A two-year field measurement of methane and nitrous oxide fluxes from rice paddies under contrasting climate conditions

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The effects of three irrigation levels (traditional normal amount of irrigation [NA100%], 70%, and 30% of the normal amount [NA70% and NA30%]) and two rice varieties (Oryza sativa L. Huayou14 and Hanyou8) on CH4 and N2O emissions were investigated over two years under contrasting climate conditions (a ‘warm and dry’ season in 2013 and a normal season in 2014). Hanyou8 was developed as a drought-resistant variety. The mean seasonal air temperature in 2013 was 2.3 °C higher than in 2014, while the amount of precipitation from transplanting to the grain-filling stage in 2013 was only 36% of that in 2014. CH4 emission rose by 93–161%, but rice grain yield fell by 7–13% in 2013, compared to 2014 under the NA100% conditions. Surface standing water depths (SSWD) were higher in Hanyou8 than in Huayou14 due to the lower water demand by Hanyou8. A reduction in the amount of irrigation water applied can effectively reduce the CH4 emissions regardless of the rice variety and climate condition. However, less irrigation during the ‘warm and dry’ season greatly decreased Huayou14 grain yield, but had little impact on Hanyou8. In contrast, N2O emission depended more on fertilization and SSWD than on rice variety.

Modern changes in global climate, including greater atmospheric concentrations of greenhouse gases (CO2, CH4, N2O, etc.), temperature shifts, higher frequency of extreme events, such as drought or heavy rainfall, and heat waves, are directly or indirectly associated with the combustion of fossil fuels, land use change and other human activities that have occurred since the Industrial Revolution1. Such changes have greatly affected terrestrial ecosystems. For example, extreme events could lead to negative and even disastrous effects on plants2.

Rice (Oryza sativa L.) is the most widely consumed staple food crop in the world, and is particularly important in Asia. The food safety and national security of some countries depends on its production. Rice cultivation is also a significant source of greenhouse gas emissions, primarily methane (CH4) and nitrous oxide (N2O). Annual CH4 emissions from rice fields have been estimated to account for about 5–19% of global CH4 emissions, and agricultural N2O emissions increased by nearly 17% between 1990 and 2005, and now account for 60% of global anthropogenic N2O emissions3. The flooded environment, created during rice cultivation, provides anaerobic conditions that favor CH4 production by methanogens. The resulting CH4 can be oxidized by methanotrophs under aerobic conditions (e.g., in the rhizosphere and at the soil–water interface) and is finally emitted to the atmosphere through soil- or water-atmosphere interfaces and by the rice plant aerenchyma4. Nitrogen fertilization and water management (e.g. alternating wetting and drying) facilitates N2O emission via the processes of nitrification and/or denitrification in rice paddies4, hence, when applied appropriately, fertilizer and management interventions can play important roles in effectively controlling CH4 and N2O emissions during rice cultivation5–9. However, rice varieties differ significantly in terms of total CH4 and N2O emissions10–13. Selecting a rice variety that results in low CH4 and N2O emissions may therefore be a promising way to mitigate greenhouse gas emissions from rice paddies.

Drought is a serious limiting factor on crop production and the most damaging stressor in modern agriculture14,15. Rice consumes 70–90% of the total amount of irrigation water used in agriculture16,17, and as roughly a half of the world’s 158 million ha of rice land is paddy rice18, the production of this crop is very susceptible to...
Table 1. Mean seasonal air and soil temperatures, total precipitation, and amount of irrigation water in the 2013 and 2014 rice growing seasons. NA100% = normal amount of irrigation, NA70% = 70% of normal irrigation, NA30% = 30% of normal irrigation.

