Potential effects of ultraviolet radiation reduction on tundra nitrous oxide and methane fluxes in maritime Antarctica

Tao Bao1, Renbin Zhu1, Pei Wang1, Wenjuan Ye1, Dawei Ma1 & Hua Xu2

Stratospheric ozone has begun to recover in Antarctica since the implementation of the Montreal Protocol. However, the effects of ultraviolet (UV) radiation on tundra greenhouse gas fluxes are rarely reported for Polar Regions. In the present study, tundra N₂O and CH₄ fluxes were measured under the simulated reduction of UV radiation in maritime Antarctica over the last three-year summers. Significantly enhanced N₂O and CH₄ emissions occurred at tundra sites under the simulated reduction of UV radiation. Compared with the ambient normal UV level, a 20% reduction in UV radiation increased tundra emissions by an average of 8 μg N₂O m⁻² h⁻¹ and 93 μg CH₄ m⁻² h⁻¹, whereas a 50% reduction in UV radiation increased their emissions by an average of 17 μg N₂O m⁻² h⁻¹ and 128 μg CH₄ m⁻² h⁻¹. No statistically significant correlation (P > 0.05) was found between N₂O and CH₄ fluxes and soil temperature, soil moisture, total carbon, total nitrogen, NO₃⁻-N and NH₄⁺-N contents. Our results confirmed that UV radiation intensity is an important factor affecting tundra N₂O and CH₄ fluxes in maritime Antarctica. Exclusion of the effects of reduced UV radiation might underestimate their budgets in Polar Regions with the recovery of stratospheric ozone.

Atmospheric nitrous oxide (N₂O) and methane (CH₄) are two main greenhouse gases (GHGs). In addition, N₂O partly contributes to stratospheric ozone depletion1. Increases in N₂O and CH₄ emissions and their roles in aggravating global warming, have caused great concern in the past three decades1. Currently, the fluxes of N₂O and CH₄ and their influencing factors have been extensively investigated from subtropical, tropical, temperate terrestrial ecosystems and boreal tundra in the Northern Hemisphere2–7. However, the related studies were conducted very late in the Antarctic terrestrial ecosystem.

Recent studies of N₂O and CH₄ fluxes from the Antarctic terrestrial ecosystem mainly concentrated on the McMurdo Dry Valleys of continental Antarctica8–11, the Antarctic Peninsula and other islands of maritime Antarctica12–13. Microtopography, mineralizing substrate availability, soil temperature, soil moisture and O₂ availability could affect tundra N₂O or CH₄ fluxes8–10,12–14,17. Climate change might affect N₂O and CH₄ emissions from the tundra, because some soil parameters, e.g., soil moisture and temperature, are associated with microbial activity and the mineralization of organic carbon and nitrogen in soils17–19. In addition, significantly enhanced N₂O and CH₄ emissions were found from penguin and seal colonies, which have been identified as "hot spots" for N₂O and CH₄ emissions in maritime Antarctica because of the high load of readily available organic carbon and nitrogen through penguin or seal excreta12,13,16. Nevertheless, the effects of solar ultraviolet (UV) radiation on N₂O and CH₄ fluxes have received little attention in the Antarctic tundra.

Strong UV (UV-A and UV-B) radiation has occurred in Antarctica because of the serious destruction of stratospheric ozone20. Enhanced UV radiation resulted in a 75% decrease in the ATP content of the microorganisms in the upper water of the Weddell Sea, Antarctica21. Pakulski et al.22 reported a 57% reduction in marine bacteria around Palmer Station during low total ozone column episodes. A significant correlation has been identified between DNA damage in Antarctic pelagic icefish eggs and UV irradiance23. The survival rates of Antarctic krill decrease in response to increased UV radiation24. Both UV-A and UV-B are major drivers of the decomposition...
of vegetation litter in the Antarctic terrestrial ecosystem through the process of photodegradation\textsuperscript{25-27}. In addition, they have the potential to affect the structure and function of Antarctic mosses, \textit{Ceratodon purpureus} and \textit{Bryum subrotundifolium}\textsuperscript{28} and to influence indirectly the soil microbial populations and activities\textsuperscript{26}. UV radiation is also a key regulator of vegetation morphology and genetic processes and is important in vegetation growth\textsuperscript{27,29}. Vegetation growth and soil microbial activities are the main factors influencing plant respiration and N\textsubscript{2}O and CH\textsubscript{4} emissions from the tundra\textsuperscript{28}. Sunlight could greatly affect N\textsubscript{2}O and CH\textsubscript{4} emissions from tundra ecosystem because of O\textsubscript{2} release via vegetation photosynthesis\textsuperscript{30}. The UV-induced release of carbon from plant litter and soils might contribute to global warming\textsuperscript{27}. Therefore, it is important to investigate the effects of UV intensity on tundra N\textsubscript{2}O and CH\textsubscript{4} fluxes and carbon and nitrogen cycles, in maritime Antarctica.

Currently, stratospheric ozone has recovered somewhat in Antarctica since the implementation of the Montreal Protocol in 1989\textsuperscript{31}. The Antarctic ozone hole has shrunk by nearly 400,000 square miles since it was discovered around 30 years ago. The ozone layer in the Polar Regions is projected to recover to pre-1980 levels by 2048, thus less solar UV radiation will reach the earth’s surface\textsuperscript{32}. However, the effects of a reduction in UV radiation on N\textsubscript{2}O and CH\textsubscript{4} emissions to date have not been investigated in the Antarctic tundra. During the austral summers of 2011/2012, 2013/2014 and 2014/2015, we selected a tundra ecosystem in the maritime Antarctica as study area (Fig. 1) and for the first time, investigated tundra N\textsubscript{2}O and CH\textsubscript{4} fluxes under the conditions of simulated reduction in UV (UV-A and UV-B) radiation, to explore whether natural UV radiation reduction could stimulate tundra N\textsubscript{2}O and CH\textsubscript{4} emissions. This is an important attempt to increase the Antarctic GHGs data sets to reasonably evaluate the potential effects of UV radiation reduction on tundra N\textsubscript{2}O and CH\textsubscript{4} fluxes.

