Cover Letter

Dear Editor,

Thanks for providing detailed reviews of our manuscript ***Interaction of soil water and groundwater during the freezing-thawing cycle: field observations and numerical modeling***. Following the suggestions of the two reviewers, we have rewritten the majority of the manuscript.

A detailed response is attached in this file. If there is any problem with the revision, please let me know.

Thank you for your consideration.

Best regards,

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Responses to the Reviewers

Reviewer #1

It's my pleasure to review hess-2020-657 "Interaction of soil water and groundwater during the freezing-thawing cycle: field observations and numerical modeling" by Xie et al. The authors quantified the impact of freezing-induced groundwater migration and lateral groundwater inflow on soil moisture profile and groundwater level dynamics at site scale using the SHAW model. This is a very specific study at a single site, and the broad implication of this study to the relevant research community is unknown and needs to be justified. In addition, additional numerical experiments should be included to better quantify the impact of freezing-induced groundwater migration and lateral groundwater inflow, and additional descriptions of the measurements and methods are also necessary. According to these, a major revision is recommended. My comments are as follows.

Response: Thanks for your comments. We agree that our study was concentrated too much on the specific study site. To avoid this problem, we added more simulation results under a series of water table depths and lateral groundwater inflow rates in subsection 3.4 and the broad implication of this study in the last paragraph of the Conclusions part (lines 434-444). We also added more details of the measurements in subsection 2.2 and simulation methods in subsection 2.3.

Major Comments:

1. This paper describes a specific case of observing and simulating the impact of freezing-induced groundwater migration and lateral groundwater inflow on soil moisture profile and groundwater level dynamics at a single site with very shallow water level ranging from 90-143cm. I think this is a very special case for the frozen areas that the water level is generally much deeper. As such, the broad implication of this study to the relevant research community should be justified. In addition, the authors are suggested to include additional numerical simulations to investigate the impact of different water level depths.

Response:

In our study area covered mainly by sand, numerical results show that when the water table depth equals 2.2 m, groundwater level is not influenced by freezing. Because areas with water table depth shallower than 2 m account for around one third of the total catchment (Jiang et al., 2018) and regions with water table depth shallower than 2 m account for around 31% of the global land area (Fan et al., 2013), the involvement of groundwater in freezing-induced water redistribution could be widespread. Although the threshold water table depth in other study areas with different climate conditions remains unknown, our study well demonstrated the necessity of properly characterizing freezing-induced water table fluctuations to quantify freezing-induced groundwater migration and its effect on engineering problems and ecological processes in cold regions. The broad implication of this study has been added in the last paragraph of the Conclusions part (lines 434-444)

We have added Figure 8 and Table 5 in subsection 3.4 to analyze the impact of freezing-induced groundwater migration under four initial water table depths (120 cm, 170 cm, 220 cm and 250 cm) and three rates of lateral groundwater inflow (0, 0.51 mm/d and 1.03mm/d). We also built three scenarios with water table depths fixed at 120 cm, 170 cm, and 220 cm. The specific settings of the 13 scenarios are shown in Table 3 in the manuscript.

2. Related to comment #1, I think detailed descriptions of the study site and all the available measurements are necessary as these given in Jiang et al. 2017,2018 cited in this paper. I found that there are at least two experimental wells and several other kinds of wells shown in Jiang et al. 2017, 2018. Why only one experimental well is investigated in this study? What’s the typical depth of groundwater level found across the whole Wudu lake catchment? How far is the Otak meteorological station from the monitoring site? What’s the accuracy of precipitation and soil moisture measurements? Did the authors perform site-specific calibration for the 5TM sensor? And how accurate can the 5TM sensor measure the liquid water content under frozen condition? What’s the typical vegetation and soil types? The measurements of soil texture and soil temperature are also suggested to include in the supplement.

Response: In the revision, we have added the details of the Wudu lake catchment and the monitoring site in subsection 2.1, including the typical vegetation (*Achnatherum splendens*), soil type (loamy sand), and range of water table depths across the whole catchment (from less than 0.5 m to around 26 m), as well as soil texture measurements at 12 depths (Table 1 in the revision).

