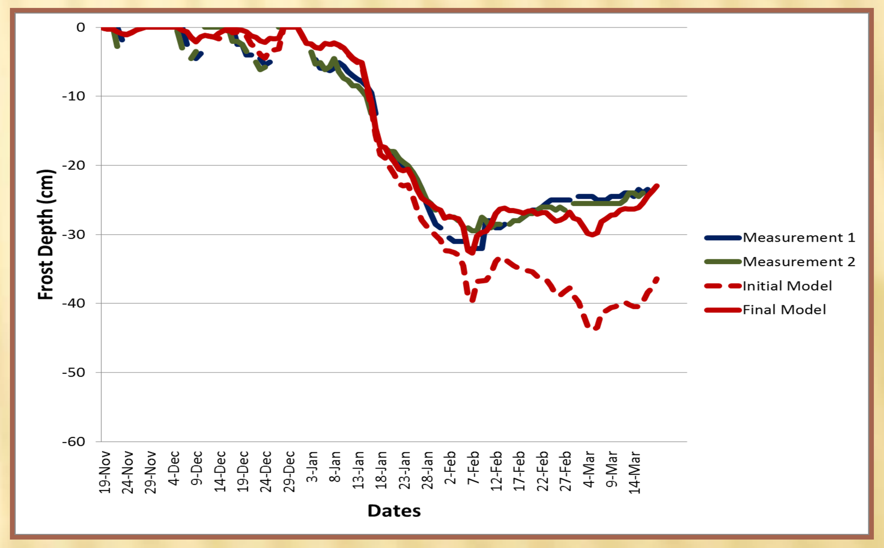
In late winter the impact of the FDD/day rate on freezing depth is weakened due to solar heating of the surface soil. To account for this change, a 'day-length' variable and a 'sun angle' variable (referred to collectively as the 'solar adjustment') was added to the 'final model'. The solar adjustment is calculated by dividing the day-length of the shortest day of the year (Winter Solstice) by the day-length for each day of the winter season. A similar calculation was made for the daily sun angle. The daily solar adjustment was calculated by averaging the two. The daily output of the 'initial model' was multiplied by the 'solar adjustment' factor to calculate a modeled freezing depth (the final model). The 2010-11 winter season was used to validate the model.

			Initial Model				Final Model
Date	FDD	FDD * Rating Curve (calculated daily freezing depth)	Freezing Depth (FD)	Day-Length (DL)	Sun-Angle (SA)	Solar Adjustment (DL+SA)/2	FD * Solar Adj. (cm)
1-Feb	-14	-1.0965	-48.3916	0.9	0.79	0.845	-40.8909
2-Feb	-10	-0.6073	-48.9989	0.9	0.79	0.845	-41.4041
3-Feb	-18	-1.8449	-50.8438	0.9	0.78	0.840	-42.7088
4-Feb	-8	-0.4359	-51.2797	0.9	0.77	0.835	-42.8185
5-Feb	-7	-0.3643	-51.644	0.89	0.77	0.830	-42.8645
6-Feb	-4	-0.1915	-51.8355	0.89	0.76	0.825	-42.7643
7-Feb	-4	-0.1915	-52.027	0.89	0.75	0.820	-42.6621
8-Feb	-17	-1.6293	-53.6563	0.88	0.74	0.810	-43.4616
9-Feb	-16	-1.4335	-55.0898	0.88	0.73	0.805	-44.3473

