Manuscript ID: nhess-2022-147

My co-authors and I would like to express our gratitude to the reviewers for their constructive feedback and suggestions for strengthening our research. The changes we have made to the attached file in response to such feedback and suggestions have been highlighted in blue to facilitate their identification. I would also like to offer my apologies for the length of time it took us to prepare this response.

Reviewer #1

In general this is an interesting contribution to the problem of black ice forecasting where where a system dynamics modelling is used, rather than a more traditional physcial based model that solves the energy and mass balances.

1. Generally, the paper is well-written, but the I recommend moving section 4.1 from the discussion to the method.

- Thanks for your insightful comment. As mentioned, Section 4.1 of the Manuscript has been moved to Section 2.4, the latter part of Section 2.3, along with Figure 9. I have modified the Discussion section so that only validation and discussion of results are handled. And I have made Sections 4.1~4.4 by stepping up Sections 4.2 and 4.2.1~4.2.4 one step at a time. The new paragraph in Section 2.4 has been amended as follows.

Lines 397-405(existing section 4.1) → Lines 283-297(new section 2.4)

2.4 Black ice multi-sensor configuration and model validation
In this paper, sensor validation was performed on the model's point where black ice was predicted to occur. To determine the generation of black ice at the prediction point of the model, a black ice multi-sensor—that connects several sensors with the control board—was configured, as shown in (Figure 9→Figure 4). The Multi-sensor consisted of a round force (FSR402), 400 water pressure (gravity: analog water pressure sensor), ultrasonic (W238), and temperature/humidity (SHT30). The round force sensor was buried in the floor, and it detected the pressure of the black ice generated from the upper part. The water pressure sensor had a principle similar to that of the round force sensor, and it detected the pressure of moisture that entered the upper part and was frozen inside. In the case of the ultrasonic sensor, the area where the ultrasonic wave was emitted faced the floor; when black ice was generated, a height difference (default of 8 cm) was detected. Finally, the temperature/humidity 405 sensor had a sensing part facing the ground, and the interval was ~ 2 cm.

2. The use of the unit for the amount of black ice is confusing. The paper both uses g/m^2

and g/m^3. To me only g/m^2 makes sense and this the most common way to express the amount of snow/ice contaminations on roads.

- Thank you for pointing this out. As a result of an additional investigation of previous studies, these studies generally expressed the amount of ice on the road surface and road moisture in g/m^2. The monitoring method of black ice generation belongs to the two-dimensional view from top to bottom, so it is correct to change the unit to g/m^2. I have unified the unit of black ice generation to g/m^2 and added a description of the unit. The following References have been added to the Manuscript.

Lines 162-163 Lines 664

- Lysbakken, K. and Norem, H.: The Amount of Salt on Road Surfaces after Salt Application, Surface Transportation Weather and Snow Removal and Ice Control Technology, 85, 2008.
  - ➔ This is a study on the road surface condition, and the amount of water is expressed in g/m^2.

Lines 162-163 Lines 668

- Nilssen, K.: Ice melting capacity of deicing chemicals in cold temperatures, 2017.
  - ➔ This is a study on road surface conditions and ice melting, and the unit of g/m^2 was used for the thin ice layer.

Lines 162-163 Lines 683

- Schulson, E.: Sliding heavy stones to the Forbidden City on ice, Proceedings of the National Academy of Sciences, 110, 19978-19979, 2013.
  - ➔ The thickness of the ice was converted into g/m^2 and explained.

3. The amount of predicted black ice (presuming the correct unit is g/m^2) seems unrealistically high, for the predictions made at 18th and 19th of December. (50 000 g/m^2 equals 50 mm of black ice) Whether the predicted predicted amounts are high, low, realistic/unrealistic are not sufficiently discussed.

- Thank you for this comment. The amount of black ice generated from the 17th to the 19th ((b) 17th: 52,021 g/m^2, (c) 18th: 26,067 g/m^2, and (d) 19th: 9,770 g/m^2) is the sum of the black ice generation for 14 hours, so it looks unrealistic. The table for the amount of black ice generated per hour during the sensing period is as follows. Although the amount of black ice generated per hour is in a realistic range (for example, 7286.524 g/m^2 is 7.3 mm), the result value (Total value in the table below) looks unrealistic when the figures for 14 hours are combined.

