

Interactive comment on “Different responses of CO₂, CH₄, and N₂O fluxes to seasonally asymmetric warming in an alpine grassland of Tianshan Mountains” by Yanming Gong et al.

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Anonymous Referee #2 General comments The manuscript “Different responses of CO₂, CH₄, and N₂O fluxes to seasonally asymmetric warming in an alpine grassland of Tianshan Mountains” by Gong et al. describes the effects of seasonal warming (growing season warming, non-growing season warming, annual warming) on CO₂, CH₄, and N₂O fluxes during 3 years at an alpine grassland site in the southern Tianshan mountains, China. I value the authors efforts to collect multi-year, and year-round data with manual chamber measurements. While I find evaluating the response of GHG fluxes to changes in temperature during different seasons highly important (es-

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pecially the non-growing season), the manuscript in its current state has several shortcomings, which I have outlined in my specific comments and line edits below. Specific comments 1) The authors discuss CO₂ fluxes, however, it is unclear which component of the CO₂ flux has been measured. It would seem that ecosystem respiration was measured, which should be stated clearly throughout the manuscript. Temperature is a well known control on respiration, but based on this study the authors can not draw conclusions on the effect of temperature on net CO₂ exchange without accounting for photosynthesis. I suggest revising the manuscript text accordingly. Response: As the anonymous referee' comment, we're measuring ecosystem respiration. We revised the manuscript text accordingly. See the revised manuscript.

2) To understand the observed interannual variations in GHG exchange in response to temperature it would be important to include information on other climate parameters as well, especially interannual variations in precipitation, soil moisture and or water table. If this data is available, I highly recommend including it and to add discussion on this topic. Response: Thank you for your precise comment. We plot the changes of precipitation, air temperature and soil moisture, and analyze the influence of soil temperature and moisture on greenhouse gas fluxes and their association effect through variance decomposition. we do not have the monitoring data of the groundwater level in Bayanbulak Grassland. We will carry out the work in the future. It was discussed and analyzed in the revised manuscript. As shown in the figure below:

Figure S2 Variation in soil water content (at 10-cm depth) under four treatments in alpine grassland from June 2017 to September 2019. GS, growing season; NGS, non-growing season; AW, warming throughout the year; NGW, warming in nongrowing season only; GW, warming in growing season only; NW, non-warming. Significant differences among AW, NGW, GW and NW from analysis of variance (ANOVA) are denoted as bars within the same season with different lowercase letters, $P < 0.05$; data points are the mean \pm standard error.

Figure S3 Variation in air temperature (inside the OTC, 50cm above the ground) un-

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der four treatments in alpine grassland from October 2016 to September 2019. GS, growing season; NGS, non-growing season; AW, warming throughout the year; NGW, warming in nongrowing season only; GW, warming in growing season only; NW, non-warming. Significant differences among AW, NGW, GW and NW from analysis of variance (ANOVA) are denoted as bars within the same season with different lowercase letters, $P < 0.05$; data points are the mean \pm standard error.

Figure S4 Variation in precipitation in the alpine grassland from October 2016 to September 2019. GS, growing season; NGS, non-growing season.

Figure S6 Influence of soil temperature and soil moisture on ecosystem respiration (Re), CH₄ uptake, and N₂O emission by variation-partitioning analysis under four treatments in the growing season and nongrowing season. a, single effect of soil temperature (%); b, single effect of soil moisture (%); c, joint effects of soil temperature and moisture (%); NGW-NGS, greenhouse gas fluxes in non-growing season under non-growing season warming treatment; NGW-GS, greenhouse gas fluxes in growing season under non-growing season warming treatment; GW-NGS, greenhouse gas fluxes in non-growing season under growing season warming treatment; GW-GS, greenhouse gas fluxes in growing season under growing season warming treatment; AW-AY, annual greenhouse gas fluxes under annual warming treatment; NW-AY, annual greenhouse gas fluxes without warming.