### Results

#### UV radiation and environmental variables between experimental treatments.

In the summer of 2011/2012, UV radiation intensity showed similar temporal variation patterns between the control site and the sites covered by 0.03 mm and 0.06 mm filter membranes (Fig. 2a). The use of filter membrane between experimental treatments significantly decreased (analysis of variance (ANOVA) and least significant difference (LSD) test, \(P < 0.05\)) the amount of UV radiation penetrating into the chamber (Table 1). Compared with the control tundra site, the UV-A and UV-B through the sites with 0.03 mm and 0.06 mm filter membrane decreased by 20\% and 50\%, respectively (Fig. 2b). The highest mean UV-A and UV-B intensity occurred at the control site (14.4 ± 2.1 mW cm\textsuperscript{-2} and 4.7 ± 0.3 mW cm\textsuperscript{-2}, respectively), followed by the site covered by 0.03 mm membrane (11.4 ± 1.6 mW cm\textsuperscript{-2} and 3.8 ± 0.3 mW cm\textsuperscript{-2}, respectively) and the lowest at the site covered by 0.06 mm membrane (7.1 ± 1.0 mW cm\textsuperscript{-2} and 2.4 ± 0.2 mW cm\textsuperscript{-2}, respectively). However, no significant differences (ANOVA and LSD test, \(P > 0.05\)) were found in terms of chamber temperatures (CTs) between the different treatment groups (Table 1) and the CTs showed similar temporal variation patterns at different tundra sites (Fig. 2c). Thus, the use of filter membranes between experimental treatments did not significantly alter chamber micrometeorological conditions, except for the UV intensity. Therefore, the filter membranes could be used to stimulate various
UV intensities and explore the effects of UV radiation on tundra N₂O and CH₄ fluxes in maritime Antarctica. In addition, soil environmental properties, including pH, soil moisture, soil total organic carbon (TOC) and total nitrogen (TN) were similar to each other among the sites: AW1, AW2 and AW3 in the western tundra; AE1, AE2 and AE3 in the eastern tundra on Ardley Island; and GW1, GW2 and GW3 in the upland tundra on Fildes Peninsula. Detailed information about the climatic conditions and soil physiochemical properties is given in Supplementary Figures S1 and Tables S1 and S2.

**Figure 2.** Variations in solar UV radiation intensity (a), transmittance (b) and chamber temperature (c) at the tundra sites with different thicknesses of UV radiation filter membrane.

| Variables                  | Control       | 0.03 mm       | 0.06 mm       |
|---------------------------|---------------|---------------|---------------|
| UV-A (mW/cm²)             | 7.5–23.8      | 6.0–18.9      | 3.8–11.9      |
| UV-B (mW/cm²)             | 3.4–6.2       | 2.8–4.7       | 1.7–3.1       |
| Chamber temperature (°C)  | 6.3–20.0      | 6.6–20.7      | 6.6–19.7      |

**Table 1.** Comparisons of UV radiation intensity and chamber temperature from the tundra observation sites with different thickness of UV radiation filter membrane. Note: The use of filter membrane between experimental treatments significantly decreased (ANOVA and LSD test, P < 0.05) the UV (UV-A and UV-B) radiation into the chamber, no significant differences (ANOVA and LSD test, P > 0.05) were found in terms of chamber temperatures between different treatment groups.
Tundra N₂O fluxes under reduced UV radiation. During the three observation periods, tundra N₂O fluxes showed similar fluctuations between experimental treatments under reduced UV radiation (Fig. 3). In the western tundra marsh on Ardley Island, the highest mean N₂O flux (24.2 ± 7.1 μg N₂O m⁻² h⁻¹ in summer 2011/2012, 8.0 ± 3.6 μg N₂O m⁻² h⁻¹ in summer 2013/2014 and 13.8 ± 4.7 μg N₂O m⁻² h⁻¹ in summer 2014/2015) occurred at the site AW3 under 50% reduction in UV radiation, followed by AW2 (12.2 ± 3.4 μg N₂O m⁻² h⁻¹ in summer 2011/2012, 4.8 ± 3.4 μg N₂O m⁻² h⁻¹ in summer 2013/2014 and 2.3 ± 3.9 μg N₂O m⁻² h⁻¹ in summer 2014/2015) under 20% reduction in UV radiation and the lowest was at the control site AW1 (mean fluxes were close to the detection limit) (Fig. 3a,b,c). Similarly, in the eastern tundra on Ardley Island substantial N₂O emissions (mean 29.5 ± 2.6 μg N₂O m⁻² h⁻¹) were observed at site AE3 under 50% reduction in UV radiation.
had an important effect on the N₂O fluxes in maritime Antarctic tundra. Tundra N₂O fluxes showed no significant intensity increased tundra CH₄ emissions by more than 77

The western tundra sites showed a large fluctuation, ranging from a mean flux of −89.5 μg CH₄ m⁻² h⁻¹ to a maximum uptake of 520.1 μg CH₄ m⁻² h⁻¹ during the observation periods (Table 2). Therefore, UV radiation intensity had an important effect on the N₂O fluxes in maritime Antarctic tundra. Tundra N₂O fluxes showed no significant correlations (Pearson correlation test, P < 0.05) between the mean CH₄ emissions and N₂O emissions in maritime Antarctica, although the N₂O fluxes fluctuated markedly between the summers of 2011/2012, 2013/2014 and 2014/2015.

ANOVA and LSD tests on the N₂O emission rates from all three sites showed a significant difference (P < 0.05) between the mean CH₄ emissions and N₂O emissions in maritime Antarctica, although the N₂O fluxes fluctuated markedly between the summers of 2011/2012, 2013/2014 and 2014/2015.

