Environmental Impacts on The Performance of Pavement Foundation Layers – Phase I - Task 3

Principal Investigator:

Bora Cetin, Ph.D.

Co-Principal Investigator:

Kristen Cetin, Ph.D.

Tuncer Edil, Ph.D.

Research Team:

Debrudra Mitra

Department of Civil and Environmental Engineering

Michigan State University

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Objectives:

Using climate data, create a data-driven model to predict the following:

1. At specific depths:
    - Soil temperatures
    - Number of freeze-thaw cycles
2. Start/end and duration of freezing & thawing period
    - Frozen period at each depth
3. Isotherms

Literature review:

Few studies are done on the prediction of the soil surface temperatures :

- Different methods implemented:
  - linear regression model, non-linear regression model, neural networks
- Majority of studies predict the soil surface temperatures at lower frequency, (e.g. monthly average)
- few on the daily soil surface temperature
- Different sets of climate variables are used (not consistent across literature)

Available Datasets:

Two available sets of data (from previous Task)

Soil temperatures, 15-minute (Dataset 1); 1-hour (Dataset 2)

Climate variables

- Air temperature;
- Relative humidity;
- Wind speed;
- Precipitation;
- Net solar radiation

Data Processing: *Variable types*

The variables are analyzed, and 2 types of variables are created:

1. Time variables *(this slide)*
2. Climate variables *(next slide)*

Four **time** variables were considered

1. Month number (1 to 12)
2. Week number (1 to 52)
3. Day of year (1 to 365)
4. Timestep (1 to 4*24 for 15-minute timestep data)

Data Processing: *15 climate variables considered*

Air temperature (AirTemp)

Relative humidity (RH)

Rain or precipitation (Rain)

Windspeed (Wind)

Radiation (rad)

Daily average:

- air temperature (avgTemp)
- relative humidity (avgRH)
- precipitation (avgRain)
- wind speed (avgWind)
- solar radiation (avgrad)

Variation in ______ WRT daily average:

- air temperature (varTemp)
- relative humidity (varRH)
- precipitation (varRain)
- windspeed (varWind)
- solar radiation (varRad)

Methodology: *Steps for model development*

1. Stepwise regression is used to choose variables
   - Independent (low correlation)
   - Most influential
2. Data is divided in training and testing datasets
3. Different models considered to predict soil temperatures
4. Performance of models are compared with measured data

Results: *Stepwise regression model (influential & independent variables)*

	Week	Month	Day of Year	Timestep	Air Temperature	Rain	RH	Wind	Radiation	Variation Air Temperature	Variation Rain	Variation RH	Variation Wind	Variation Radiation	Average Air Temperature	Average Rain	Average RH	Average Wind	Average Radiation
Week	1																		
Month	1	1																	
DayofYear	1	1	1																
Timestep	0	0	0	1															
AirTemp	0.22	0.21	0.22	0.11	1														
Rain	0.02	0.02	0.02	0.01	0.04	1													
RH	0.22	0.22	0.22	-0.25	-0.24	0.09	1												
Wind	-0.09	-0.09	-0.09	0.04	-0.11	0.01	-0.23	1											
rad	0	0	0	0.04	0.46	-0.03	-0.5	0.18	1										
varTemp	0	0	0	0.4	0.27	-0.01	-0.55	0.26	0.5	1									
varRain	0	0	0	0.01	0	0.96	0.03	0.02	-0.02	-0.01	1								
varRH	0	0	0	-0.36	-0.21	0.04	0.71	-0.27	-0.51	-0.78	0.04	1							
varWind	0	0	0	0.05	0.1	0.02	-0.27	0.71	0.35	0.37	0.02	-0.38	1						
varRad	0	0	0	0.04	0.15	-0.02	-0.4	0.28	0.91	0.55	-0.02	-0.56	0.39	1					
avgTemp	0.22	0.22	0.22	0	0.96	0.04	-0.09	-0.18	0.34	0	0	0	0	0	1				
avgRain	0.09	0.09	0.09	0	0.15	0.26	0.24	0	-0.04	0	0	0	0	0	0.16	1			
avgRH	0.31	0.31	0.31	0	-0.13	0.09	0.71	-0.06	-0.2	0	0	0	0	0	-0.13	0.34	1		
avgWind	-0.12	-0.12	-0.12	0	-0.25	0	-0.06	0.71	-0.11	0	0	0	0	0	-0.26	0	-0.08	1	
avgrad	-0.01	-0.01	-0.01	0	0.77	-0.02	-0.33	-0.18	0.42	0	0	0	0	0	0.8	-0.09	-0.46	-0.25	1

