Environmental Impacts on the Performance of Pavement Foundation Layers-Phase I

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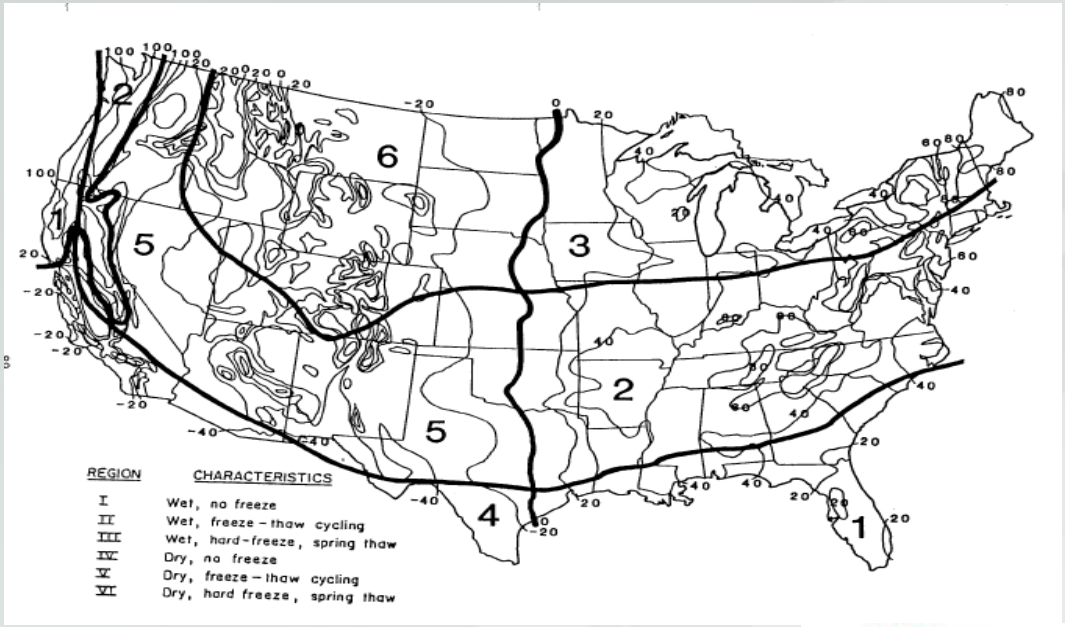
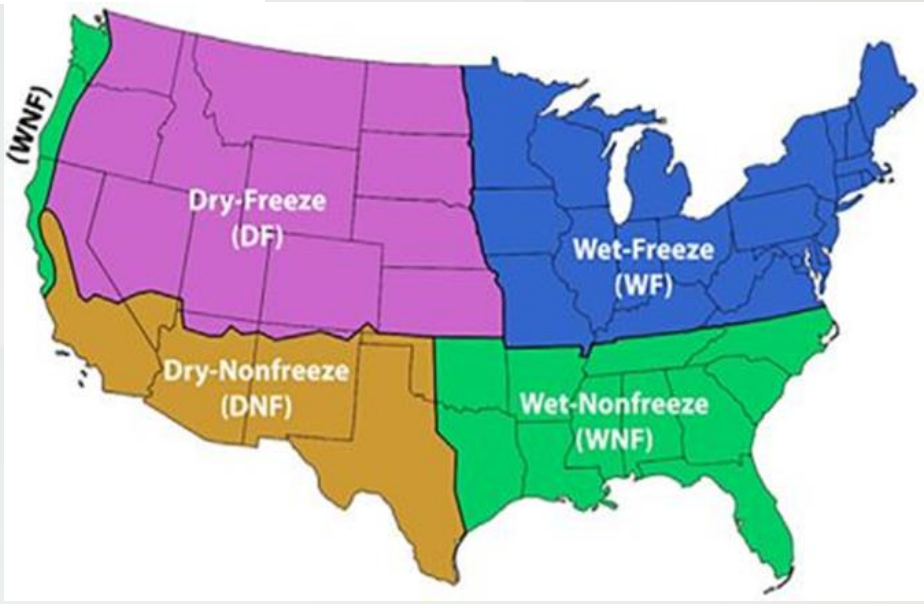
PROBLEM STATEMENT





PROBLEM STATEMENT

Freezing → **Thaw Weakening**

Ice Lensing → Frost Boil → Rutting → Potholes

https://myferndalenews.com/frost-boils-reason-emergency-road-restrictions_55759/

https://porthawkesburyreporter.com/spring-weight-restrictions-partially-lift

SEASONAL LOAD RESTRICTION (SLR)

Avoid additional loads

- Keep the damage minimum
- Organize heavy vehicles/ keep the adverse effect minimum

(Image: patch.com)

Determining SLR:

- ❑Subsurface Instrumentation
- ❑In-situ Stiffness Testing
- ❑Modeling

INSTRUMENTATION

- Instrumented with an array of:
  - Soil Moisture
  - Temperature
- Weather Station to measure climate data
  - On site
  - Road Weather Information Systems (RWIS)
  - Environmental Sensing Stations
  - Modern Era Retrospective Analysis for Research and Applications (MERRA)

Overview of Research Plan

- **Task 1** – Initial Memorandum on Expected Research Benefits and Potential Implementation Steps
- **Task 2** – Field Data Collection
- **Task 3** – Modelling Analyses
- **Task 4** – Final Report

Objective of this Study:

(1) Clean and pre-process the soil & weather data

(2) Develop a data-driven model that uses weather data as input to:

- Predict the soil temperature and certain depths
- Predict the number of freeze thaw cycles at certain depths and start/end time, and duration of cycles over time

(3) Create a tool to provide soil temperature and number/duration of freeze-thaw cycles that implements the model

Literature review:

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

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

Literature review:

Other studies that predicted soil temperatures:

1. Predict daily average temperature using superposition of two models: predict monthly average temperature and daily average temperature amplitude using *air temperature, solar radiation, wind speed, relative humidity and day of year* [Xing et al., 2018]

2. Estimate daily soil surface temperature using *mean, maximum and minimum air temperature, relative humidity, sunshine hours and solar radiation* [Talaee et al., 2013]

3. Predict daily soil surface temperature using parameters like *average air temperature, total solar radiation, average relative humidity, average dew point temperature, average wind speed and total potential evapotranspiration* [Kim et al., 2014]

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(1) Input Data:

Dataset 1 (of 2):

Temperature and moisture data of 6 different locations are available within 2-mile span of roadway at Monticello, Minnesota

- Cell 185; Cell 186; Cell 188; Cell 189; Cell 127; Cell 728

Frequency: 15-minute time intervals

Time period: August 2017 to December 2019

Climate data: air temperature, relative humidity, wind speed, net radiation, precipitation

(1) Input Data (Dataset 1):

Temperature data collected at 12 different depths for all stations

Cell no.	Cell 185	Cell 186	Cell 188	Cell 189	Cell 127	Cell 728
	Depth (in)					
TC_1	2.8	3	3	3	3	3
TC_2	3.8	4	4	4	4	4
TC_3	9.3	9.5	9.5	9.5	6.5	6.5
TC_4	14.8	15	15	15	9	9
TC_5	15.8	16	16	16	10	10
TC_6	18.3	18.5	18.5	18.5	12	14
TC_7	19.3	19.5	19.5	19.5	18	18.5
TC_8	23.8	24	24	24	24	24
TC_9	35.8	36	36	36	36	36
TC_10	47.8	48	48	48	48	48
TC_11	59.8	60	60	60	60	60
TC_12	71.8	72	72	72	72	72

Moisture data collected at 4 depths for all locations

Cell no.	Cell 185	Cell 186	Cell 188	Cell 189	Cell 127	Cell 728
	Depth (in)					
EC_1	5	5	5	5	6.5	8.5
EC_2	14	14	14	14	29	19.5
EC_3	17	17	17	17	36	24
EC_4	20.5	20.5	20.5	20.5		36

(1) Input Data:

Dataset 2 (of 2):

Temperature and moisture data for 2 different counties in are Minnesota: Olmsted and Koochiching

Frequency: 1-hour time intervals

Time period: 2005-2012, 2012-2019 (Koochiching); 2000-2007, 2010-2017 (Olmsted)

Climate data (same as other dataset): air temperature, relative humidity, wind speed, net radiation, precipitation

(1) Input Data (Dataset 2):

Temperature/moisture sensor locations for the two-time spans

Dataset location	Time span	Depth of temperature sensors
Koochiching	2005 to 2010	10; 40; 70; 90; 120; 180; 240; 300; 360; 420; 480; 540; 600; 720; 840; 960
	2012 to 2019	10; 30; 50; 80; 120; 150; 180; 210; 240; 300; 360; 420; 480; 540; 600; 640; 780; 910
Olmsted	2000 to 2007	25; 60; 90; 120; 180; 240; 300; 360; 420; 480; 600; 720; 840; 960; 1080
	2010 to 2017	10; 25; 50; 70; 130; 190; 250; 310; 370; 430; 490; 550; 610; 730; 850; 970

Dataset location	Time span	Depth of moisture sensors
Koochiching	2005 to 2010	N/A
	2012 to 2019	80, 120, 150, 180, 210, 240, 300, 360, 420, 480, 540, 600, 780, 910
Olmsted	2000 to 2007	60, 90, 120, 180, 240, 300, 360, 420, 480, 600, 720, 840, 960, 1080
	2010 to 2017	70, 130, 190, 250, 310, 370, 430, 490, 550, 610, 730, 850, 970

(1) Input Data: *preprocessing*

Dataset 1: Percent (%) missing temperature data

	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12
Cell 185	2	2	2	2	2	2	2	2	12	2	87	2
Cell 186	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	11	< 1	< 1	< 1
Cell 188	< 1	< 1	0	0	0	0	0	0	0	0	0	0
Cell 189	< 1	< 1	0	0	0	0	0	0	NA	0	0	0
Cell 127	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cell 728	< 1	< 1	< 1	0	0	0	0	0	0	0	0	0

Outliers: identified and removed from the dataset

Missing Data:

- Number of missing elements were very small *(other than TC9 and TC11 in Dataset 1)*
- Data imputation was used to fill in missing elements as appropriate

Dataset 2 had very little missing data

(1) Input data: *Freeze-thaw cycle calculations*

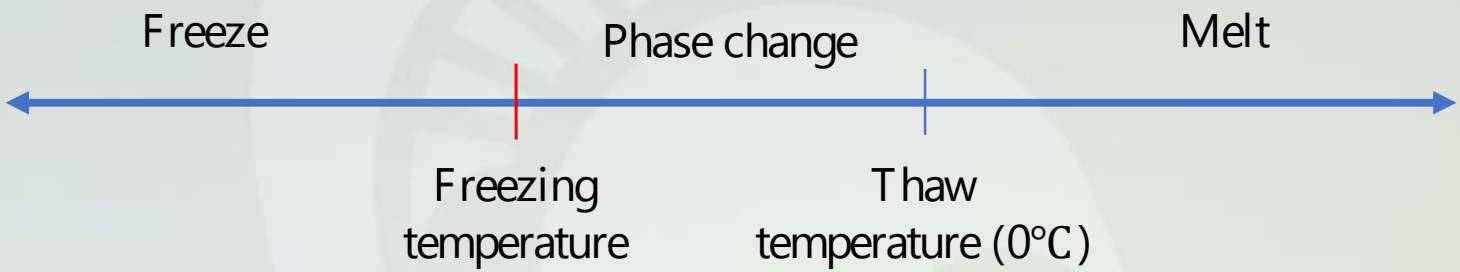
Justification: Number of freeze-thaw cycles significantly impacts the soil properties

Number of freeze thaw cycles depends on:

- Freezing temperature
- Thaw temperature (can be different from freezing temperature)
- Time the soil temperature is lower than the freezing and higher than the thaw temperature

(1) Input data: *Freeze-thaw cycle calculation*

To undergo a complete freeze-thaw cycle, soil temperature needs to be higher than thaw temperature and then it needs to be lower than freezing temperature.