**Tundra CH₄ fluxes under reduced UV radiation.** During the summers of 2013/2014 and 2014/2015, the western tundra sites showed a large fluctuation, ranging from −324.9 to 594.4 μg CH₄ m⁻² h⁻¹, with a mean of 89.5 ± 24.4 μg CH₄ m⁻² h⁻¹ (Fig. 3a,b). Relatively strong CH₄ uptake occurred at the control site AW1, with a mean flux of −11.4 ± 41.2 μg CH₄ m⁻² h⁻¹. The flux at site AW2 under 20% reduction in UV radiation ranged between a weak sink and a weak source, with the mean of 122.4 ± 33.9 μg CH₄ m⁻² h⁻¹. The CH₄ flux at site AW3 under 50% reduction in UV radiation ranged between a weak sink (as low as −66.9 μg CH₄ m⁻² h⁻¹) and a strong source (up to 594.4 μg CH₄ m⁻² h⁻¹), with the greatest mean CH₄ emission rate (157.7 ± 40.9 μg CH₄ m⁻² h⁻¹) among all the sites. Similarly, the upland tundra acted as stronger CH₄ sink at the control site GW1 (mean −102.4 ± 88.3 μg CH₄ m⁻² h⁻¹) compared with site GW2 (mean −143.5 ± 58.9 μg CH₄ m⁻² h⁻¹) under 50% reduction in UV radiation, whereas tundra site GW3 under 50% reduction in UV radiation showed weak CH₄ emission (mean ± 42.5 ± 94.5 μg CH₄ m⁻² h⁻¹) in summer 2014/2015 (Fig. 5c). Therefore, the reduction of UV radiation decreased tundra CH₄ uptake rates over all three sites and could even convert the tundra from CH₄ sinks into net sources in maritime Antarctica.

There were significant differences (ANOVA and LSD test, P < 0.05) between the mean CH₄ fluxes under the different UV radiation intensities for all tundra sites (Fig. 4). Relative to the controls, the 20% reduction in UV intensity increased tundra CH₄ emissions by more than 77 μg CH₄ m⁻² h⁻¹, reaching as high as 109 μg CH₄ m⁻² h⁻¹. The 50% reduction in UV intensity increased tundra CH₄ emissions by more than 106 μg CH₄ m⁻² h⁻¹, reaching as high as 150 μg CH₄ m⁻² h⁻¹ during the observation periods (Table 3). Therefore, UV radiation intensity had an impact on tundra CH₄ fluxes in maritime Antarctica. Except for 0 cm soil temperature, CH₄ fluxes

- **Figure 4.** Comparisons of tundra N₂O and CH₄ fluxes under different UV radiation intensities in maritime Antarctica. Note: All the data from the sites AW1–AW3, AE1–AE3 and GW1–GW3 were analyzed for N₂O and CH₄ fluxes. For all the tundra sites, there were significant differences (ANOVA and LSD tests, P < 0.05) between the mean N₂O, CH₄ fluxes under the different UV radiation intensities.
showed no significant correlations (Pearson correlation analysis, $P > 0.05$) with total organic carbon, soil moisture, total nitrogen, 5 cm soil temperature, 10 cm soil temperature and NO$_3^-$-N and NH$_4^+$-N contents (Table S3), indicating that these environmental variables might not be the key factors affecting tundra CH$_4$ fluxes.

### Discussion

In this study, no significant correlation (Pearson correlation analysis, $P > 0.05$) was found between tundra N$_2$O fluxes and soil biogeochemical properties (Table S3). However, reduced UV radiation significantly (ANOVA and LSD test, $P < 0.05$) increased tundra N$_2$O emissions in maritime Antarctica, confirming that the variability in UV radiation has an important effect on tundra N$_2$O fluxes and a reduction in UV radiation might increase tundra vegetation N$_2$O production. Some wetland plants can produce and release some N$_2$O via the physiological reaction of plant tissues$^{33,34}$. Generally nitrate reductase (NR), which is responsible for reducing nitrate into nitrite in some plants, plays a key role in the nitrogen metabolism pathway$^{29}$. Furthermore, the reduction in UV radiation significantly stimulated the activities of NR and glutamine synthetase in plants$^{35,36}$. In maritime Antarctica, tundra vegetation might also produce some N$_2$O, which is probably related to the content of nitrate and the activity of

### Table 2.

| Observation period | Control | 0.03 mm | 0.06 mm | Difference |
|--------------------|---------|---------|---------|------------|
| Range              | Mean ± SE | Range | Mean ± SE | Range | Mean ± SE | $\Delta T_{0.03}$ (Control-0.03 mm) | $\Delta T_{0.06}$ (Control-0.06 mm) |
| 2011/2012          | $-16.1–26.8$ | $14.3 ± 4.8$ | $4.3–68.9$ | $26.8 ± 4.9$ | $-14.1$ | $-14.6$ |
| 2013/2014          | $-8.8–18.7$ | $4.8 ± 3.4$ | $-15.1–18.8$ | $8.0 ± 3.6$ | $-5.3$ | $-8.5$ |
| 2014/2015          | $-1.7–42.1$ | $1.9 ± 0.5$ | $-15.1–68.9$ | $11.7 ± 3.1$ | $-4.8$ | $-14.6$ |
| Comprehensive      | $-16.1–36.8$ | $7.2 ± 1.2$ | $-15.1–68.9$ | $17.3 ± 2.8$ | $-8.3$ | $-18.4$ |

The CH$_4$ flux from the western and upland tundra sites during the summers of 2013/2014 and 2014/2015. Panels a and b shows the western tundra CH$_4$ flux under the different UV radiation intensities in the summers of 2013/2014 and 2014/2015; panel c shows the upland tundra CH$_4$ flux under the different UV radiation intensities in 2014/2015 summer. The squares represent the mean fluxes and solid lines represent median values. Boxes enclose the interquartile range; whiskers show the full range. ANOVA and the LSD test on the CH$_4$ emission rates from all three sites showed a significant difference ($P < 0.05$) between the sites with different UV-radiation treatments.