Although we have another monitoring well (DK 1 as shown in Jiang et al., 2018), the water table depth is as deep as around 15 m. Due to the deep water table depth, there is no interaction between soil water and groundwater induced by freezing. All other wells shown on the map of water table elevation in Jiang et al. (2018) are domestic wells for drinking. Therefore, only the monitoring DK2 is used in the current study.

We have added more details of the Otak meteorological station, which is a national meteorological station 35 km away from the study site. The accuracy of precipitation measurements is ±0.1 mm. The descriptions can be found in subsection 2.1 of the revision (lines 94-102).

The 5TM sensors, which measure the soil dielectric permittivity to represent liquid soil water content, have an accuracy of around ±2% volumetric water content (VWC) and a resolution of 0.1% VWC. We have performed site-specific calibration for the sensors by the comparing the VWC measured by the 5TM sensors and by the gravimetric method. We have added more detailed descriptions about the 5TM sensors in subsection 2.2 (lines 119-124).

3. The authors indicated that “we find snowfall did not infiltrate into the soil column due to the low permeability of frozen soil”, which I think is questionable. If the permeability of frozen soil is so low that the snowmelt cannot infiltrate into the soil, how can the freezing-induced groundwater migration enter the soil column? What’s the mechanism behind this? I am curious how the authors simulate the snow process? What’s the accuracy of snowfall measurements and snowmelt simulations?

Response: Thanks for pointing out the problem of the sentence “we find snowfall did not infiltrate into the soil column due to the low permeability of frozen soil”. After referring to several references (Iwata et al., 2008; Zhao et al., 2013; Mohammed et al., 2018), we realize that although infiltration of snowmelt would be impeded by the low permeability of frozen soil, the majority of snowmelt can be infiltrated into the frozen zone. Unfortunately, because we did not set the parameter representing “ponding for rainfall and snowmelt” correctly, our model results led to the wrong conclusion that “snowfall could not infiltrate into the soil column”. After correcting the parameter representing “ponding for rainfall and snowmelt”, we find the amount of infiltration from snowmelt equals 3.23 mm, which accounts for 28% of the total snowfall. We have updated all figures and re-calculated the water budget by including infiltration from snowmelt. We also added some description on how SHAW simulate the snow process in the subsection 2.3 of the revision (lines 190-199).

Concerning the question of “If the permeability of frozen soil is so low that the snowmelt cannot infiltrate into the soil, how can the freezing-induced groundwater migration enter the soil column?”, we want to clarify that due to cryosuction at the freezing front, groundwater migrates through the unfrozen zone which lies above the water table and below the freezing front, and gets frozen near the freezing front. However, as the freezing front goes deeper, the ice content and total water content in the frozen zone above the freezing front change little (Figures 6 and 8).

4. Detailed descriptions of how the authors determine the hydraulic parameters are necessary. Did the authors measure the soil texture and other relevant hydraulic parameters such as porosity, bulk density and saturated hydraulic conductivity? Why the saturated hydraulic conductivity estimated for the second layer (0.7-1.0 m) is so different from other two layers? How the authors determine the permeability of aquifer?

Response: We measured particle size by the Mastersizer 2000 instrument (Malvern Instruments, England) and the bulk density with the cutting-ring method, the results of which are listed in Table 1. Based on the average contents of clay, silt and sand in each of the three layers, initial estimates of hydraulic parameters (θ_r, θ_s, α, n) are estimated by the Rosetta pedotransfer function (Schaap and Leij 1998; Zhang and Schaap 2017). We further calibrated the hydraulic parameters by fitting the simulated and measured soil water content. The details of soil parameter measurement have been added in subsection 2.2 (lines 125-131).

We measured the saturated hydraulic conductivity of soil samples from each layer by HYPROP (www.metergroup.com/environment/products/hyprop-2/). The soil samples with low clay content above 70 cm and below 100 cm were measured to be around 18.0 cm/h, while that with higher clay content at the depth ranging between 70 and 100 cm is measured to be 0.8 cm/h. The different saturated hydraulic conductivity is caused by the slight difference in clay and silt. The hydraulic conductivity of aquifer is the same to the saturated hydraulic conductivity of the third layer. We have added the descriptions of how the authors determine the hydraulic parameters in subsection 2.4 (lines 228-235).

5. Detailed descriptions of the SHAW model and its implementation are necessary. For instance, how the model compute the permeability of frozen soil? How the authors include the lateral groundwater inflow into the SHAW model? How the authors determine the temperature at the lower boundary? What are the state variables need to be determined before the simulations? What's the time step of simulations? How the authors consider the impact of vegetation processes?

