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Response to Reviewer 1

General Comments:

This manuscripts investigates the predictability of seasonal sea ice in the Pacific-Arctic sector. The authors develop and use a regional linear Markov model with a suite of atmosphere-ocean variables. They find that prediction skill of this model is improved relative to a similar previous pan-Arctic model and that there are key sources of predictability for sea ice in different seasons of the Pacific-Arctic sector. The paper is well-written, the structure makes sense, and the figures are clear. I find the use of this regional statistical model interesting and the results are clear and novel, but I think there are a few flaws in the development of this model that may have an impact on the key results.

Thank you very much for your great efforts on our manuscript. We also appreciate your valuable comments. We are confident that the revision made based upon these comments have resulted in an improved version of our paper. Please see the details in the following replies to the specific comments.

The main concern I have is if the authors are missing a key source of predictability for summer Arctic sea ice: sea ice thickness. Numerous studies going back to the seminal work by Blanchard-Wrigglesworth et al., (2011) have shown that sea ice thickness is a key source of predictability for summer Arctic sea ice. In this Markov model, it is excluded, with no clear reason why. I think the authors should add this variable or motivate why it is excluded in a clear fashion. For instance, rather than stating in words why it is not included, it would be nice to see supporting figures that show what happens when it is included. Or, the main figures of the paper should be revised/updated with this variable included. Similarly, the authors exclude subsurface ocean heat content as a variable. This too has been shown to be a key source of predictability for wintertime Arctic sea ice. In the detailed comments below I have suggested how the authors can improve this by including SIT (PIOMAS) or OHC (ORAS5).

Thanks for the valuable suggestions. Following the suggestions, we have added OHC and SIT in the model and recombined variables in the model experiments. The new variable-combinations was shown in Table 1.

Table 1. Variable combinations in cross-validated experiments. V1 represents the No. 1 variable-combination. √ represents the variable included in the corresponding combination.

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12
SIC	√	√	√	√	√	√	√	√	√	√	√	√
OHC		√		√	√	√	√	√	√	√	√	√

SST	√	√						√	√	√
SIT			√							√
SAT				√						√
Surface net turbulent heat flux						√			√	√
Surface net radiative flux					√			√		√
850hPa GPH, U, V							√			√

The updated predictive skill measured by PGS and mean RMSE for each lead time in each season are calculated and shown in Figure 1. We find that both OHC and SIT contribute substantially to predictability. Based on the PGS and RMSE, we primarily chose three superior model configurations marked by black boxes in Figure 1. we spatially average the SIC prediction skill from these superior models with 1- to 12-month leads (Figures 2 and 3). Based on the construction principle same to the original manuscript, we finally chose V9M16, V11M20, V5M10, and V5M7 in winter, spring, summer, and autumn respectively. The updated model shows more skill than the model developed in the original manuscript. In addition, based on the updated model, we have modified all relevant contents throughout the manuscript.

