General response

Comment

1. My main criticism of the paper is that the model used has not been adequately explained. It would not be possible for someone using the same or a different model to reproduce the work without a great deal of extra information. In my specific comments, I try to identify and ask questions at points in the text where vague language is used, or where important details are omitted. To allow comparison of their work, I encourage the authors to be as explicit and detailed as possible about how they achieved their results. Examples of open questions regarding how the model works:

Line70: what is meant by "double-layer" explicit solution? Is the Qfrost software publically available (e.g. on GitHub) – if so, why not reference it? If the model is well-documented, this might be a sufficient means of answering many of the questions regarding the method.

Response

Most likely, the comment appeared due to incorrect translation, since the explicit two-layer scheme, the method of balances and the enthalpy formulation of Stefan's problem are all standard terms used for numerical calculations of the ground heat transfer. Therefore, «the explicit two-layer scheme» has to be used instead of a « double-layer explicit solution». So the corrected sentence would be: «The explicit two-layer scheme is applied using the balance method and the enthalpy formulation of the problem».

Unfortunately, the Qfrost software for geocryological modeling (Certificate of the State Registration No. 2016614404 of 22) is no more available on-line despite the fact that according to the idea of its main developer Denis Pesotsky it had to be publicly available for free (previously, the program was posted at http://www.qfrost.net). But due to his early death, the web page no longer works and the software and its usage and distribution are limited to his colleagues and collaborators at Moscow University. Nevertheless, we hope to make it available soon. But the code is in open access on GitHub https://github.com/kriolog/qfrost . We are not sure it is worth inserting into the article since there is a large part of the information in Russian

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Comment

Line 80: "extrapolated" – what method was used to extrapolate results from monolithic stratigraphies to more complex stratigraphies? Introducing changes in porosity, grain size, thermal properties, etc. would presumably change the temperature field solutions?

Response

We consider two cases to extrapolate our results:
In the first case, we consider the uniform alternation of homogeneous layers with a relatively low thickness (relative to the total thickness of the permafrost). The linear interpolation is simply performed in accordance with the percentage of the thickness of permafrost obtained during modeling for two "pure" soils at a given moment.

The second case relates to the two-layer structure of the section when a sufficiently thick (as compared with the permafrost thickness) homogeneous layer is underlined by a second homogeneous layer of unlimited thickness. Then the following considerations are valid. If the thickness of the upper layer is zero, then the thickness of the permafrost is equal to the result of simulation for "pure" rocks/sediments of the second layer. If the thickness of the upper layer is equal to (or more) the thickness of the permafrost obtained for the first layer, then the problem

becomes single-layer and the thickness of the permafrost is equal to that of the first layer. Therefore, when the thickness of the upper layer changes from zero to the thickness of the permafrost of the first layer, the thickness of the two-layer section changes from the thickness of the permafrost of the second layer to the permafrost thickness the first layer. Therefore, as a first approximation, this change is linear (which is not entirely true) and a simple linear interpolation formula can be obtained.

Comment

On **line 82**, all rocks (please replace) were assumed to be saline – why? how saline was the sediment assumed to be? Did salinities vary with depth? Was salt diffusion permitted? How did salt content affect the freezing characteristic curve or liquid water of frozen material? - How are discontinuities avoided at the borders between domains/subdomains/areas/subareas?

Response

A very high degree of averaging over the properties was used for the modeling caused by the lack of data on the water area. The rare drilling data showed the salinization of sediments through the entire drilling depth. So there was not possible to take into account the salt diffusion, and the salinity did not vary with the depth

We will add the next text after the sentence « All rocks and sediments were assumed to be saline from top to bottom of the modeling domain» Line 82 :

All reference rocks and sediments were considered saline; the concentration of pore saline solution corresponding to that of seawater (23 ‰) was used. Thermophysical properties, the content of unfrozen water and the heat of the phase transitions of water in the pores, the freezing point of the deposits was set taking into account the indicated salinization.