No color: | correlation coefficient| < 0.3

Green: 0.3 < |correlation coefficient| < 0.7;

Yellow: correlation coefficient| > 0.7 *(High correlations)*

Results: *Stepwise regression model (influential & independent variables)*

High correlation (> 0.7)

Time variables:

(Week - Month);

(Week - Day of Year);

Climate variables:

(Rain – variation Rain); (RH – variation RH); (Wind – variation Wind);

(Radiation – variation Radiation); (variation RH – variation Temp);

(Air Temperature – Average Air Temperature);

(Air Temperature – average Radiation);

(average Air Temperature – average Radiation)

Remaining variables used for this study:

1. *Day of Year;* 2. *Time step;*

3. *Air temperature,* 4. *Radiation,* 5.*Variation in air temperature,*

6. *Variation in rain,* 7. *Variation in RH,* 8. *Variation in wind*

Data Division: *First dataset*

Dates available: January 2018 to April 2019

<u>Data division:</u>

Training data: all of 2018, which (~75% of data)

Testing data: 2019, January to April

Data Division: *Second dataset*

Dates available: January 2000 to February 2007

Data division

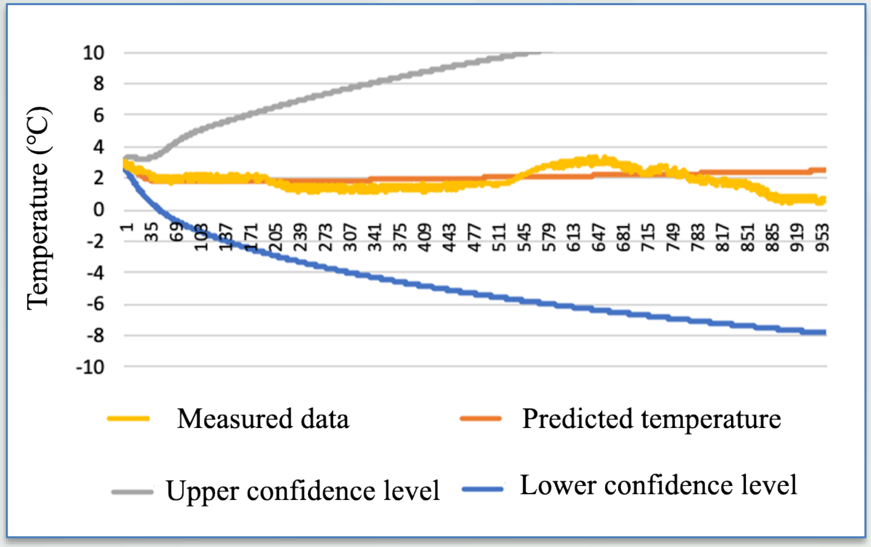
Training data: 2000 to Feb 2005 (~79% of data)

Testing data: Sept 2005 to Feb 2007

Model Selection

Various models were considered to predict soil temperature (time series data)

- Vector Auto Regression
- Vector Auto Regression Moving Average
- Vector Error Correction Models



However, these models are unable to predict the soil temperature trends

Model Selection

- Thus, non-linear regression model is used in this study
- 4th order polynomial model is utilized
- Two different methods were considered:

Model 1: *Individual depth*

Predict the soil temperatures at each depth using climate parameters

Model 2: *Individual depth: Daily average + variation WRT daily*

predict daily average soil temperature at each dept + timestep-based variation with respect to the daily average temperature

Model Selection : *Variables*

Model 1: *Individual depth*

Variables used (same a previously mentioned):

1. Day of Year
2 .Time step
3. Air temperature,
4. Radiation,
5. Variation in air temperature,
6. Variation in rain,
7. Variation in RH,
8. Variation in wind

Model Selection : *Variables*

Model 2: *Individual depth: Daily average + variation WRT daily*

Daily average temperatures:

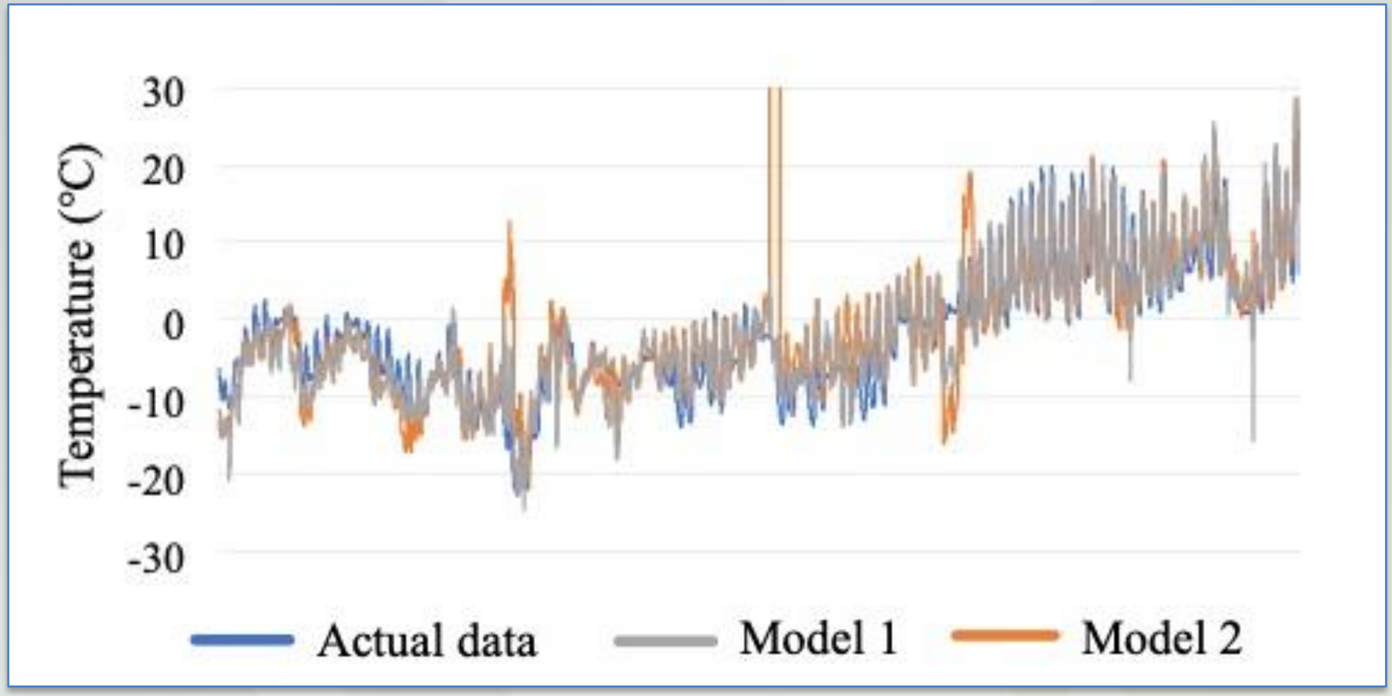
1. Day of Year,
2. Time step,
3. Average Air temp,
4. Average rain,
5. Average RH,
6. Average wind

+

Variation with respect to daily average values:

1. Day of Year;
2 .Time step;
3. Air temperature,
4. Radiation,
5. Variation in air temp,
6. Variation in rain,
7. Variation in RH,
8. Variation in wind