![Figure 5](image-url)
The increase in N2O emissions might also be caused by stimulation of tundra vegetation growth under reduced UV radiation. The response of tundra vegetation photosynthetic rates and vegetation-soil respiration rates to the change in light intensity was almost immediate in the static chambers. Reduced UV radiation significantly increased photosynthesis, the leaf cross-section, and the proportion of aerenchyma in most of wetland plants. The growth of the two phanerogamic Antarctic plants, Deschampsia antarctica and Colobanthus quitensis, appeared to be affected by manipulated surface solar UV levels during the extreme ozone depletion in field experiments and leaf growth of Deschampsia antarctica decreased with elevated UV-B. Plant growth affected the available nitrogen, soluble organic carbon and O2 in the soil; and accelerated N2O production and release from the plant-soil system. In addition, plants also serve as a conduit to transport the N2O produced in the soil to the atmosphere. Therefore, the stimulation of tundra vegetation growth under reduced UV radiation might influence soil properties and further promote N2O emissions from the soil-vegetation system.

In addition, N2O is produced naturally through nitrification and denitrification by soil microorganisms. Although UV radiation cannot penetrate into the soil below 5 mm, enhanced UV radiation may impose indirect effects on the dynamics of microbial communities, mainly via its direct influence on vegetation growth and physiological metabolism, which in turn reduces the absorption of available N and affects root secretion. Many studies have shown that reduced UV radiation significantly increased total abundance and activities of bacteria, such as nitrifiers and denitrifiers, in the rhizosphere soil of wetland vegetation. Therefore, reduced UV radiation might increase the activities of tundra soil microorganisms associated with the nitrogen cycle in maritime Antarctica.

Similarly, the lack of a significant correlation (Pearson correlation analysis, P > 0.05) between tundra CH4 fluxes and soil properties (Table S3) indicated that soil temperature, soil moisture and other soil properties had an insignificant effect on tundra CH4 fluxes. In this study, the reduction of UV intensity could significantly (ANOVA and LSD test, P < 0.05) increase tundra CH4 emission in maritime Antarctica, which was very similar to that observed at peatland sites in Finland. Direct effects of UV radiation on CH4 producing or oxidizing bacteria were not likely because solar radiation penetrates only a few centimeters into the ground. However, there are some indirect effects between UV radiation and CH4 emission, because the reduction of UV radiation induced changes in root exudates, which indirectly affect CH4 production in the soil. Unlike higher plants, lichens and mosses in Antarctica lack a well-developed root system; therefore, most C/N organic material entering the extracellular pools in polar soils probably comes from root and microbial turnover. Vegetation root exudates provide carbon and energy sources for the growth of methanogens, thus promoting CH4 production in the tundra. Intense UV radiation might decrease the distribution of carbohydrates into the roots of vegetation in the Antarctic summer, which was thought to be the major reason why enhanced UV radiation inhibited CH4 emissions in wetlands. UV radiation induced changes in the contents of soil root exudates and decreased UV radiation led to an increase of 15.8% in the rate of CH4 emissions from the wetlands. Therefore, decreased UV radiation stimulated the secretion of root exudates, which might be an important mechanism underlying the effect of UV radiation on CH4 emissions from tundra wetland.

By contrast, in general, ground vegetation might exhibit morphological changes under different ultraviolet intensities. Outdoor species may be sensitive to an increase in UV and decreased UV radiation significantly increased the leaf cross section and proportion of aerenchyma in most wetland plants. In our study area, tundra vegetation, including short mosses and lichens, grow very close to the ground and some of them were even buried in the tundra soils; therefore aerenchymatous tissue of tundra vegetation might have an important role in transporting CH4 from the soil to the atmosphere. In this experiment, the increased cross-sectional area of the plant aerenchyma caused by the reduction of UV radiation is one possible explanation for the stimulated transport of CH4 from the soil to the atmosphere. However, it remains unclear whether the stomatal functioning controls CH4 transport through the mosses or lichens. If the UV induces changes in the stomatal conductance of tundra plants, as shown in several studies with higher plants, it could alter CH4 emission rates. Therefore, the reduction in UV radiation might stimulate CH4 emission by affecting tundra vegetation development.

Table 3. Tundra CH4 fluxes under different experimental treatments in the summers of 2013/2014 and 2014/2015. Note: The ultraviolet radiation through the control site was not affected, the solar UV radiation through the site with 0.03 mm polyester filter membrane decreased by 20% and through 0.06 mm decreased by 50%. Analysis of variance (ANOVA) and the Least Significant Difference (LSD) test on the CH4 emission rates from all three sites showed a significant difference (P < 0.05) between the sites with different UV-radiation treatments. The tundra CH4 was not observed in 2011/2012 summer.
In this study, atmospheric photochemical reactions in the chamber should also be considered. The UV-induced photolysis of N\textsubscript{2}O comprises approximately 90% of the global N\textsubscript{2}O sink\textsuperscript{24} and it is very likely that the enhanced N\textsubscript{2}O emissions under lower UV intensity were caused by reduced photolysis of N\textsubscript{2}O. In addition, an important atmospheric sink for CH\textsubscript{4} is the reaction between OH and CH\textsubscript{4}\textsuperscript{25} and less OH might be generated when UV radiation is reduced in the chambers, thus the “apparent” CH\textsubscript{4} flux from the tundra sites might also be enhanced when the chambers are covered by the thicker filter membranes. More research is needed to test these hypotheses in the future. In general, our results indicated that a reduction of natural UV radiation significantly (ANOVA and LSD test, P < 0.05) increased tundra N\textsubscript{2}O and CH\textsubscript{4} emissions compared with the control under ambient UV levels (Tables 2 and 3). Solar UV radiation might have an important effect on N\textsubscript{2}O and CH\textsubscript{4} budgets in the maritime Antarctic tundra. Although strong solar UV radiation still exists in maritime Antarctica, recovery of stratospheric ozone has occurred since the implementation of the Montreal Protocol in 1989 and the amount of solar UV radiation reaching the earth's surface would be decreased\textsuperscript{31,32}. The effects of UV radiation on tundra N\textsubscript{2}O and CH\textsubscript{4} fluxes and their budgets, should be evaluated in the Arctic and Antarctic regions. The exclusion of its effects might underestimate N\textsubscript{2}O and CH\textsubscript{4} budgets in the tundra ecosystem of Polar Regions. To assess the regional N\textsubscript{2}O and CH\textsubscript{4} budget precisely, long-term measurements of GHG fluxes should be designed in the Antarctic or Arctic tundra ecosystems to show effects of UV radiation intensities on N\textsubscript{2}O and CH\textsubscript{4} fluxes.