	16th (g/m^2)	17th (g/m^2)	18th (g/m^2)	19th (g/m^2)
AM 0	0	0	0	0
AM 1	4.703768	0	0	42.19465
AM 2	13.43411	0	0	75.57897
AM 3	27.35065	0	0	125.5276

AM 4	40.34503	0	0	149.5643
AM 5	70.43864	0	1483.693	266.8406
AM 6	71.22914	0	1907.632	472.6097
AM 7	71.22914	0	2260.974	755.2013
AM 8	71.22914	7286.524	2595.929	755.2013
AM 9	71.22914	7850.426	2910.015	755.2013
AM 10	0	8408.506	3278.66	2059
AM 11	0	9156.224	3876.928	1826.048
AM 12	0	9443.289	3876.928	1476.62
PM 13	0	9876.263	3876.928	1010.715
Total	441	52021.23	26067.69	9,770

Although it is stated that 50000 g/m^2 (50 mm) occurred during the 14 hours of each day, the average is 3,571 g/m^2 (3.571 mm). The sum of the amount of black ice generated for each hour for 14 hours does not realistically reflect the trend of the amount of black ice generated. To compensate for the unrealistic value, I changed the black ice generation value for 14 hours to an average value and corrected the relevant parts of the result.

Lines 382-390(before correction) → *Lines 399-407(after correction)*

Figure (8→9) shows the simulation results of the amount and location of black ice predicted by the system dynamics modelling in GIS (Esri). The results of simulating the amount and location of black ice in units of 1 m2 were exaggerated using the buffer function in GIS. Figure (8→9) (a)–(d) shows the predicted location and generated amount of black ice between December 16–19. The raster information of each black ice map was the ~~sum~~ average of the black ice generated from 00:00 AM to 13:00 PM on the selected day. The maximum amount black ice formed during the 14-h period was ~~(a) 441 g/m^3, (b) 52,021 g/m^3, (c) 26,067 g/m^3, and (d) 9,770 g/m^3~~ (a) 31.5 g/m^2, (b) 3715.79 g/m^2, (c) 1861.93 g/m^2, and (d) 697.86 g/m^2, respectively, for each scenario date and the total amount of black ice generated, i.e. the ~~sum~~ average of all scenarios, was ~~88,300~~ 1,576.79 g/m^2 [Figure (8→9) (e)]. The days with the highest amount of black ice were December 16 and 17, when freezing rain and snow occurred, respectively (Figure (8→9) (b) and (c), respectively), and it was found that road moisture was higher and road temperature was lower than on the other days.