Response: We have added more detailed description of the SHAW model in subsection 2.3 in the revision (lines 160-166, lines 170-172, and lines 187-200). The hydraulic conductivity of both unfrozen soil and frozen soil is computed by the van Genuchten and Mualem equation. However, when the porosity of frozen soil is decreased to 0.13, the permeability is assumed to be zero. The details can be found in subsection 2.3 of the revision (lines 187-189).

The SHAW model calculates the lateral flow rate based on the assigned horizontal hydraulic gradient and saturated hydraulic conductivity. Specifically, a constant horizontal hydraulic gradient is assigned at one node within the saturated zone. This is described in subsection 2.3 of the revision (lines 169-171).

For the lower boundary condition, we have two different settings in the revision. For the base case model (field site model), we use the measured soil temperature at 150 cm as the bottom temperature boundary condition to insure the accuracy of model calibration. After model calibration, we change the length of the soil column into 250 cm to account for the scenarios with deeper water table depths, and use the force-restore approach (Hirota et al., 2002) embedded in the SHAW model to obtain temperature at the lower boundary. The details can be found in subsection 2.4 of the revision (lines 249-255).

The stable variables of the model include soil temperature and soil water content. We use the initial conditions of soil water content and soil temperature on 29 OCT 2015 for spin-up, which is run for 30 days to obtain the initial conditions before the start of freezing (28 NOV 2015). The time step of simulations is one hour. Because the grass in our study site fades during the freezing and thawing stages, we do not consider the influence of plants in the model. These contents are described in subsection 2.4 of the revision (lines 206-207 and lines 221-223).

6. Four numerical experiments are conducted to investigate the impact of soil heterogeneity and lateral groundwater on the simulations. I do not find the necessary to quantify the impact of soil heterogeneity. Instead, I think the authors can consider following additional experiments such as simulations without impact of groundwater, simulations with deeper water level depth, and simulations with changing rates of lateral groundwater inflow. It's not clear why the authors fix the rate of lateral groundwater inflow.

Response: Thanks for your suggestions. We have deleted the investigation of the impact of soil heterogeneity in the revision. We added Figure 8 and Table 5 in subsection 3.4 to analyze the impact of freezing-induced groundwater migration under four initial water table depths (120 cm, 170 cm, 220 cm and 250 cm) and three rates of lateral groundwater inflow (0, 0.51 mm/d and 1.03mm/d). We also built three scenarios with water table depths fixed at 120 cm, 170 cm, and 220 cm.

Minor Comments:

1. The authors are suggested to merge Figures 4 and 5, and the info of precipitation is suggested to include in the figure. The scale for the temperature can be set at 10~-20.

Response: Thanks for your suggestions. Figure 4 shows the sensitivity of measured liquid water content to temperature drop from above 0℃ to below 0℃, and well demonstrates that 5TM sensors can be used to monitor liquid water content during the freezing period. We respectfully disagree to merge figures 4 and 5. Moreover, because the amount of precipitation has been shown in Figure 3, we prefer not to show them again in Figure 4. The scale for temperature at 10 cm, 20 cm and 30 cm is 10~-20. Because of the much smaller temperature variations at 50 cm, 70 cm and 90 cm, we follow the suggestion of Reviewer 2 and set the scale to be 10~-5.

2. Why there is not increase found for the simulation of total water content at 10 cm as shown in Figure 5?

Response: The low total water content in the shallow part of the soil profile is caused by the low initial soil water content as well as the long distance away from the water table. As shown in Figure 8, when the initial water table depth increases, the zone with low total water content becomes thicker.

3. It is suggested to plot the measured frost depth and WTD in all the subplots of Figure 6. In addition, how the authors determine the frost depth?

Response: Thanks for the suggestion. We have added the measured frost depth in all subplots as suggested, and added the measured water table depth in all subplots with an initial water table depth of 120 cm. The measured frost depth is determined by the dates of start of freezing and end of thawing as shown in Figure 4 in the manuscript.

4. For all the simulations, it is suggested to show how they affect both soil liquid water content and temperature simulations, as well as to list the corresponding error statistics.

