Modeling Ice Block Expedition of 1959: how ice deteriorated in the journey

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1 Introduction

A million tons of ice was shipped from Norway each year during the golden age of ice trade to England, India, South America, China and Australia. The business that involved transporting natural ice for commercial purposes stated at 1806, flourished in the end of 19th-century and was replaced by plant ice until World War I ("Ice Trade," 2022). A primary concern of the ice transportation is the melt loss. Luckily, there is a record to follow. In 1959, a three-ton block of ice from Mo i Rana by the Arctic Circle was trucked to Libreville by the Equator in an advertisement of insulation materials. The event left enough details and measurements: 2714 Kg ice remained with only 11% mass loss("Ice Block Expedition of 1959," 2022) in a 27 days long journey. Using the EAR5 climate reanalysis dataset (Muñoz Sabater, 2021), this study is able to simulate the 1959 ice block expedition by surface energy balance equations and heat transfer equations, which is a new perspective on this event and the topic of ice trade.

The specific objective of this study is to (1) establish an ice deterioration model by 1D surface energy balance equation and 3D heat equation (2) simulate the event under different scenarios (3) demonstrate changes between the climate of 1959 and 2021. The first section will describe the data and model settings. Then, the model is constructed under certain scenarios, and the simulations will be discussed.

2 Data and Method

The 3050 Kg of ice was harvested from Svartisen glaciers, Norway, and then was placed in a specially constructed iron container, which was insulated with wood and glass wool. The journey began at 09:15 a.m. on 22th February, 1959. The first segments passed by major European cities, arriving in Marseille on 28th February. After crossing the Mediterranean Sea, the expedition traveled over Sahara for 579 hours until arriving in Libreville, Gabon. Google Maps re-planned the routes; thus, the distance and average speed may be different with original roadbooks (Figure 1a).

Figure 1.c describes the study object in three layers: metal box (thickness 0.02 m), insolation materials (thickness 0.25m) and ice block (dimension 1.49x1.49 m). The assumptions about heat transfer are (1) the surface temperature of ice is 0° Celsius, (2) there is no convention through the box. (3) all materials are homogenous in dimension and time. Table 1 gives the materials properties.

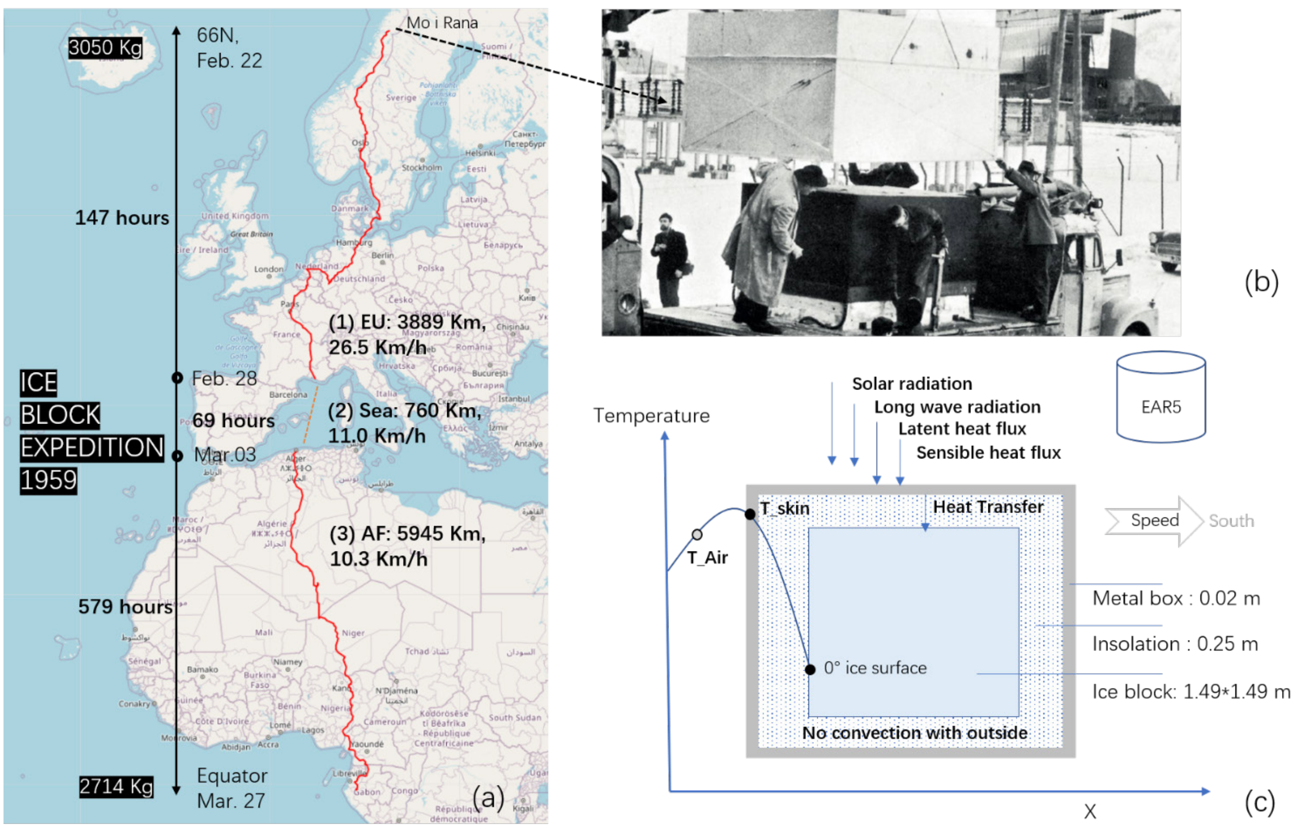


Figure 1. *The concept of ice deterioration modeling. (a) 9834 Km and 726 hours driving. The track is planned by google map, which is not exactly same with the original expedition. The travelling hours and speed are estimated approximately. (b) loading the truck. the photo source:* [*https://www.nrk.no*](https://www.nrk.no) *(c) 3 layers illustration. And all materials are assumed homogenous.*

Table 1. *Characteristics of materials.*

Type	Properties	density [Kg/m3]	heat capacity [J/(KgK)]	albedo	emissivity	Heat conductivity [W/(mK)]	Diffusivity [mm2/s]	Thickness [m]
-	Ice	917	2108	0.5	0.97	2.3	1.19	-
-	Water	1000	4182	-	0.97	-	-	-
Box	Aluminum	2700	890	0.61	0.25	237	-	0.02
Box	Galvanized steel	7800	470	0.61	0.04	52	-	0.02
Box	Pine wood	510	2301	0.15	0.90	0.11	-	0.02
Insulation	Glass wool	20	840	-	-	0.04	1.79	0.25
Insulation	Clay-Sawdust (10%)	1648	838	-	-	0.63	0.45	0.25
Insulation	Sawdust	210	900	-	-	0.08	0.42	0.25

EAR 5 Land hourly dataset offers all environment variables, including (1) Solar radiation (2) Long wave radiation (3) Latent heat flux (4) Sensible heat flux (5) Surface pressure (6) Wind speed in 10 m (7) Surface Skin temperature. (8) Total precipitation. (9) Dew temperature. The modeling does the data process when deals with the raw dataset (Figure 2). Frist, EAR couple with the location and time to make a one-dimension dataset because the truck is moving. Second, the conversion was applying e.g., the logarithmic profile is used to turn wind speed from 10 m to 2 m. And then, the wind speed is the aggregation of u-component, v-component (a positive v wind is from the south) and moving speed.

Figure 3 displays the meteorological conditions of the trip. The average ski temperature is 292.2 K, slightly higher than air temperature (291.6 K). Skin temperature could be over 325 K, which is 15 K more than air temperature under the solar radiation of Sahara, but lower than air temperature at night. For comparison, Figure 4 shows the weather conditions for the same period in 2021.

The model has two parts, energy balance part on box surface and heat transfer part inside the box. The link between the two is the temperature of the box. We can calculate the heat transfer by Fourier's law because we assume the skin temperature of ice is zero degree Celsius, and temperature of box could be solved by one-dimensional energy balance model. Then, we get the mass loss by melt energy, which is equal to the amount of heat transfer (Figure 2).