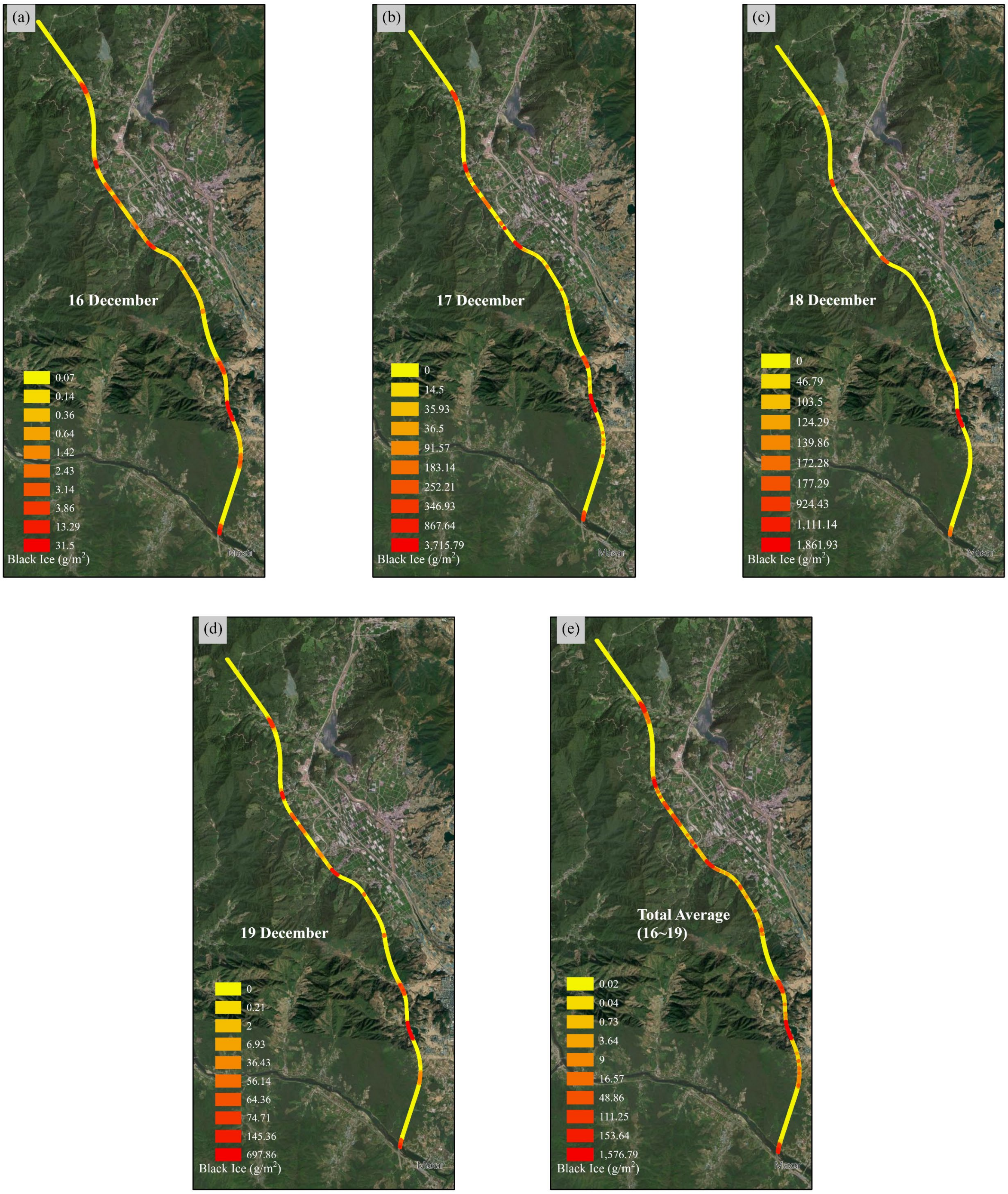

Figure *(8→9)*: Simulation of black ice occurrence prediction results of system dynamics in units of 1 m2 on GIS.

(a), (b), (c), and (d) show the amount and location of black ice from December 16–19. (e) The average of the amount and location of black ice from December 16–19. (Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community.)

----------- Below are answers to comments in PDF files attached by the reviewer. -----------

1. Although snow often creates slippery conditions, it is normally not causing "black ice"
So when snow gets compacted by the traffic, it is easier detectable than black ice. However, the situation of a wet road that freezes is also a common situation for black ice formation.

Thank you for pointing this out. My model simulates snow melting and then freezing. As mentioned, the snow is easy for drivers to detect, but it is challenging to prepare for a situation in which the snow melts into the road and then freezes again. The following text has been added to the snow scenario to avoid confusion.

Line 26
Meteorological conditions such as fog, freezing rain, and snow (melted and re-frozen) lead to the formation of black ice in dark and cold places, such as bridges, tunnel entrances, and shady roads.

2. This statement is not generally true but specific for a certain studied area. This should be mentioned. (whole south korea, or a certain district)

Thank you for this comment. In order to emphasize the study area of the line 31, the following sentence was added for the characteristics of Suncheon, where the model of this paper was tested.

Line 31-32
Therefore, it is essential to implement measures to prevent traffic accidents.

→ Therefore, it is essential to devise measures to prevent ice-related traffic accidents in many mountainous and shady areas, such as Suncheon City in Korea.

3. typo? Powersim?

Thank you for pointing this out. "Powrsim" is a typo of the original word "Powersim," and I have corrected the word. Sorry for the confusion by not reviewing thoroughly.

4. typo? Parameter Design?

Thank you for pointing this out. "Prameter Design" is a typo of the original word "Parameter Design." I have corrected the word. Sorry for the confusion by not reviewing thoroughly.

5. I don't understand the category for river system (t=0-13 hours). Arn't these constants in time?

Yes, strictly speaking, the River System is constant over time. Still, all physical phenomena in the model are expressed over time, so even if there is no change value, it is defined within the category of "0-13 hours".

6. In my understanding, the cloudcover can both be proportional and inverse propostional with the road temperature, dependent on the position of the sun (day/night)

Thanks for your insightful comment. Modelling hours are from 00:00 AM to 13:00 PM. Cloud cover(Cloudy) and Road Temperature have a linear relationship. However, since there is no solar radiation energy from 00:00 AM to 7:00 AM, the actual proportional relationship between the cloud cover and the ground temperature is not established. When the sun rises after 7:00 AM, Cloud Cover and Road Temperature have a real proportional relationship. Therefore, the Cloudy factor is expressed as + (proportion) on the causal map to comprehensively describe the part that has no influence or is proportional.