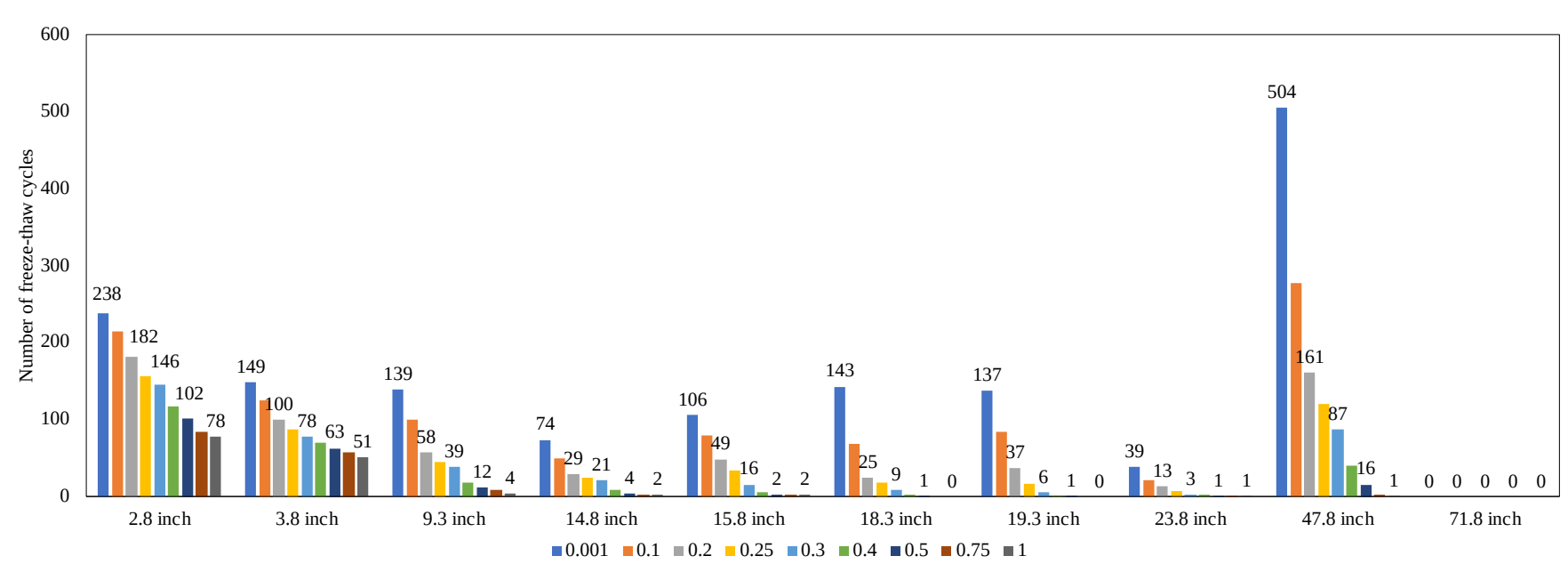
Thaw temperature is 0°C

9 different freezing temperatures are considered:

Ranging from -0.001 °C, to -1 °C

(1) Input data: *Freeze-thaw cycle calculation*

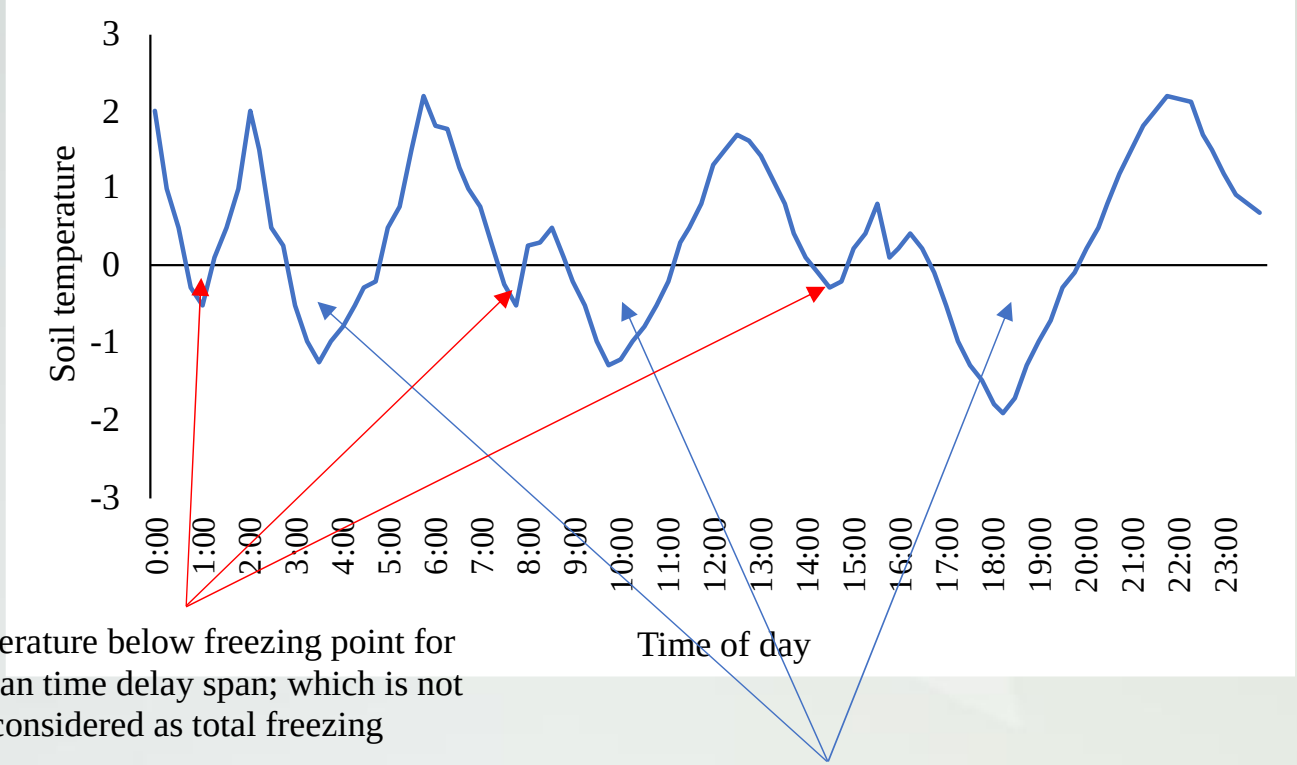
The variation in number of cycles at different depth are shown below (Cell 185, Dataset 1, for 2018 (1 year, Jan-Dec), similar data in other locations)



- increase freezing temperature, number of cycles reduces significantly
- If assume larger freezing temperatures, # of cycles reduces with depth (makes sense); if assume smaller at deeper depths it increases significantly (doesn't make sense)

(1) Input data: *Freeze-thaw cycle calculations*

"**Time delay**" is defined as a minimum period of time required for a half of a freeze-thaw cycle to be completed in order for it to count as a F-T cycle



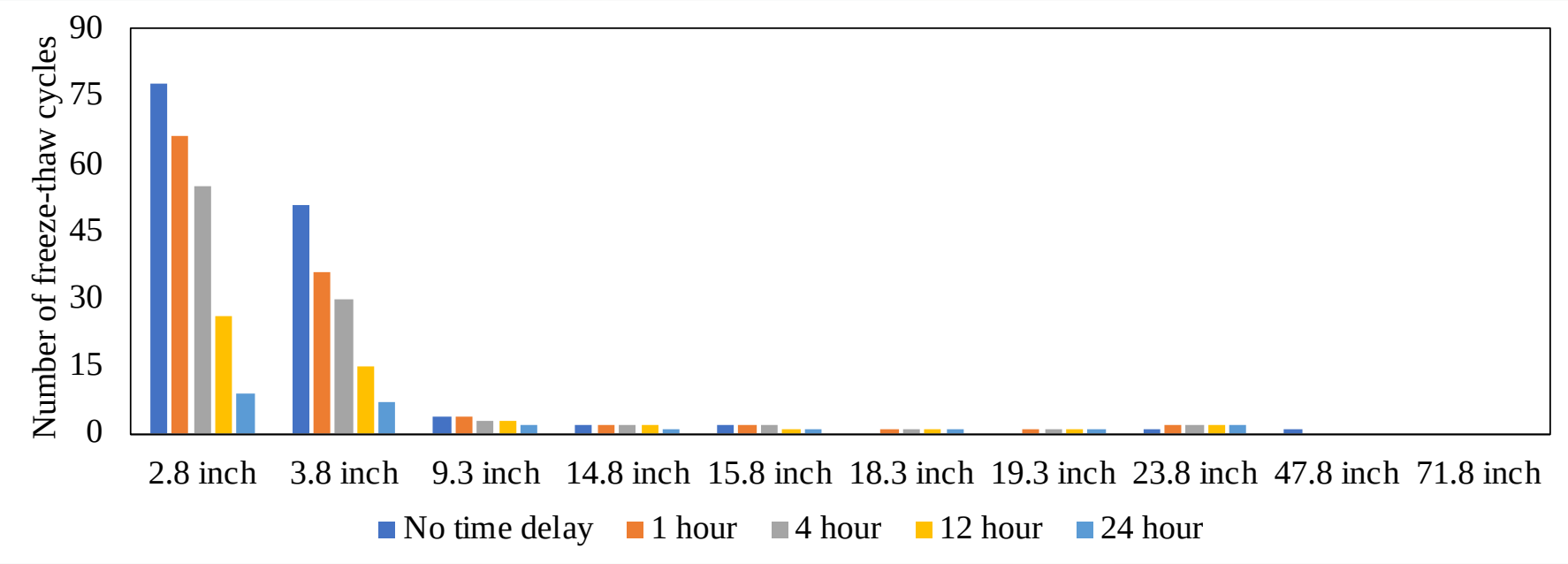
Temperature below freezing point for less than time delay span; which is not considered as total freezing