As for the question about the borders between domains/subdomains/areas/subareas we suggest to insert the following text in the section that describes the methodology:

The zoning is determined by the allocation of territorial units that are characterized by uniformity of formation conditions and, accordingly, by similar (on the given scale of the studies) parameters of permafrost: its distribution, thickness, depths of the top (Kudryavtsev V.A.(Ed.) Methods of Cryogenic Survey. Moscow State University, Moscow, 358 pp, 1979 (in Russian).

Comment

As a result, claims are made in the paper, but there is not enough information given to the reader to be able to judge whether the claim is justified or on what basis it has been made. For example: - section 4.2 lists 8 controls on the “pattern of permafrost distribution”, but 2 of the 8 (lithology and properties or rocks, and Holocene climate optimum) are not described in any detail, making it impossible for the reader to follow the argument or design studies that reproduce the work. A 3rd control (thermal effect of river waters) is not even modeled, so it is not clear how the authors can conclude that this acts as a control. It seems to be an assumption in the model design, but not enough information is provided for the reader to be able to judge. -

Response

Thank you, you are absolutely right, the influence of control factors within the periglacial is not visualized. Therefore, we are going to give four figures showing the dynamics of the Kara shelf permafrost (top and base) for the past 125 Kyr. The results obtained during modeling for the following aspects for the southwestern and northeastern areas will be presented: 1) different deposit temperatures within the same sea depths, lithology, heat flux etc. (eg. in cryochrons (for example, MIS-2) in the NE it's 11 degrees lower than in the SW) 2) the same for the different sea

depths (120 and 5 m), 3) different heat flux, 4) different lithology (eg. sand and clay silt). We did not model the influence of the dammed basin, but it is shown in Fig.7 and described in the paper above Figure 7. The influence of rivers is described according to actual data. An increase in water temperature in the Holocene optimum took place only in the southwestern part, the heated water came from the Barents Sea and is also described in the paper.

Comment

Tables 2-7 lists the model output for "depths to permafrost top" – but what is meant by "permafrost top" has not been defined anywhere. Does this correspond to an isotherm, the presence of any ice, or of some minimum amount of ice? Or does the model output the depth of the phase change boundary?

Response

The permafrost top corresponds to the -1.8 isotherm, according to the saline concentration in the seawater that was set for the pores of the deposits. This would be added to the text.

Comment

3. The language used in the paper is sometimes imprecise or even incorrect; the paper should be proof-read by an native-speaker with some background in the topic. As examples: a. "cold": is probably being used to refer to cryotic conditions, or to conditions below the freezing point. As it stands, it is a vague descriptor. b. "rock": is used to refer to earth material, including either rock or sediment, consolidated or unconsolidated material. In English, "rock" is used to refer only to bedrock material, and would exclude sedimentary deposits of terrestrial, marine or other origin. As it stands, all instances of the use of "rock" need to be replaced with something more precise. c. More examples are given below in the specific comments.

Response

Accepted, thank you for a very important comment: «cold» will be changed to «cryotic»:

As for the rocks, we would replace the «rock» for the «ground» (i.e. soil and rock) or «deposits» wherever it is necessary

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Comment

4. The abstract is extremely short and does not provide enough information for a reader to decide whether he/she wants to read the paper. It needs to introduce the larger context for the study, the central question/focus/hypothesis, more detail on the method. It should report key results, findings and conclusions, and may suggest implications or outlook based on the study.

Response

Accepted, the abstract is extended according to the comment:

The evolution of permafrost in the Kara shelf is reconstructed for the past 125 Ka. The work includes zoning of the shelf according to geological history, compiling sea-level and ground temperature scenarios within the distinguished zones, and forward modeling to evaluate the thickness of permafrost and the extent of frozen, cryotic and unfrozen ground. Special attention is given to the scenarios of the evolution of ground temperature in key stages of history that determined the current state of the Kara shelf permafrost zone: characterization of the extensiveness and duration of the existence of the sea during the marine isotope stage MIS -3, the spread of glaciation and dammed basins in MIS-2.The present shelf is divided into continuous,