7. It is not clear to me where you got the meteorological data from? both air temperatute and Cloud cover are spatially variables. have you taken them from a single meteorological station, or from are these the output of meteorological models (as grid data, or modelled for each point in your GIS simulation?

Thank you for this comment. Weather data were acquired from Automated Synoptic Observing System (ASOS) in Korea, and the received data are Air Temperature, Cloud Cover, and Road Temperature. Air Temperature and Cloud Cover are data obtained from weather stations, and although they have spatial characteristics, they are defined as meteorological data. Neither air temperature nor cloud cover data is a grid concept, but data for a single unit in Suncheon-si, Jeollanam-do. Additional modelling was performed on the actual figures to impart variability to the temperature and cloud cover factors. Random numbers were assigned in the range of 5% of the total size and entered into a $1m^2$ grid.

8. This is confusing. What is proper definition of V_RT? is it the (predicted/simulated) road surface temperature?

Sorry for the confusion. V_{RT} is a new variable introduced to simultaneously express the stock-flow model for H, L_b, T_a, and C factors. The formulas of these factors are all the same, and there was concern that the quality of the thesis would deteriorate if they were written individually. Therefore, a new variable (V_{RT}) was applied and expressed simultaneously. Added the following text for proper names for V_{RT}.

Line 181 → Line 183

Each factor is entered into the system dynamics by the following stock-flow model: variables (V_{RT}, Variable referring to road temperature) related to road temperature were entered using Eq. (1).

9. I am (still) confused here. I believe you mean that V_RT is predicted on using the parameters H, L_b, T_a and C. Right?

As I said, V_{RT} is not a predicted value but a variable that can be substituted for H, L_b, T_a, and C. Sorry for the confusion.

10. Why are you integrating? is it a form of "running average" over the surface temperature? or do you calculate one single value for each 13 hour period?

Thank you for this comment. V_{RT} is a concept that encompasses all of H, L_b, T_a, and C, and each of them is as follows (Eq. (1)). I have intended V_{RT} to be a variable representing the factors, not the combined value of the elements.

$$V_{RT} = \int (V_{RT}')_t + (V_{RT})_{t=0} \tag{1}$$

$$\rightarrow$$

$$H = \int (H')_t + H_{t=0}$$

$$L_b = \int (L_b')_t + (L_b)_{t=0}$$

$$T_a = \int (T_a')_t + (T_a)_{t=0}$$

$$C = \int (C')_t + C_{t=0}$$

11. How about rain during the day at temperatures above 0°C and a subsequent drop in road temperature? At least in scandinavia this is also a very common case (more common than your case 1)

The phenomenon of rain falling at temperatures above 0°C and Freezing after Freezing was reflected in the model. The following Eq. (9) shows the accumulation of road moisture and when the temperature drops below zero by Eq. (15).

$$M_r = \sum_{t=0}^{t=13} (MoP + C - Fr)_t, \tag{9}$$

$$Fr = f(T_r, M_r, P) = \begin{cases} M_r \ (P > 0 \ and \ T_r < 1) \\ M_r \ (P = 0 \ and \ T_r < 0) \end{cases} \tag{15}$$

12. Same comment here as previous: please give V_RM a proper name.

Added the following text for proper names for V_{RM}.

Line 230 → Line 233

The aforementioned Pv, Pr, Sw, and Sm can be substituted for the variable VRM (Variable referring to road moisture)

13. The image is of to poor resolution to read the small text. Didn't you have 4 input variables, rather than the 3 shown here?

Thanks for your insightful comment. I have inserted a picture with improved resolution, as shown below. As in Eq. (1), there are four variables (hillshade, bridge location, air temperature, Cloudy). However, the bridge locations are not used in the training process of the DNN but were used in numerical modelling to correct the test results.