Response: Thanks for the suggestion. To show how ice content, soil liquid water content and temperature simulations respond to freezing and thawing, we have added subplots of ice content, soil liquid water content and temperature in Figure 6. The RMSEs of soil liquid water content and soil temperature are listed in Figure 5. Because we already have 12 subplots in Figure 8, we only show the distribution of total water content.

5. For the description of soil evaporation in Section 3.3, can the authors provide validation data? If not, I don't find the necessary to include this subsection. Instead, the impact of different numerical experiments on both soil liquid water content and temperature simulations can be shown in detail.

Response: Thanks for your suggestion. We have deleted the subsection on soil evaporation because we have no measured data to validate the simulated results.

6. For the Table S1, it's suggested to remove 110cm and 150cm since there are not measurements recorded for these two depths. Besides, it's suggested to add the measured soil temperature and lateral groundwater inflow in the supplement.

Response: Thanks for your suggestions. We have removed 110 cm and 150 cm in Table S1. In fact, the measured soil temperature is already listed in Table S2 of supplement material.

We want to clarify that we do not have measured lateral groundwater inflow data. The rate of lateral groundwater inflow was initially estimated by Jiang et al. (2017) based on water table fluctuations in the unfrozen period. In the current study, we estimated the rate of lateral groundwater inflow by fitting the simulated water level and measured water level during the freezing-thawing stage.

Reviewer #2

The work presented by Xie et al. (2021) investigated the interaction of soil water and groundwater mainly via the lateral groundwater flow and freezing or thawing induced water migration during the freezing-thawing cycle in a semi-arid region with shallow groundwater. They conducted field observations and numerical experiments and further analyzed the water budget components. The role of lateral groundwater flow and the freezing-thawing process was demonstrated important in the tested area. I found this work is interesting while there are some concerns about the current version of the manuscript necessary to be addressed from my perspective.

First, the existence of freezing-induced water gain and lateral groundwater flow is mostly postulated from the observations and not directly measured. This renders that you have to demonstrate the reliability and uncertainties of your observations (e.g., liquid water content, the occurrence of thawed water infiltration, frost depth, …).

Response: Thanks for your comments. We have added more details of the accuracy of our observations in subsection 2.2 (lines 119-124) and the reliability of our observations in subsection 3.1 by explaining how liquid water content, total water content, ice content and temperature respond to freezing and thawing (lines 264-284).

Second, as most of the analysis part is based on the SHAW model simulations. I think the authors should put a bit more words on the SHAW model setup (e.g., bottom boundary condition settings, how groundwater is considered), model performance, and uncertainty (e.g., simulation of freezing/thawing dates, statistical performance). Thus, I suggest more dedicated efforts should be made before its publication in the HESS journal.

Response: Thanks for your suggestions. We have added more detailed description of model setup in subsection 2.4. As explained in the Introduction part and illustrated in Figure 1, the water table separating saturated and unsaturated zones is dynamic and can respond to freezing and thawing. The lower boundary condition of the field case model is explained in lines 207-208, while that of the 13 scenarios for sensitivity analysis is explained in lines 241-251.

We have added detailed description of model performance by including a new Figure 6 “The evolution of simulated soil temperature, ice content, liquid water content and total water content at the field site” and a new paragraph in lines 308-317.

We agree that our model has uncertainty. We have added the RMSEs of soil temperature and liquid water content in Figure 5. The simulated freezing/thawing dates slightly deviate the measured dates, which are listed below (Table S1). Because they are close enough, we prefer not to list the simulated dates in the text, but only show the measured freezing/thawing dates in all subplots of Figure 6. We have added a sentence “There is a good match between simulated and measured frost depth, the latter of which is determined by the dates of start of freezing and end of thawing as shown in Figure 4.” in line 308-310.

Table S1 A comparison of measured and simulated dates of freezing and thawing

Depth	The date of start of freezing		The date of end of thawing	
(cm)	Measured	Simulated	Measured	Simulated
10	02 DEC	02 DEC	14 MAR	14 MAR
20	15 DEC	13 DEC	15 MAR	15 MAR
30	16 DEC	19 DEC	16 MAR	16 MAR
50	9 JAN	7 JAN	22 MAR	22 MAR
70	23 JAN	24 JAN	28 MAR	26 MAR

My specific comments are as follows:

Abstract:

Line 22-23: I notice that in your figures (Figure 4) the unit of soil water content is cm3/cm3, please keep consistent.