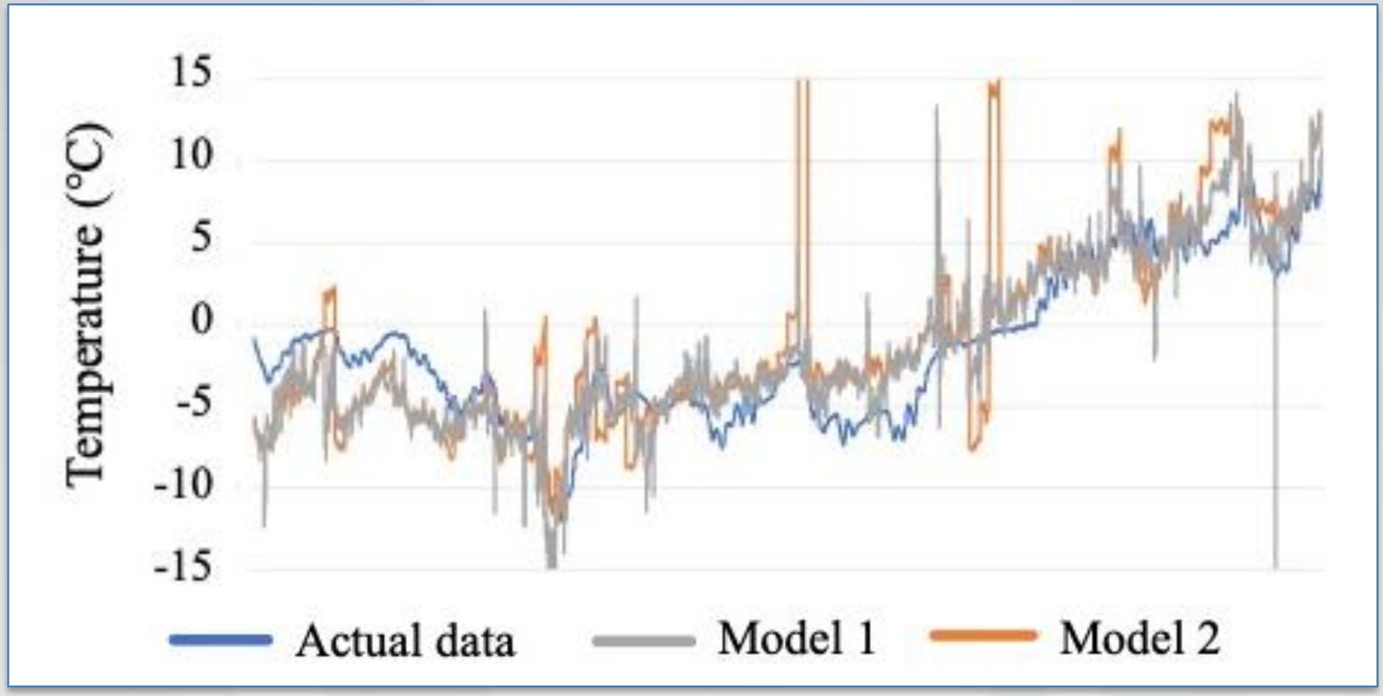
Results: *Temperature prediction*



Soil temperature at a depth of ***3 inch***

- Both the models can predict the temperature at the top surface
- Model 2 resulted in a few *spikes*

Results: *Temperature prediction*



Soil temperature at a depth of ***14 inch***

- Model 2, *predicts the overall trend* of the temperature for most of the timespan.
- Several *spikes* can be seen that deviates significantly for Model 2
- Model 1 *did not generate spikes*; but the *prediction deviates moe* from the measured soil temperature than Model 1.

Model Selection: *Improvements*

To reduce the spikes in temperature prediction, two different filters are developed.

Filter 1: Limit the variation in each timestep to a reasonable value

Filter 2: Remove the predicted temperatures which were significantly higher or lower than the temperature bound

Model Selection : *Filter 1*

An example data of a cell location is given below:

Cell 728	T1	T2	T3	T4	T5	T6	T7	T8
	3 inch	4 inch	6.5 inch	9 inch	10 inch	14 inch	18.5 inch	24 inch
Range -5 to 5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Range -4 to 4	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Range -3 to 3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Range -2 to 2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Range -1 to 1	0.995	0.998	1.000	1.000	1.000	1.000	1.000	1.000
Range -0.5 to 0.5	0.922	0.953	0.998	0.999	0.999	1.000	1.000	1.000
Range -0.25 to 0.25	0.751	0.804	0.933	0.986	0.993	0.999	0.999	1.000
Range -0.1 to 0.1	0.412	0.451	0.564	0.714	0.758	0.912	0.896	0.906

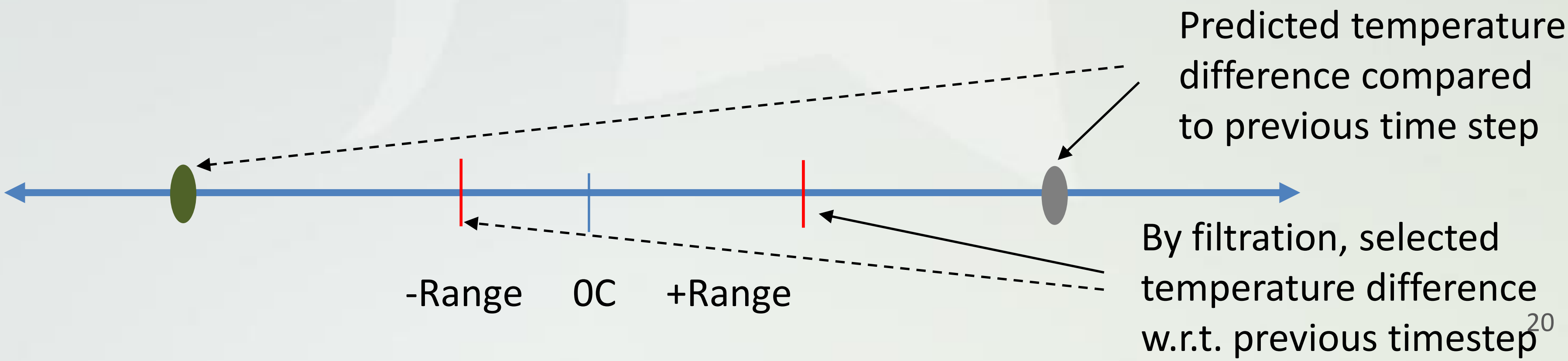
- The variation in predicted temperature in consecutive timesteps are evaluated
- Cells are colored where 99% of the data is considered for each depth