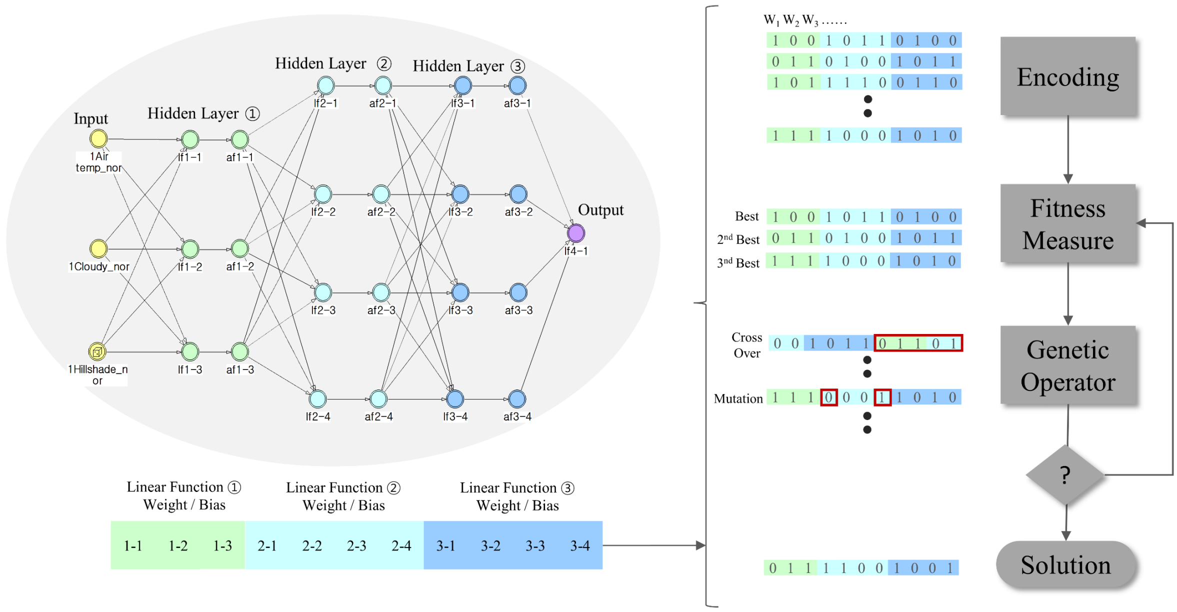

Figure 3: Structure of system dynamics of deep neural network for Road temperature modelling. (a) Change the parameters of DNN in the form of the chromosome. (b) The fitness function of the chromosome is evaluated and input to the Genetic operator. (c) It performs selection to select chromosomes with high fitness, crossover to mix gene values, and mutations to simulate mutations in gene values. (d) Choose a solution based on the goodness of fit.

14. Why g/m^3? shouldn't this be the mass per area? (so the mass of precipitation that falls on each m2)?

Thank you for this comment. I have answered the main question 2 above.

15. F_r is not defined. i suppose it is the mass of the water that has turned into ice, so it is also in g/m^3 but I am guessing here.

Thank you for this kind comment. As mentioned, Fr stands for Freezing. With reference to the case mentioned in Main Answer 2, the unit has been unified as g/m^2. Fr is mentioned in Eq.(15) below. The related sentences and Eq. (15) have been modified to avoid confusion.

Line 238(new)

Fr means freezing per hour, as in Eq. (15).

$$Fr = f(T_r, M_r, P) = \begin{cases} M_r \ (P > 0 \ and \ T_r < 1) \\ M_r \ (P = 0 \ and \ T_r < 0) \end{cases} \tag{15}$$

16. shouldn't this be "per m^2"?

Thank you for this comment. I have unified the space unit occupied by water or ice from m^3 to m^2.

17. why Pi*r^2?

Thank you for this comment. I made a mistake while updating my model. "Pi*r^2" is the formula of my old model, and in the latest version, Eq.(10) has been modified as follows. The models treated in the paper reflect the latest equations. This formula expresses the amount of precipitation in g/m^2 in 100 (cm^2) units. Sorry for the confusion by not reviewing thoroughly.

$$MoP(g/m^3) = \frac{\pi r^2 P}{10} \tag{10}$$

$$\rightarrow$$

$$MoP\left(\frac{g}{m^2}\right) = 100(cm) * 100(cm) * P * 0.1$$

18. why is this the case? Has this a physical reason?

Thank you for this comment. This statement reflects the results presented by Imacho et al through an experimental study. The study stated that if the road surface temperature is between -1 and 1 degree Celsius and is wet by precipitation, it would freeze. If it exceeds 1 degree Celsius, it is not freezing even if the road surface is wet. I have added the following reference.

Line 271, Line 637

Imacho, N., Nakamura, T., and Hashiba, K.: Road icing detection and forecasting system using optical fiber sensors for use in road management in winter, Hitachi Cable Review, 21, 29-34, 2002.

19. strange sentence..... precipitation [....] dropped below zero?

Thank you for pointing this out. There seems to have been a mistake in the translation process. Sorry for not reviewing it more thoroughly; it has been modified as follows.

Line 304 → Line 317

On December 17, ~~precipitation and~~ the temperature dropped below zero and coincided, the precipitation amount was 0.7 mm, and the lowest temperature was –4.1°C, which was analyzed to be freezing rain.