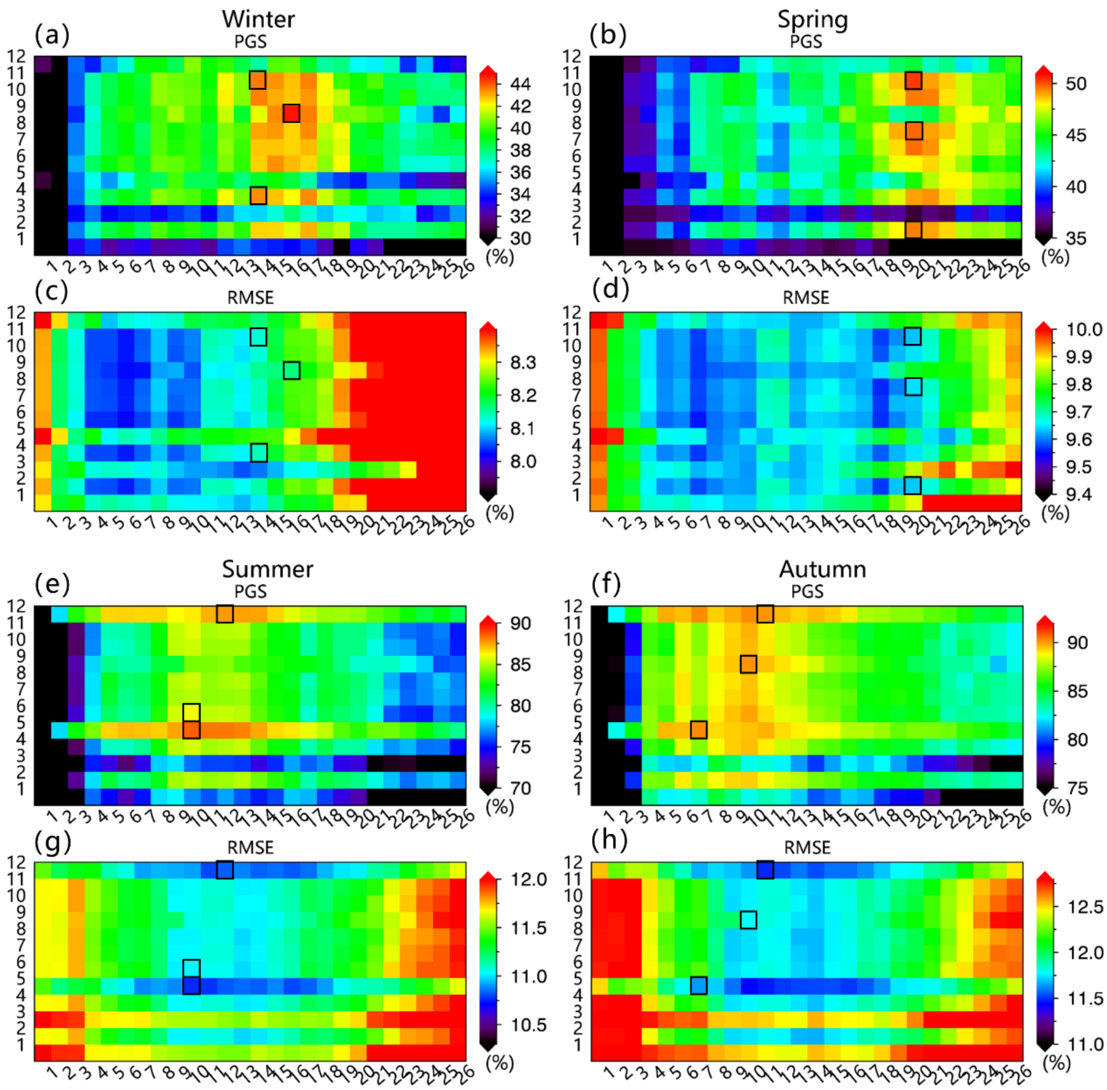

Figure 1. Mean PGS and mean RMSE between the observations and predictions in four seasons. (a) Mean PGS is obtained by averaging all lead months for winter predictions. The x-axis represents the number of MEOF modes, and the y-axis represents the combination of the variables corresponding to Table 1. (b, e, and f) are the same as (a) except for spring, summer, and autumn respectively. (c, d, g, and h) are the same as (a, b, e, and f) except for RMSE.