discontinuous to sporadic, and sporadic permafrost. Cryotic deposits occur at the west and northwest water zone and correspond to areas of MIS-2 glaciation. Permafrost occurs in the periglacial domain that is a zone of modern sea depth from 0 to 100 m, adjacent to the continent. The distribution of permafrost is mostly sporadic in the southeast of this zone, while it is mostly continuous in the northeast. The thickness of permafrost does not exceed 100 m in the southeast and ranges from 100 to 300 m in the northeast. Unfrozen deposits are confined to the estuaries of large rivers and the deepwater part of the St. Anna trench. The modeling results are correlated to the available field data and are presented as geocryological maps. The formation of frozen, cryotic and unfrozen ground of the region is inferred to depend on the spread of ice sheets, sea level, and duration of shelf freezing and thawing periods

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Comment

5. The reference list is incomplete. Vasiliev & Rekant (2018) are missing, for example. The reference list needs to be cross-checked with the submitted paper. Some reference citations still include initials (see Fig. 4 caption, for example).

Response

Accepted, thank you

Line 32 «Vasiliev & Rekant (2018)» changed to «Vasilyev et al., 2018»
Figure caption to Fig. 2 was corrected:
«Baranskaya and Romanenko et al. (2018)» changed to «Baranskaya et al. (2018)»
Gusev et al. (2013a) changed to Gusev et al. (2013) and the according reference was corrected:
Gusev E.A., Bolshiyanov D.Yu., Dymov V.A., Sharin V.V., Arslanov Kh.A.: Holocene marine terraces of southern islands of the Franz Joseph Land archipelago. Problemy Arktiki i Antarktiki, 97 (3), 103-108, 2013
the next references were added to the reference list:
Gusev E. A., Molod'kov A. N. Structure of sediments of the final stage of the Kazantsevo transgression (MIS 5) in the north of Western Siberia. Doklady Earth Sciences, 443(2), 458-461, 2012
Romanovskii, N.N., Hubberten, H.-W., Gavrilov, A.V., Eliseeva, A.A., Tipenko, G.S. Offshore permafrost and gas hydrate stability zone on the shelf of East Siberian Seas // Geo-Marine Letters, 2005, v. 25, N 2-3, p. 167-182.
Kudryavtsev V.A.(Ed.) Methods of Cryogenic Survey. Moscow State University, Moscow,358 pp, 1979 (in Russian).

the next references were deleted:
Gusev E.A., Anikina N.Yu., Arslanov Kh.A., Bondarenko S.A., Derevyanko L.G., Molod'kov A.N., Pushina Z.V., RekantP.V., Stepanova G.V.: Quaternary tratigraphy and pleogeography in Sibiryakov Island for the past 50 000 years. Proceedings of the Russian Geographical Society, 145 (4), 65-79, 2013b.
Gusev, E.A., Sharin, V.V., Dymov, V.A.,Kachurina, N.V., Arslanov, Kh.A, 2012. Shallow sediments in the northern Kara shelf: New data. Razvedka i Okhrana Nedr, 8, 87-90, 2009.
Trofimov V.T. (Ed.): The Yamal Peninsula (Engineering-Geological Review). Moscow State University, Moscow, 278 pp,1975 (in Russian).
The reference «Flint R.F.: Glacial and Pleistocene geology. N.Y., J. Wiley a. sons, 553 pp., 1957» was moved from Line 485 to 473
Lines 585-589 the reference was corrected : Streletskaya I.D., Shpolanskaya N.A., Kritsuk L.N., Surkov A.V.: Cenozoic deposits in the Yamal Peninsula and the problem of their origin. Vestnik Moscow University, Ser. 5. Geografiya 3, 50-57, 2009

Lines 620-624 Yershov E.D. changed to Yershov E.D. (Ed.)
The initials from Fig. 4 caption were deleted
The article has been carefully checked and corrected in accordance with the changed links.