20. Did the training dataset also include the measured road surface temperature? I guess it needs to be so, but it is not mentioned. related to this, the "training reliability" means the deviation between the real (measured) road temperature and the predicted road temperature?

I agree with the reviewer's opinion. The road surface temperature was included as a label in the training dataset, and I have added the following text. "training reliability" is the concept of 100% minus MAPE (Mean Absolute Error). This paper evaluated the validity based on 80%, and DNN showed the highest test value (average 94.5%). As mentioned, "training reliability" means the deviation between the actual (measured) road temperature and the predicted road temperature.

Line 331~332 → Line 349~350

A total of 1498 training sets were used for parameter optimization (weight and bias), and each consisted of hill shade, air temperature, cloudy conditions, and road temperature.

21. Just a comment: These numbers are probably too high because at such large amounts the water will drain off the road by run-off, and the traffic removes water by spray-off.

Thank you so much for the valuable and good comments. It seems that "large amounts the water will drain off the road by run-off, and the traffic removes water by spray-off" have not been carefully considered. All these aspects will be regarded if follow-up studies are conducted in the future.

22. Please check the unit. I presume it needs to be g/m^2 throughout the paper

Thank you for this comment. I have answered the main question 2 above.

23. Are these numbers reasonable? If the unit is g/m^2 it means an accumulated black ice layer of 88 mm, which seems unreasonably large (1 mm equals 1000 g/m2 water)

Thank you for this comment. I have answered the main question 3 above.

24. This part belongs to my opinion to the method, not the discussion

Thank you for this comment. I have answered the main question 1 above.

25. Are you meaning the weight of the black ice that is accumulated on the sensor?

Yes, Water Pressure Sensor and Round Pressure Sensor express the weight of ice accumulated on the sensor. This method is the principle of measuring the pressure when water turns into a solid. It is due to the property that water increases in volume by about 9% as it freezes. More precisely than weight, it is the pressure caused by the solidification of black ice.

Reviewer #2

By mixing System Dynamics and GIS, this study overcomes the weakness of System Dynamics, which is challenging to use spatial information. Since Black Ice Prediction in this paper was performed on various scenarios using spatial and meteorological data, so it is judged to be differentiated from traditional studies.

The paper is well written but needs to be improved further. Additional considerations should be given to the following.

1. The units must be unified. For example, g/m^3 and g/m^2 are virtually the same.

- Thank you for pointing this out. As a result of additional research on References, contrary to my intention of expressing the amount of black ice as g/m^3 considering the three-dimensional space, other studies usually indicate snow, water, and other liquids on the road surface as g/m^2. Therefore, I have adopted g/m^2 between g/m^3 and g/m^2. I have changed the unit of Evaporation, Condensation, Road Moisture, and Black Ice in Table 2 to g/m^2 and the unit of the corresponding part of the Manuscript. The following References have been added to the Manuscript.

Lines 162-163 Lines 664

- Lysbakken, K. and Norem, H.: The Amount of Salt on Road Surfaces after Salt Application, Surface Transportation Weather and Snow Removal and Ice Control Technology, 85, 2008.
  - ➔ This is a study on the road surface condition, and the amount of water is expressed in g/m^2.

Lines 162-163 Lines 668

- Nilssen, K.: Ice melting capacity of deicing chemicals in cold temperatures, 2017.
  - ➔ This is a study on road surface conditions and ice melting, and the unit of g/m^2 was used for the thin ice layer.

Lines 162-163 Lines 683

- Schulson, E.: Sliding heavy stones to the Forbidden City on ice, Proceedings of the National Academy of Sciences, 110, 19978-19979, 2013.
  - ➔ The thickness of the ice was converted into g/m^2 and explained.

2. The map in Figure 4 should also show the total length of the test road, and this is because it does not cover the entire Suncheon Wanju highway, so the scope should be seen more intuitively.

- We agree with the Referee's comment. The total length of the Suncheon-Wanju Highway is 117.8 km, but the section in Gurye-gun, Jeollanam-do, South Korea, is about 16 km long. As mentioned by Referee, I have inserted the length of the Suncheon-Wanju Highway in Gurye-gun, Jeollanam-do, into the map and caption composing Figure

4(before correction).