The physic equations are attached in Appendix 1. The time step of computation in the iteration is 1 second.

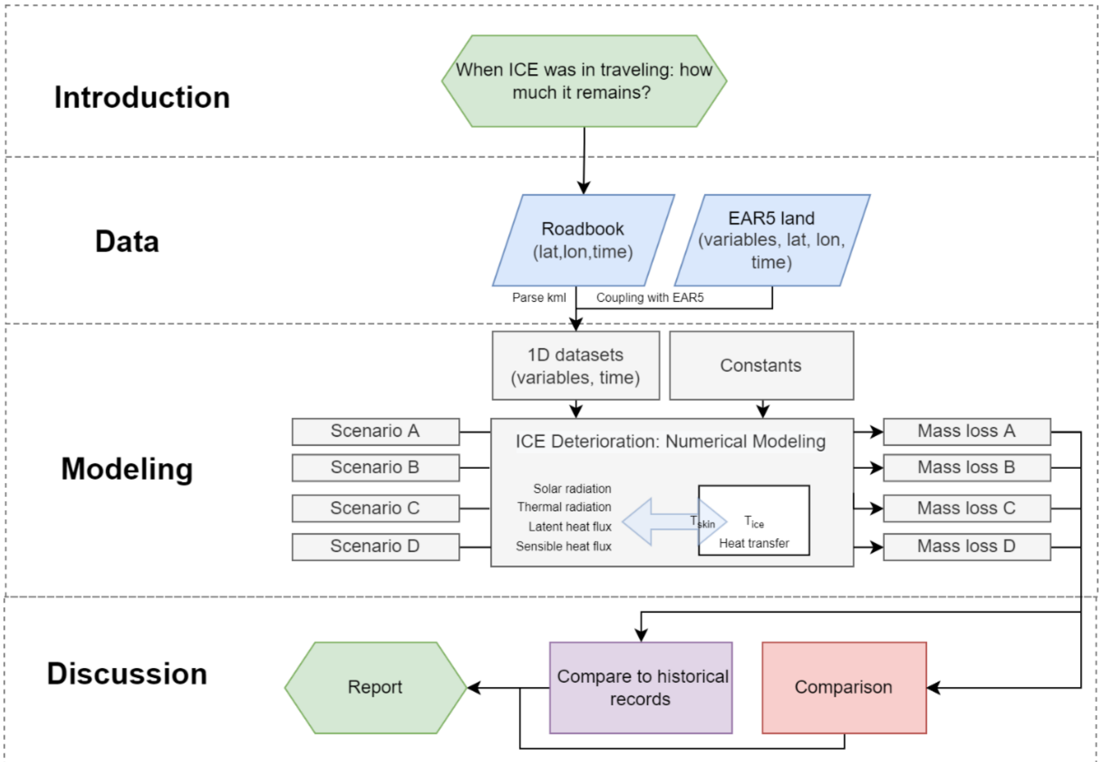


Figure 2. *The workflows.*

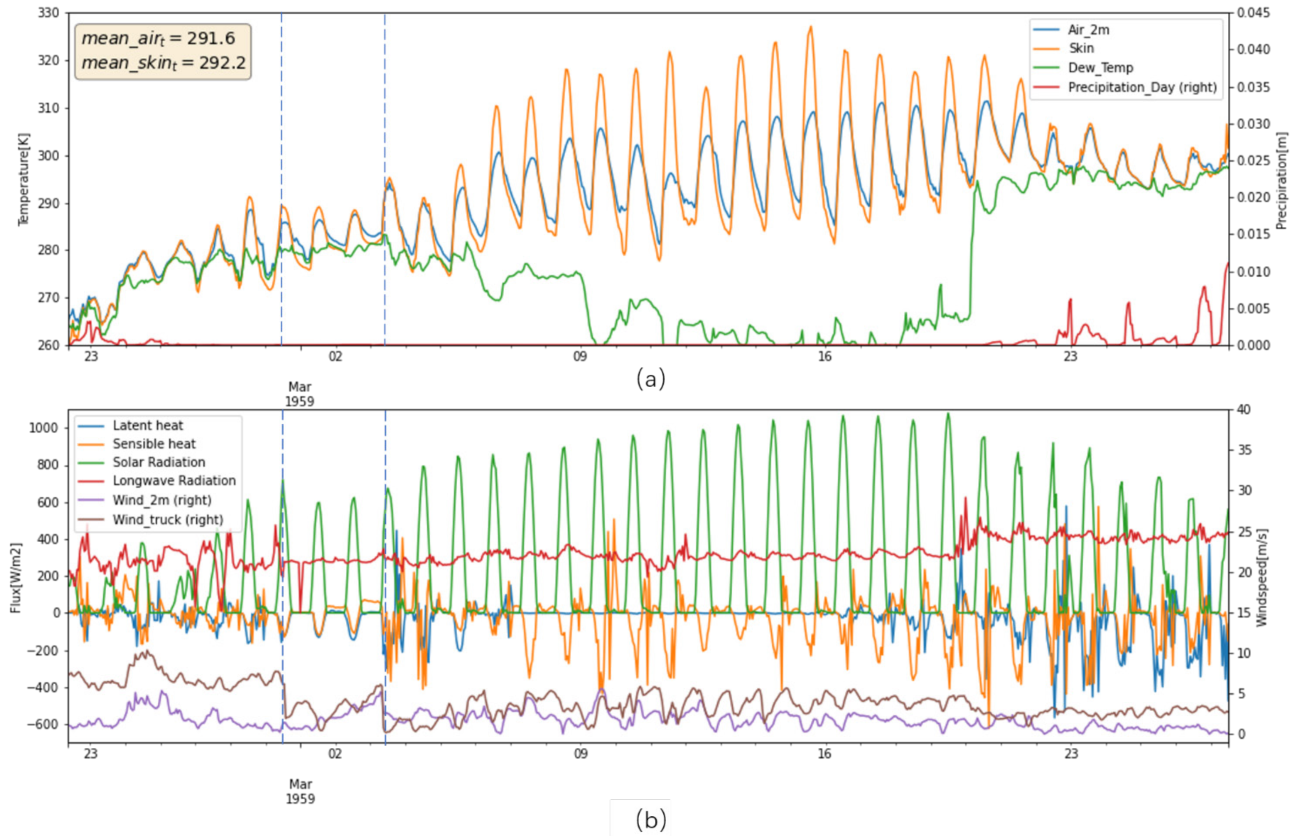


Figure 3. *The hourly weather condition of ice block expedition 1959. All radiation and turbulence flux are defined as downward positive. And the dash lines in blue separate the trip intro Europe/ Mediterranean/ Africa parts.*