Comment

6. This paper stays true to the general phenonmenon of Russian authors citing mostly Russian work, and Canadian/Alaskan researchers citing mostly North American. For citations dealing with regionally specific processes, this is understandable. But neglecting to look at how the North American community has approached modelling the exact same processes under different conditions is harmful in two ways: it exposes the work to the criticism of being too narrow in its approach, and it makes it less likely that the work will be found and cited by North Americans. I encourage the authors to show their familiarity with the field by referring to the work of researchers from outside of their region, who have presented novel ideas in the field of subsea permafrost modelling. Some examples: - Whitehouse, P. L., Allen, M. B., Milne, G. A. Glacial isostatic adjustment as a control on coastal processes: an example from the Siberian Arctic, Geology, 35,747–750,doi:10.1130/G23437A.1,2007. –anything from the group of Romanovsky and Nicholsky (e.g. Nicolsky, D., Shakhova, N. Modeling sub-sea permafrost in the East Siberian Arctic Shelf: the Dmitry Laptev Strait. Environmental Research Letters, 5(1), 15006, 2010.). - anything from Taylor, A. (e.g. Taylor, A. E., S. R. Dallimore, P. R. Hill, D. R. Issler, S. Blasco, Wright, F. Numerical model of the geothermal regime on the Beaufort Shelf, Arctic Canada since the Last Interglacial, J. Geophys. Res. Earth Surf. , 118, doi:10.1002/2013JF002859, 2013.).

1) This phenomenon on mathematical modeling is quite understandable. Soviet (Russian) permafrost scientists started the modeling back in the 1960s. (Sharbatyan A.A. To the history of the development of permafrost (on the example of the West Siberian Plain) // Transactions of the Institute of permafrost. Academy of Sciences of the USSR, v. XIX, 1962). Modeling was carried out on extremely slow analog devices. For the shelf, the first modeling was carried out in 1969 (Molochushkin E.N. Thermal conditions of rocks in the southeastern part of the Laptev Sea. Abstract of thesis , 1970). The methodology and simulation results were widely debated in the former USSR in the late 1970s – early 80s. Therefore, the literature on modeling in Russian is at least an order of magnitude more extensive than in English, which, in fact, determines its greater citation.

However, it should be noted that Russian-language literature is widely represented in the international database. In addition to the references cited in this article, the state of mapping of the submarine cryolithozone by Russian researchers at the turn of the 20th and19th centuries is characterized in the next paper: Gavrilov A.V. (2001) Geocryological Mapping of Arctic Shelves. In: Paepe R., Melnikov V.P., Van Overloop E., Gorokhov V.D. (eds) Permafrost Response on Economic Development, Environmental Security and Natural Resources. NATO Science Series (Series 2. Environment Security), vol 76. Springer, Dordrecht.

In current work the authors used the developments from N.E. Shakhova and D. Nikolsky for construction the scenarios. Moreover, D. Nicolsky et al., 2012 used data of modern warming to set the Holocene temperature of bottom water, while we did set more realistic data - the reconstructed temperatures in each of the Holocene warmings and coolings. Besides, in the present paper, the authors tried to take into account the increase in the temperature of bottom water in the coastal zone warmed up in summer, which occurred during the transgression of the sea on each section of the shelf

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Specific comments:

Comment

Line 13: the use of as a unit does not follow SI.

Response

Kyr corrected to Ka

Comment

Line 24: “In the latest ... earliest ...” needs correction.

Response

By late 1970s - early 1980s

Comment

Line 45: “raised high” – please quantify

Response

Corrected, +45, +55,+60 m

Comment

Line 49: add “and” and remove “and so on”

Response

Done

Comment

Line 58: replace “provide their progress” with “extend their work”?

Response

Thank you, we changed this according to your suggestion.