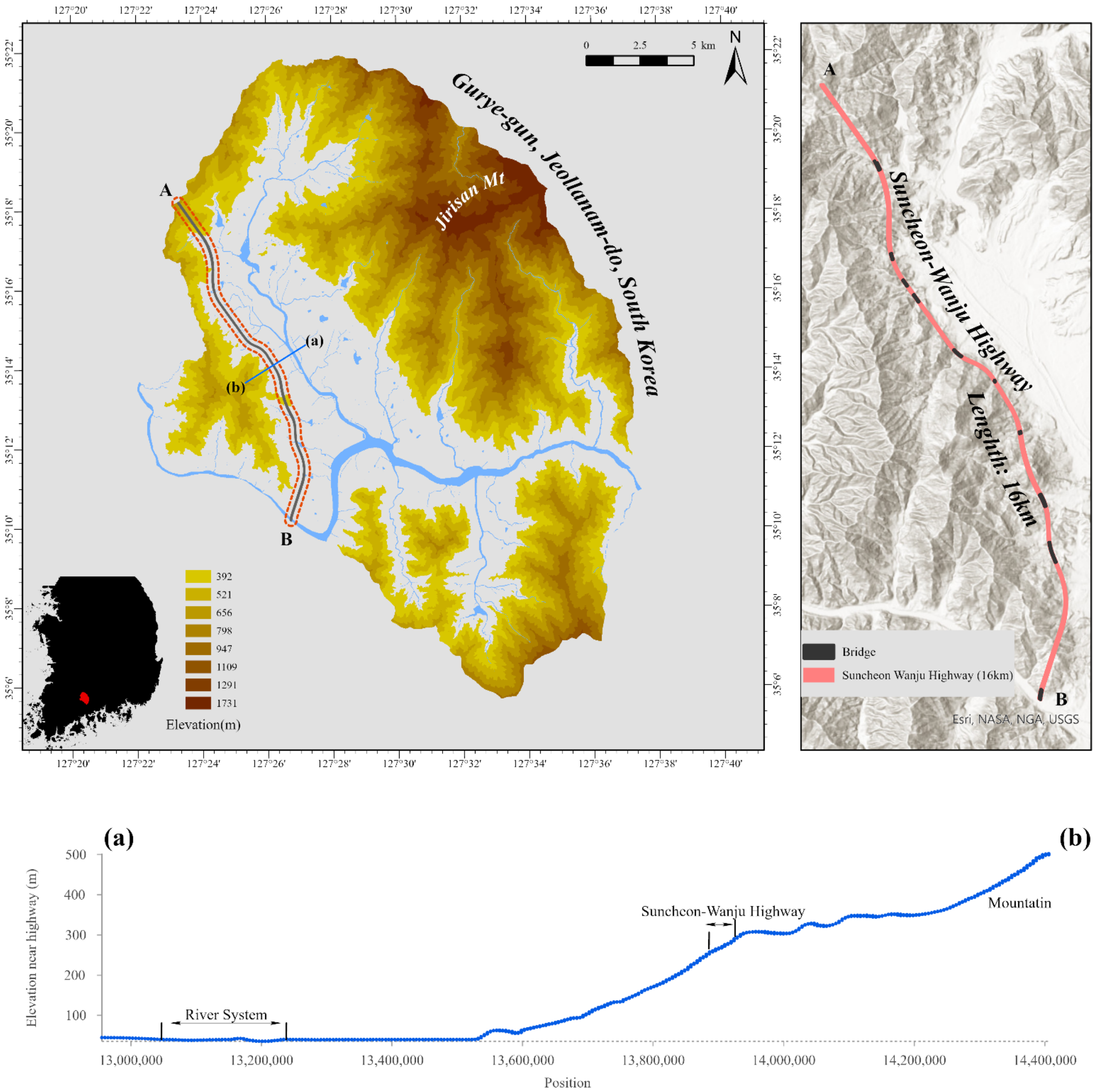

Figure (4→5): Suncheon-Wanju highway, Gurye-gun, Jeollanam-do, a research area for system dynamics model.

The Suncheon-Wanju Expressway in Gurye-gun (16km), Jeollanam-do runs from point A (35°18'S) to point B (35°10'S). If the section from (a) to (b) is selected and the cross-section is analysed, mountains and water systems are observed to the left and right.

3. The map in Figure 10 should include a background illustration so that the reader can monitor the installation environment of the sensing system. In connection with the modeling results, it would be great if the reader could understand the environment in which the sensor is installed more intuitively.

- Thank you for this comment. The environment where the sensor has been installed is the area where black ice was predicted in the System Dynamics model, and the site is mainly of bridges and shady areas. As mentioned by Referee, I have added the actual map to Figure 10 and modified the legend and symbol of the multi-sensor buried location so that readers of this paper can observe the environment in which the sensor is installed on a map.