3) Adding discussion on whether the warming treatment with OTCs impacted other environmental variables (such as soil moisture, snow depth) would be needed in order to assess the effectiveness of the warming treatment and validity of results. Shortly reporting results on the achieved temperature increase in the warmed plots compared to control treatments in the results section would be helpful as well (this is only shown in the supplementary material Fig S1). Response: Thank you for your precise comment. Yes, warming treatment with OTCs impacted soil moisture and snow depth. The change of snow depth mainly affects the soil moisture, therefore, we focused on the analysis of how warming affects the greenhouse gas flux by affecting soil moisture

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(Figure S6). We added the information in the revised manuscript.

4) Introduction as well as discussion and conclusion remain rather superficial. This manuscript would greatly benefit from some streamlining, clearly stating the objectives and relevance of this study, and a more thorough literature review and comparison to other studies. For example, this study reports rather large CH₄ uptake rates. How do these rates compare to what is observed in other studies from similar ecosystems? Based on the findings of this study, can larger-scale conclusions be drawn on what impact warming will have on CH₄ uptake in these ecosystems? The study also reports all three GHGs, which is a strength of this study, as measurements of N₂O fluxes in particular are rare in colder climates. The authors could highlight this in their study, and provide some comparison to other studies. And while investigating the effect of temperature on fluxes was clearly the aim of this study, some acknowledgement of drivers of GHG fluxes other than temperature would be useful to include. Response: Thank you for your precise comment. We revised the manuscript and added the information of your comments. For example, L86-112, "The 3rd and 4rd assessment report of the Inter-Governmental Panel on Climate Change (IPCC) proposed that, against the backdrop of global warming, the temperature change will show that the warming amplitude in winter is greater than that in summer, and the warming amplitude at high latitude is greater than that at low latitude, and confirmed that the warming shows asymmetric trends on a seasonal scale (Easterling et al., 1997; IPCC, 2001; IPCC, 2007)." L116-121, "Experimental warming is known to influence the Re, CH₄ uptake and N₂O emission (Parn et al., 2018; Treat et al., 2018; Wang et al., 2019). Information on Re, CH₄ uptake and N₂O emission and their sensitivity to warming, will enhance our understanding of ecosystem C and N cycling processes and improve our predictions of the response of ecosystems to global climate change (Li et al., 2020; Wang et al., 2019)." L124-129, "A study of the Alaskan tundra found that summer warming (open-top chambers to increase growing season air temperatures) significantly increased the growing season ecosystem respiration by about 20 % (Natali et al., 2011). Compared with the slight effect of winter warming on the CO₂ fluxes in the growing season, warm-

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ing increased CO₂ fluxes during the snow-covered period by more than 50% (Natali et al., 2011).” L175-187, “A recent study showed that seasonal variations in carbon flux were more related to air temperature in the meadow steppe (Zhao et al., 2019). Another study found that experimental warming enhanced CH₄ uptake in the relatively arid alpine steppe, but had no significant effects on CH₄ emission in the moist swamp meadow (Li et al., 2020). Wu et al. (2020) also showed that the warming did not significantly affect soil CH₄ uptake fluxes in the alpine meadow of the Tibetan Plateau. Furthermore, a global meta-analysis (Wang et al., 2019) showed that experimental warming stimulates C fluxes in grassland ecosystems, and the response of C fluxes to warming strongly varies across the different grassland types, with higher warming responses in cold than in temperate and semi-arid grasslands. Across the data set, Li et al. (2019) demonstrated that whole day or whole year warming treatment significantly enhanced N₂O emissions, but daytime, nighttime or short season warming did not have significant effects.” L192-203, “For example, over longer time periods of warming, accelerated decomposition and increased plant N uptake may decrease soil organic C and N pools (Wu et al., 2012), and the microbial community with variable C use efficiency may reduce the temperature sensitivity of heterotrophic respiration (Zhou et al., 2011).” L207-210, “Therefore, we hypothesize that warming in non-growing season will stimulate greenhouse, e gas flux (especially during non-growing season) in alpine steppe. However, continuous warming throughout the year and during the growing season will weaken the sensitivity of greenhouse gas flux to warming.” L421-438, “Ecosystem CH₄ flux is the net result of CH₄ production and consumption occur simultaneously under the action of methanogenic archaea and methane-oxidizing bacteria (e.g., Mer and Roger, 2001; Blodau, 2002; Galbally et al., 2008). CH₄ fluxes are dependent on temperature, pH, and the availability of substrate (e.g., Moore & Dalva, 1997; Treat et al., 2015). For example, lower levels of soil moisture would decrease C release, indicating that drier soils are the major CH₄ sink (Denman et al., 2007). The CH₄ uptake observed during the three growing and non-growing seasons implied that the alpine grassland soil could act as an atmospheric CH₄ sink, which agrees