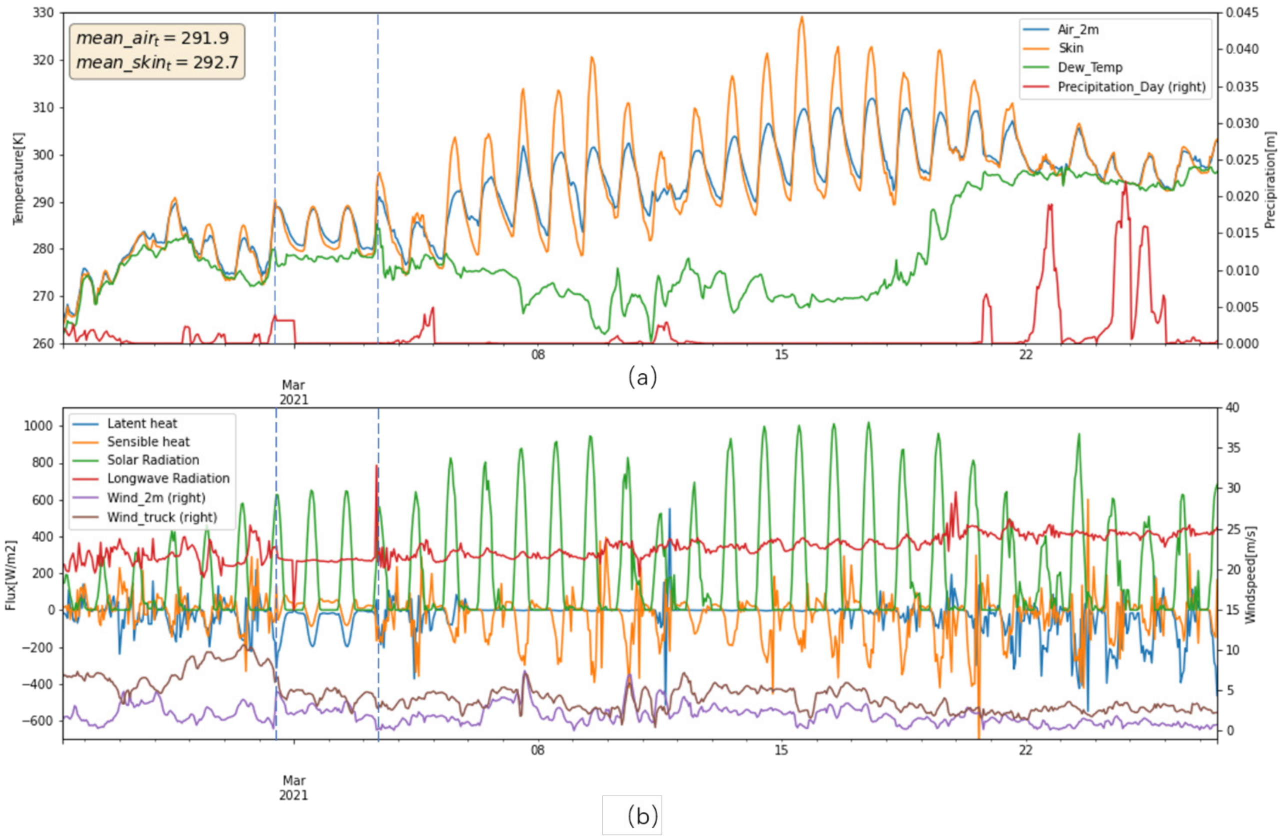


Figure 4. *The hourly weather condition of 2021.*

3 1D energy balance model

3.1 Ice without any cover, 1959 vs 2021

The scenario starts with a simplest assumption that the ice surface is without any cover. The albedo of ice is 0.5 and emissivity is 0.97. We can calculate each energy components one by one. To begin this process, the actual vapor pressure e_{actual} is calculated by dew temperature, and the specific vapor pressure of ice surface e_{ice} is calculated by surface temperature T_{ice_skin} (equals to 0 degree Celsius). So, the vapor deficit is e_{ice} - e_{actual}, and temperature gradient is T_{air} - T_{ice_skin}.

The scenario is to give control groups to help better understand how the cover and the insolation protect ice from melting under weather condition 1959 and 2021. Figure 4 shows that the air temperature of 2021 is 0.3 K higher than 1959, the relative windspeed of 2021 (4.3 m/s) is heavier than

1959 (3.9 m/s). There was an unusual rainy day in Sahara on 12th Mar. 2021, which increased humidity (or dew temperature) and reduced the solar radiation on that day.

The simulations show that 5.59 m of ice melted in the scenario of 1959, and 6.50 m in 2021. The Solar radiation contributed more melt energy (18.5%) in 1959. Latent heat flux and longwave radiation contributed more in 2021, which are 20.4% to 15.5%, 3.1% to 1.0%, compared with 1959. Furthermore, the ice block (1.49×1.49 m) would have melted away on 8th Mar. 1959 or 6th Mar. 2021, if ice block expedition was carried out under the scenarios (Figure 5). Also, on some days, longwave radiation, latent heat flux and sensible heat flux can be negative (Figure 6).

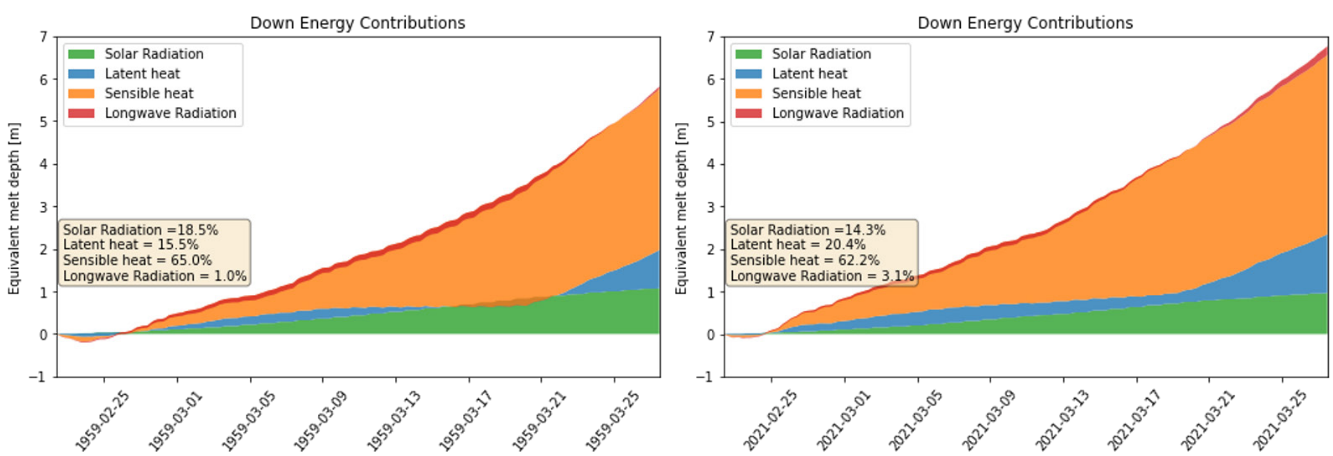


Figure 5. *Melt energy contributions of bare ice on truck (left: 1959, right: 2021).*

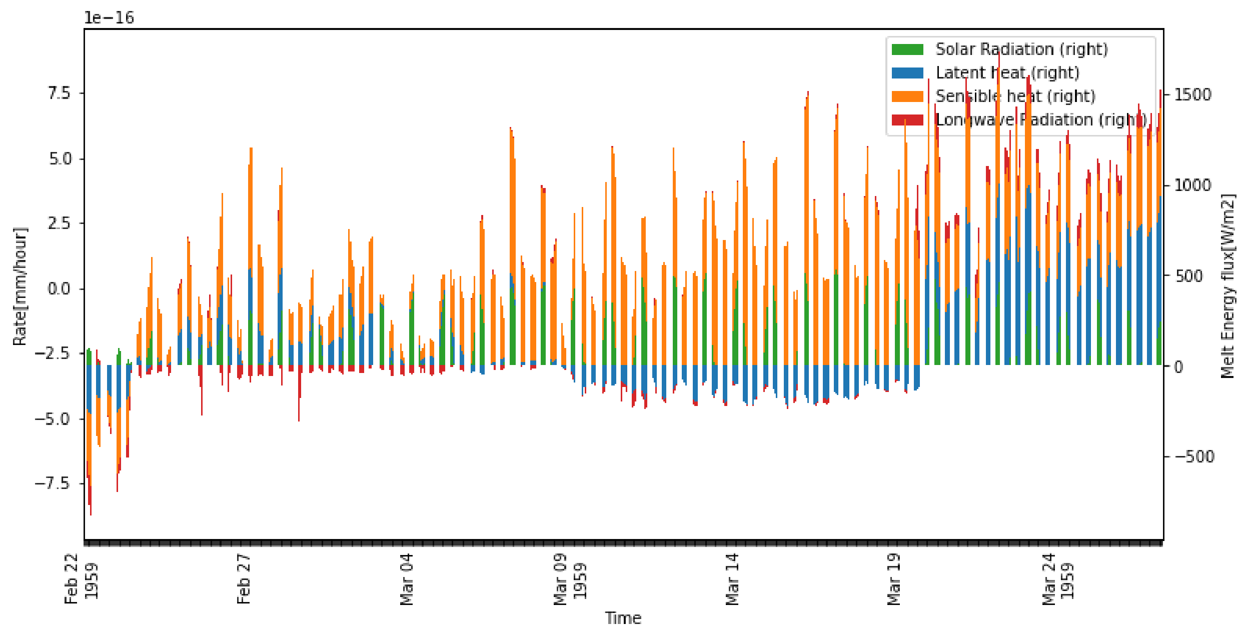


Figure 6. *The energy balance on ice surface (1959). The negative value indicate that the heat is moving away from the surface, and vice versa.*

3.2 Steel box, aluminum box and wooden box

Three types boxes were used in the simulation: (1) Galvanized steel is one of the most popular steel types with a zinc-iron coating, which is also widely used as roof material for high albedo (0.61). (2) Aluminum has the same high albedo (0.61), but with 4.6 times the thermal conductivity of steel and higher emissivity (0.25 to 0.04). (3) Wood is another commonly used box material in ice trade business with ultra-low thermal conductivity but low albedo. albedo or thermal conductivity, which one is more important? The scenario is intended to illustrate the considerations of select good box for ice shipment.