Model Selection : *Filter 1*

Based on the values obtained from all locations, following ranges are selected considering 99% of data selection:

Depth	Acceptable Variation Range
3 inch to 9 inch	From -1 to 1
9-inch	From -0.5 to 0.5
More than 9-inch depth	From -0.25 to 0.25

- If the change is out bound, then maximum effective range is selected as the change in temperature from the previous



Model Selection : *Filter 2*

Remove the outliers in predicted value if the temperature is outside the bounds of the max/min soil temperatures at each depth

If the predicted value is out of bounds, then previous predicted value is used

Temperature (℃)	9 inch	15 inch	16 inch	19.5 inch	24 inch	48 inch	72 inch
Maximum value	42	40	38	34	32	28	26
Minimum value	-24	-22	-22	-14	-10	-4	0

Model Selection : *Model comparison*

Root mean square error (RMSE) values are evaluated:

$$RMSE = \frac{1}{n}\sqrt{\sum (T_{predicted} - T_{actual})^2}$$

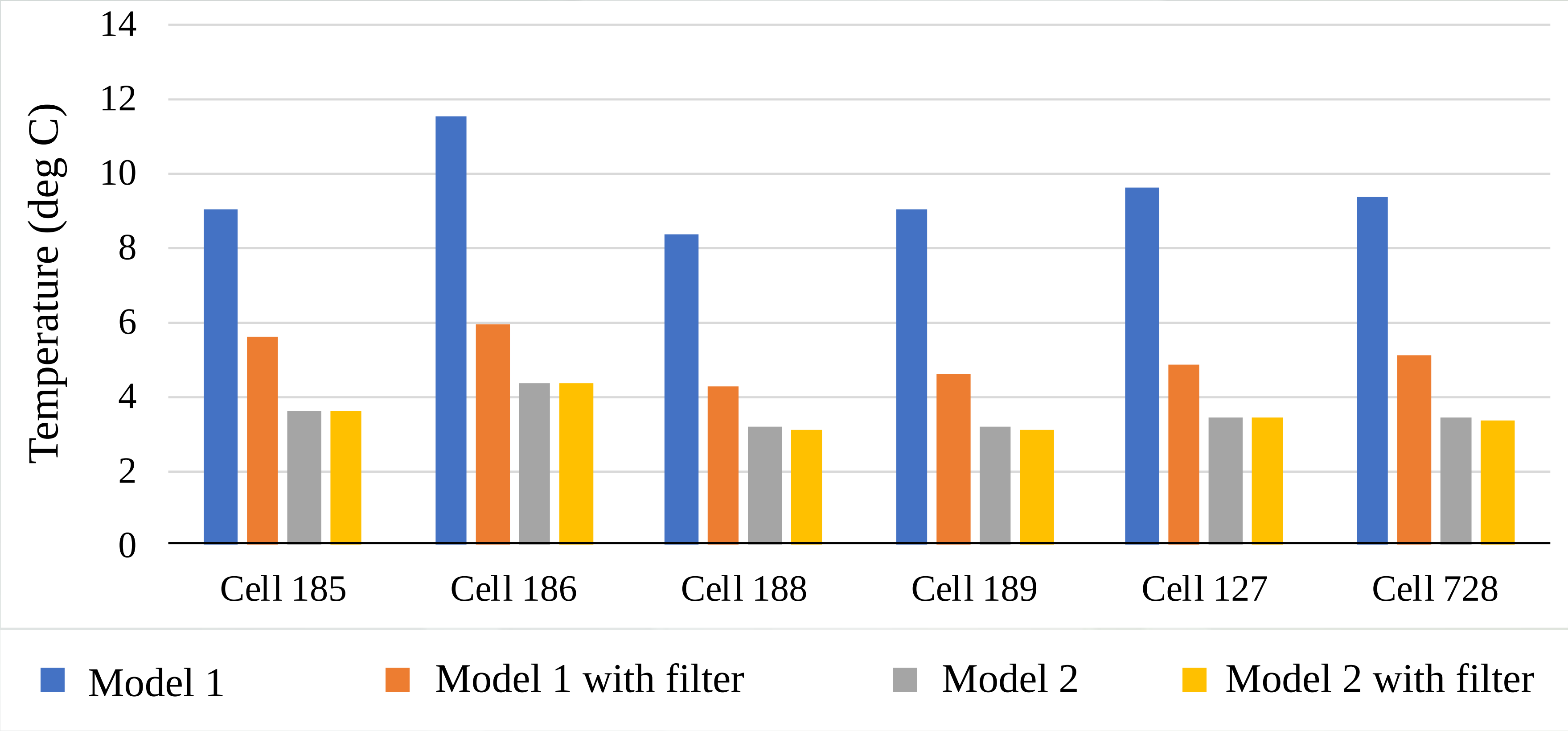
Where,

n is the number of data points

$T_{predicted}$ is the predicted temperature at each point

T_{actual} is the actual temperature at each point

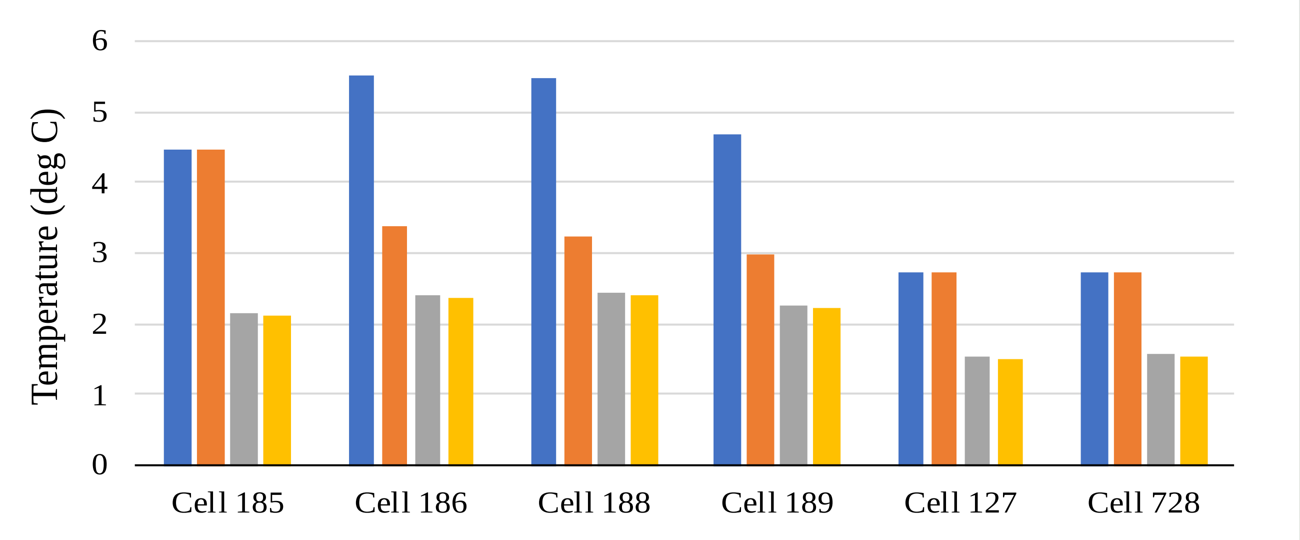
Model Selection : *Model comparison*



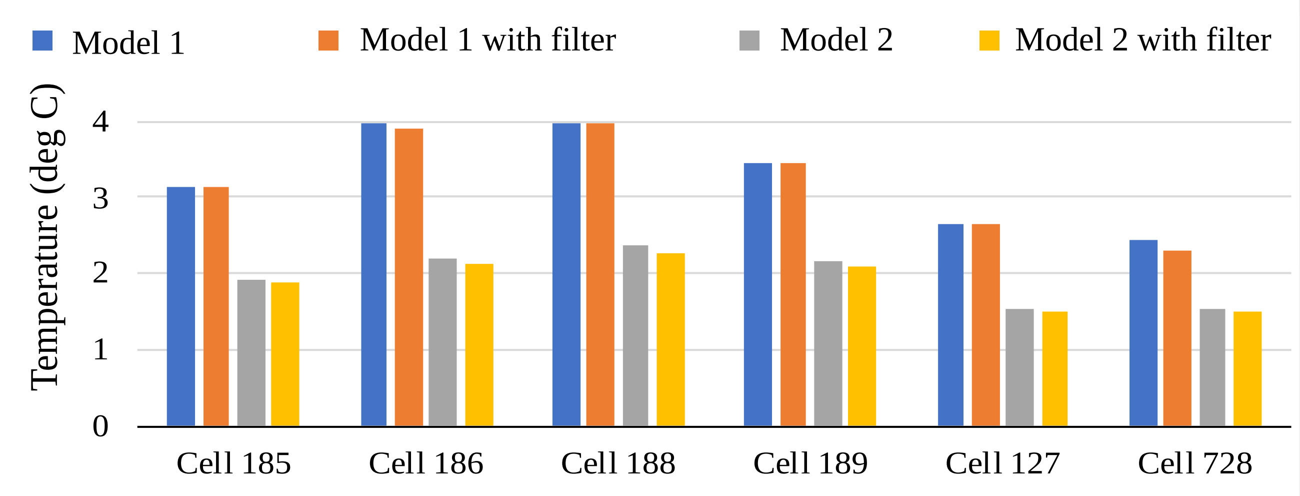
*RMSE values for testing dataset at **3-inch** depth*