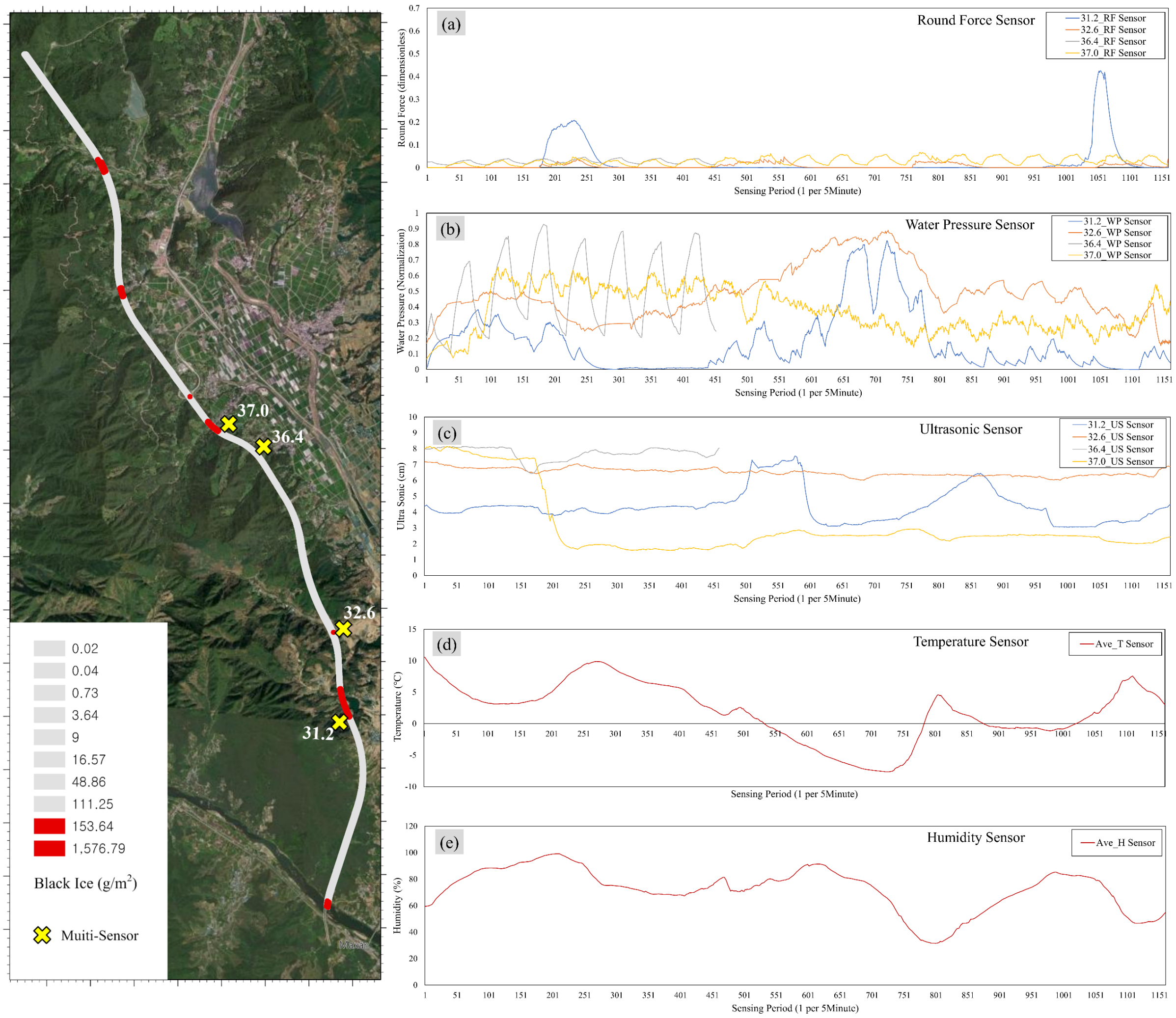

Figure 10: The location of occurrence of black ice (top 2 levels) and data collection results for each sensor. Points 31.2, 32.6, and 37.0 are the experimental group, and points 36.4 are the comparison group. (a) Data graph of the round force sensor. (b) Data graph of the water pressure sensor. (c) Data graph of ultrasonic sensor. (d) Average of temperature from temperature/humidity sensor. (e) Average of humidity from temperature/humidity sensor. (Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community.)