The effect of box material on total thermal resistance is shown in Table 2. The thermal performance between steel-glasswool and aluminum-glasswool is negligible because insolation layer is thick and well-insulated. The wood box does have some contribution, a 2.83% improvement over the original insulation. Overall, the heat transfer flux for steel, aluminum and wood box with same insulation layer are 42.62 W/s, 42.63 W/s and 41.42 W/s for a given size and temperature difference.

Table 2. *Overall heat transfer coefficient of different scenarios.*

Box	Box thickness [m]	Insulation	Insolation thickness [m]	**Overall heat transfer coefficient [W/(m2K)]**	Area size	Temperature difference [K]*	**Heat transfer flux [W/s]**
-	-	Glass wool	0.25	0.160000	1.49×1.49×6	20	42.62592
Steel	0.02	Glass wool	0.25	0.159990	1.49×1.49×6	20	42.62335
Aluminum	0.02	Glass wool	0.25	0.159998	1.49×1.49×6	20	42.62592
Wood	0.02	Glass wool	0.25	0.155477	1.49×1.49×6	20	41.42095

In the simulation, the latent heat is assumed to be as same as bare soil, because the evaporation is difficult to estimate when the saturation is unknown. The skin temperature of box is the result of energy balance and heat transfer. Figure 7 and 8 shows the simulation results. As described in Table 2, the heat transfer coefficients of steel box and aluminum box are close, thus, the higher temperature, the more energy is transferred into ice, resulting in severe melting.

(1) The melting amount of ice in steel-glasswool box is 372.9Kg, which is higher than 352.3 Kg of melt ice in aluminum-glasswool box, because the average skin temperature of steel, 294.3 K, is higher than the latter (293.1 K). Appendix 2 explains the energy partitioning on three types of box surface, where longwave radiation and sensible heat is two important cooling mechanisms, since the metal surfaces are hotter than air temperature most of time. And the same albedo results the same input of solar radiation, but aluminum has higher emissivity of 0.25 to cool it down, compared with 0.04 of steel (see Table 1).

(2) Wood-glasswool box has the best thermal insulation performance with the similar result (375.9 Kg) to steel-glasswool box. Higher albedo brings it extreme temperature, even though the emissivity is high as well.

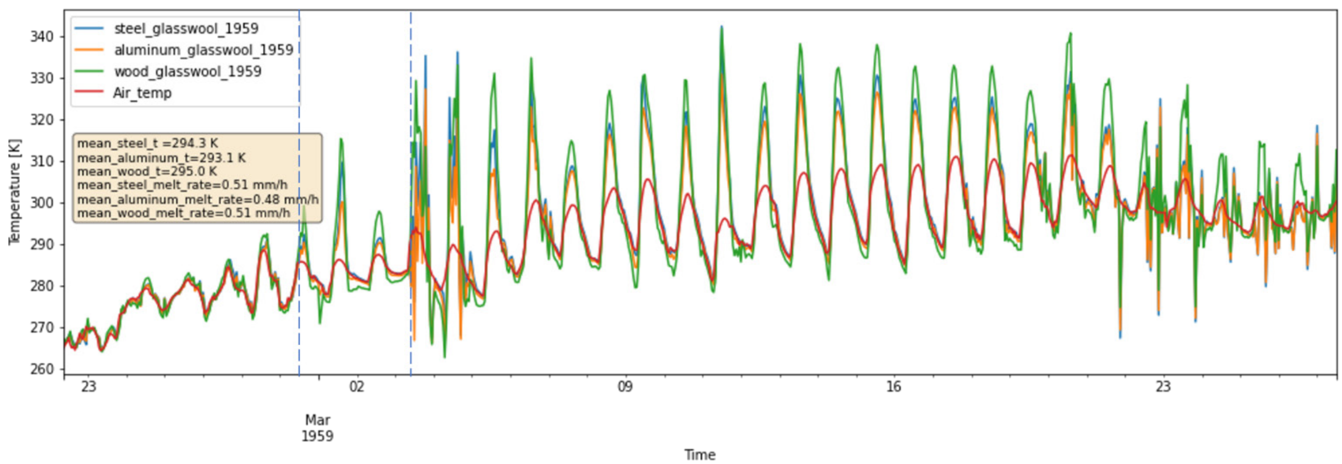


Figure 7. *Melt simulations of box surface temperature.*

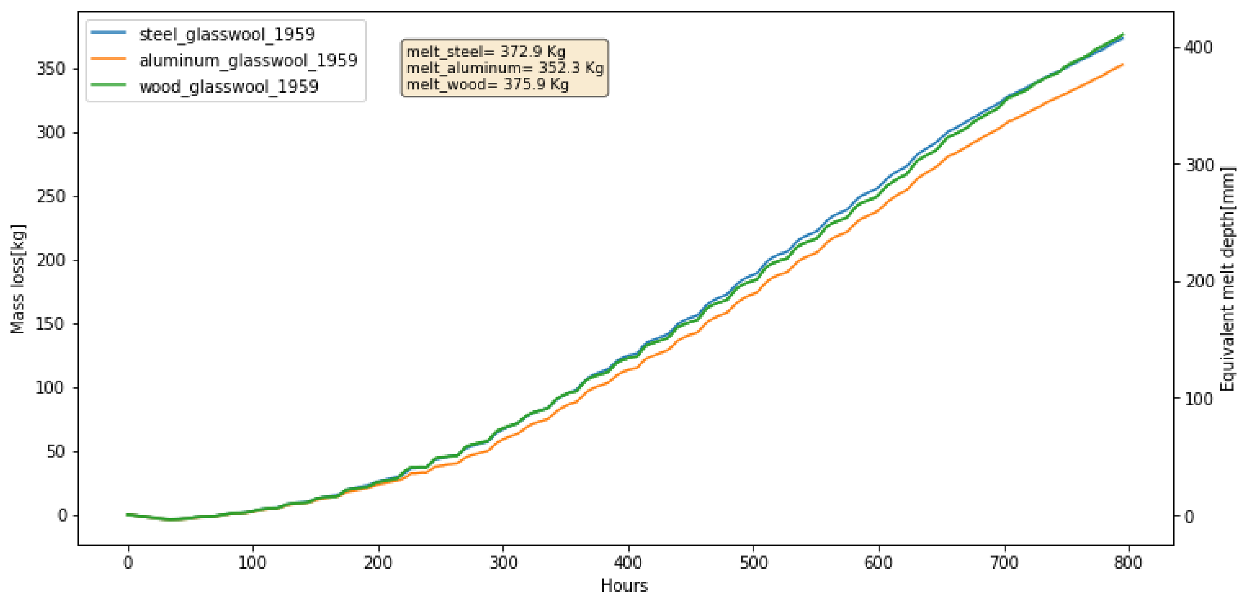


Figure 8. *Melt simulations of total melt.*

3.3 Glass wool, sawdust and clay-sawdust brick

Glass wool is an excellent insulating product, and was widely used after the Second World War. Sawdust is a more common insulation solution in the ice trade. At the time, lumber industry considered sawdust to be a problem because of no other use, which was solved by the ice trade. Clay-sawdust brick is a new type of lightweight building brick. The 10% sawdust component can significantly improve thermal performance of the brick, making building more energy efficient (Charai et al., 2020).