| Rice season | Treatments | Mean seasonal air temperature (°C) | Mean seasonal soil temperature (°C) | Seasonal total precipitation (mm) | Precipitation from June to September (mm) | Amount of irrigation (mm) | Water input from June to September (mm) |
|-------------|------------|------------------------------------|------------------------------------|---------------------------------|----------------------------------------|------------------------|--------------------------------------|
| 2013 ('warm and dry') | NA100% | 26.7 | 27.8 | 492.1 | 271.8 | 611.7 | 883.5 |
| 2013 ('warm and dry') | NA70% | 27.7 | 27.7 | 492.1 | 271.8 | 428.3 | 706.1 |
| 2013 ('warm and dry') | NA30% | 28.0 | 28.0 | 492.1 | 271.8 | 185.0 | 456.8 |
| 2014 (normal) | NA100% | 24.4 | 24.7 | 762.7 | 762.7 | 116.7 | 879.4 |
| 2014 (normal) | NA70% | 24.7 | 24.7 | 762.7 | 762.7 | 81.7 | 844.4 |
| 2014 (normal) | NA30% | 24.8 | 24.8 | 762.7 | 762.7 | 35.0 | 797.7 |

Results and Discussion

Irrigation management and SSWD dynamics under contrasting climate conditions. The total precipitation was 492.1 and 762.7 mm over the whole rice cultivation periods of 2013 and 2014, respectively (Table 1). In the ‘warm and dry’ rice season of 2013, only 271.8 mm (~55.2% of the total) of precipitation occurred from June to September, which is the period of active rice plant growth and development. In contrast, total precipitation in the normal rice season of 2014 occurred between June and September. Additionally, the total amount of evaporation was 591.6 and 481.6 mm in 2013 and 2014, respectively. Therefore, to satisfy the plant demand for water during growth and development, irrigation was applied up to 12 times in 2013 to keep the water table in the plots similar to traditional irrigation management (Fig. 1a). However, irrigation was applied only three times in 2014 (Fig. 1b). The total amount of irrigation in the NA100% plot was 611.7 mm in 2013 compared to only 116.7 mm in 2014 (Table 1). Consequently, the effective water inputs (precipitation + irrigation) from June to September for the NA100% plots were similar for the ‘warm and dry’ season (883.5 mm) and the normal season (879.4 mm). In contrast, the total water inputs in the NA70% and NA30% plots from June to September in 2013 were only 83% and 57% of those in 2014 (Table 1).
Similar trends in SSWD were observed for all treatments in both seasons when the rice plants were small before MD (Fig. 2). The maximum SSWD reached similar values (approximately 6–7 cm). However, there were considerable differences in SSWD after MD between the rice varieties in 2013 (Fig. 2a,b). Under the same water inputs (precipitation + irrigation), the SSWDs of Hanyou8 in the NA100% and NA70% plots were significantly higher than those of Huayou14. Hanyou8 was developed as a drought-resistant variety and requires less water to maintain growth and development. The average evapotranspiration rate for Hanyou8 was 5.4 mm day$^{-1}$, a significantly lower rate than for Huayou14 (6.2 mm day$^{-1}$), which probably resulted in higher SSWDs in the NA100% and NA70% plots when the WDR (Hanyou8) variety was grown compared to the common rice variety. However, the SSWD in the NA30% plots for both varieties was almost zero after MD in 2013 due to the reduced water input (Fig. 2a,b). In contrast, Hanyou8 mean SSWD was not significantly different to Huayou14 after MD in 2014. Furthermore, the SSWDs in the NA30% plots were similar to NA70% for both varieties in 2014 (Fig. 2c,d). Irrigation management appeared to have a lower effect on SSWD at the different irrigation levels due to higher precipitation in 2014.