Temperature below freezing point for more than time delay span (1 hour here); considered as complete freezing

(1) Input Data: *Freeze-thaw cycle calculations*

4 different **time delays** considered: 1-hour, 4-hour, 12-hour and 24-hour

The variation in number of cycles at different depth are shown below (Cell 185**, Dataset 1,** for 2018 (1 year, Jan-Dec))



Increasing the time delay reduces the number of cycles calculated at shallower depths

(1) Input Data: *Freeze-thaw cycle calculations*

Final Method chosen:

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

(1) Input Data: *Summary*

2 input datasets of weather/soil data used as input

- Quality controlled and pre-processed

Freeze-thaw calculation method chosen

- Based on the updated MnDot method:
  - 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

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(2) 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

(2) Data Processing: *Model input variables*

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)

(2) Data Processing: *Model input variables*

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)

(2) Model Development: *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)*

(2) Model Development: *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*

(2) Model Development: *Data Division*

Dataset 1:

Dates available: January 2018 to April 2019

Data division:

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

Testing data: 2019, January to April

Dataset 2:

Dates available: January 2000 to February 2007

Data division:

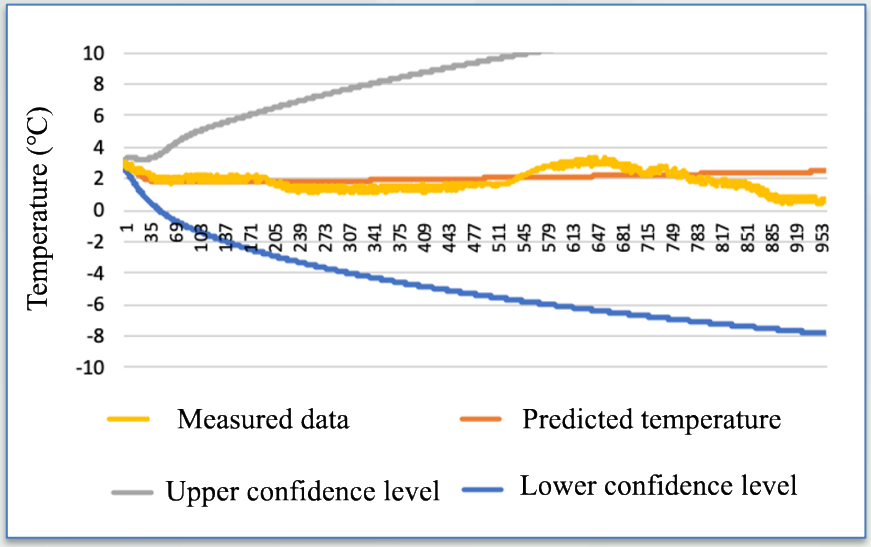
Training data: 2005 to Feb 2005, which (~79% of data)

Testing data: Sept 2005 to Feb 2007

(2) 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 were unable to predict the soil temperature trends at this data frequency

(2) Model Selection

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

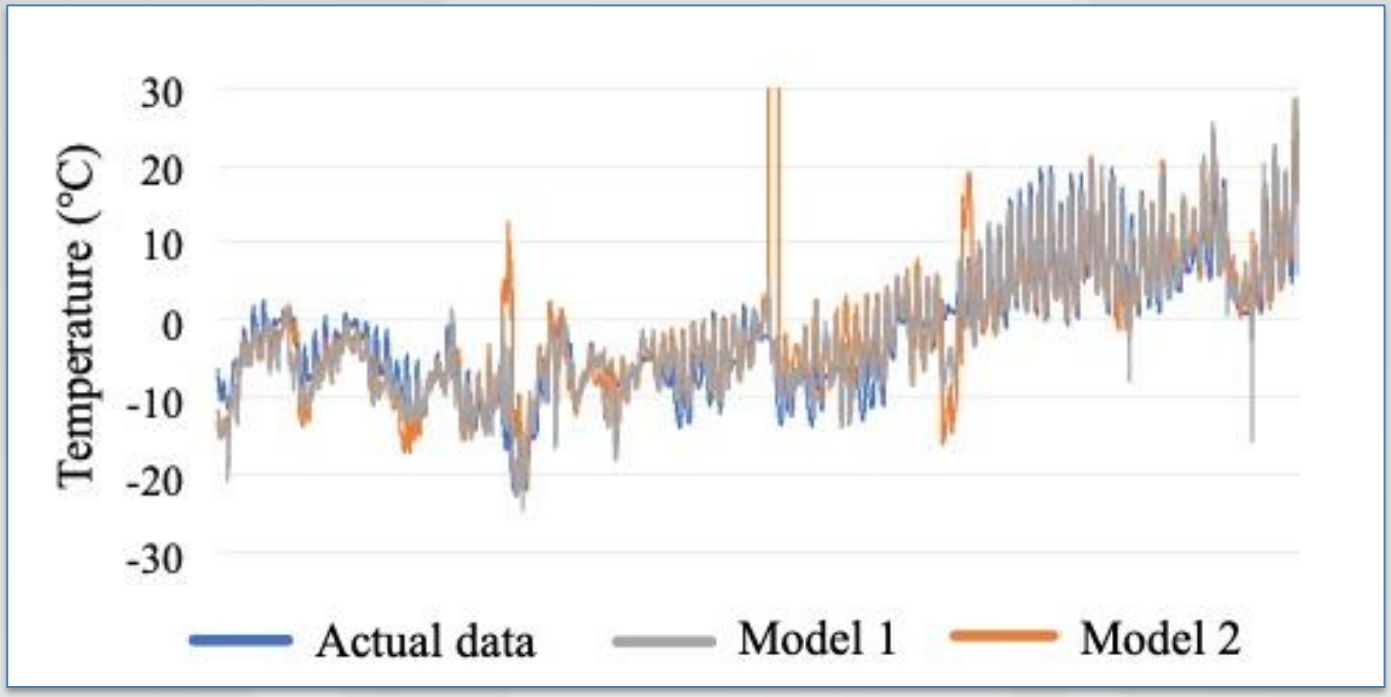
Model 1: *Individual depths*

Predict the soil temperatures at each depth using climate parameters

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

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

(2) Model Selection: *Temperature prediction*



Example soil temperature

- Both the models can generally predict the temperature
- Models have a few spikes in predictions

(2) 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

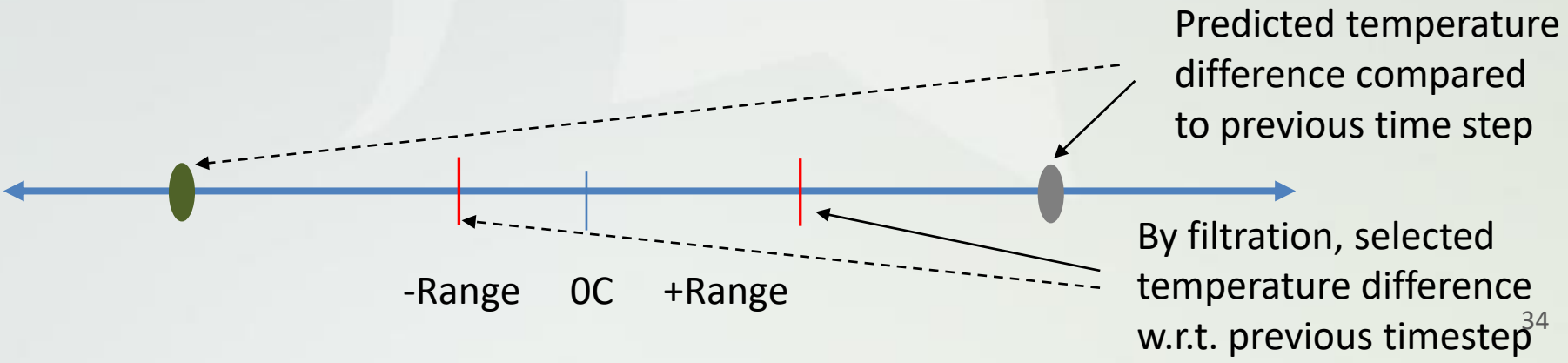
Filter 2: Remove the predicted temperatures which were significantly higher or lower than the temperature bound