Figure 9 demonstrate the different mass loss and box temperature in each scenario. By improving thermal conductivity from 0.08 W/(mK) (sawdust) to 0.04 W/(mK) (glass wool), the amount of mass loss dropped to 50.4%.

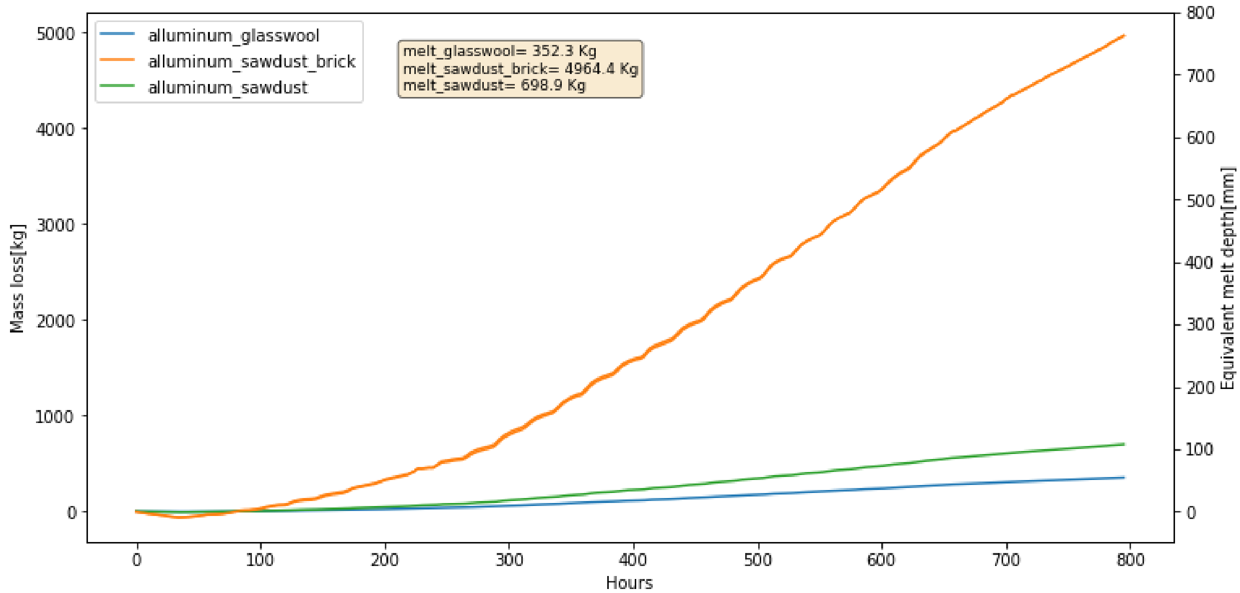


Figure 9. *Melt simulations of total melt.*

3.4 1959, 2021 and the original records

In original records, only four liters of water had been shed when the truck arrived in Algiers on 3th March 1959. When crossing the Sahara, on average 15 liters melted each day. Finally, only 336 kg ice lost in end of expedition, which is 11.0% of the total mass.

In the simulations, Figure 9 display that ice mass loss of 352.3 Kg and 348.2 Kg in 1959 and 2021, with 322.8 Kg in 2020 as a reference, which is opposite to the scenario of bare ice. In ice without cover scenario, the bare ice in 2021 melt more than 1959 due to higher air temperature, and more contributions from latent heat and longwave radiation. However, if there is a cover upon ice, the melt mechanism would be different, because the cover does not have phase change. Thus, the longwave radiation and sensible heat actually are going to be cooling component not the melt energy component when it is warmer than air temperature. If water is available, the evaporation would take heat away as well. Figure 11 shows the fluctuate of the surface temperature of aluminum box, where box in 1959 is warmer than 2021. The detailed energy partitioning on surface could be found in Appendix 3.

Table 3 show that, in the scenario of aluminum_glasswool_1959, the mass loss is 26.5 Kg until Algiers, 14.3 Kg per day in desert, 352.3 Kg in the final destination, which are slightly different with the original records.

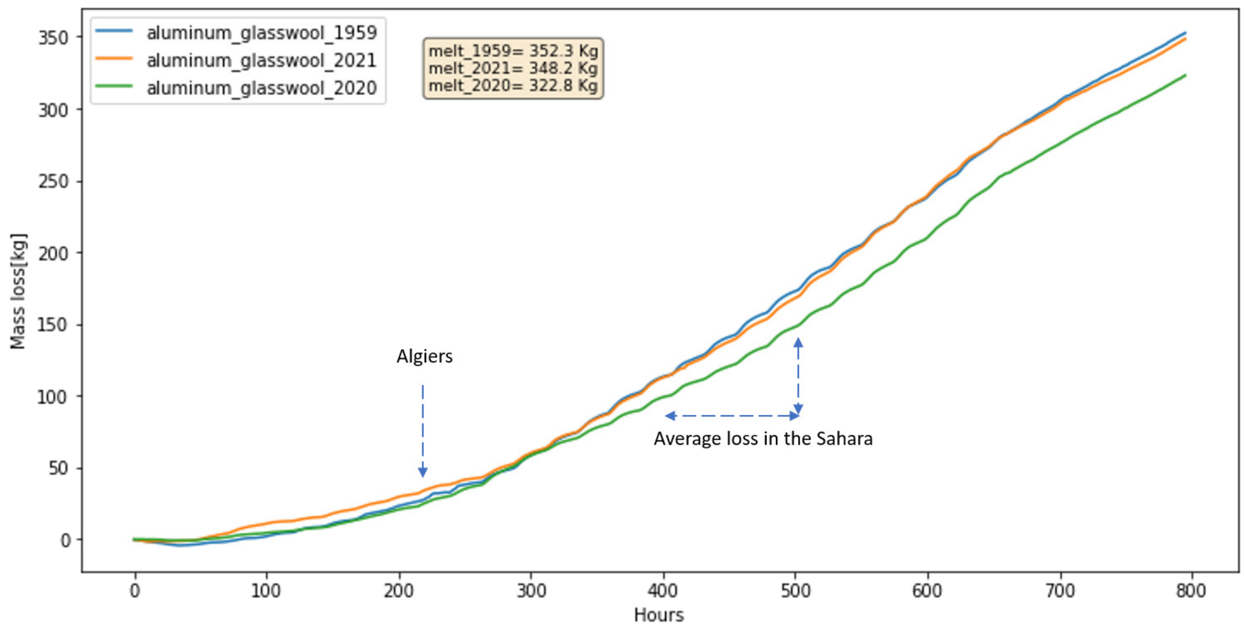


Figure 10. *Box surface temperature of 1959, 2021 and 2020.*

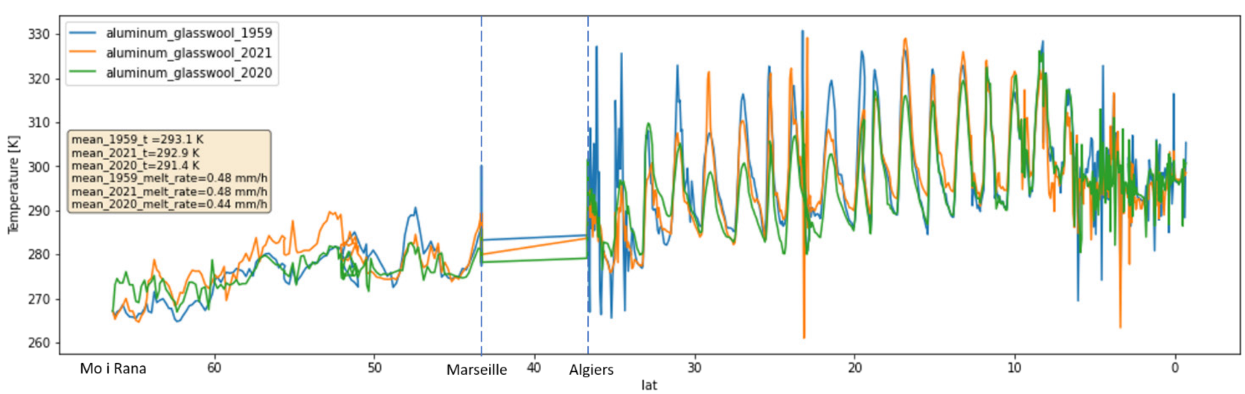


Figure 11. *Melt simulation of total mass loss 1959, 2021 and 2020.*

Table 3. *Comparison between original record and simulations.*

Event	Initial Mass [Kg]	Insulation	Insulation thickness[m]	Mass lost Algiers [Kg]	Mass loss Sahara [Kg/day]	Mass loss In total [Kg]
Original records	3050	Mainly glass wool	-	About 4	About 15	336
Aluminum_glasswool_1959	3050	Glass wool	0.25	26.5	14.3	352.3
Aluminum_glasswool_2021	3050	Glass wool	0.25	32.0	13.2	348.2
Aluminum_glasswool_2020	3050	Glass wool	0.25	23.0	11.7	322.8