Model 2 has better performance; filters help improve model performance

Model Selection : *Model comparison*



*RMSE values for testing dataset at **18.5-inch** depth*



*RMSE values for testing dataset at **24-inch** depth*

Freeze-thaw cycle calculation

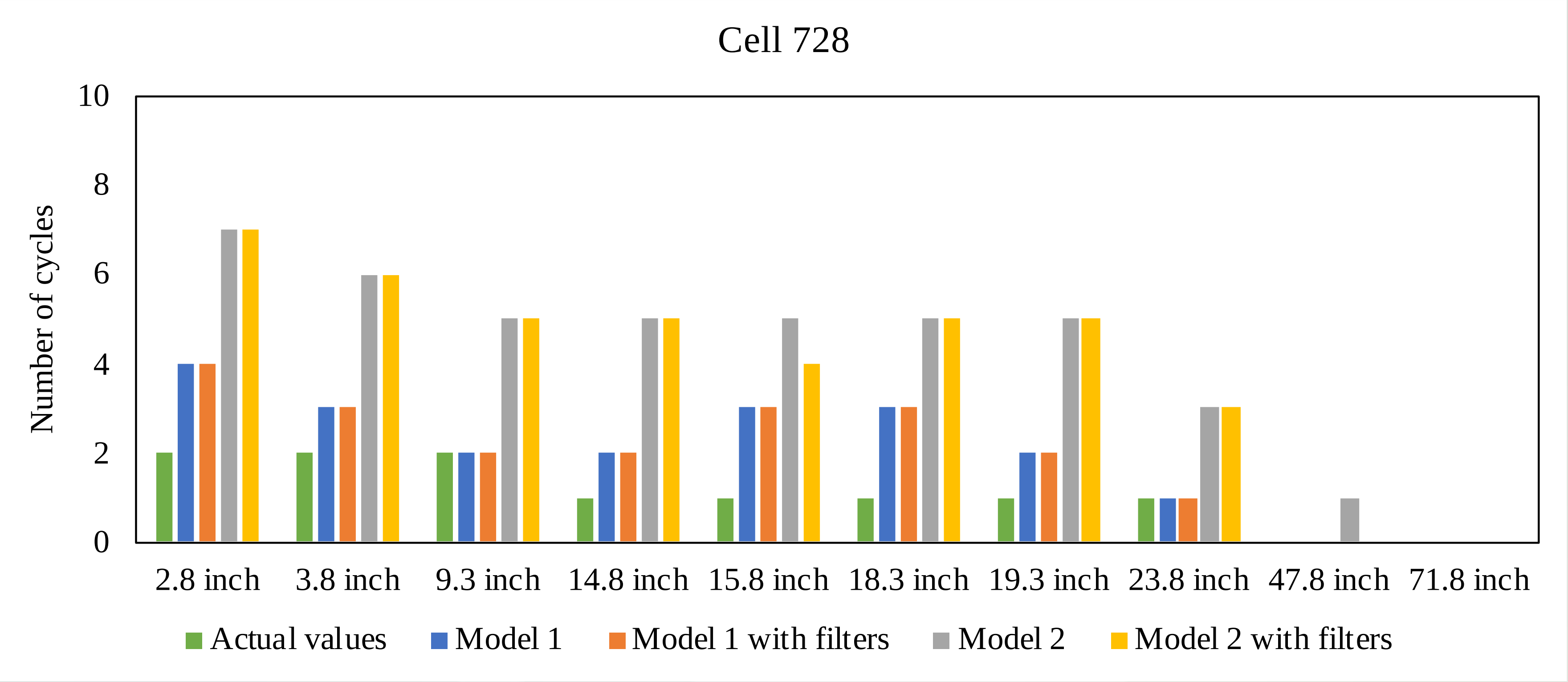
Number of freeze thaw cycles depends on:

- Freezing temperature
- Thaw temperature
- Time the soil temperature is lower than the freezing and higher than the thaw temperature