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with the findings of many previous studies in similar region (Li et al., 2015; Wei et al., 2015; Zhao et al., 2017; Wu et al., 2020). As well as, our results demonstrated that warming increased CH₄ uptake in the growing season, but decreased CH₄ uptake in the non-growing season in the alpine grassland, similar to the results from other grassland ecosystems (Lin et al., 2015; Zhu et al., 2015; Wu et al., 2020). Moreover, a warming-induced soil moisture decrease may be a potential mechanism for the positive influence of warming on soil CH₄ uptake in the alpine grassland (Lin et al., 2015). Our results also demonstrated that seasonally asymmetric warming did not significantly affect the response rate of CH₄ uptake to temperature increase (Figure 2 d-f, $P > 0.05$).” L441-502, “Unlike CH₄ fluxes in alpine grasslands, Treat et al. (2018) confirmed that nongrowing season wetland were small CH₄ sources, and uplands varied from CH₄ sinks to CH₄ sources.” L515-518, “As well as N₂O emissions was positively related to soil temperature, Pärn et al. (2018) found that N₂O emission from organic soils increases with rising soil NO₃⁻, follows a bell-shaped distribution with soil moisture.”

5) The discussion is rather short and exclusively focuses on the response rate of the three gases to temperature, while some of the rather interesting key findings of this study are not addressed (such as for example increasing annual CH₄ uptake with warming, or increasing N₂O emissions with warming during the non-growing season). It also looks like the site displayed emission peaks of N₂O during the shoulder periods, especially spring, which might be an important point to mention in the discussion (see for example: Wagner-Riddle et al. (2017). Globally important nitrous oxide emissions from croplands induced by freeze–thaw cycles. *Nature Geoscience* 10(4):279-83). Response: Thank you for your precise comment. We revise the sections according to your comments. See the revised manuscript, L421-438, “Ecosystem CH₄ flux is the net result of CH₄ production and consumption occur simultaneously under the action of methanogenic archaea and methane-oxidizing bacteria (e.g., Mer and Roger, 2001; Blodau, 2002; Galbally et al., 2008). CH₄ fluxes are dependent on temperature, pH, and the availability of substrate (e.g., Moore & Dalva, 1997; Treat et al., 2015). For example, lower levels of soil moisture would decrease C release, indicating that drier soils

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are the major CH₄ sink (Denman et al., 2007). The CH₄ uptake observed during the three growing and non-growing seasons implied that the alpine grassland soil could act as an atmospheric CH₄ sink, which agrees with the findings of many previous studies in similar region (Li et al., 2015; Wei et al., 2015; Zhao et al., 2017; Wu et al., 2020). As well as, our results demonstrated that warming increased CH₄ uptake in the growing season, but decreased CH₄ uptake in the non-growing season in the alpine grassland, similar to the results from other grassland ecosystems (Lin et al., 2015; Zhu et al., 2015; Wu et al., 2020). Moreover, a warming-induced soil moisture decrease may be a potential mechanism for the positive influence of warming on soil CH₄ uptake in the alpine grassland (Lin et al., 2015). Our results also demonstrated that seasonally asymmetric warming did not significantly affect the response rate of CH₄ uptake to temperature increase (Figure 2 d-f, $P > 0.05$). L441-502, “Unlike CH₄ fluxes in alpine grasslands, Treat et al. (2018) confirmed that nongrowing season wetland were small CH₄ sources, and uplands varied from CH₄ sinks to CH₄ sources.” We also revised the sections about “increasing N₂O emissions with warming during the non-growing season”, and refer to the references you provided. L512-518, “However, our results displayed emissions peaks of N₂O during the freeze–thaw periods (e.g., May 2017, June 2018 and April 2019). Warming increased N₂O emissions in the thawing period owing to disrupt the gas diffusion barrier and greater C and N availability for microbial activity (Nyborg et al., 1997). Wagner-Riddle et al. (2017) also confirmed that the magnitude of freeze–thaw-induced N₂O emissions was related to the number of days with soil temperatures below 0 °C”