4 Heat equation model

The surface energy balance model can only give the amount of heat transfer, which is assumed to be melt energy. But the real changes within the box are still unknow, e.g. (1) What is the temperature distribution of the ice block, or how does the temperature of the ice core fluctuate? (2) How long does it take for ice to melt after warming up to 0 degree Celsius.

The actual situation is rather complicated to simulate because the heat transfer mechanism changes when there is a gap between insulation material and the ice block after melting begins. Normal heat conduction turns into the convection of air and water, as well as thermal radiation. At the same time the ice block will no longer be a regular cubic.

Here is a simplification of melting process. An ice block consists of 149×149 nodes. It is Assumed that the heat flux acts only on the outer nodes of ice block to warm it up. Once the node of ice reach 0 degree Celsius, heat accumulates until a phase change and the new outer nodes begin to storage heat. And the heat diffusion is happening from the outer node to the inner node except where the nodes have done phase change.

The heat flux is given by heat conductivity which is as same as the surface energy model. The box temperature is from the scenario aluminum_glasswool_1959. And the ice temperature starts from -6 degree Celsius, then is updated in iteration of heat conductivity and heat diffusion.

Figure 12 shows that the warming up of ice core from -6° to 0° takes about 175 hours by heat diffusivity. The 1g of ice takes 334 joules to melt into water, which means the ice need storage the energy that equivalent to warm it 0° to 158.4°. Figure 13 zoom in on a corner of the cubic ice. The first 1 cm layer takes less 100 hours to reach 0°, melts by 400 hours. And for the next every 100 hours, 1cm layer disappears.

The first layer is equal to 122.1 Kg, the second is 118.9 Kg. The third layer is 115.7 Kg, but it does not go completely. The remain storage energy in temperature is 10.8 K. So, a rough estimation is the (1-10/158.4) *115.7 = 107.8 Kg. Then, the accumulative mass loss is 348.8 Kg.

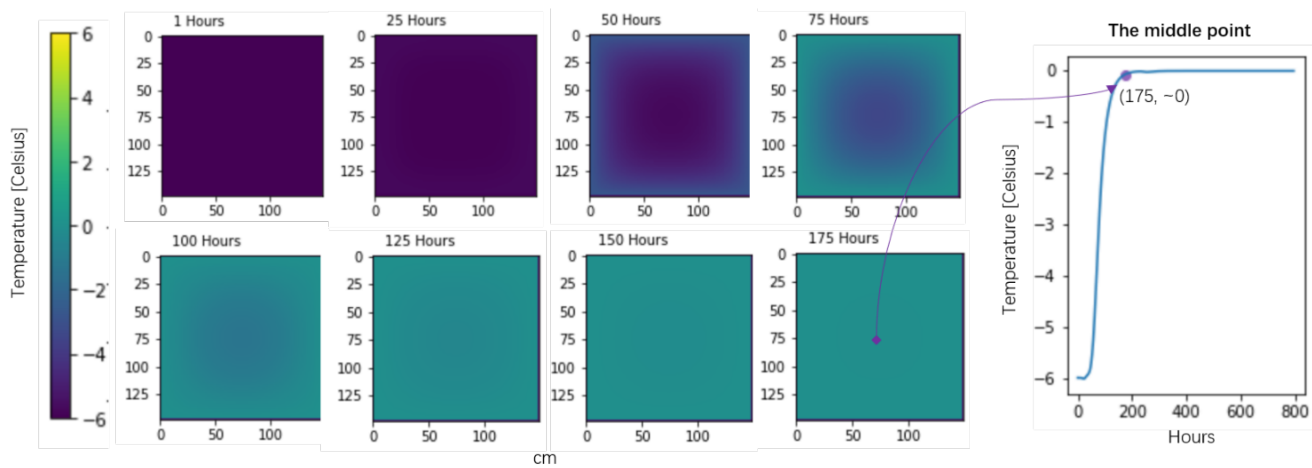


Figure 12. *Warming up process of heat diffusivity. (Scenario* aluminum_glasswool_1959*).*

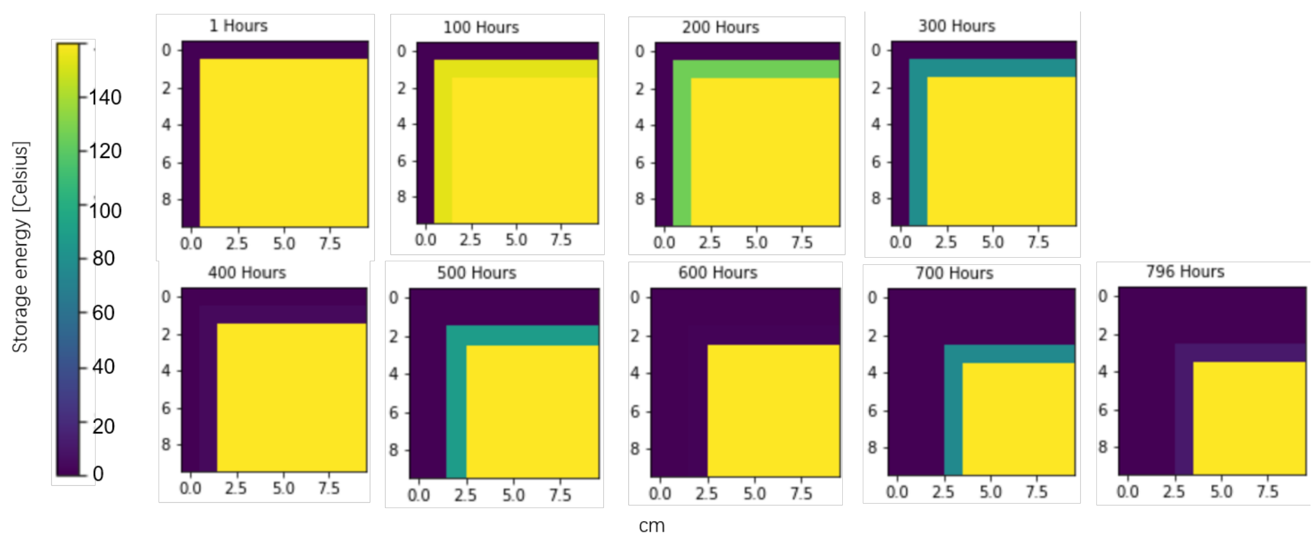


Figure 13. *Ripe process of a corner of the cubic ice. The storage energy is expressed in equivalent temperature (334* joules equals to heat it up 158.4°*).*

5 Discussions

5.1 How the cover and insulation material prevent ice from melting

Due to the changes in energy input & output (or downward & upward) on surface, the covering and insulating layers will chenge the mechanism of ice melt. Net shortwave radiation is a downward energy. The higher of albedo, the lower the energy input. There are several ways to cool down the surface. Sensible heat flux contributes cooling down if the saturated surface temperature is higher than the dew temperature. Thermal radiation and sensible heat flux could also be negative if the surface temperature is higher than air temperature. In contrast, ice surface is hardly to have upward heat fluxs.