Based on the updated MnDot method, the following is used to evaluate the number of freeze-thaw cycles

- Freezing temperature is -1°C
- Thaw temperature is 0°C
- Time delay to ensure freezing is 24 hours
- Time delay to ensure thaw is 5 hours

Results : *Freeze-thaw cycle count*



Model 1 (with filters) has better accuracy in prediction of # of freeze-thaw cycles compared to Model 2

Results: *Freeze-thaw duration*

The starting and ending time of the freezing period and its duration is calculated and compared with the predicted result

Identify: duration each depth is frozen; freezing and thawing period

Results: *Freeze-thaw duration*

Cell 185						
Depths	Method	Number of cycles	Frozen start day	Frozen end day	Frozen duration	Total Frozen duration
9.5 inch	*Actual value*	*1*	*Jan-02*	*Mar-08*	*65*	*65*
	Method 1	3	Jan-02	Jan-07	5	60
			Jan-09	Feb-23	45	
			Feb-26	Mar-08	10	
14.8 inch	*Actual value*	*1*	*Jan-02*	*Mar-15*	*72*	*72*
	Method 1	1	Jan-02	Mar-09	66	66
15.8 inch	*Actual value*	*1*	*Jan-03*	*Mar-16*	*72*	*72*
	Method 1	1	Jan-02	Mar-09	66	66
18.3 inch	*Actual value*	*1*	*Jan-19*	*Mar-18*	*58*	*58*
	Method 1	1	Jan-02	Mar-03	60	60
19.3 inch	*Actual value*	*1*	*Jan-20*	*Mar-18*	*57*	*57*
	Method 1	2	Jan-02	Jan-07	5	57
			Jan-10	Mar-03	52	
23.8 inch	*Actual value*	*1*	*Jan-22*	*Mar-20*	*57*	*57*
	Method 1	2	Jan-02	Jan-07	5	57
			Jan-10	Mar-03	52	
47.8 inch	Actual value	0	-	-	-	-
	Method 1	0	-	-	-	-
71.8 inch	Actual value	0	-	-	-	-
	Method 1	0	-	-	-	-

Method 1 best predicts the freezing start/end day and duration

Results: *Freeze-thaw duration*

Cell location	Freezing period		Thawing period	
	Actual value	Predicted	Actual value	Predicted
Cell 185	Jan 2 – Mar 8	Jan 2 – Mar 3	Mar 8 – Mar 20	Mar 3- Mar 9
Cell 186	Jan 2 – Mar 9	Jan 2 – Mar 8	Mar 9 – Mar 25	Mar 8- Mar 9
Cell 188	Jan 2 – Mar 8	Jan 2 – Mar 2	Mar 8 – Mar 29	Mar 2- Mar 9
Cell 189	Jan 2 – Mar 9	Jan 2 – Feb 14	Mar 9 – Apr 1	Feb 14- Mar 9
Cell 127	Jan 2 – Mar 8	Jan 2 – Mar 10	Mar 8 – Mar 23	Mar 8- Mar 15
Cell 728	Jan 2 – Mar 15	Jan 2 – Mar 10	Mar 15 – Mar 23	Mar 10- Mar 15

Conclusions

2 different models using non-linear regression models

***Model 1**: Individual depth*

***Model 2**: Individual depth: Daily average + variation WRT daily*

2 filters used to improve model performance

Choose best model to predict :

- Soil temperatures: **Model 1 w/ filters**
- Number of freeze-thaw cycles: **Model 2 w/filters**
- Start/end and duration of freezing & thawing period: **both but Model 1 w/filters is better**

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Extra slides

Result : *Freeze-thaw cycle duration*

Cell location	Freezing period		Thawing period	
	Actual value	Predicted	Actual value	Predicted
Cell 185	Jan 2 – Mar 8	Jan 2 – Mar 3	Mar 8 – Mar 20	Mar 3- Mar 9
Cell 186	Jan 2 – Mar 9	Jan 2 – Mar 8	Mar 9 – Mar 25	Mar 8- Mar 9
Cell 188	Jan 2 – Mar 8	Jan 2 – Mar 2	Mar 8 – Mar 29	Mar 2- Mar 9
Cell 189	Jan 2 – Mar 9	Jan 2 – Feb 14	Mar 9 – Apr 1	Feb 14- Mar 9
Cell 127	Jan 2 – Mar 8	Jan 2 – Mar 10	Mar 8 – Mar 23	Mar 8- Mar 15
Cell 728	Jan 2 – Mar 15	Jan 2 – Mar 10	Mar 15 – Mar 23	Mar 10- Mar 15

Temperature Isotherms