Methods

Study area and investigation sites. One research area was located on Ardley Island (62° 13′ S, 58° 56′ W; an area of 2.0 × 1.5 km) (Fig. 1). This island is recognized by the Scientific Committee of Antarctic Research as an area of special scientific interest. The western region of this island is a coastal lowland tundra marsh and the vegetation cover was reduced to 95%. The middle on this island is a non-level, hilly and relatively dry upland tundra with vegetation coverage of 90–95%\textsuperscript{14}. The middle upland and western lowland tundra are free of active penguin populations. The active penguin populations only concentrate in the east of this island\textsuperscript{12} and tundra patches have formed in the marginal zones of penguin nesting sites and are almost totally (90–95%) covered by mosses, algae and lichens in the east\textsuperscript{15}.

Another research area was situated on Filde Peninsula (61° 51′−62° 15′ S, 57° 30′−59° 00′ W; an area of 30 km\textsuperscript{2}) in the southwestern area of King George Island (Fig. 1a,b). Communities of mosses and lichens represent the vegetation on this peninsula. An upland tundra was well-developed in the northwest of the Chinese Great Wall Station, at a distance of about 500 m from the station. The upland tundra was nearly dry, with an elevation of around 40 m a.s.l. The sampling ground was totally covered by mosses (Bryum Pseudotriquetrum and Bryum muilenbeckii) and lichens (Usnea sp.), with a depth of around 5–10 cm for the vegetation layer. Under the vegetation cover is an organic clay layer, with the depth of around 10–15 cm. A more detailed description about the study area was given by Zhu et al.\textsuperscript{15}.

During the summers of 2011/2012, 2013/2014 and 2014/2015, three observation sites were set up in the western tundra marsh on Ardley Island, equipped with three chamber collars each. The chambers were covered by special polyester filter membranes (Mylar-D, 0.03-mm/0.06-mm thick; DuPont Co., Wilmington, DE, USA), which removed part of the UV-A and UV-B wavelengths and had no effect on other wavelengths of light\textsuperscript{30}, to simulate the effect of natural UV-radiation reduction on tundra GHG fluxes: (1) the control site AW1 had transparent chambers; (2) site AW2 had transparent chambers covered by a 0.03-mm filter membrane; and (3) site AW3 had transparent chambers covered by a 0.06-mm filter membrane (Fig. 1c). In addition, during the summer of 2012/2013, three other observation sites were established in the eastern tundra of Ardley Island: (1) the control site AE1 had transparent chambers; (2) site AE2 had transparent chambers covered by a 0.03-mm filter membrane; and (3) site AE3 had transparent chambers covered by a 0.06-mm filter membrane (Fig. 1c). During the summers of 2014/2015, N\textsubscript{2}O and CH\textsubscript{4} fluxes were also measured at three observation sites in the upland tundra on the Filde Peninsula: (1) the control site GW1 had transparent chambers; (2) site GW2 had transparent chambers covered by a 0.03-mm filter membrane; (3) site GW3 had transparent chambers covered by a 0.06-mm filter membrane (Fig. 1b). There were no differences in the dominant vegetation species and phytomass among the three sites in each study area\textsuperscript{15}. These observation sites were characteristic of the typical surface and vegetation within the tundra ecosystems in maritime Antarctica.

UV radiation measurement. To test whether the UV radiation polyester filter membrane with different thicknesses could decrease solar ultraviolet radiation, we used an UV radiation instrument (Photoelectric Instrument Factory, Beijing Normal University, Beijing, China) with UV radiation sensors and data loggers (model UV-II) to measure the UV intensity. The sensors, which were manually mounted under the chambers with different thickness polyester filter membrane, collected UV data at 5-min intervals and the measured data displayed by the instrument was the radiant exposure (mW cm\textsuperscript{−2}). The instrument was calibrated by the manufacturer and was used within the one-year interval of the validity for this calibration. The order of measurements was randomized to ensure that the measuring sequence did not bias the results and each site had three replicate measurements. During the period from Dec 24, 2011 to Feb 5, 2012, the UV radiation intensity was measured eight times at sites AW1, AW2 and AW3. These data indicated that the filter membrane significantly (ANOVA and LSD test, P < 0.05) decreased the UV radiation transmitted to the chamber (Fig. 2a). The UV radiation through site AW1 plots was not affected, the UV-A and UV-B decreased by 20% through the site AW2 plots and by 50% through the AW3 plots (Fig. 2b).