Line edits Abstract: L13-14: specify whether CO₂ fluxes are ecosystem respiration or net ecosystem exchange, not clear if the reported numbers are net CO₂ losses to the atmosphere. Also, do these numbers represent the total range of fluxes between 2016 and 2019? It might be more meaningful to present growing season as well as annual mean or median fluxes in the abstract, as fluxes, especially for CH₄ and N₂O, are highly variable. Response: Thank you for your precise comment. CO₂ fluxes are ecosystem respiration, we defined it exactly in the revised manuscript. See L122 “Ecosystem

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respiration (expressed by CO₂ flux), N₂O, and CH₄ fluxes were measured using static chambers. . .” We agree with this comment, and we revised as “annual mean of CO₂, CH₄ and N₂O fluxes in growing season were 42.83 mg C m⁻² h⁻¹, -41.57 μg C m⁻² h⁻¹, and 4.98 μg N m⁻² h⁻¹, respectively.” See L13-14.

L14-15: this is counter intuitive and does not match with what is shown in supplementary figure S3 (where CO₂ and N₂O fluxes show a clear positive correlation with soil temperature, and CH₄ uptake increases with increases temperature). Please rephrase. Response: Thank you for your precise comment. We have revised this section as “The CO₂ and N₂O fluxes were positively correlated with soil temperature, and the CH₄ uptake increased with the increase in temperature.”

L16-18: “the variation in GHG flux under seasonally asymmetric warming was different between the growing season and the non-growing season”: this statement is vague, please be more specific and state clearly what was observed. Response: Thank you for your precise comment. We revised this sentence as “Furthermore, warming in non-growing season increased CO₂ and CH₄ fluxes in both growing season and non-growing season. However, the increase of N₂O flux was mainly caused by the warming of the growing season.” See L16-18 of the revised manuscript.

L18-24: a short explanation of the term “response rate” might be needed in this context. Response: We added a sentence to illustrate the term “response rate”, the sentence is “the response rate was defined as the change of GHG flux caused by the increase of soil temperature under warming treatment,” See L19-20 of the revised manuscript.

L24-27: A clear summary statement with the specific implications of this study would be needed here. Response: we revised the sentence as “We have confirmed the stimulating effect of warming in non-growing season on CO₂ and CH₄ fluxes, that long-term annual warming weakened the sensitivity of CO₂ and N₂O fluxes to temperature increase, and that warming in growing season reduced the sensitivity of CO₂ fluxes to temperature increase.” See L37-41 of the revised manuscript.

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Introduction: L38: daytime/nighttime differences are not addressed in this study. Consider removing from the introduction or add results and discussion to address this issue. Response: we removed “and between daytime and nighttime” from the introduction. Relevant references were also deleted. See L52 of the revised manuscript.

L34-36: Yes, but I would advise caution with this statement (considering the larger than average warming in higher latitudes and Arctic amplification). Response: We accepted the comment and removed the sentence. Relevant references were also deleted. See L48 of the revised manuscript.

L39: 3rd assessment report. Response: we revised the term as “3rd”. See L50 of the revised manuscript.

L48: delete “in the atmosphere” Response: we deleted “in the atmosphere”. See L68 of the revised manuscript.

L47-49: some rephrasing might be needed (considering that water vapour is a major GHG present in Earth’s atmosphere as well). Response: we revised the sentence as “Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) are the three of the major greenhouse gases (GHGs) in the atmosphere”. See L68-69 of the revised manuscript.

L47-50: a general statement with some background information on the influence of temperature on GHG production and emissions would be useful for the reader in this context. Response: we added the statement as “Experimental warming is known to influence the ecosystem respiration, CH₄ uptake and N₂O emission (Parn et al., 2018; Treat et al., 2018; Wang et al., 2019). Information on ecosystem respiration, CH₄ uptake and N₂O emission and their sensitivity to warming, will enhance our understanding of ecosystem C and N cycling processes and improve our predictions of the response of ecosystems to global climate change (Li et al., 2020; Wang et al., 2019).” See L71-76 of the revised manuscript.