CH$_4$ emissions under contrasting climate conditions. The CH$_4$ flux from all plots increased from the beginning, and peaked for the first time at 25–30 days after transplanting, then rapidly decreased to zero due to MD. Thereafter, CH$_4$ fluxes from the NA100% and NA70% plots increased, peaked for a second time at 80–100 days after transplanting, and decreased afterwards until the end of the seasons. However, CH$_4$ fluxes from the NA30% plot were very low after MD (Fig. 3). Consequently, the NA100% plots had the largest CH$_4$ emissions for both rice varieties (Table 2). The average total CH$_4$ emissions from the NA100% plots was 122 kg CH$_4$ ha$^{-1}$ (the range was from 47.8 to 252 kg CH$_4$ ha$^{-1}$ in this study), which was within the range of 5.4–275 kg CH$_4$ ha$^{-1}$ range recorded in numerous other studies where paddies were subject to traditional water management regimes (i.e. NA100% condition) and a N fertilizer application rate of 200–250 kg N ha$^{-1}$, which is typical for the Yangtze River delta zone. A significant difference in total CH$_4$ emissions was observed among irrigation levels ($P < 0.01$, Table 2). The NA70% and NA30% plots respectively reduced total CH$_4$ emissions by 31–53% and 32–77% in both seasons compared to the NA100% plots. Similarly, Hou et al. reported that controlled irrigation (NA30%) mitigated CH$_4$ emissions by 82% relative to traditional irrigation (NA100%)$.^32$ Wang et al. found that intermittent irrigation (corresponding to NA70%) and constant moisture (corresponding to NA30%) reduced CH$_4$ emissions by 25% and 58%, respectively, compared to the continuous flooding condition (NA100%).$^{36}$ Reductions in irrigation water to the rice paddies led to a lower SSWD and even no standing water above the surface. This increased oxygen penetration into the soil and led to soil organic C being oxidized to CO$_2$ instead of CH$_4$, which ultimately suppressed CH$_4$ emissions. In this study, reducing the amount of irrigation was found to mitigate CH$_4$ emissions not only under normal climate condition but also in the ‘warm and dry’ season.

There was a significant difference in CH$_4$ emissions between Huayou14 and Hanyou8 ($P < 0.05$, Table 2). The CH$_4$ emissions from Huayou14 were always lower than from Hanyou8, especially in the NA100% and NA70%
Figure 2. Seasonal variation in surface standing water depth (SSWD) in the 2013 (a) Huayou14; (b) Hanyou8 and 2014 (c) Huayou14; (d) Hanyou8 rice growing seasons. Abbreviations: NA100% = normal amount of irrigation, NA70% = 70% of normal irrigation, NA30% = 30% of normal irrigation. Gray belts represent the mid-season drainage periods. Error bars represent standard errors of the means.

Figure 3. Seasonal variation in CH₄ fluxes in the 2013 (a) Huayou14; (b) Hanyou8 and 2014 (c) Huayou14; (d) Hanyou8 rice growing seasons. Abbreviations: NA100% = normal amount of irrigation, NA70% = 70% of normal irrigation, NA30% = 30% of normal irrigation, BF = base fertilizer, TF = tillering fertilizer, HF = heading fertilizer. Gray belts represent the periods of mid-season drainage. Arrows denote the fertilization date, and error bars represent standard errors of the means.
could potentially enhance CH$_4$ production and emission$^{40,41}$. Under higher air/soil temperature conditions, more and made the SSWD values higher than or similar to those in 2014. Secondly, the higher air/soil temperature less precipitation in 2013, large amounts of irrigation water were added to the plots to meet rice growth demand
elevated temperature enhanced CH$_4$ emissions in 73 studies, but depressed emissions in 41 studies$^{30}$. These studies possible reasons for the relatively higher CH$_4$ emissions in the ‘warm and dry’ season. Firstly, although there was