In situ N\textsubscript{2}O and CH\textsubscript{4} flux measurement. A static chamber technique was used to measure N\textsubscript{2}O and CH\textsubscript{4} fluxes from the tundra sites\textsuperscript{31,32}. Gas samples were taken from the clear plexiglass chambers (area: 0.25 m\textsuperscript{2}, volume: 0.06 m\textsuperscript{3}) placed on the PVC collars installed at the measurement sites. The collars were pushed 5 cm into the soil and air samples were taken within the headspace after 0, 10 and 20 min using a both ends needle. Gas samples
were immediately transferred to 17.8 ml glass vials, which had been evacuated in advance\(^{14,15}\). More information on the *in situ* \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) flux measurements is given in Supplementary Materials S1. During the summer of 2011/2012, \( \text{N}_2\text{O} \) fluxes were measured at the sites (AW1, AW2, AW3 and AE1, AE2, AE3) from Dec 1, 2011 to Feb 21, 2012. During the summer of 2013/2014, \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) fluxes were simultaneously measured at the western sites (AW1, AW2 and AW3) from Feb 14 to Mar 14, 2014. During the summer of 2014/2015, their fluxes were measured at the sites (AW1, AW2, AW3 and GW1, GW2, GW3) from Dec 1, 2014 to Feb 21, 2015.

**Analysis of \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) concentrations and calculation of flux.** The methods of analyzing \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) concentrations and flux calculation were described in detail in our previous papers\(^{12,15}\). In brief, gas samples were analyzed using gas chromatography (GC-HP5890 II, USA; Shimadzu GC-14B, Japan; Shimadzu GC-12A, Japan) to measure \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) concentrations. Their emission fluxes were calculated by fitting the experimental data to a linear least squares plot (\( \text{N}_2\text{O} \) and \( \text{CH}_4 \) concentrations vs. time). More information is given in Supplementary Materials S2.

**Measurements of environmental variables and soil properties.** Soil temperatures (\( \text{ST}_0 \), \( \text{ST}_5 \) and \( \text{ST}_{10} \)) were measured *in situ* using a ground thermometer inserted into the corresponding depth at the sampling sites. Meteorological data, e.g. air temperature (AT), daily sunlight time (ST), precipitation and total daily radiation (TDR) were acquired at the weather station of Great Wall Station. Soil samples were collected in the chamber plots after the fieldwork was completed in the summers of 2011/2012 and 2014/2015. The soils were sampled using a PVC tube (height: 15 cm; diameter: 6 cm), which was sealed and stored at 4 °C until analysis. Soil moisture was determined by oven drying at 105 °C to a constant weight. Each soil sample was homogenized manually and a subsample (fresh weight: 10 g) was extracted with 100 mL of 1 M KCl for 1 h and then filtered and analyzed for \( \text{NH}_4^+ \), \( \text{N}_2\text{O} \), \( \text{NO}_3^- \), and \( \text{NH}_3 \), which were determined using a colorimetric method based on Berthelot’s reaction and ion chromatography\(^{14,15}\). The TOC content in the soils was determined by the chemical volumetric method\(^{12}\) and TN was analyzed using automatic elemental analysis (Elementar Vario EL, Hanau, Germany). The pH was determined after a 1:3 (soil:solution) dilution of soil with distilled water\(^{15}\).

**Statistical analysis.** The standard error (SE) was used to estimate the uncertainty of the mean of individual fluxes. All the data for \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) fluxes were expressed as the mean ± SE. Differences in \( \text{N}_2\text{O} \) fluxes or \( \text{CH}_4 \) fluxes under different UV radiation intensities were examined using one-way repeated ANOVA and LSD tests at the \( P = 0.05 \) level. The relationships between soil parameters and \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) fluxes were addressed using Pearson correlation analysis (\( P = 0.05 \) level). The contribution of the reduction in UV radiation to tundra \( \text{N}_2\text{O} \) or \( \text{CH}_4 \) fluxes was calculated as: \( \text{CT}_{0.03} = \text{MF}_{0.03} \times \text{MF}_{\text{con}} \) and \( \text{CT}_{0.06} = \text{MF}_{0.06} \times \text{MF}_{\text{con}} \). \( \text{CT}_{0.03} \) and \( \text{CT}_{0.06} \) indicate the contribution of the 20% and 50% reduction in UV radiation to tundra \( \text{N}_2\text{O} \) or \( \text{CH}_4 \) fluxes, respectively. \( \text{MF}_{0.03} \) and \( \text{MF}_{0.06} \) indicate the mean \( \text{N}_2\text{O} \) or \( \text{CH}_4 \) fluxes under the 20% and 50% reduction in UV radiation and under the control at the ambient UV level, respectively. All statistical analyses were performed using SPSS 20.0 (http://www.spss.com.cn/) and Microsoft Excel 2016 (https://products.office.com/zh-cn/excel) for Windows 10.