An ideal passive cooling surface is capable of following the air temperature during the day, and below it at night. During the day, high albedo and smooth surface are stratagies. When comes to night, low heat capacity makes cooling easier; and high emisivity helps in most of time; moreover, if water is present, latent heat can bring surface temperature as low as the dew temperature. There is nothing we can do on rainy days, the latent heat would reset all surfaces to dew temperature.

5.2 The uncertainties of energy balance-based simulation

We don't know what exactly is going on under the control surface when we apply energy balance equations, which is the disadvantage of this method.

(1) There are several inconsistencies with the actual expedition in preparation. The materials properties are crucial to simulation. And the real case is not just the 3-layers-structure but multiple layers. We can approximately assume that the total heat resistance is equal to that of glass wool. However, when glass wool is damp, it will reduce insulation performance, which was not considered in the simulation and partially explains the difference in mass loss midway (Table 3). Additionally, relative wind speed, and turbulence coefficients are the approximately calculations.

(2) The EAR5-Land dataset can provide hourly variables with a resolution of 9 Km. Variables cannot represent the true observations. For example, the air temperature of the Sahara was said to exceed 50° by the original records. However the highest records of the dataset was 37°. Most likely neither is true. Secondly, due to unavailable of data, the 69-hours-cross-sea weather was actually replaced by the local weather in Marseille.

(3) Latent heat flux for bare soil was used to represent the latent heat component on surface. Because it is impossible to estimate the actual evaporation of the surface, particularly the potential evaporation in the desert is huge.

(4) Initial temperature was set to -6°. The initial condition, or the cold content, is far less than fusion energy of ice. Without a phase change, 334 joules heat would heat 1 gram of ice from 0° to 158.4°. Therefore, an mistake of 1° will result in a 0.63% error estimate of mass loss.

5.3 3D heat equations

We do only present a simplified case. The numerical solution for 3D heat equation does present computational problems. In 2D practice, a 1cm node size is insufficient to see the mass loss because the 1cm thickness layer with 1.49×1.49×6 m size is equal to 122.1 Kg of ice. The mass loss estimated by 2D heat equation is 348.8 Kg, and the result from 1D energy balance model is 352.3.

To be noticed (1) 1D energy balance model assumed the temperature of ice surface is 0° to avoid calculations on multiple control surface, but heat equation do not have this assumption. (2) Solving partial differential equation numerically is just an approximately estimation.

6 Conclusions

This study reproduces the ice block expedition 1959 in multiple scenarios using surface energy balance models and heat equations. The results include (1) how the ice would melt without the cover and insulation. (2) The influence of box material and insulation material. (3) how long do the warming up and ripe phase take. The study compared between simulation 1959, 2021. If there are only bare ice, the 2021 would be the first to melt away, and the 1959 would survive 2 more days. If there is covering and insulation, the 1959 lost even more. This is because the melting mechanism behaves differently on the ice surface and the cover surface.

There are some results that are very close the original records. The simulations shows that only about 3 cm thick, or 348.8 Kg to 352.3 Kg of the ice block melted. The heat equation simulation revealed temperature distribution of ice inside the box. The ice block takes 175 hours warming up from -6° to 0° in the expedition.

Transporting ice to the tropics in the 19th century was totally manageable business. Using a white-covered wooden box filled with double thickness is able to achieve the same insulation effect as glass wool, which is fully expected by simulations. We can use the ice block expedition of 1959 as a baseline. If we do a expedition again, the melt loss of transporting ice is not expected over than 1959. And, the simulations do not support blaming it to climate change because there is a covering upon ice.

References

Charai, M., Sghiouri, H., Mezrhab, A., Karkri, M., Elhammouti, K., & Nasri, H. (2020). Thermal Performance and Characterization of a Sawdust-Clay Composite Material. *Procedia Manufacturing*, *46*, 690–697. https://doi.org/10.1016/j.promfg.2020.03.098

Ice block expedition of 1959. (2022). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Ice_block_expedition_of_1959&oldid=1077983606

Ice trade. (2022). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Ice_trade&oldid=1074188712

Muñoz Sabater, J. (2021). *ERA5-Land hourly data from 1950 to 1980, Copernicus Climate Change Service (C3S) Climate Data Store (CDS)[data set]*.

Appendix 1: Physics Equations

For the surface, the change of energy ∂_E over specific time ∂_t could be described by surface energy balance:

$$\frac{\partial_E}{\partial_t} = LW \downarrow + LW \uparrow + SW \downarrow + SW \uparrow + SF + LF + \; Q_{heatflux}$$

Net longwave radiation and shortwave radiation:

$$LW_{net} = \; L_{in} - (\varepsilon \cdot \sigma \cdot {T_s}^4 + (1-\varepsilon) \cdot L_{in})$$

$$SW_{net} = SW_{in}(1-\alpha)$$

Where L_{in} is the incoming long radiation, emissivity ε. Further, Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}\ \mathrm{Wm}^{-2} K^{-4}$, T_s is surface temperature in Kelvin. SW_{in} is the incoming short radiation, and α is albedo of the surface.

Sensible heat flux and latent heat flux is given by:

$$Q_{sen} = \rho_a \cdot c_{pa} \cdot A \cdot u \cdot (T_{air} - T_s)$$

$$Q_{lat} = -\,\rho_a \cdot L_v \cdot A \cdot u \cdot \frac{0.622 \cdot (e_s - e_{actual})}{P}$$

Where $\rho_a$is air density, c_{pa} is air specific heat capacity, A is turbulent exchange coefficient, L_v is latent heat of vaporization, u is the wind speed, P is air pressure, $(T_{air} - T_s)$ is temperature difference, and $(e_{air} - e_s)$ is vapor pressure difference.

Heat flux in one-dimensional is given by Fourier's law:

$$q = -k \cdot \frac{dT}{dx}$$

Or, heat flux could be derived from Fick's second law (heat equation) in 3-D:

$$\left(\frac{\partial^2{}_T}{\partial_{x^2}} + \frac{\partial^2{}_T}{\partial_{y^2}} + \frac{\partial^2{}_T}{\partial_{z^2}}\right) + \frac{q}{k} = \frac{\rho \cdot c_p}{k} \cdot \frac{\partial_T}{\partial_t}$$

Where T is temperature,t is time, x, y, z is the length of dimensions, and k is heat conductivity, ρ is density, c is specific heat capacity, q is the heat generation flux.

The equation to estimate the mean wind speed u_z at height z (meters) above the ground is:

$$u_z = \frac{u_*}{k}[\ln(\frac{z-d}{z_0})]$$

where u_* is the friction velocity (m/s), k is the Von Kármán constant (~0.41).

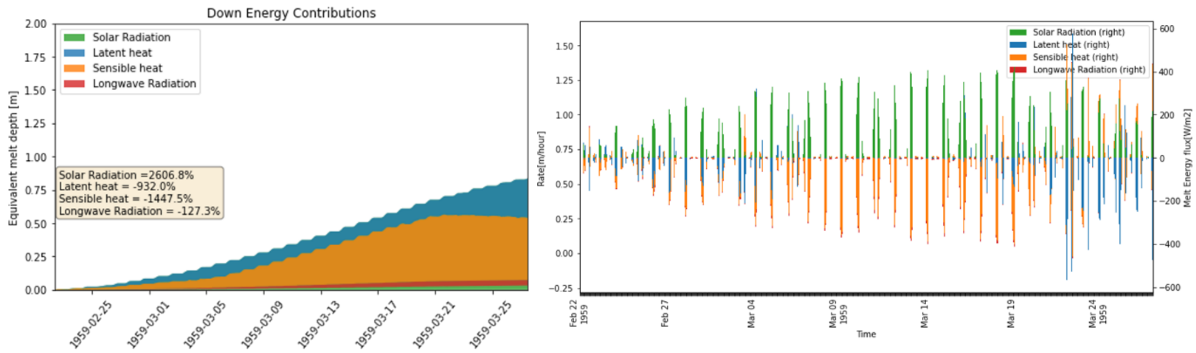
Overall heat transfer coefficient is:

$$U = \frac{1}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + .. + \frac{L_i}{k_i}}$$