(2) 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



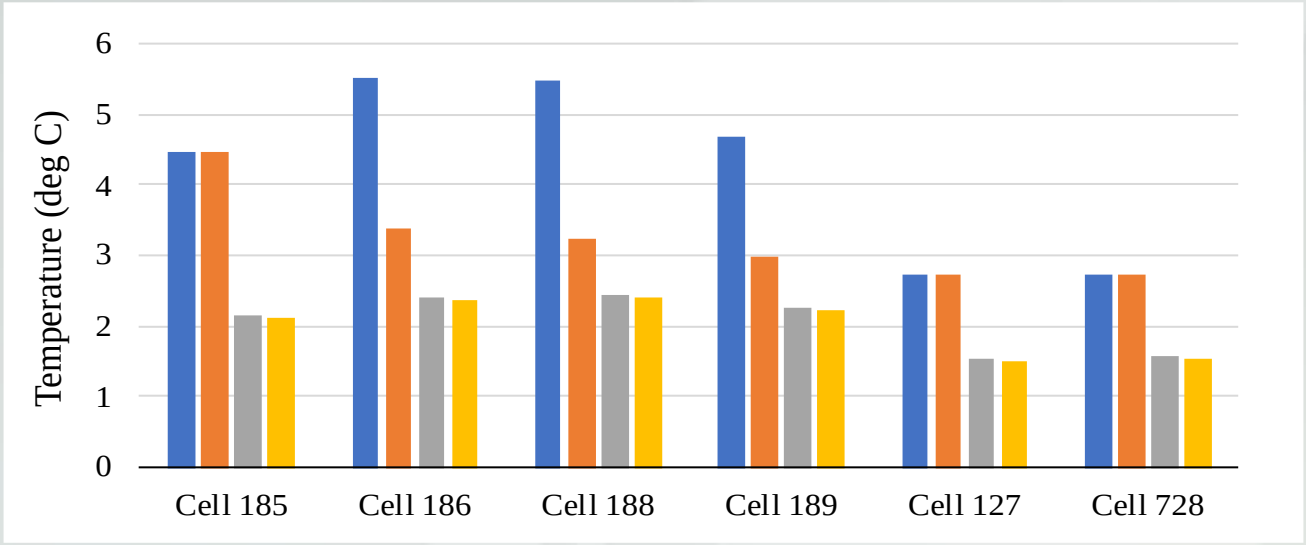
(2) Model Selection : *Filter 2*

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

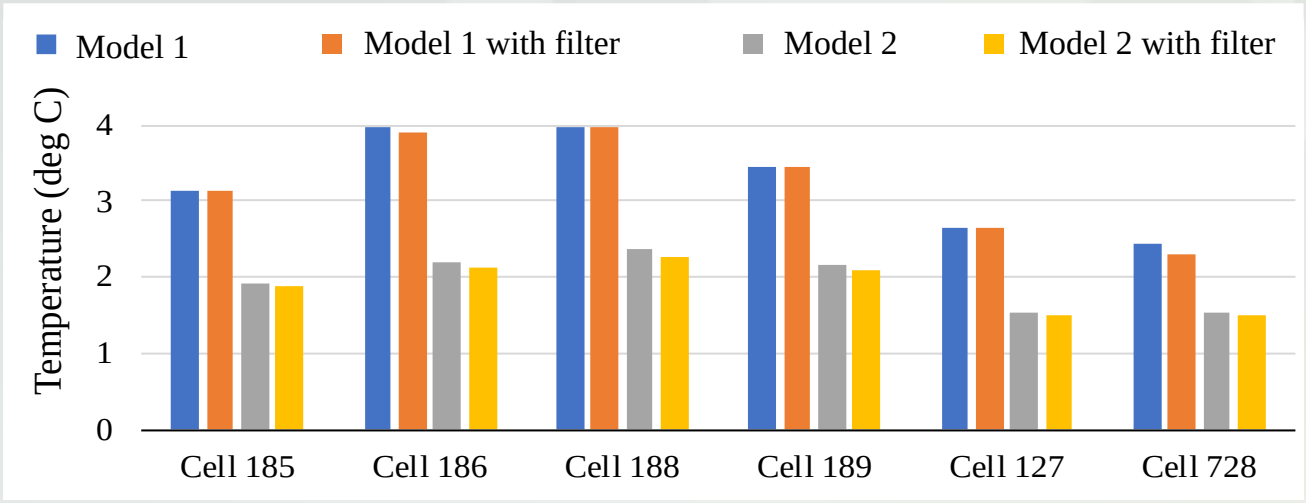
If the predicted value is out of bounds, then previous predicted value is used

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

(2) Model Selection : *Model comparison*



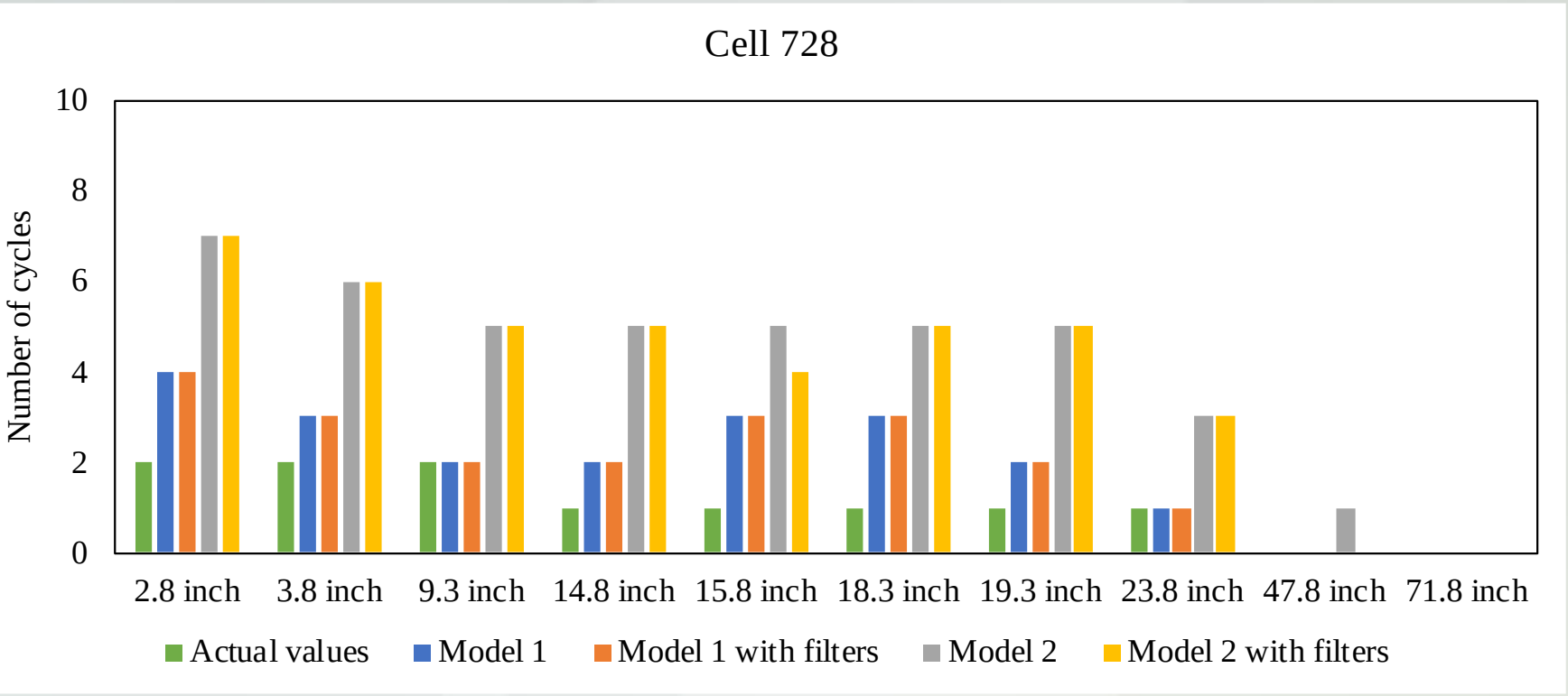
*RMSE values for testing dataset at **18.5-inch** depth*



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

Model 2 has slightly better performance in predicting temperature; filters help improve model performance

(2) Model Results : *Freeze-thaw cycle count*



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

(2) Model 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

(2) Model 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

(2) Model Development: *Summary*

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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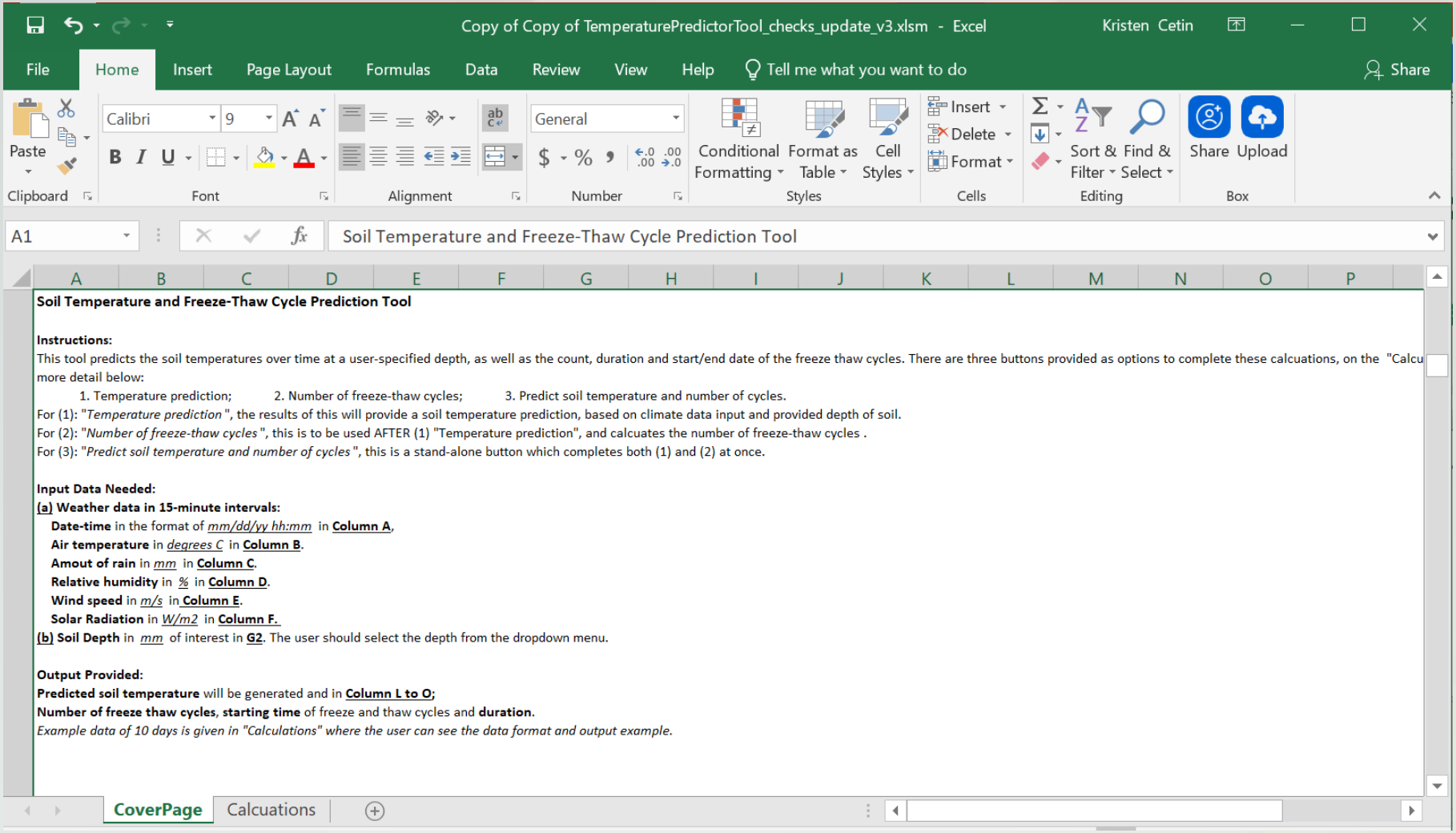
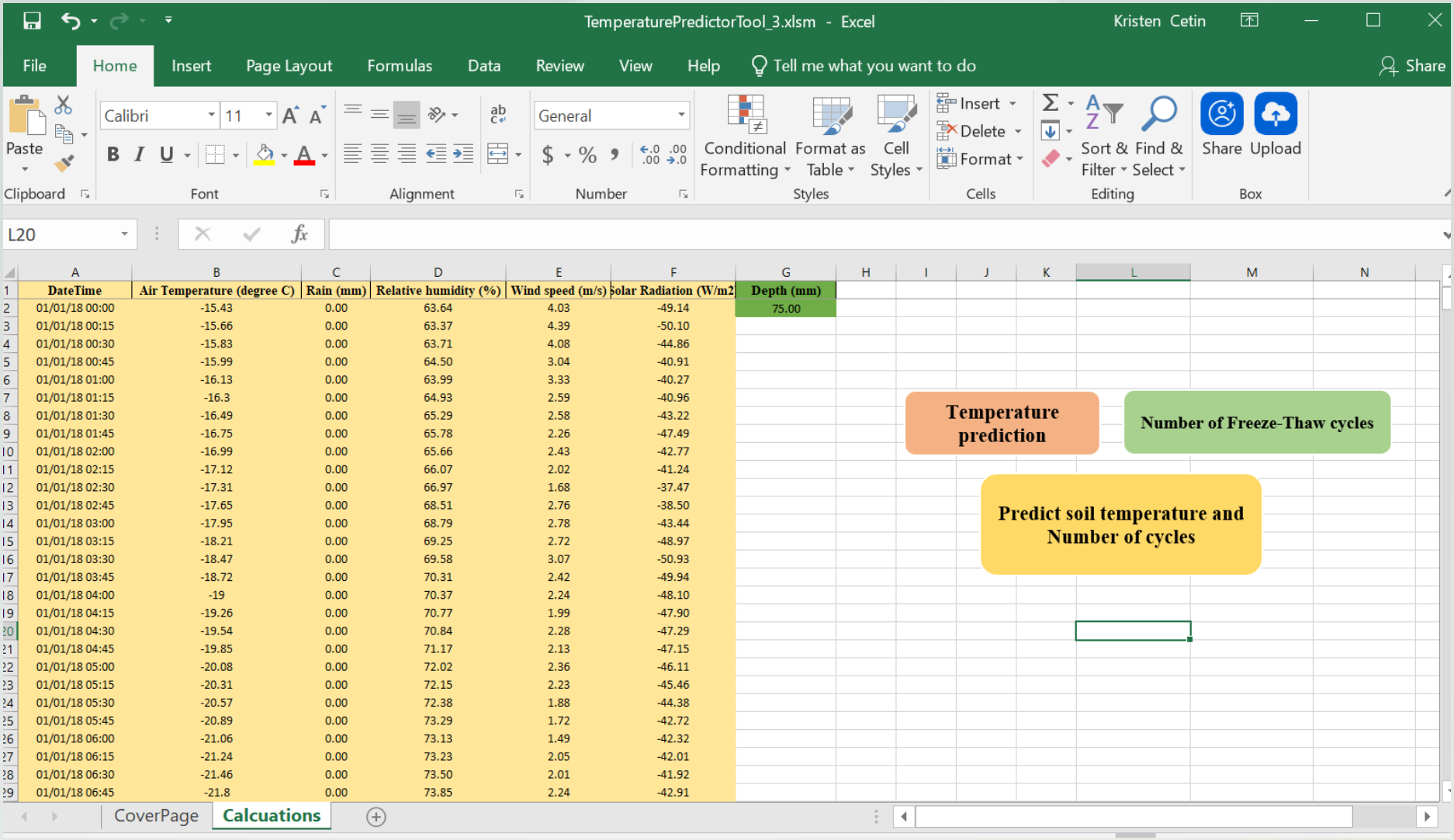
(3) Tool Development : *Description (Directions/Cover Page)*