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L50: Please check those % numbers (radiative forcing of CO₂ is larger than that of CH₄). Response: we checked those % numbers, and revised as “. . .and their contributions to global warming are 60 %, 20 %, and 6 %”. See L70 of the revised manuscript.

L50-52: Not sure whether this statement is correct. At least in northern or high-elevation regions with less accessible sites, warming treatments are often conducted during the summer months. Some rephrasing might be needed. Response: we revised this statement as “most studies focus on the influence of warming during the summer months on GHG flux in terrestrial ecosystems”. See L77-78 of the revised manuscript.

L55: please specify whether “CO₂ flux” in this context refers to increased CO₂ emissions or increased net uptake, and under what conditions this increase occurred (warming treatment or naturally warmer summer?). Response: In light of this comment, we have revised this sentence as “A study of the Alaskan tundra found that summer warming (open-top chambers to increase growing season air temperatures) significantly increased the growing season ecosystem respiration by about 20 % (Natali et al., 2011).” See L80-83 of the revised manuscript.

L56-57: for simplicity, replace “the effect of increased temperature in winter” with “the effect of winter warming”. Response: we replaced “the effect of increased temperature in winter” with “the slight effect of winter warming”. See L83 of the revised manuscript.

L56-58: This sentence is not quite clear. Does this mean winter warming did not affect growing season CO₂ fluxes, but winter warming did increase CO₂ fluxes during the nongrowing season? Consider rephrasing. Response: we revised the sentence as “Compared with the slight effect of winter warming on the CO₂ fluxes in the growing season, warming increased CO₂ fluxes during the snow-covered period by more than 50% (Natali et al., 2011)”. See L83-85 of the revised manuscript.

L58-60: replace “absorption” with “uptake. Response: we replaced “absorption” with “uptake”. See L86 of the revised manuscript.

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L62: start sentence with “A study by xx (2012) in an alpine grassland ecosystem showed: : :” Response: Thank you for your accurate comments. We have revised them. See L118-119 of the revised manuscript.

L69: consider added examples for biotic and abiotic factors here. Response: Thank you for your accurate comments. We added the sentence as “For example, over longer time periods of warming, accelerated decomposition and increased plant N uptake may decrease soil organic C and N pools (Wu et al., 2012), and the microbial community with variable C use efficiency may reduce the temperature sensitivity of heterotrophic respiration (Zhou et al., 2011).” See 139-148 of the revised manuscript. Wu, Z., Dijkstra, P., Koch, G. W., & Hungate, B. A. (2012). Biogeochemical and ecological feedbacks in grassland responses to warming. *Nature Climate Change*, 2, 458–461. <https://doi.org/10.1038/nclimate1486> Zhou, J., Xue, K., Xie, J., Deng, Y. e., Wu, L., Cheng, X., . . . Luo, Y. (2011). Microbial mediation of carbon cycle feedbacks to climate warming. *Nature Climate Change*, 2, 106–110. <https://doi.org/10.1038/nclimate1331>

L75-81: This is rather vague and I suggest to be more specific and clearly state the overall aim of this study. Response: we revised as “Therefore, we hypothesize that warming in non-growing season will stimulate greenhouse gas flux (especially during non-growing season) in alpine steppe. However, continuous warming throughout the year and during the growing season will weaken the sensitivity of greenhouse gas flux to warming. The current short communication will help to evaluate the uncertainty with respect to GHG flux in response to increasing temperatures against the backdrop of global climate change, by carrying out seasonally asymmetrical warming studies in alpine grasslands.” See 152-158 of the revised manuscript.

Methods: L87: Is permafrost present at the site? If yes, it would be useful to add this information. Response: Yes, permafrost is present at the site. We added the information as “There was permafrost present at Bayanbulak alpine grassland, and the average maximum frozen depth was more than 250 cm (from 2000 to 2011, Zhang et

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al., 2018).” See L164-166 of the revised manuscript.