There were several possible reasons for the relatively higher CH$_4$ emissions in the ‘warm and dry’ season of 2013 than in the normal season of 2014 ($P < 0.01$, Table 2). It is difficult to control climate conditions in field experiments, so there is little data available from field experiments but model simulations have been used to compare CH$_4$ and N$_2$O under contrasting climate conditions. By employing the DNDC biogeochemical model to simulate greenhouse gas emissions in Chinese rice growing fields between 1971 and 2010, Tian $et$ $al.$ found that CH$_4$ emission was enhanced during the second 20 years (1991–2010) compared to the first 20 years (1971–1990) due to a 0.5°C increase in air temperature$^{29}$. In this study, the CH$_4$ emissions from the NA100% plots by Huayou14 and Hanyou8 increased by $18.8 \pm 4.7$ and $19.9 \pm 1.5$ kg CH$_4$ ha$^{-1}$ in the ‘warm and dry’ season of 2013 compared to normal seasons of 2014 ($19.9 \pm 1.5$ and $22.6 \pm 2.2$ kg CH$_4$ ha$^{-1}$, respectively), which may enhance CH$_4$ production by changing the quantity and quality of the root exudates$^{39}$. However, when the amount of irrigation water was reduced, CH$_4$ emission was mitigated more in the Hanyou8 plots (average reduction of 52% and 73% by NA70% and NA30%, respectively, compared to NA100%) than that in the Huayou14 plots (average reduction of 34% and 42% by NA70% and NA30%, respectively, compared to NA100%) (Table 2).

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Table 2. Seasonal total CH$_4$ and N$_2$O emissions in the 2013 and 2014 rice growing seasons. Numbers in the table represent means ± standard errors. H8 = Hanyou8, H14 = Huayou14, NA100% = normal amount of irrigation, NA70% = 70% of normal irrigation, NA30% = 30% of normal irrigation, IM = Irrigation management, RV = Rice Variety. * $P < 0.05$, ** $P < 0.01$, ns = not significance at 0.05 level.

| Treatments | CH$_4$ emission (kg CH$_4$ ha$^{-1}$) | N$_2$O emission (kg N$_2$O ha$^{-1}$) |
|------------|--------------------------------------|--------------------------------------|
|            | 2013 | 2014 | 2013 | 2014 |
| H14-NA100% | 92.3 ± 18.8 | 47.8 ± 14.7 | 0.6 ± 0.2 | 1.8 ± 0.4 |
| H14-NA70% | 63.4 ± 19.9 | 30.6 ± 6.0 | 1.5 ± 0.5 | 2.2 ± 0.8 |
| H14-NA30% | 44.9 ± 3.2 | 32.6 ± 4.9 | 0.8 ± 0.4 | 2.7 ± 0.6 |
| H8-NA100% | 252.2 ± 108.2 | 96.5 ± 31.4 | 0.2 ± 0.3 | 2.0 ± 0.8 |
| H8-NA70% | 117.8 ± 17.8 | 47.9 ± 16.7 | 0.4 ± 0.3 | 2.6 ± 0.2 |
| H8-NA30% | 58.7 ± 13.3 | 29.7 ± 6.2 | 0.5 ± 1.0 | 8.9 ± 6.4 |

Analysis of variance

| Source of variation | df | Mean square | F | P |
|---------------------|----|-------------|---|---|
| IM                  | 4  | 6922.3      |  | ns|
| RV                  | 3  | 6922.3      |  | ns|
| Year                | 1  | 6922.3      |  | ns|
| IM × RV             | 12 | 6922.3      |  | ns|
| IM × Year           | 4  | 6922.3      |  | ns|
| RV × Year           | 3  | 6922.3      |  | ns|
| IM × RV × Year      | 12 | 6922.3      |  | ns|

N$_2$O emissions under contrasting climate conditions. As shown in Fig. 4, clear N$_2$O fluxes peaks were detected mainly in the NA30% or NA70% plots for both varieties. However, at all the irrigation levels, no significant differences in N$_2$O emissions were observed between Hanyou8 and Huayou14 in either season. Most of the