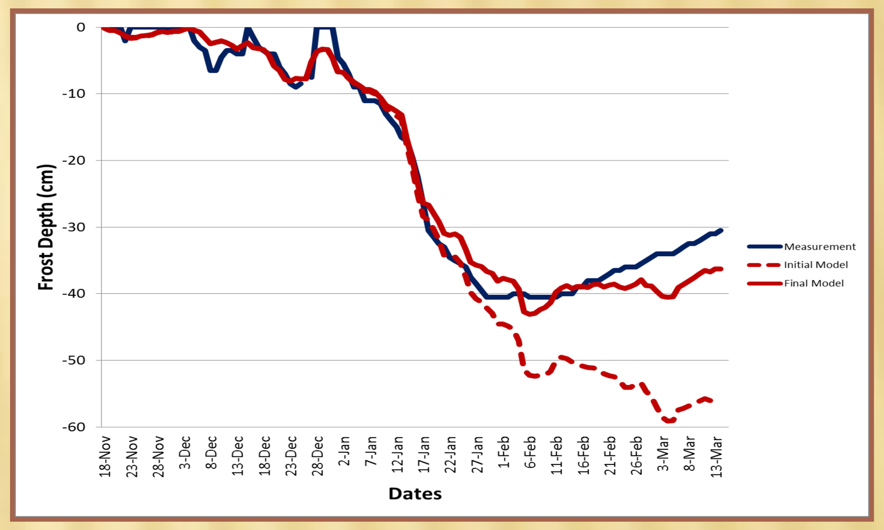
Sample calculations

RESULTS

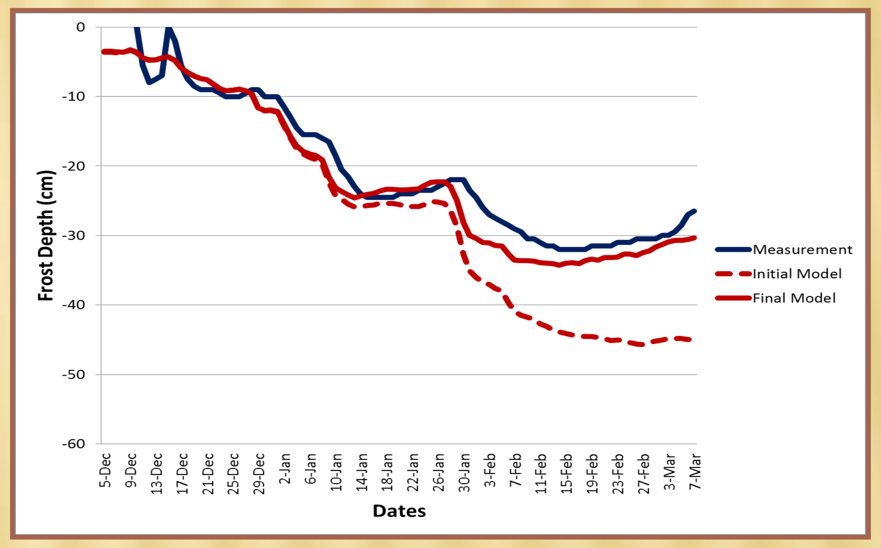
Measured and modeled soil frost progression and depth through 2008-10, and validated for 2010-11.



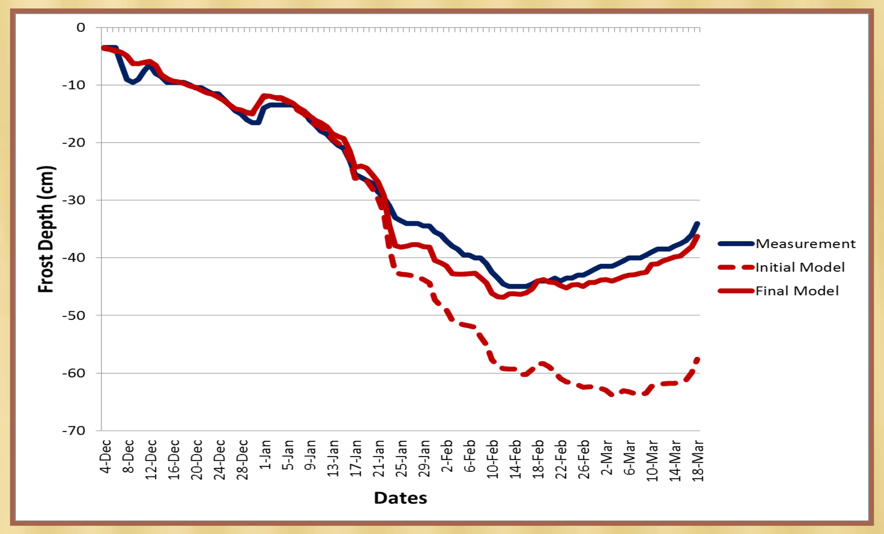
Site 1: 2008-09



Site 2: 2008-09



Site 2: 2009-10



Site 2: 2010-11 Model Validation

CONCLUSION

The frost tubes worked well in ease of use and in accurately predicting frost depth. The model output accurately predicted the maximum depth of frost line penetration, the cusp between frost line penetration and thawing at depth, and the rate of thawing at depth. Correlations between measured and modeled values were very strong ($R^2>0.96$) and absolute values were usually well within 5 cm. This frost line model can be used to predict frost depth where snow cover is absent, or when potential frost depth maximums are to be determined.