L93: in addition to soil, vegetation and temperature it would be useful to add some information related to typical soil moisture/water table levels at the site, since that is important for discussing GHG exchange and observed interannual differences. Response: Thank you for your comments, we added the sentence as “and the average annual soil moisture was 5.9 % (2017-2019)”. See L182 of the revised manuscript.

L95: please provide description and dimensions of open-top chambers. Response: we added the description and dimensions of open-top chambers as “The open-top chambers (OTCs) were made of 5 mm thick tempered glass. To reduce the impact of precipitation and snow, the OTC with a hexagonal round table which was 100cm high, and the diameters of the bottom and top were 100 cm and 60 cm, respectively.” See L183-186 of the revised manuscript.

L101-108: please provide some more details regarding flux measurement and analysis. E.g., were pre-installed collars used for the flux measurement? Were the chambers equipped with a fan and pressure equilibration tube? Were chambers transparent or opaque? Please also mention the sign convention in this context (i.e. positive fluxes = emissions?). Response: we revised these sentences as “Gas samples were taken 0, 10, 20 and 30 minutes after the lid of the static chamber was sealed in between 12:00 and 14:00 (GMT + 8) every day. The rate of ecosystem respiration, CH₄ and N₂O fluxes were calculated based on the change in concentration of CO₂, N₂O and CH₄ in each chamber over time by a linear or non-linear equation ($P < 0.05$, $r^2 > 0.95$) (the positive flux value was emission, and the negative flux value was uptake; Liu et al. 2012; Wang et al. 2013).” See L194-202 of the revised manuscript. Wang K, Zheng X, Pihlatie M, Vesala T, Liu C, Haapanala S, Liu H (2013) Comparison between static chamber and tunable diode laser-based eddy covariance techniques for measuring nitrous oxide fluxes from a cotton field. *Agric For Meteorol* 171:9–19. Liu C, Wang K, Zheng X (2012) Responses of N₂O and CH₄ fluxes to fertilizer nitrogen addition rates in an irrigated wheat-maize cropping system in northern China. *Biogeosciences*

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L105: please add the total number of sampling times. L105-108: What quality criteria were used to accept or reject fluxes? E.g. r^2 , RMSE, minimum number of sampling points during one flux measurements? This information is not provided in the cited reference (Chen et al 2013). Response: we added the total number of sampling times as “Gas samples were 232, collecting once or twice a week”. And revised L105-108 as “Gas samples were taken 0, 10, 20 and 30 minutes after the lid of the static chamber was sealed in between 12:00 and 14:00 (GMT + 8) every day. The rate of ecosystem respiration, CH₄ and N₂O fluxes were calculated based on the change in concentration of CO₂, N₂O and CH₄ in each chamber over time by a linear or non-linear equation ($P < 0.05$, $R^2 > 0.95$) (the positive flux value was emission, and the negative flux value was uptake; Liu et al. 2012; Wang et al. 2013).” We deleted the cited reference (Chen et al 2013) and added the cited references (Liu et al. 2012; Wang et al. 2013). See L192-204 of the revised manuscript.

Results: L124-125: In addition to the range, it would be useful to provide mean/median values here. I also suggest to add a few sentences describing the general pattern of fluxes as this site, before presenting the treatment results, to provide the reader with a general overview (for example stating that the site acted as a net CH₄ sink, with negligible CH₄ emissions, and small N₂O source). Response: Thank you for your precise comment. We revised the sentences as “Our study showed that the Bayanbulak alpine grassland was a small ecosystem respiration (CO₂ flux), a net CH₄ sink, and a negligible N₂O source. The annual mean of CO₂, CH₄ and N₂O fluxes in growing season were 42.83 mg C m⁻² h⁻¹, -41.57 μg C m⁻² h⁻¹, and 4.98 μg N m⁻² h⁻¹ from October 2016 to September 2019, respectively (Fig. 1).” See L219-233 the revised manuscript.