Response: We have deleted this sentence but we have added all the unit of soil water content, which is cm3/cm3 in the revision.

1 Introduction:

Line 44: "… and further decrease the hydraulic conductivity of frozen soils" please explain or clarify.

Response: Thanks for your comments. The sentence has been modified into "As a result of cryosuction generated by Soil freezing, water from the unfrozen zone would migrate to the freezing front." (lines 39-41).

Line 99-103: these sentence does not belong here, I think it should better be in the Introduction part.

Response: Thanks for your suggestions. We do find that these sentences are not appropriate to be put here and have deleted them in the revision.

2 Method

Please clearly present the soil texture (fraction of sand, clay, silt, organic matter) information.

Response: We have added the fraction of sand, clay, silt in Table 1. However, we have not measured the organic matter and did not consider the influence of organic matter in our model.

Are the 5TM sensors calibrated on this site? What about the measuring accuracy of 5TM sensors regarding the soil moisture and temperature?

Response: We have performed site-specific calibration for the sensors by the comparing the VWC measured by the 5TM sensors and by the gravimetric method. The 5TM sensors have an accuracy of around ±2% for the volumetric water content and around ±1℃ for the temperature. These contents are described in subsection 2.3 of the revision (lines 119-124).

Line 112-114: From my understanding, Figure 1 cannot directly tell us that the increase of groundwater table depth is due to the freezing-induced water migration. Please carefully rephrase this sentence.

Response: Thanks for pointing out this. We totally agree. We have modified the sentence into "As shown in Fig. 2, water table depth increases from 115 cm on 28 NOV 2015 to 143 cm on 29 JAN 2016, which corresponds to the stage with an increasing frost depth." (lines 132-134)

2.3 Model inputs

Line 174: "… soil column is set to be 155 cm." I can understand that you want to use the measured soil temperature (150 cm) as the bottom boundary condition. While for the other numerical scenarios, you use 200 cm for the soil column. I think either you keep all the numerical scenarios as 200cm, or you should explain a little bit the potential uncertainties regarding the results.

Response: Thanks for your suggestions. We have re-run all models in the revision and used two different lower boundary conditions. For the base case model (field site model), we use the measured soil temperature at 150 cm as the bottom temperature boundary condition to insure the accuracy of model calibration. After model calibration, we change the length of the soil column into 250 cm to account for the scenarios with deeper water table depths, and use the force-restore approach (Hirota et al., 2002) embedded in the SHAW model to obtain temperature at the lower boundary. The details can be found in subsection 2.4 of the revision (lines 204-208 and lines 241-255).

Line 176: Please explain in more detail about the lateral groundwater flow in SHAW. And how did you calibrate the lateral groundwater flow as 1.03mm/d?

Response: The lateral groundwater inflow is added to the saturated zone of the 1D soil column. Specifically, we assign a constant horizontal hydraulic gradient at one node within the saturated zone. The SHAW model calculates the lateral flow rate based on the assigned horizontal hydraulic gradient and saturated hydraulic conductivity. The rate of lateral groundwater inflow was estimated by Jiang et al. (2017) to range from 0.96 mm/d to 1.16 mm/d based on water table fluctuations in the unfrozen period. In the current study, the rate of lateral groundwater inflow is estimated by fitting the simulated and measured water level during the freezing-thawing stage. We find a lateral inflow rate of 1.03 mm/d leads to the best fit of water table depth (with the lowest RMSE). The details can be found in lines 169-171 and lines 234-235.

Line 187: For the bottom boundary conditions, I have a sense that the setting of the bottom boundary condition can affect the simulations. Please explain why you set the bottom as the no-flux boundary condition. Is it the more realistic condition for that site or for the better simulations?

Response: To account for the effect of groundwater, a saturated zone should be included in the soil column. As we demonstrated in the manuscript, a constant head lower boundary condition would overestimate freezing-induced groundwater migration toward the freezing front. Because the water level fluctuations are not independent from the atmospheric conditions, a specified-head lower boundary condition is not justified. Therefore, a closed soil column with a no-flow lower boundary condition is the best choice to identify how the groundwater level responds to freezing-induced water migration, lateral groundwater flow, and infiltration of thawed water. This lower boundary condition leads to an accurate estimation of freezing-induced groundwater level decline as well as freezing-induced water gain in the frozen zone.