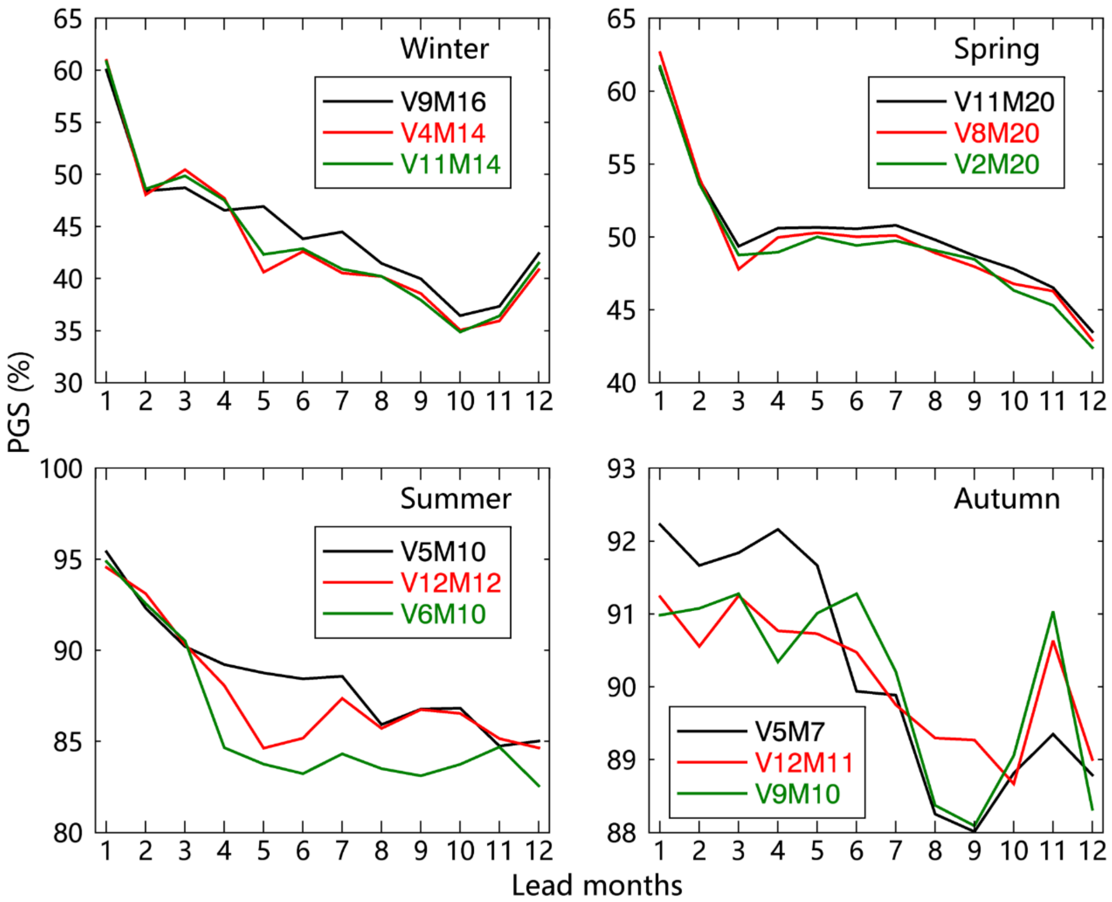

Figure 2. PGS for the preliminary selection of superior models in each season.