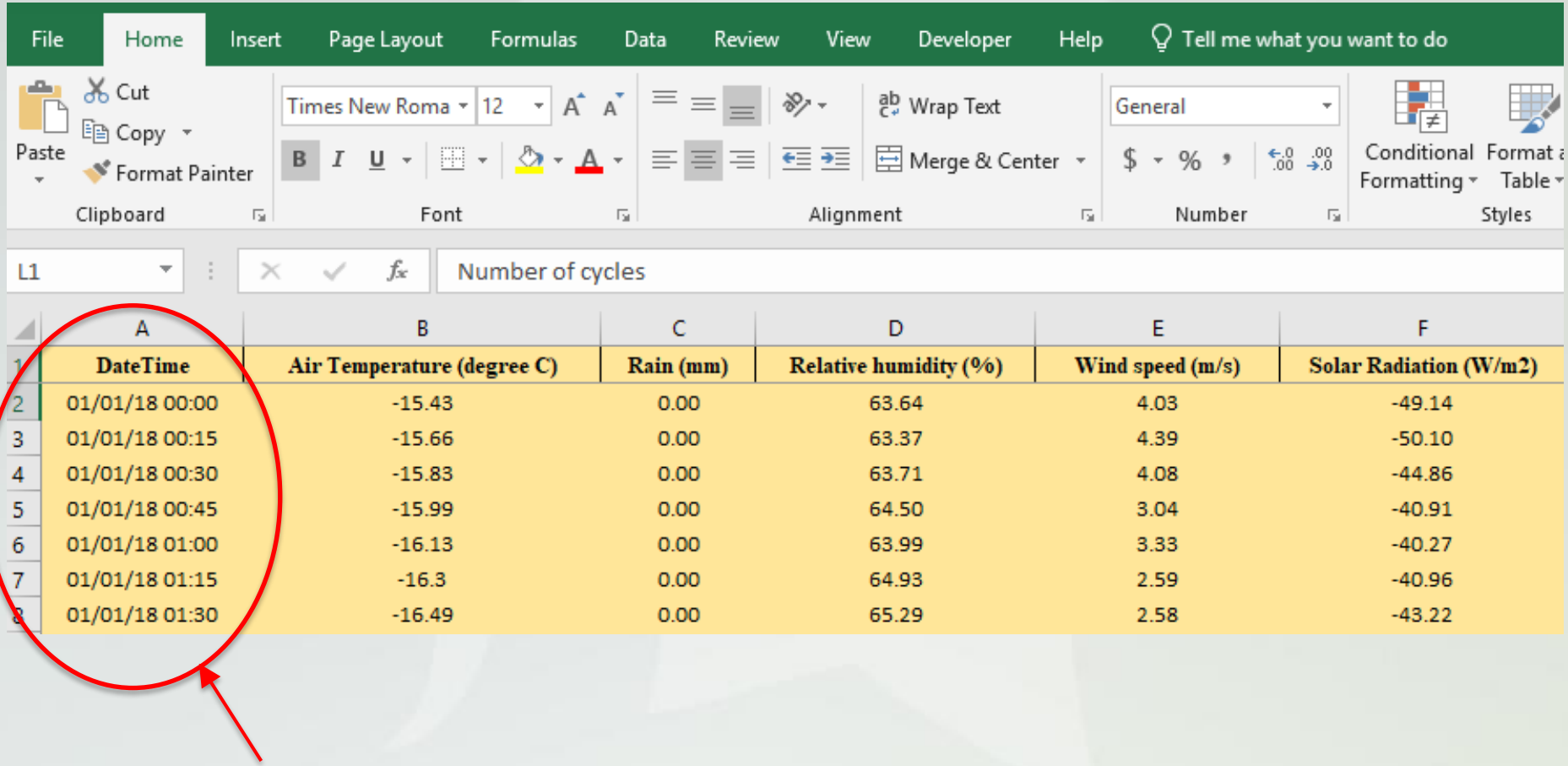


(3) Tool Development: *Description (Calculations)*



DateTime	Air Temperature (degree C)	Rain (mm)	Relative humidity (%)	Wind speed (m/s)	Solar Radiation (W/m2)	Depth (mm)
01/01/18 00:00	-15.43	0.00	63.64	4.03	-49.14	75.00
01/01/18 00:15	-15.66	0.00	63.37	4.39	-50.10	
01/01/18 00:30	-15.83	0.00	63.71	4.08	-44.86	
01/01/18 00:45	-15.99	0.00	64.50	3.04	-40.91	
01/01/18 01:00	-16.13	0.00	63.99	3.33	-40.27	
01/01/18 01:15	-16.3	0.00	64.93	2.59	-40.96	
01/01/18 01:30	-16.49	0.00	65.29	2.58	-43.22	
01/01/18 01:45	-16.75	0.00	65.78	2.26	-47.49	
01/01/18 02:00	-16.99	0.00	65.66	2.43	-42.77	
01/01/18 02:15	-17.12	0.00	66.07	2.02	-41.24	
01/01/18 02:30	-17.31	0.00	66.97	1.68	-37.47	
01/01/18 02:45	-17.65	0.00	68.51	2.76	-38.50	
01/01/18 03:00	-17.95	0.00	68.79	2.78	-43.44	
01/01/18 03:15	-18.21	0.00	69.25	2.72	-48.97	
01/01/18 03:30	-18.47	0.00	69.58	3.07	-50.93	
01/01/18 03:45	-18.72	0.00	70.31	2.42	-49.94	
01/01/18 04:00	-19	0.00	70.37	2.24	-48.10	
01/01/18 04:15	-19.26	0.00	70.77	1.99	-47.90	
01/01/18 04:30	-19.54	0.00	70.84	2.28	-47.29	
01/01/18 04:45	-19.85	0.00	71.17	2.13	-47.15	
01/01/18 05:00	-20.08	0.00	72.02	2.36	-46.11	
01/01/18 05:15	-20.31	0.00	72.15	2.23	-45.46	
01/01/18 05:30	-20.57	0.00	72.38	1.88	-44.38	
01/01/18 05:45	-20.89	0.00	73.29	1.72	-42.72	
01/01/18 06:00	-21.06	0.00	73.13	1.49	-42.32	
01/01/18 06:15	-21.24	0.00	73.23	2.05	-42.01	
01/01/18 06:30	-21.46	0.00	73.50	2.01	-41.92	
01/01/18 06:45	-21.8	0.00	73.85	2.24	-42.91	