Comment

Line 59: what is meant with “geocryological results”? Please specify

+

Line 61: “obtained estimates” – of what? Please specify

Response

corrected sentence:

The work includes compiling a database of paleogeographic, geological, tectonic, and geocryological conditions used further for dividing the region according to geological history and for creating possible scenarios of sea level and ground temperature variations that serve as boundary conditions in heat transfer modeling

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Comment

Fig. 1. This figure provides an overview of the method, but uses many general or non-specific terms that reduce the amount of information communicated: - in the top box, what is meant by “environmental data”? - in the second box, what is meant by “conditions”? - in the left third box, delete “dynamics” (adds nothing to “history”) - in the third right box and in the fourth left box, replace“rocks”-in the fourth right box: “density of the heat flow from the depths” is usually referred to “geothermal heat flux” - in the fifth box: “Testing ... of the model” is almost entirely free of content. How was which model tested? More specific word choice could make this box informative - the lowest box is actually two steps: “coordination” and “mapping” - what is meant by “coordination”? This question is never really answered in the paper, but is critical for understanding what was done. Does the model output get changed in some way by comparison with field data? Where and where not? How? These are important points for anyone wanting to reproduce or apply the method in the same or in other geographical regions.

Response

The figure will be adjusted in accordance with the comments using more specific terms

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Comment

Line 72: “Permafrost dynamics were...”

Response

Sorry, but we don’t get why it has to be plural here

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Comment

Line 73: “including...” suggests that other scenarios/conditions were NOT included? How many and why not?

Response

Thank you for the notice. The sentence will be corrected to sound more clear:

The permafrost dynamics was simulated for numerous paleoclimate scenarios that cover the full range of presumable conditions in the Arctic shelves. The total number of paleo-scenarios for the Kara sea used in the course of mathematical modeling was 40.

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Comment

Line 77: how were regions of different geothermal heat flux mapped or determined?

Response

In accordance with the data of geothermal studies (Khutorskoy et al., 2013), the Kara shelf is characterized by a heat flux density of 50 to 75 mW /m^2. There is very few no point-referenced data. Therefore, the technique involves modeling for two extreme density values. Based on the simulation results and actual data, it was possible to draw conclusions about the heat flux values characteristic of various tectonic structures.

Comment

Line 79 and in all following text: modelling was probably not restricted to the “rock”.

Response

corrected

The modeling was performed for several uniform reference rock and soil types in order to reduce the number of possible solutions in the conditions of high lithological diversity in the area.

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Comment

Line 87: “subsea permafrost had presumably fully degraded...” – this statement requires a reference, especially in light of modelling, for example by Romanovsky, N. N., showing permafrost elsewhere persisting through interglacials; this point is important, since other researchers have shown that a systematic bias in model results is obtained depending on the initial conditions. Such results show that setting permafrost to zero at the interglacial will introduce a warm bias, that at least would need to be tested.

Response

Romanovsky’s conclusions are about the Laptev Sea shelf, where there are almost no marine terraces of MIS-5e. The very different conditions occured for the Kara region, where the entire north of the West Siberian Plain had been covered by the sea from 140 to 120 Ka.

Link to MIS-5e : The State Geological Map of the Russian Federation Scale 1:1000000 (third generation). Ser. West Siberia, Sheet R-42, Yamal Peninsula, 2015 (in Russian).; Map of Quaternary deposits in the Russian Federation, scale 1:2 500 000, Explanatory note. Minprirody, Rosnedra, VSEGEI, VNII Okeangeologiya, 2010 (in Russian).

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Comment

Fig. 2: it looks like only 14 sites out of more than 100 are located on the shelf, i.e. pertain to subsea permafrost. Is this correct? Please add a description of the red line (which is currently not described until Fig. 8).

Response

Yes, it is correct. There are few publications containing data on submarine permafrost in Fig. 2. They are actually few. But the figure is called: Late Pleistocene geology of the Kara region: data coverage. They are the paleogeographic data necessary for scenario and mathematical modeling. The red line description, which is research region boundary will be added on Fig 2,3,6

Comment
Line 106: “the existence of a number of idea about its development...” is not a peculiarity of any region, it is true of every region!
Response
It’s true, thank you. Corrected sentence:
There is number of ideas about the paleogeography of the Kara region and its development in the Late Pleistocene.