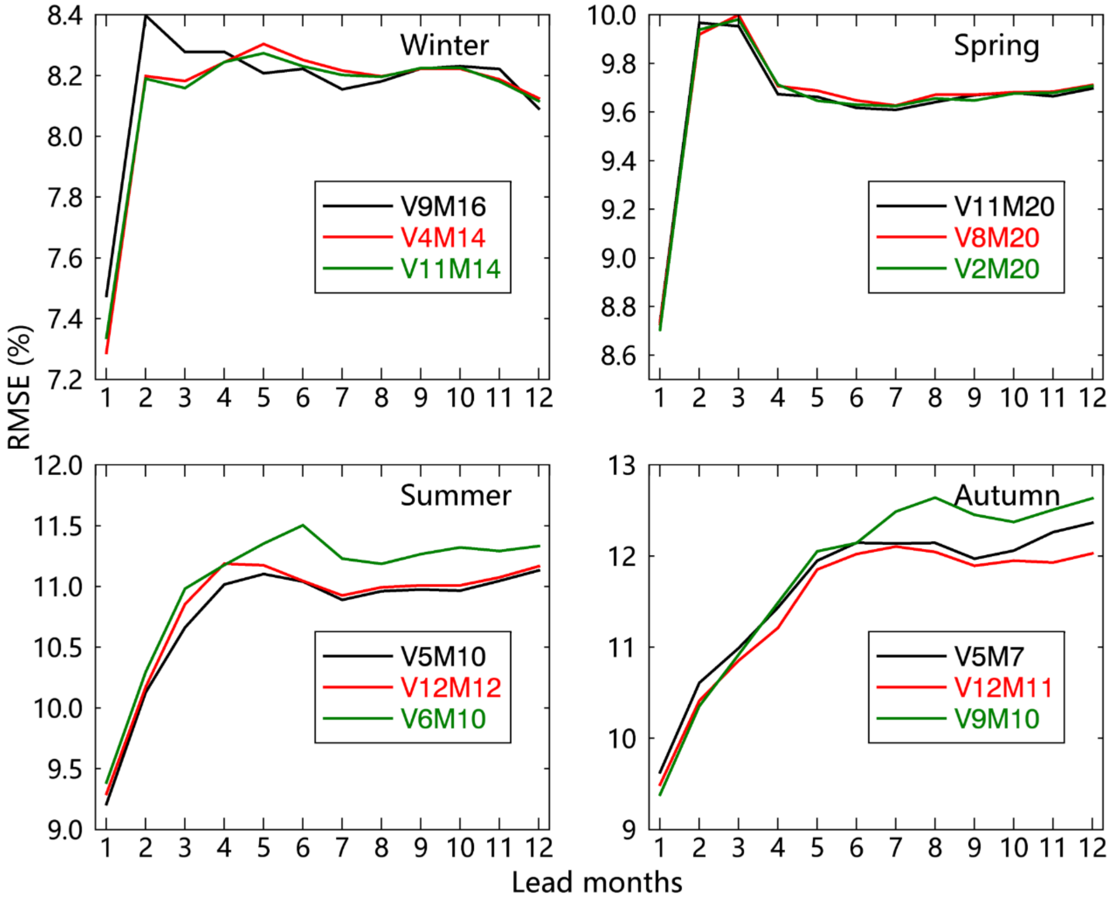

Figure 3. Same as Figure 2 but for RMSE.

Specific Comments:

Data and Methodology:

The Model:

L147-148: It seems this spatial domain (40°N to 84°N, 120°E to 240°E) captures much (if not all) of the Pacific-Arctic sector. But, it feels a bit arbitrary where exactly the longitudinal domains end. For instance, if the same analysis is performed from 90°E to 270°E, are the results similar? Given that the authors base some of this domain choice on regions that exhibit different sea ice variability (i.e., Figure 1), if the authors instead calculated regional sea ice area domains and computed the standard deviation of each region, then grouped the regions by similar magnitudes of variability, will the results be similar? To me this seems like a more precise way of quantifying the Pacific-Sector as regions like the Canadian Archipelago or Laptev Sea could be included or excluded. Basically, I'd like for the authors to conduct this sensitivity analysis and either provide a short explanation of why the results are insensitive to the exact domain or add some supporting information to justify this choice.

Thanks. According to your suggestions, we have conducted the sensitivity analysis in the Pacific-Sector defined by 90°E to 270°E, 120°E to 240°E and 135°E to 225°E respectively. The result was shown in Figure 4. The predictive skills calculated from these three spatial domains show a distinct feature that OHC has a higher capability in sea ice prediction relative to SST. The high prediction skill calculated from 120°E-240°E or 135°E-225°E is mainly concentrated in the models with 13 to 18 modes in winter and with 19 to 24 modes in spring. In summer and autumn, the skill patterns from the three study areas show high similarity that the models with V5 and V12 are prominent. These skill patterns also exist different features. The prediction skill from 90°E-270°E is relatively scattered and low in the cold season compared to that from two small study areas. In addition, the model skill from 135°E-225°E is relatively low in the warm season. Therefore, we choose 120°E-240°E as the spatial domain of the Pacific-Arctic sector. We have provided a detailed explanation in the revision.