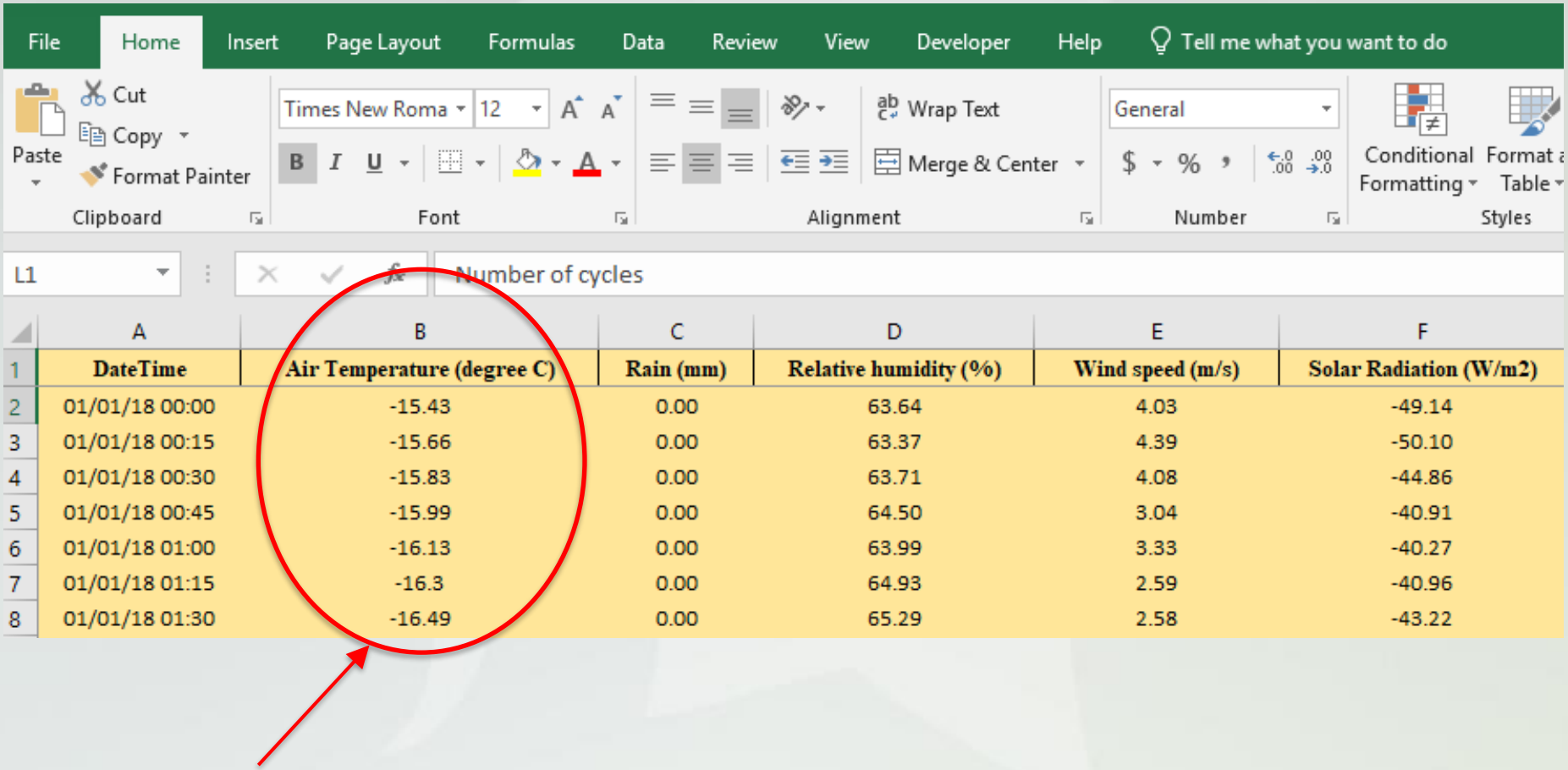
(3) Tool Development: *Description (Inputs)*



	A	B	C	D	E	F
1	DateTime	Air Temperature (degree C)	Rain (mm)	Relative humidity (%)	Wind speed (m/s)	Solar Radiation (W/m2)
2	01/01/18 00:00	-15.43	0.00	63.64	4.03	-49.14
3	01/01/18 00:15	-15.66	0.00	63.37	4.39	-50.10
4	01/01/18 00:30	-15.83	0.00	63.71	4.08	-44.86
5	01/01/18 00:45	-15.99	0.00	64.50	3.04	-40.91
6	01/01/18 01:00	-16.13	0.00	63.99	3.33	-40.27
7	01/01/18 01:15	-16.3	0.00	64.93	2.59	-40.96
8	01/01/18 01:30	-16.49	0.00	65.29	2.58	-43.22

Column A: *date and time of day* in "*mm/dd/yy hh:mm*" with a timestep of **15 minutes**

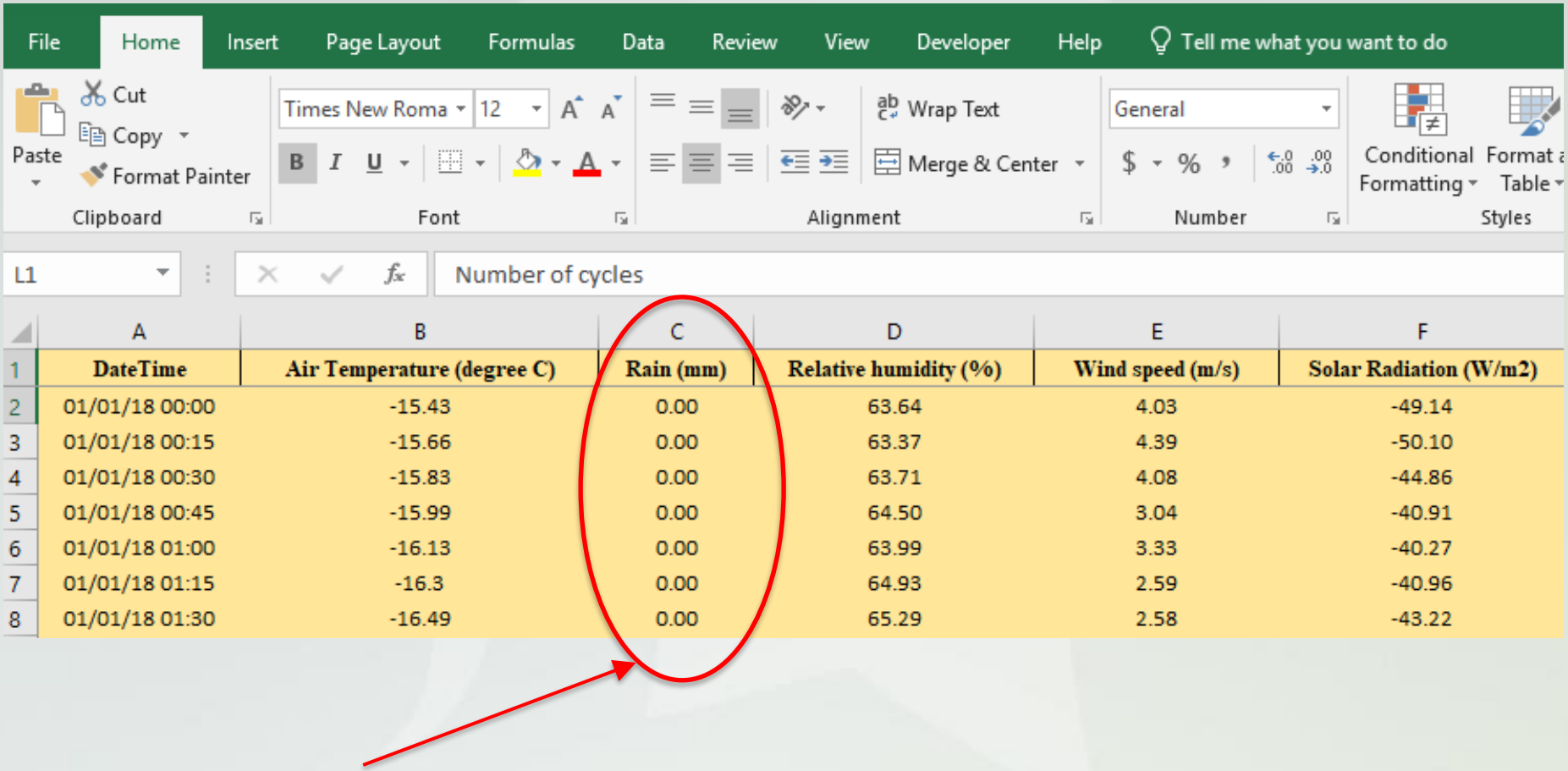
(3) Tool Development: *Description (Inputs)*



	A	B	C	D	E	F
1	DateTime	Air Temperature (degree C)	Rain (mm)	Relative humidity (%)	Wind speed (m/s)	Solar Radiation (W/m2)
2	01/01/18 00:00	-15.43	0.00	63.64	4.03	-49.14
3	01/01/18 00:15	-15.66	0.00	63.37	4.39	-50.10
4	01/01/18 00:30	-15.83	0.00	63.71	4.08	-44.86
5	01/01/18 00:45	-15.99	0.00	64.50	3.04	-40.91
6	01/01/18 01:00	-16.13	0.00	63.99	3.33	-40.27
7	01/01/18 01:15	-16.3	0.00	64.93	2.59	-40.96
8	01/01/18 01:30	-16.49	0.00	65.29	2.58	-43.22

Column B: *Outside air temperature* in **°C**

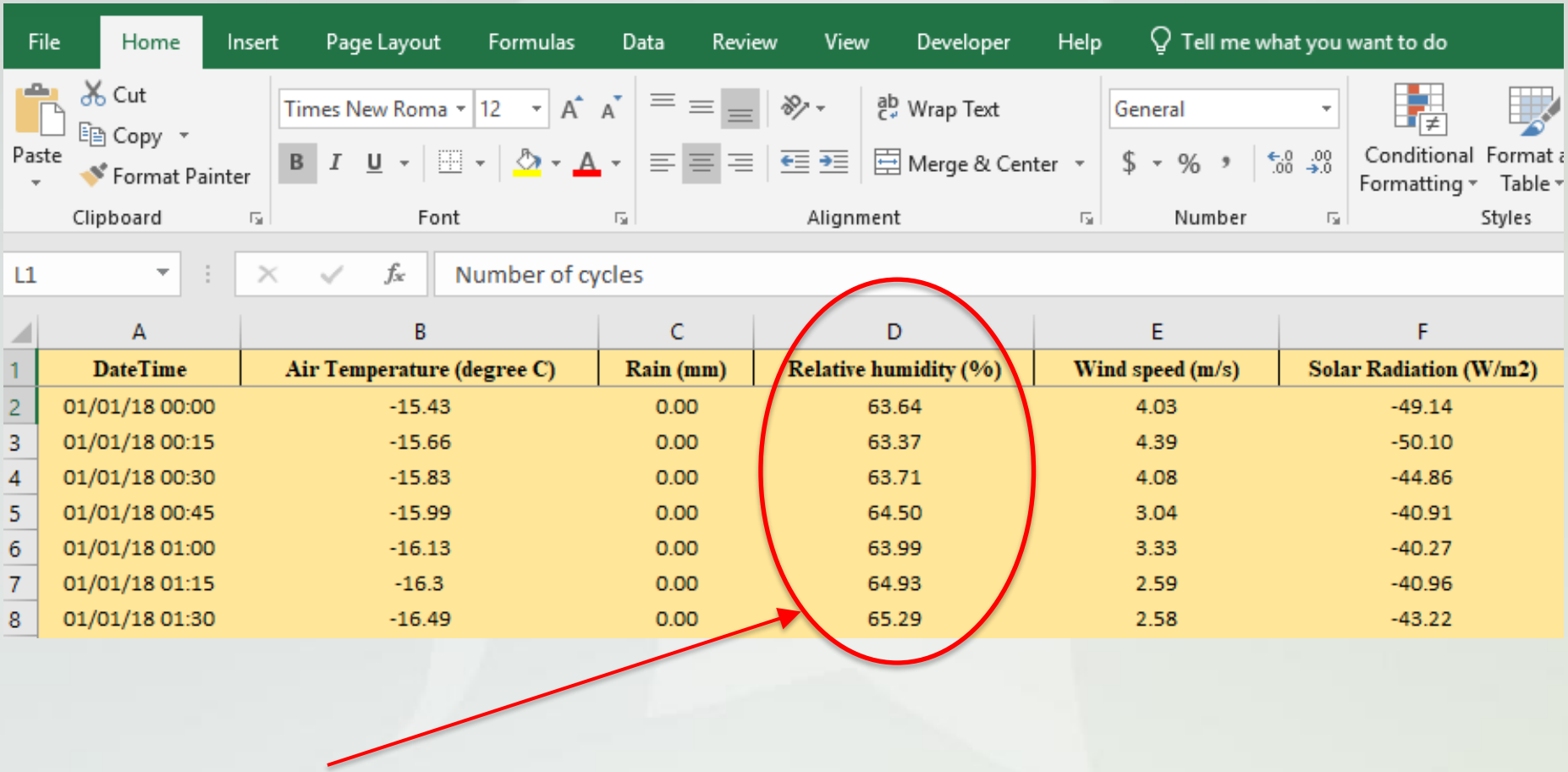
(3) Tool Development: *Description (Inputs)*