Comment
Line 115: dammed lakes are invoked to explain the unfrozen zone. Why is the sensible and convective heat transport at the river bed and in the estuarine regions not sufficient to explain the absence of frozen material? Surely the rivers maintain and have maintained positive benthic temperatures for long periods?
Response
The riverbeds are lines. Here there is a large area of the flatten bottom and river valleys are traced incomparably worse than on the periglacial shelf of the Laptev and East Siberian seas. There bathymetry shows that the rivers functioned the entire period of MIS-2. But it is absent on the West Siberian shelf. Instead of river deltas to the west and east of the coast of Western Siberia, the estuaries of the Ob, Taz, and other rivers deeply protrude into the land. And even the small river Gyda has an estuary, the width of which is almost the same as the length of the Gydy river, and the length of the estuary is like 3-4 Gyda rivers. This has to be an ice-barrier basin. This is an assumption. But it is well confirmed by talik on the water continuation of the rivers of Western Siberia, and estuaries deeply protruding into the land. The question is how could the Ob and the Yenisei, flowing through the whole Western and Middle Siberia, carrying a mass of sediment (since they drain the Altai and Sayan mountain systems), form not a delta, such as Lena, but estuaries? In our opinion, the assumption is very realistic.

Comment
Line 119: “Insignificance of the severity” is convoluted language that should be simplified.
Response
Accepted, changed to «…the poor expression of the ancient valley network…»

Comment
Line 154: explain the abbreviation “MMP”
Response
corrected. It’s permafrost now

Comment
Line 156: “sea level” rather than “sealevel”
Response
corrected

Comment
Line 201: on what basis was it decided how long each portion of the shelf spent in the coastal zone (400-2000 years)? Why were waters in this zone saline? – is this not the zone most affected by the freshwater layer above the halocline, by snow melt and river runoff? Dmitrenko et al (2011) show

the freshwater nature of the coastal zone in the Laptev Sea. And why was this zone warmer? Bedfast ice can result in cooling of the seabed from 0 – 2 m water depth. A little more justification and specification of these boundary conditions, which determine the most immediate and rapid response of permafrost to inundation by seawater, are necessary.

Response

It is known that at sea depths from 2 to 7 m in the 1970s (Zhigarev, 1981), up to 10 m in the 2000s. (Dmitrenko) the mean annual temperature of bottom waters in the Laptev Sea is positive and bottom sediments thaw from above. For the Kara Sea, there are no such data on isobath intervals, but it is known that temperatures are generally lower. Therefore, we assumed that the interval of isobaths with such water temperatures was limited to 5-6 m. Episodes with such water temperatures occurred on the shelf during the postglacial transgression even in its initial periods, since the July temperature is reconstructed for pre-Holocene warming (allered) exceeding 2 ° C the temperature of the 1980s. (Velichko et al., 2000). Therefore, we constructed scenarios for these episodes. To determine their duration, dated data on the absolute altitudes of the sea level during the transgression of the Laptev Sea were used (Bauch et al., 2001). The transgression rate was not the same. The shortest episodes (400 and 375 years) of positive temperatures are determined for periods 15-11 and 10-9 ka respectively. The longest intervals were 11–10, 9–5, and 5–0 Ka with 1000, 750 and >5000 years according to simple calculations.

Comment

Fig. 8: The map shows permafrost thickness, which can clearly result as output from 1D numerical modelling. What conditions were applied to determine zonation of permafrost based on continuity (continuous,discontinuous,sporadic)? I.e. how do conclusions about distribution result from 1D modelling? Caption: why are only “fragments” of the map shown? Why not present the reader with the whole map?

Response

A paleogeographic scenario was constructed, consisting of a series of paleotemperature curves (or scenarios), in which the main factors that formed the modern permafrost were taken into account. Among these factors were: zoning, sectoral, fluctuations in sea level and its depth, which determined the period of freezing during shelf drainage and the thawing period when it was in the flooded state, the period of glaciation and thickness of the ice sheet, geothermal gradient, ground composition and properties, area, within which the water temperature rose at the Holocene optimum etc. In accordance with the indicated curves, modeling was carried out, the results of which reflected the influence on the permafrost of all of the above factors.

The whole map is being prepared for publication in the atlas