L131-136: talking about an increase and decrease in CH₄ flux is slightly confusing in this context, as the authors mainly observed CH₄ uptake. The 6.4% increase in CH₄ flux in the AW treatment that the authors report here is in fact an increase in CH₄ uptake, according to Fig. S2. This would mean a decrease in CH₄ from an

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atmospheric point of view, and I suggest to rephrase this whole section accordingly. To avoid confusion, it might be useful to refer to uptake and emissions, rather than fluxes, throughout the manuscript. Response: Thank you for your precise comment. we rephrased this whole section accordingly. “The AW temperature change induced a 6.4% increase in CH₄ uptake in the growing season and a 3.8% decrease in the nongrowing season. The GW treatment resulted in 7.1% and 10.2% increases in CH₄ uptake in the growing and nongrowing seasons, respectively. On the contrary, the NGW generated a 10.6% and 9.2 % decrease in CH₄ uptake in the growing and nongrowing seasons, respectively (Figure S3 b).” See L240-245 the revised manuscript.

L126-140: are all these reported %changes significant (standard errors seem rather large)? It would be useful to add information regarding statistical significance in Fig S2 and manuscript text. Response: Thank you for your precise comment. One-way ANOVA results of Re, CH₄ uptake and N₂O emissions among the four warming treatments were not significant ($P > 0.05$). We added this information in the revised manuscript. See L250-251 of the revised manuscript.

L126 and throughout: please specify which CO₂ flux component is discussed (see specific comments above). Response: Thank you for your precise comment. We revised “CO₂ flux” as “ecosystem respiration” and abbreviation for Re in the whole manuscript.

L143: delete “extremely”. Response: Thank you for your precise comment. We deleted “extremely”. See L334 of the revised manuscript.

L141-144: Do the authors mean interannual differences between growing seasons? Response: Yes, Ecosystem respiration (Re), CH₄ uptake, and N₂O emissions were distinguished between growing seasons and non-growing seasons in interannual and intertreatment two-way repeated-measure ANOVA. The interannual differences in Re, CH₄ uptake, and N₂O emissions were all due to the growing season, except for significant differences in N₂O emissions during the non-growing season. (Figure 1)

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L141-145: Generally, this section is not very clear and would benefit from some rephrasing. It would be important to state that interannual differences were larger than impact of warming treatment (for CO₂ and N₂O) according to Fig. 1, whereas warming treatment had a significant impact on CH₄ fluxes. Response: Thank you for your precise comment. We have added the sentences as “Therefore, interannual differences were larger than impact of warming treatment (for Re and N₂O emissions) according to Fig. 1, whereas warming treatment had a significant impact on CH₄ uptake.” in order to better express the meaning of this section. See L381-383 of the revised manuscript.

L147-148: I suggest simplifying “CH₄ flux showed significantly decreasing trends with increasing soil temperature” to something like “we observed increasing CH₄ uptake with increasing soil temperature”. Response: Thank you for your precise comment. We revised as “we observed increasing CH₄ uptake with increasing soil temperature”, See L385-386 of the revised manuscript.

Discussion and conclusion: Please see my specific comments above regarding the discussion section, as well as: L166-171: It would be useful to include some background information on mechanisms behind CH₄ fluxes for the reader, i.e. when do emissions occur, what conditions promote CH₄ uptake, why would temperature increase CH₄ uptake, etc. Response: Thank you for your precise comment. We revised this section as “Ecosystem CH₄ flux is the net result of CH₄ production and consumption occur simultaneously under the action of methanogenic archaea and methane-oxidizing bacteria (e.g., Mer and Roger, 2001; Blodau, 2002; Galbally et al., 2008). CH₄ fluxes are dependent on temperature, pH, and the availability of substrate (e.g., Moore & Dalva, 1997; Treat et al., 2015). For example, lower levels of soil moisture would decrease C release, indicating that drier soils are the major CH₄ sink (Denman et al., 2007). The CH₄ uptake observed during the three growing and non-growing seasons implied that the alpine grassland soil could act as an atmospheric CH₄ sink, which agrees with the findings of many previous studies in similar region (Li et al., 2015; Wei et al., 2015; Zhao et al., 2017; Wu et al., 2020). As well as, our results demonstrated that warm-