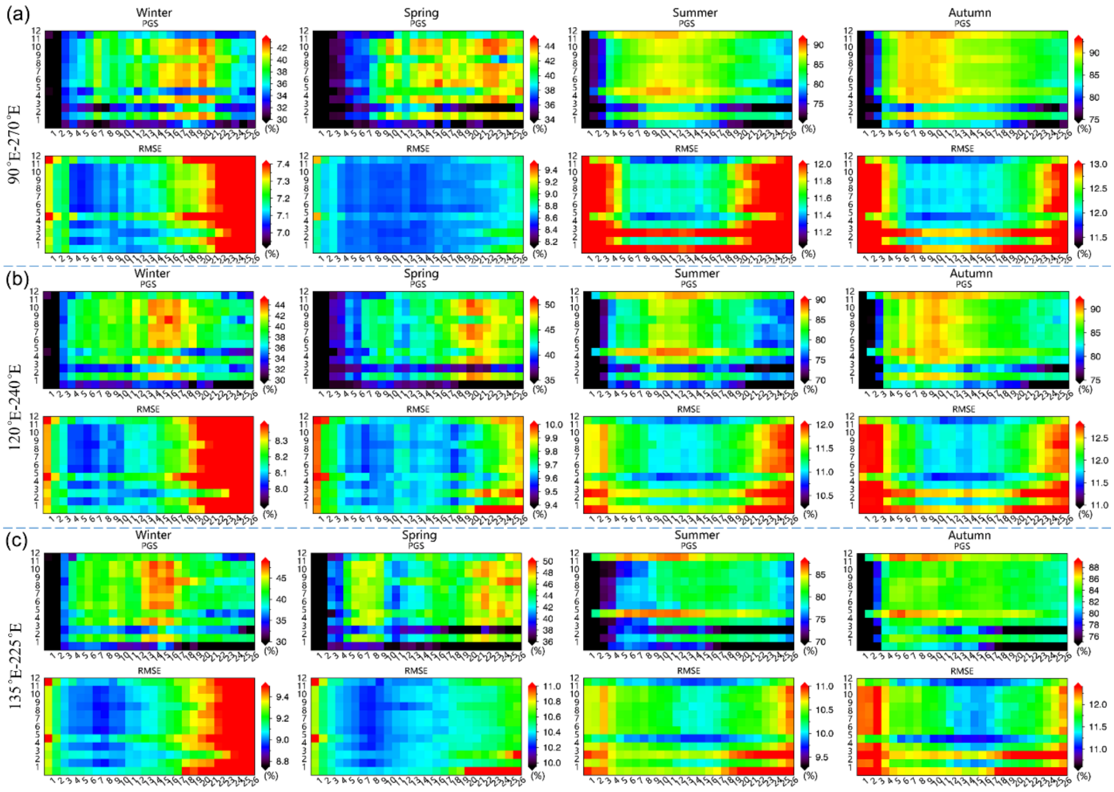

Figure 4. Same as Figure 1 but for three study areas defined by 90°E to 270°E, 120°E to 240°E and 135°E to 225°E respectively. The predictive skills corresponding to these three study areas are shown in panels (a), (b), and (c) respectively.

L148-149: Similarly, can the authors perform the same analysis on sea ice concentration from 0 to 100% instead of 15% to 95%? It is unclear why the authors chose this limit. I can understand the 15% threshold (eliminating area and extent), but why 95%? It would be nice to see the analysis performed without these cutoffs and if they differ, an explanation as to why.

We are sorry for the unclear content. We did perform the analysis on sea ice concentration from 0 to 100%. These cutoffs of 15% to 95% are only used to limit the study area for sea ice cover. Because there has no ice-variability in the open water area and the central Arctic Basin. The area has no ice-variability and therefore no predictability.

In addition, to show the methodology more clearly, we will change the cutoff from SIC (15%-95%) to SIC (15%-100%) in our revision.

L159-161: I can understand why the authors chose this combination of atmospheric and oceanic variables. But, it appears one key variable is missing: sea ice thickness. Why have the authors omitted this variable? Over the past few years, numerous studies have shown that sea ice thickness is a key source of predictability of Arctic sea ice, particularly for the summer. This, to me, is my biggest concern with this manuscript. I'd like the authors to include sea ice thickness (SIT; from PIOMAS most likely) in their analyses, as I think the results will be different. Perhaps this model may even be more skillful.

Thanks for the valuable suggestions. Following the suggestion, we have added sea ice thickness (SIT; from PIOMAS) in the model and recombined variables in the model experiments. The new variable-combinations was shown in Table 1. The updated predictive skill measured by PGS and mean RMSE for each lead time in each season are calculated and shown in Figure 1. We find that SIT contributes substantially to predictability. Based on the PGS and RMSE, we primarily chose three superior model configurations marked by black boxes in Figure 1. we spatially average the SIC prediction skill from these superior models with 1- to 12-month leads (Figures 2 and 3). Based on the construction principle same to the original manuscript, we finally chose V9M16, V11M20, V5M10, and V5M7 in winter, spring, summer, and autumn respectively. The updated model shows more skill than the model developed in the original manuscript. In addition, based on the updated model, we have modified all relevant contents throughout the manuscript.

This also pertains to the ocean domain. What about including sub-surface ocean heat content (OHC)? This has also been shown to be an important source of predictability for Arctic sea ice, particularly on the Pacific side in the wintertime. The authors can include this variability using Ocean Reanalysis System 5 (ORAS5). I think including this variable will improve the weaknesses of the model (as stated in Lines 590-594).