	A	B	C	D	E	F
1	DateTime	Air Temperature (degree C)	Rain (mm)	Relative humidity (%)	Wind speed (m/s)	Solar Radiation (W/m2)
2	01/01/18 00:00	-15.43	0.00	63.64	4.03	-49.14
3	01/01/18 00:15	-15.66	0.00	63.37	4.39	-50.10
4	01/01/18 00:30	-15.83	0.00	63.71	4.08	-44.86
5	01/01/18 00:45	-15.99	0.00	64.50	3.04	-40.91
6	01/01/18 01:00	-16.13	0.00	63.99	3.33	-40.27
7	01/01/18 01:15	-16.3	0.00	64.93	2.59	-40.96
8	01/01/18 01:30	-16.49	0.00	65.29	2.58	-43.22

Column C: Total *rainfall* in **mm**

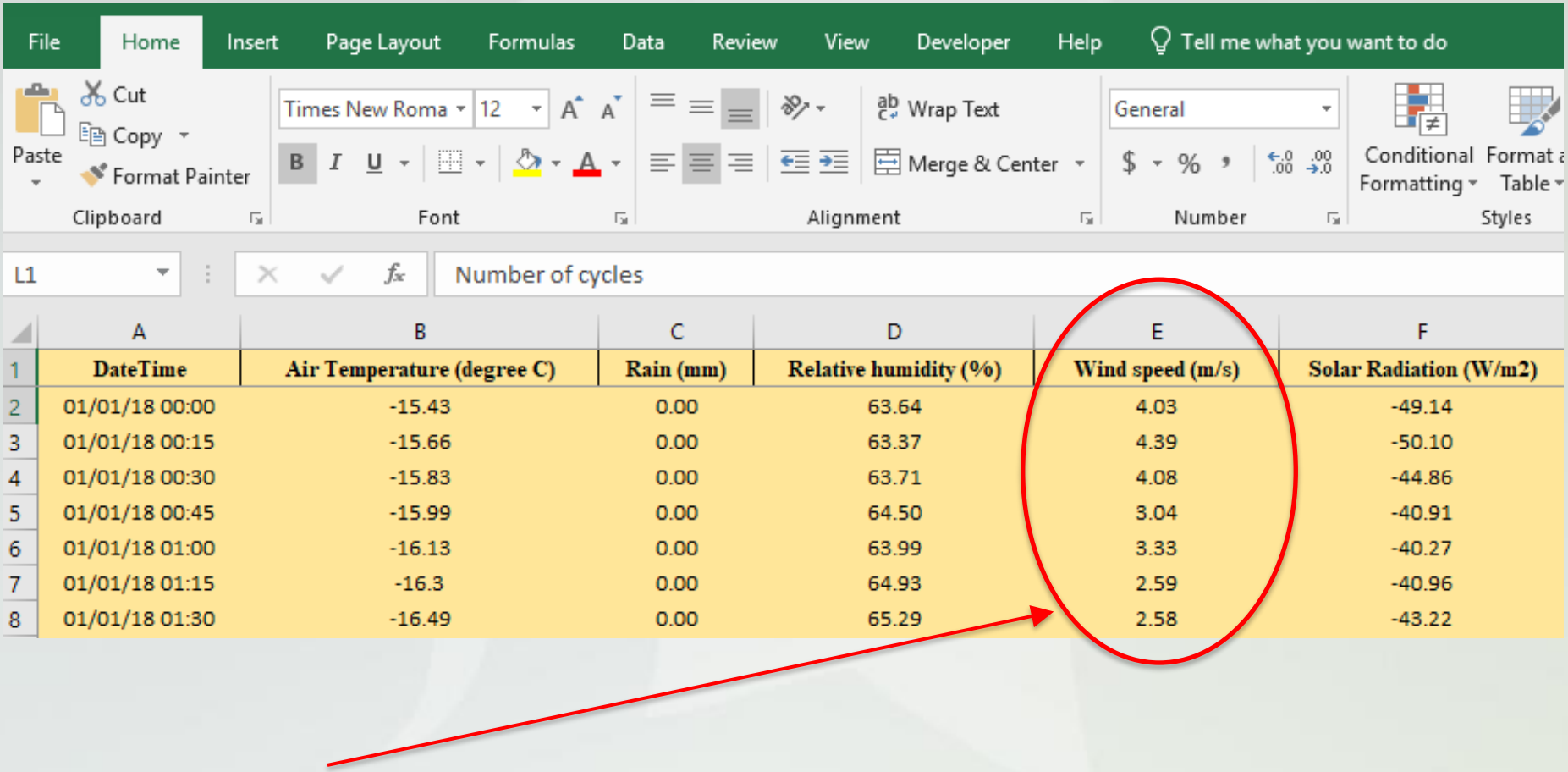
(3) Tool Development: *Description (Inputs)*



	A	B	C	D	E	F
1	DateTime	Air Temperature (degree C)	Rain (mm)	Relative humidity (%)	Wind speed (m/s)	Solar Radiation (W/m2)
2	01/01/18 00:00	-15.43	0.00	63.64	4.03	-49.14
3	01/01/18 00:15	-15.66	0.00	63.37	4.39	-50.10
4	01/01/18 00:30	-15.83	0.00	63.71	4.08	-44.86
5	01/01/18 00:45	-15.99	0.00	64.50	3.04	-40.91
6	01/01/18 01:00	-16.13	0.00	63.99	3.33	-40.27
7	01/01/18 01:15	-16.3	0.00	64.93	2.59	-40.96
8	01/01/18 01:30	-16.49	0.00	65.29	2.58	-43.22

Column D: *Relative humidity* values in **%**

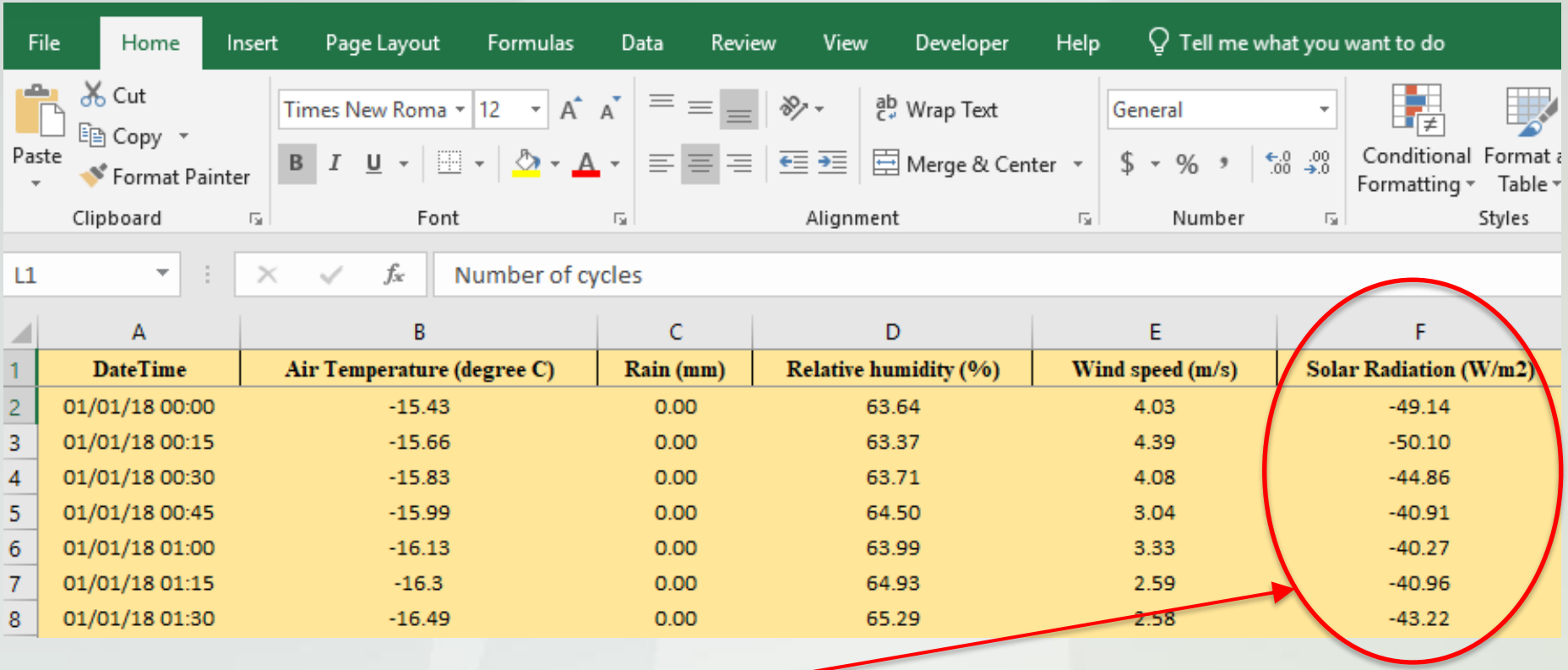
(3) Tool Development: *Description (Inputs)*



	A	B	C	D	E	F
1	DateTime	Air Temperature (degree C)	Rain (mm)	Relative humidity (%)	Wind speed (m/s)	Solar Radiation (W/m2)
2	01/01/18 00:00	-15.43	0.00	63.64	4.03	-49.14
3	01/01/18 00:15	-15.66	0.00	63.37	4.39	-50.10
4	01/01/18 00:30	-15.83	0.00	63.71	4.08	-44.86
5	01/01/18 00:45	-15.99	0.00	64.50	3.04	-40.91
6	01/01/18 01:00	-16.13	0.00	63.99	3.33	-40.27
7	01/01/18 01:15	-16.3	0.00	64.93	2.59	-40.96
8	01/01/18 01:30	-16.49	0.00	65.29	2.58	-43.22