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ing increased CH₄ uptake in the growing season, but decreased CH₄ uptake in the non-growing season in the alpine grassland, similar to the results from other grassland ecosystems (Lin et al., 2015; Zhu et al., 2015; Wu et al., 2020). Moreover, a warming-induced soil moisture decrease may be a potential mechanism for the positive influence of warming on soil CH₄ uptake in the alpine grassland (Lin et al., 2015). Our results also demonstrated that seasonally asymmetric warming did not significantly affect the response rate of CH₄ uptake to temperature increase (Figure 2 d-f, $P > 0.05$). Hu et al. (2016) suggested that asymmetrical responses of CH₄ fluxes to warming and cooling should be taken into account when evaluating the effects of climate change on CH₄ uptake in the alpine meadow on the Tibetan plateau. The latest research confirmed that warming in the Arctic had been more apparent in the non-growing season than in the typical growing season (Bao et al., 2020). Hereby, Bao et al. (2020) found that the CH₄ emissions during spring thaw and autumn freeze contribute to about a quarter of annual total CH₄ emissions. That experimental warming is stimulating soil CH₄ uptake in the growing season implies that the grasslands of the Bayanbulak may have potential to remove more CH₄ from the atmosphere under future global warming conditions.” See L421-508 of the revised manuscript.

L176-177: for the nongrowing season contribution of CH₄ fluxes a comparison to other ecosystems would be useful; see for example Treat, C.C., Bloom, A.A. and Marushchak, M.E., 2018. Nongrowing season methane emissions—a significant component of annual emissions across northern ecosystems. *Global change biology*, 24(8), pp.3331-3343. Response: Thank you for your precise comment. We added the sentences as “Unlike CH₄ fluxes in alpine grasslands, Treat et al. (2018) confirmed that nongrowing season wetland were small CH₄ sources, and uplands varied from CH₄ sinks to CH₄ sources.” See L441-502 of the revised manuscript.

L178-186: please see my specific comment regarding discussion of other environmental variables besides temperature. N₂O in particular is rarely depend on just on variable, and the effect of temperature may often be masked by other variables such as

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water table, and mineral nitrogen availability. This may require at least short mention in the discussion section. See for example Pärn, J. et al. 2018. Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots. Nature communications, 9(1), pp.1-8. Response: Thank you for your precise comment. We added the sentences as “As well as N2O emissions was positively related to soil temperature, Pärn et al. (2018) found that N2O emission from organic soils increases with rising soil NO₃⁻, follows a bell-shaped distribution with soil moisture.” See L515-518 of the revised manuscript.

Figures: Fig. 2: please add r² and P-values for all figure panels (even for nonsignificant relationships). Fig S2: please add number of measurement times for growing season / non-growing season mean. Also, please specify in y-axis or figure caption which component of the CO₂ flux is shown (ER?). As panel b shows CH₄ uptake, I suggest to flip the y-axis, showing zero on top and negative values at the bottom. Overall, I would suggest to use boxplots (including quartile ranges and outliers) rather than barplots in this figure, to capture the full range of fluxes, as it would be important to show e.g. also the occurrence of emissions (for CH₄) or uptake (for N₂O). The authors may also consider moving this figure into the main text. Response: Thank you for your precise comment. We added r² and P-values for all figure panels of the Fig. 2. Based on these comments, we redrew Fig. S2 using boxplots, added number of measurement times for growing season / non-growing season mean. We also moved this figure into the main text.

Interactive comment on Biogeosciences Discuss., <https://doi.org/10.5194/bg-2020-396>, 2020.

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Different responses of ecosystem respiration, CH₄ uptake, and N₂O emissions to seasonally asymmetric warming in an alpine grassland of Tianshan Mountains

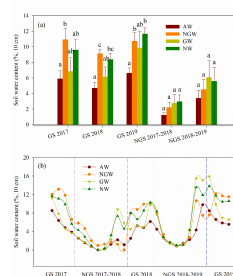


Figure S2 Variation in soil water content (at 10-cm depth) under four treatments in alpine grassland from June 2017 to September 2019. GS, growing season; NGS, non-growing season; AW, warming throughout the year; NGW, warming in nongrowing season only; GW, warming in growing season only; NW, non-warming. Significant differences among AW, NGW, GW and NW from analysis of variance (ANOVA) are denoted as bars within the same season with different lowercase letters, $P < 0.05$; data points are the mean \pm standard error.

Fig. 1.

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