Line 204: For presenting the different simulation scenarios (A, B, C, D), I would suggest that you include them as a table, listing the main difference among all the simulation scenarios (or numerical experiments).

Response: Thanks for your suggestions. We have included Table 3 to show the main difference among all the simulation scenarios in the revision. We have added Figure 8 and Table 5 in subsection 3.4 to analyze the impact of freezing-induced groundwater migration under four initial water table depths (120 cm, 170 cm, 220 cm and 250 cm) and three rates of lateral groundwater inflow (0, 0.51 mm/d and 1.03mm/d). We also build three scenarios with water table depths fixed at 120 cm, 170 cm, and 220 cm.

Table 2: I think the row with “Calibrated parameters” should be below the row with “Initial parameters”.

Response: We have deleted this table.

3 Results and discussion

Figure 4: the scale of soil temperature should be finer (e.g., [-5, 10] oC) for Figure 4d, e, f. In addition, I think there also be freezing or thawing periods for 90cm. Please zoom in and clarify.

Response: Thanks for your suggestions. We have modified the scales of soil temperature in Figure 4. According to our measurements, the temperature of 90 cm never drop below 0℃, therefore, there is no freezing or thawing periods in the 90cm, and we have zoomed in the scale of temperature.

Line 248: please explain how to define the "occurrence of thawed water infiltration".

Response: In the revision, we have changed the sentence “From 29 JAN, there is a trend of rising water level, which is one month earlier than the occurrence of thawed water infiltration during the thawing stage.” into “the trend of rising water level from 29 JAN to 29 FEB, when frozen soil has not been thawed yet, is attributed to lateral groundwater inflow” (lines 291-292).

Figure 5: I suggest that the statistical performance should be added here to demonstrate the capability of the SHAW model in simulating soil moisture and temperature.

Response: We agree and have added the statistical performance (RMSE) on Figure 5 in the revision.

Section 3.2: please also add some text to describe how the model captures the observed freezing or thawing dates.

Response: Thanks for your suggestions. We have added a sentence “There is a good match between simulated and measured frost depth, the latter of which is determined by the dates of start of freezing and end of thawing as shown in Figure 4.” in line 308-310.

Figure 6: for better comparison, please present the observed frost depth and water table depth for all four subplots. In addition, how is the frost depth measured?

Response: We have added the measured frost depth in all subplots as suggested, and added the measured water table depth in all subplots with an initial water table depth of 120 cm. The measured frost depth is determined by the dates of start of freezing and end of thawing as shown in Figure 4 in the manuscript.

Table 3: please clarify the frozen zone and how you calculate TWC.

Response: In Table 5, the frozen zone represents the zone from the surface to the maximum frost depth. The mean TWC is calculated by total water content in the frozen zone (S_{FZ}) divided by the frost depth, while the ΔTWC is calculated by total water content change in the frozen zone (ΔS_{FZ}) divided by the maximum frost depth (FD). We have added how we calculate mean TWC and ΔTWC in lines397-398.

Section 3.3: as you present two subplots in Figure 8, it is better to say what you want to say about the comparison here. The effect of snow can be clearly identified (Figure 8), the role or the amount of snowfall should be stated from the water budget closure perspective.

Response: Thanks for your suggestions. We have re-run the model by properly characterizing the behavior of snow and have deleted the evaporation of the homogenous case in the revision. Figure 7 in the revision has only one subplot to show the simulated evaporation process in our study site. We have updated the water budget calculation by including the snowmelt infiltration in subsect. 3.3.

4 Conclusions

I suggest adding some text describing that how well the SHAW model can capture the observed soil moisture, temperature, frost depth, and groundwater table depth.

Response: Thanks for your suggestions. We have add a sentence as “The observed fluctuating soil water contents and groundwater level induced by freezing and thawing are well reproduced by the calibrated model, which increases our understanding of water balance as well as freezing-induced water migration during the freezing-thawing cycle.” (lines 422-425).

Line 380: “a model is built…” should better be “a series of numerical experiments were set up to …” or something similar.

Response: Thanks for your suggestions. We have rewritten the sentence as “Based on a series of models with different initial water table depths during the freezing-thawing cycle, …” (line 434).

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