**References**

1. IPCC. *IPCC Climate Change 2013: The Physical Science Basis*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (2013).
2. Oechel, W. C. *et al*. Acclimation of ecosystem CO2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature* **406**, 978–981 (2000).
3. Corrada, C., Kolle, O., Walter, K., Zimov, S. A. & Schulze, E.-D. Carbon dioxide and methane exchange of a north-east Siberian tussock tundra. *Glob. Change Biol.* **11**, 1910–1925 (2005).
4. Repo, M. E. *et al*. Large \( \text{N}_2\text{O} \) emissions from cryoturbated peat soil in tundra. *Nat. Geosci.* **2**, 189–192 (2009).
5. Maruschak, M. E. *et al*. Hot spots for nitrous oxide emissions found in different types of permafrost peatlands. *Glob. Change Biol.* **17**, 2601–2614 (2011).
6. Ullah, S. & Moore, T. R. Biogeochemical controls on methane, nitrous oxide and carbon dioxide fluxes from deciduous forest soils in eastern Canada. *J. Geophys. Res.* **116**, G03010 (2011).
7. Kirschke, S. *et al*. Three decades of global methane sources and sinks. *Nat. Geosci.* **6**, 813–823 (2013).
8. Burkins, M. B., Virginia, R. A. & Wall, D. H. Organic carbon cycling in Taylor Valley, Antarctica: quantifying soil reservoir and soil respiration. *Glob. Change Biol.* **7**, 113–125 (2001).
9. Gregorich, E. G. *et al*. Emissions of \( \text{CO}_2 \), \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) from lakeshore soils in an Antarctic dry valleys. *Soil Biol. Biochem.* **38**, 3120–3129 (2006).
10. Barret, J. E., Virginia, R. A., Parson, A. N. & Wall, D. H. Soil carbon turnover in the McMurdo Dry Valleys, Antarctica. *Soil Biol. Biochem.* **38**, 3019–3034 (2006).
11. Ball, B. A. & Virginia, R. A. Controls on diel soil \( \text{CO}_2 \) flux across moisture gradients in a polar desert. *Antarct. Sci.* **27**, 527–534 (2013).
12. Sun, L. G., Zhu, R. B., Xie, Z. Q. & Xing, G. X. Emissions of nitrous oxide and methane from Antarctic tundra: role of penguin dropping deposition. *Atmos. Environ.* **36**, 4977–4982 (2002).
13. Convey, P. & Smith, R. I. L. Response of terrestrial Antarctic ecosystems to climate change. *Plant Ecol.* **182**, 1–10 (2006).
14. Zhu, R. B., Liu, Y. S., Xu, H., Ma, D. W. & Jiang, S. Marine animals significantly increase tundra \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) emissions in maritime Antarctica. *J. Geophys. Res.* **118**, 1773–1792 (2013).
15. Zhu, R. B., Ma, D. W. & Xu, H. Summertime \( \text{N}_2\text{O} \), \( \text{CH}_4 \) and \( \text{CO}_2 \) exchanges from a tundra marsh and an upland tundra in maritime Antarctica. *Atmos. Environ.* **83**, 269–281 (2014).
16. Zhu, R. B., Sun, L. G. & Ding, W. X. Nitrous oxide emissions from tundra soil and snowpack in the maritime Antarctic. *Chemosphere* **59**, 1667–1675 (2005).
17. Bohlin, S., Huijbers, A., Convey, P. & Aerts, R. Climate change effects on organic matter decomposition rates in ecosystems from the Maritime Antarctic and Falkland Islands. *Glob. Change Biol.* **13**, 2642–2653 (2007).
18. Hopkins, D. W. *et al*. Carbon, nitrogen and temperature controls on microbial activity in soils from an Antarctic dry valley. *Soil Biol. Biochem.* **38**, 3130–3140 (2006).
19. Carvalho, J. V. S. *et al*. Impact of expected global warming on C mineralization in maritime Antarctic soils: results of laboratory experiments. *Antarct. Sci.* **22**, 485–493 (2010).
20. Thompson, D. W. et al. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nat. Geosci.* **4**, 741–749 (2011).

21. Vosjan, J. H., Döhler, G. & Nieuwland, G. Effect of UV-B irradiance on the ATP content of microorganisms of the Weddell Sea (Antarctica). *NL. J. Sea Res.* **25**, 391–393 (1990).

22. Pakulski, J. D., Kase, J. P., Meador, J. A. & Jeffrey, W. H. Effect of stratospheric ozone depletion and enhanced ultraviolet radiation on marine bacteria at Palmer Station, Antarctica in the early austral spring. *Photochem. Photobiol.* **84**, 215–221 (2008).

23. Malloy, K. D., Holman, M. A., Mitchell, D. & Detrich, H. W. Solar UV-B-induced DNA damage and photobiological DNA repair in Antarctic zooplankton. *PNAS.* **94**, 1258–1263 (1997).

24. Ban, S. et al. Effect of solar ultraviolet radiation on survival of krill larvae and copepods in Antarctic Ocean. *Polar Biol.* **30**, 1295–1302 (2007).

25. Stewart, K. J., Brummell, M. E., Farrell, R. E. & Siciliano, S. D. *N*₂*O* flux from plant-soil systems in polar deserts switch between sources and sinks under different light conditions. *Soil Biol. Biochem.* **48**, 69–77 (2012).

26. Krywult, M., Smykla, J. & Wincenciak, A. The presence of nitrates and the impact of ultraviolet radiation as factors that determine nitrate reductase activity and nitrogen concentrations in *Deschampsia antarctica Desv.* around penguin rookeries on King George Island, Maritime Antarctica. *Water Air Soil Poll.* **224**, 1563 (2013).

27. Bornman, J. F. et al. Solar ultraviolet radiation and ozone depletion-driven climate change: effects on terrestrial ecosystems. *Photoch. Photobiol. Sci.* **14**, 88–107 (2015).

28. Green, T. G. A., Kulle, D., Pannewitz, S., Sancho, L. G. & Schroeter, B. UV–A protection in mosses growing in continental Antarctica. *Polar Biol.* **28**, 822–827 (2005).

29. He, Y. et al. Effect of enhanced UV-B radiation on methane emission in a paddy field and rice root exudation of low-molecular-weight organic acids. *Photoch. Photobiol. Sci.* **15**, 739–743 (2016).

30. Li, F., Zhu, R., Hao, T., Wang, Q. & Xu, H. Sunlight stimulates methane uptake and nitrous oxide emission from the High Arctic tundra. *Sci. Total Environ.* **572**, 1150–1160 (2016).

31. Steinbrecht, W. et al. Ozone and temperature trends in the upper stratosphere at five stations of the Network for the Detection of Atmospheric Composition Change. *Int. J. Remote Sens.* **30**, 3875–3886 (2009).

32. Bais, A. F., Tourpali, K. & Kazantzidis, A. Projections of UV radiation changes in the 21st century: impact of ozone recovery and cloud effects. *Atmos. Chem. Phys.* **11**, 7533–7545 (2011).

33. Hakata, M., Takahashi, M., Zumft, W., Sakamoto, A. & Morikawa, H. Conversion of the nitrate nitrogen and nitrogen dioxide to nitrous oxides in plants. *Acta Biotechnol.* **23**, 249–257 (2003).