Thanks for the valuable suggestions. Following the suggestion, we have added sub-surface ocean heat content (OHC) using Ocean Reanalysis System 5 (ORAS5) in the model and recombined variables in the model experiments. The new variable-combinations was shown in Table 1. The updated predictive skill measured by PGS and mean RMSE for each lead time in each season are calculated and shown in Figure 1. We find that OHC contributes substantially to predictability. Based on the PGS and RMSE, we primarily chose three superior model configurations marked by black boxes in Figure 1. we spatially average the SIC prediction skill from these superior models with 1- to 12-month leads (Figures 2 and 3). Based on the construction principle same to the original manuscript, we finally chose V9M16, V11M20, V5M10, and V5M7 in winter, spring, summer, and autumn respectively.

The OHC indeed provides more memory for winter predictions in the Bering Sea and the Sea of Okhotsk compared with SST and improves the weaknesses of the model stated in Lines 590-594 in the original manuscript. We have updated all relevant contents throughout the manuscript.

Finally, it is shown that SIC contributes to the trends and gives prediction skill. But, why even include this at all? It would be more interesting if the authors could develop this regional Markov model without SIC so that it is predicting SIC/SIA. Perhaps I am missing the motivation to include this. If that is the case, please add a justification in this section.

Thanks, as the trends are parts of the total variability, we decide to retain the SIC trends in anomalies while building the model. It's worth mentioning that the model still retains skill for detrended sea ice extent predictions up to 6 month lead times.

The success of the Markov model is attributed to its ability to capture the covariability in the coupled air-sea-ice system. Thus, the Markov model can't capture the covariability well when coupled climate system without sea ice and can't play an advantage in sea ice prediction, which is different from the regression model.

L166-186: The introduction of the Markov model could be slightly more clear. In particular, the bolded variables are not present in Eqs. (2)-(4). Does that make them not matrices? As it stands, I think they should be matrices.

Yes, they are matrices, we will change it, thank you so much. We will also add more explanation on the Markov model and make it more clear.

Model construction and assessments:

Construct an optimal model for each season:

L280-283: I think this cross-validation experiment will be greatly impacted by the addition of SIT and OHC (and/or removal of SIC). This section may need to be reworked with these variables included.

Thanks for the valuable suggestions. Following the suggestion, we have added SIT and OHC in the model and recombined variables in the model experiments. The new variable-combinations was shown in Table 1. The updated predictive skill measured by PGS and mean RMSE for each lead time in each season are calculated and shown in Figure 1. We find that SIT contributes substantially to predictability. Based on the PGS and RMSE, we primarily chose three superior model configurations marked by black boxes in Figure 1. we spatially average the SIC prediction skill from these superior models with 1- to 12-

month leads (Figures 2 and 3). Based on the construction principle same to the original manuscript, we finally chose V9M16, V11M20, V5M10, and V5M7 in winter, spring, summer, and autumn respectively. The updated model shows more skill than the model developed in the original manuscript. In addition, based on the updated model, we have modified all relevant contents throughout the manuscript.

Conclusions:

L521: I think this paper would benefit from a clear "Discussion" section and then the "Conclusion" section can be streamlined and the results would be clearer.

According to your suggestion, we will improve the structure of the manuscript by dividing section 3 Model construction and assessments into two parts: 3 Model construction and 4 Discussion.

Technical Comments:

Introduction:

L17: Add hyphen to Pacfic-Arctic? Also, consider keeping it uniform across the paper: Pacific-Arctic instead of switching to Arctic-Pacific

We have changed it.

L41: Consider changing "shrinking" to "decreasing" and adding extent, so that it states "The decreasing Arctic sea ice extent contributes…"

We have changed it.

L48: Consider changing to "The rapid retreat of summer Arctic sea ice extent has also created…"

We have changed it.

L60: Change "which" to "and".

We have changed it.

L88: This sentence does not make sense. Can the authors reframe this? I am not sure what "is initialized in the spring". Is this in reference to the spring predictability barrier?

We are sorry for the unclear content. We have reframed this sentence to 'Many works have shown evidence for an Arctic sea ice spring predictability barrier.'

L522: Add hyphen (check hyphens throughout the manuscript)

We have changed it.