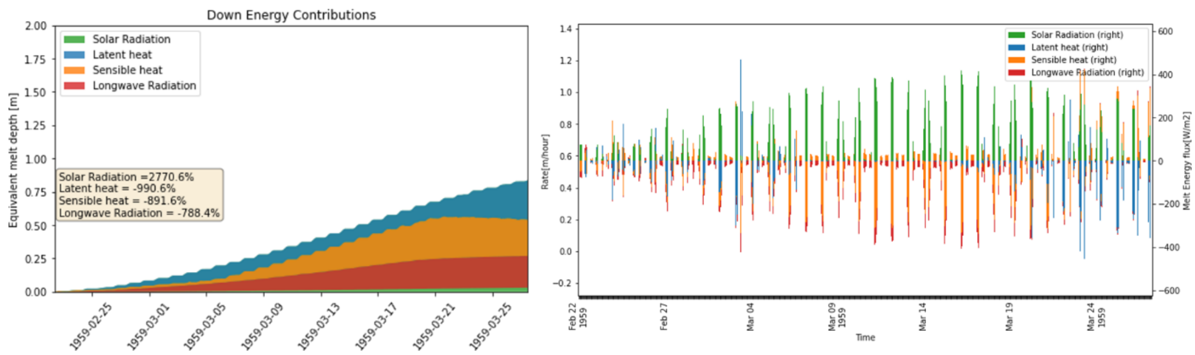
Where U is overall heat coefficient [W /(m^{2}k)], k is the material heat conductivity [W /(mk)], L is the thickness [m].

Appendix 2: Energy Partitioning on Three Types of Box Surface

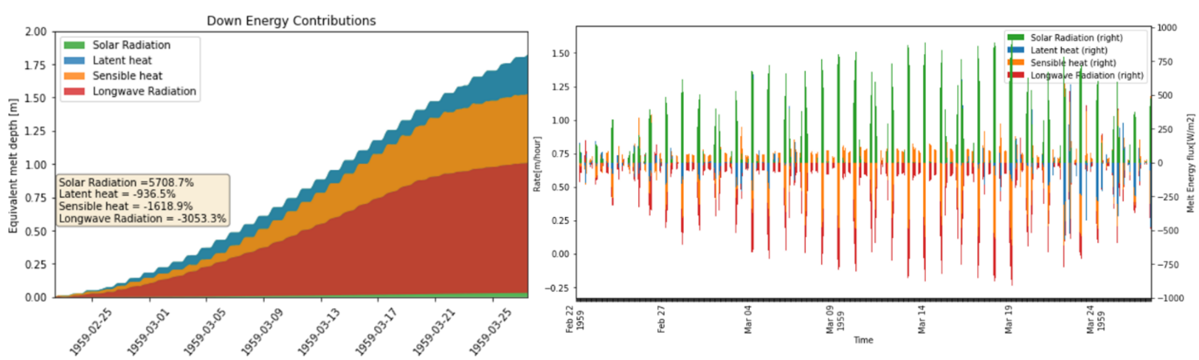
Steel_glasswool_1959



Aluminum_glasswool_1959



Wood_glasswool_1959



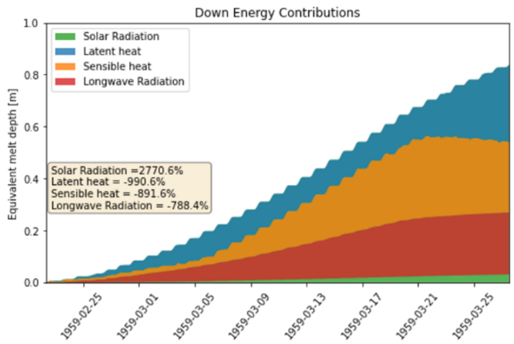
The stackplot looks so strange when the variables become negative and subtract each other. Here is a full explanation. For a thin layer of surface:

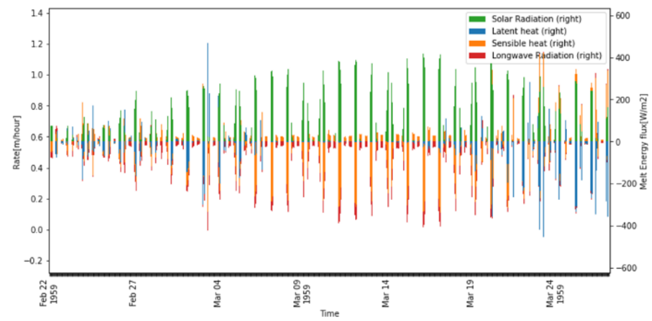
$$E = (positive + negetive) * t$$

Here the positive is SW (solar radiation), and negative is the rest of energy partition. E.g., in the first row, SW×t/E = 2606.8%. If sum with the rest of energy partition, the result is E (100%). The y-axes give the amount of E, which is equivalent to the energy of melting 0.75 m cubic ice (1×1 m in 0 degree Celsius). If there is no insulation ($Q_{heatflow} = 0$), 0.75m is how much the ice will melt.

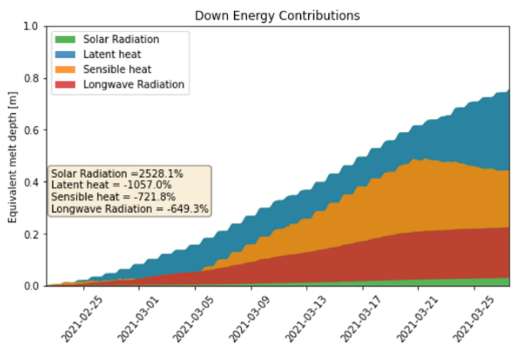
Appendix 3: Energy Partitioning on Box Surface of 1959,2021 and 2020

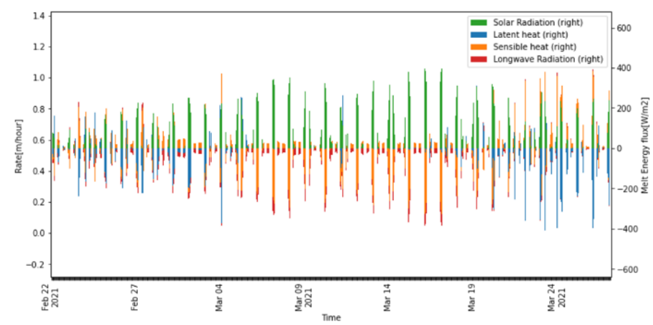
Aluminum _glasswool _1959



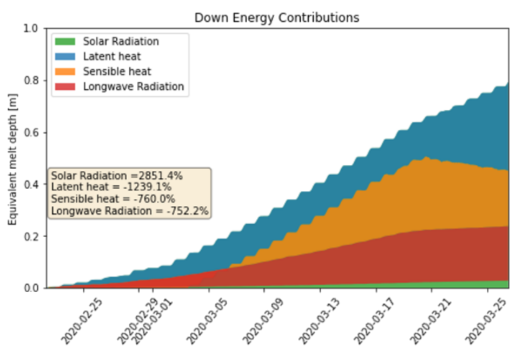


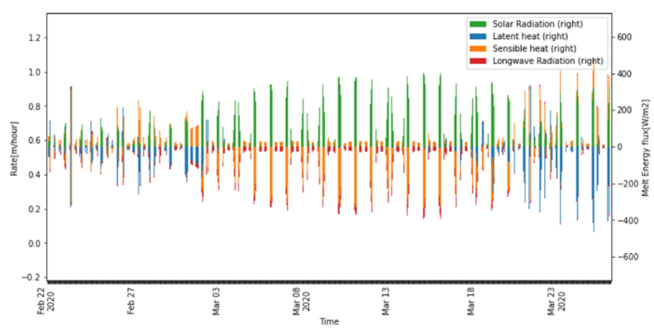
Aluminum _glasswool _2021





Aluminum _glasswool _2020





Appendix 4: A code of coupling 2D heat equation and heat conductivity

Please refer to
https://github.com/liuh886/the_ice_block_expedition_1959
jupyter notebook/main.ipynb/Step3.