34. Robson, T. M. et al. Reduction of solar UV-B mediates changes in the Sphagnum capitulum microenvironment and the peatland microfungal community. *Oecologia* **140**, 480–490 (2004).

35. Quaggiotti, S., Trentin, A. R., Vecchia, F. D. & Ghissi, R. Response of maize (*Zea mays L.*) nitrate reductase to UV-B radiation. *Plant Sci.* **167**, 107–116 (2004).

36. Hu, Z. H. et al. Impacts of enhanced UV-B radiation on respiration rate, *CH₄* and *N₂O* emission fluxes from rice paddy. *Environ. Sci. Technol.* **32**, 3018–3022 (2011).

37. Ding, W., Zhu, R. B., Ma, D. W. & Xu, H. Summertime fluxes of *N₂O*, *CH₄* and *CO₂* from the littoral zone of Lake Daming, East China. Effects of environmental conditions. *Antarct. Sci.* **25**, 752–762 (2013).

38. Del Grosso, S. J. et al. General model for *N₂O* and *N₂* gas emissions from soils due to denitrification. *Global Biogeochem Cycles* **14**, 1045–1060 (2000).

39. Xiong, F. S. & Day, T. A. Effect of solar ultraviolet-B radiation during springtime ozone depletion on photosynthesis and biomass production of Antarctic vascular plants. *Plant Physiol.* **125**, 738–751 (2011).

40. Rotzma, J. et al. Consequences of depletion on stratospheric ozone for terrestrial Antarctic ecosystems: the response of *Deschampsia antarctica* to enhanced UV-B radiation in a controlled environment. *Plant Ecol.* **154**, 101–115 (2001).

41. Hink, L., Nicol, G. W. & Prosper, J. J. Arabica produce lower yields of N₂O than bacteria during aerobic ammonia oxidation in soil. *Environ. Microbiol.* **19**, 4829–4837 (2017).

42. Bang-Andreasen, T., Schostag, M., Priemé, A., Elberling, B. & Jacobsen, C. S. Potential microbial contamination during sampling of permafrost soil assessed by tracers. *Environ. Sci. Technol.* **51**, 107–116 (2017).

43. Johnson, D., Campbell, C. D., Lee, J. A. & Callaghan, T. V. Arctic microorganisms respond more to elevated UV-B radiation than *CO₂*. *Nature* **416**, 82–83 (2002).

44. Niemi, R. et al. Elevated UV-B radiation alters fluxes of methane and carbon dioxide in peatland microcosms. *Glob. Change Biol.* **8**, 361–371 (2002).

45. Erickson, D. J. III, Sulzberger, B., Zepp, R. G. & Austin, A. T. Effects of stratospheric ozone depletion, solar UV radiation and climate change on biogeochemical cycling: Interactions and feedbacks. *Photochem. Photobiol. Sci.* **14**, 127–148 (2015).

46. Johnson, M. G. et al. Evolution of niche preference in Sphagnum peat mosses. *Evolution* **69**, 90–103 (2015).

47. Liu, D., Ding, W., Yuan, J., Xiang, J. & Lin, Y. Substrate and/or substrate-driven changes in the abundance of methanogenic archaea cause seasonal variation of methane production potential in species-specific freshwater wetlands. *Appl. Microbiol. Biotechnol.* **98**, 4711–4721 (2014).

48. Olszewska, P., Dutkiewicz, E. M. & Olech, M. Trace elements concentrations in selected moss and lichen species collected within Antarctic research stations. *Pol. J. Ecol.* **55**, 39 (2007).

49. Roberts, P., Newsham, K. K., Bardgett, R. D., Farrar, J. F. & Lenton, T. M. Vegetation cover regulates the quantity, quality and temporal dynamics of dissolved organic carbon and nitrogen in Antarctic soils. *Polar Biol.* **32**, 999–1008 (2009).

50. Zhuang, X., Chu, D., Li, Y., Wang, L. & Wu, Y. Effect of elevated UV-B radiation on *CH₄* emissions from the stands of *Spartina alterniflora* and *Phragmites australis* in a coastal salt marsh. *Aquat. Bot.* **111**, 150–156 (2013).

51. Robson, T., Klem, K., Urban, O. & Jansen, M. A. Re-interpreting plant morphological responses to UV-B radiation. *Plant Cell Environ.* **38**, 856–866 (2015).

52. Jansen, M. A. & Van Den Noort, R. E. Ultraviolet-B radiation induces complex alterations in stomatal behaviour. *Physiol. Plantarum* **110**, 189–194 (2000).

53. Von Fischer, J. C. & Hedin, L. O. Controls on soil methane fluxes: tests of biophysical mechanisms using stable isotope tracers. *Glob. Biogeochem. Cycles* **21**, GB2007, https://doi.org/10.1029/2006GB002687 (2007).

54. Griffith, D. W. T., Toon, G. C., Sen, B., Blavier, J.-F. & Toth, R. A. Vertical profiles of nitrous oxide isotopomer fractionation measured in the stratosphere. *Geophys. Res. Lett.* **27**, 2485–2488 (2000).

55. Tyler, S. C., Aise, H. O., Rice, A. L., Cicerone, R. J. & Tuzo, E. C. Experimentally determined kinetic isotope effects in the reaction of *CH₂* with Cl. Implications for atmospheric Cl. *Geophys. Res. Lett.* **27**, 1715–1718 (2000).

56. Robson, T. M. et al. Six years of solar UV-B manipulations affect growth of *Sphagnum* and vascular plants in a Tierra del Fuego peatland. *New Phytol.* **160**, 379–389 (2003).

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Author Contributions
R.B.Z., T.B. and H.X. developed the idea and designed the experiments, D.W.M. and T.B. collected the samples from the Antarctica, T.B., P.W., W.J.Y. and D.W.M. analyzed the samples, R.B.Z. and T.B. analyzed the data and wrote the manuscript. All authors have reviewed this manuscript.

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