Column E: *Wind speed* in **m/s**

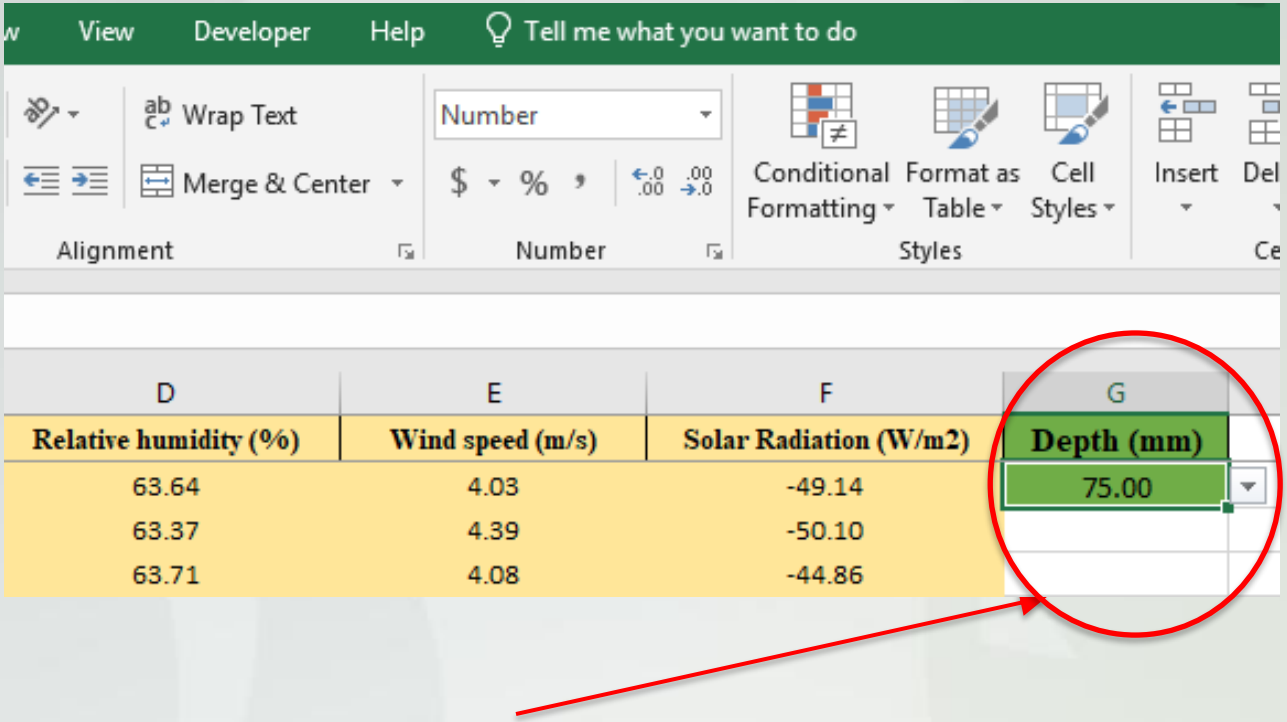
(3) Tool Development: *Description (Inputs)*



	A	B	C	D	E	F
1	DateTime	Air Temperature (degree C)	Rain (mm)	Relative humidity (%)	Wind speed (m/s)	Solar Radiation (W/m2)
2	01/01/18 00:00	-15.43	0.00	63.64	4.03	-49.14
3	01/01/18 00:15	-15.66	0.00	63.37	4.39	-50.10
4	01/01/18 00:30	-15.83	0.00	63.71	4.08	-44.86
5	01/01/18 00:45	-15.99	0.00	64.50	3.04	-40.91
6	01/01/18 01:00	-16.13	0.00	63.99	3.33	-40.27
7	01/01/18 01:15	-16.3	0.00	64.93	2.59	-40.96
8	01/01/18 01:30	-16.49	0.00	65.29	2.58	-43.22

Column F: *Solar radiation* in **W/m²**

(3) Tool Development: *Description (Inputs)*



Column G: *soil depth* in **mm** for which temperature needs to be estimated.

There is a drop down button for the user can select specific depths.

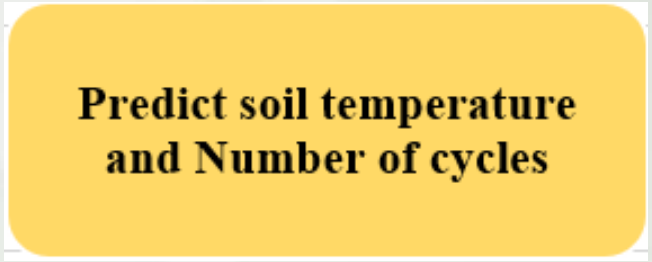
(3) Tool Development : *Description (Running the Calculations)*

The tool has three buttons :

1. Temperature prediction

2. Number of freeze thaw cycles (and start time/duration)

3. Predict soil temperature and number of cycles *(Note this does the calculations of both (1) and (2) together*



(3) Tool Development : *Description (Running the Calculations)*

Temperature prediction

Number of Freeze-Thaw cycles

Predict soil temperature and Number of cycles

1. Temperature prediction

Based on the given climate input and soil depth, predicts soil temperature at each timestep.

F	G	AF	AG	AH	AI
Solar Radiation (W/m2)	**Depth (mm)**		Temperature prediction		
-49.14	75.00		-11.2023		
-50.10			-11.0578		
-44.86			-11.0963		
-40.91			-11.4808		
-40.27			-11.4674		

(3) Tool Development: *Description (Running the Calculations)*

Temperature prediction

Number of Freeze-Thaw cycles

Predict soil temperature and Number of cycles

2. Number of freeze thaw cycles

Based on the predicted temperature (and climate data) it calculates the following at the specified depth:

1. number of freeze-thaw cycles
2. Starting time of freeze and thaw
3. duration of freeze-thaw cycles

L	M	N	O
Number of cycles	Freezing start time	Thaw start time	Duration of cycle
5	1/2/2018	1/7/2018	6
	1/8/2018	2/22/2018	45
	2/25/2018	2/28/2018	3
	3/3/2018	3/6/2018	3

(3) Tool Development: *Description (Running the Calculations)*

Temperature prediction

Number of Freeze-Thaw cycles

Predict soil temperature and Number of cycles

3. Predict soil temperature and number of cycles

Completes calculation of both (1) and (2) together, i.e. soil temperatures and number and duration of freeze-thaw cycles

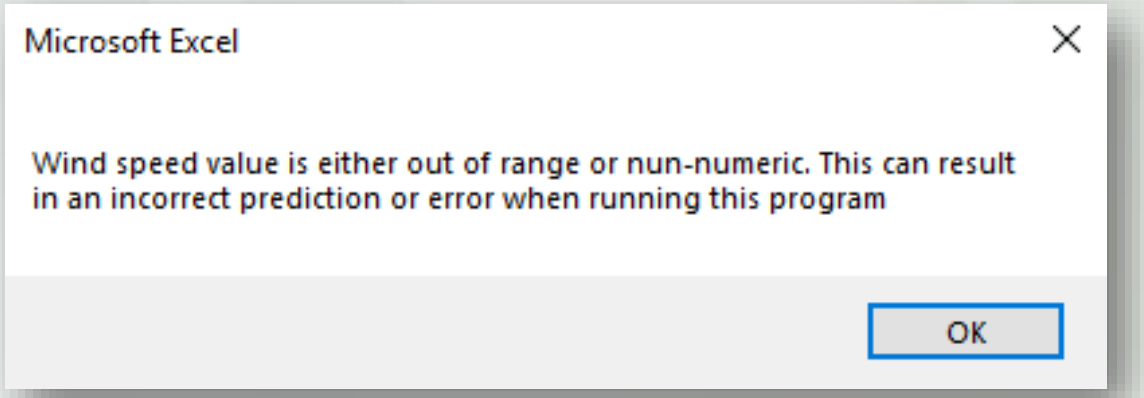
G	H	I	J	K	L	M	N	O
Depth (mm)		Temperat	Duration		**Number of cycles**	Freezing start time	Thaw start time	Duration of cycle
75.00		-11.2023			**1**	1/2/2018	1/7/2018	6
		-11.0578						

(3) Tool Development: *Checks before running*

Once user presses any of the buttons, the tool will first check whether all the inputs are valid, i.e.

- Are all input values numerical (non-text)
- Are all values for each column a reasonable value

If not, the tool will generate a message showing that some of the variables/data are not valid and the result generated may not be correct.

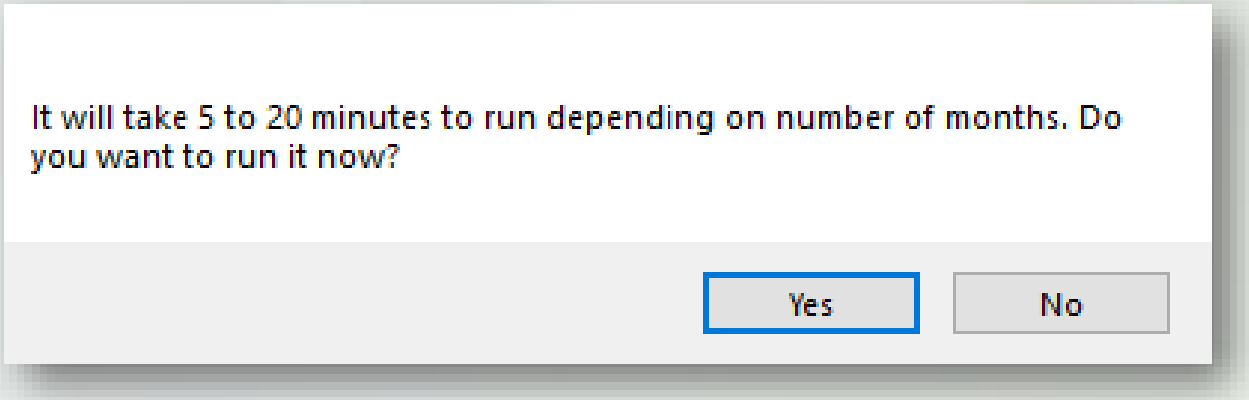


(3) Tool Development: *Checks before running*

After that, the tool checks with the user to ask if it is ok to run the program.

Depending on the during of the data input, the tool requires some time to calculate and provide results to the user. The tool will then ask if this is ok with the user.

The user can select ‘Yes’, which results in the code running; or ‘No’ in which case the program will terminate.



(3) Tool Development: *Summary*

The tool has been developed in Excel to predict for a user-specified depth:

1. *Soil temperature*
2. *Number of freeze-thaw cycles*
3. *Starting time of freezing and thawing*
4. *Duration of the cycles*

Debugging checks have also been implemented in the tool to provide the user some information about the input data and possible errors.

Questions?

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