N$_2$O emissions under contrasting climate conditions. As shown in Fig. 4, clear N$_2$O fluxes peaks were detected mainly in the NA30% or NA70% plots for both varieties. However, at all the irrigation levels, no significant differences in N$_2$O emissions were observed between Hanyou8 and Huayou14 in either season. Most of the
N₂O flux peaks were detected after fertilization, regardless of the rice variety. The influence of fertilization on N₂O emissions was relatively transitory and vigorous (Fig. 4). The average total N₂O emission was 1.2 kg N₂O ha⁻¹ and ranged from 0.2 to 2.0 kg N₂O ha⁻¹ in the NA100% plots, which was consistent with the values (0.4–5.3 kg N₂O ha⁻¹) recorded in many previous studies from the same region on paddies subjected to similar water management regimes and N fertilizer application rates.\(^9,32–35,46\)

The NA70% and NA30% plots increased total N₂O emissions by 22–146% and 26–338%, respectively, compared to the NA100% plots. However, no significant differences in total N₂O emissions were detected amongst the irrigation treatments (Table 2). Hou et al. also found that N₂O emissions under controlled irrigation (NA30%) increased by 135% relative to traditional irrigation (NA100%)\(^33\). Reductions in irrigation water to the rice paddies frequently subject the soil to alternating wet/dry conditions, which stimulates N₂O producers activity and increases N₂O emissions\(^4\). The increased N₂O emissions in the NA70% and NA30% plots after fertilization, relative to the NA100% plot, are probably due to the abundant, newly-added N\(^6\) and the suitable soil moisture conditions\(^33\). Finally, there was no significant difference in total N₂O emissions between Huayou14 and Hanyou8 (Table 2).

There were larger and more N₂O flux peaks in the normal season of 2014 than in the ‘warm and dry’ season of 2013. Similarly, Tian et al. also suggested that an increase in precipitation could enhance N₂O emissions after the DNDC model simulation.\(^29\) Alternative wet and dry soil conditions caused by frequent precipitation would enhance N₂O production through nitrification and denitrification in 2014.\(^47\) However, in this study, the SSWD when fertilizer was applied may play an important role in controlling N₂O emissions. The averaged SSWD over all treatments was higher after fertilization in the ‘warm and dry’ season of 2013 (5.3 cm and 1.9 cm after base and heading fertilization, respectively) than in the normal season of 2014 (2.6 cm and 1.0 cm after base and heading fertilization, respectively) (Fig. 2). In a freshwater marsh, Yang et al. also found that a lower water table position (−11 to 0 cm) enhanced N₂O emissions relative to higher water tables (+2 to +14 cm)\(^48\). Similarly, in a northern boreal fen located in north-western Finland, Lohila et al. reported that the highest N₂O fluxes occurred when the SSWD was about 4 cm, whereas atmospheric N₂O was consumed when the SSWD was 15 cm\(^49\). When the SSWD is lower, less N₂O dissolves into the surface standing water and more N₂O is probably quickly released into the atmosphere. In contrast, higher SSWD could restrict the availability of oxygen and therefore favor the formation of molecular nitrogen (N\(_2\)) instead of N₂O. Hence, in this study, N₂O emission might be more related to fertilization and SSWD rather than rice variety and high air temperature.

**Rice grain yield and equivalent CO₂ emissions (CO₂-eq) under contrasting climate conditions.** In the NA100% plots, the average rice yield was 9.3 t ha⁻¹ with a range of 8.7–10.1 t ha⁻¹ (Table 3), which was higher than that recorded in other studies (4.8–9.3 t ha⁻¹) conducted in the same region\(^7,9,32–35,46\). The potentially
negative effect of less precipitation on rice grain yield may be offset by irrigation in the ‘warm and dry’ season. However, rice grain yield significantly decreased with the reduction in the amount of irrigation ($P < 0.01$, Table 3). In the ‘warm and dry’ season, the Huayou14 yield loss was 10% in the NA30% plots compared to the NA100% plots, which was greater than the yield loss recorded for Hanyou8 (6%). This indicates that Hanyou8 is more drought-resistant with regards to rice grain yield, which agrees with the results reported by Luo20.

Recently, Kim et al. used the CERES-Rice 4.0 crop simulation model to investigate the effects of climate change on rice grain yield in the temperate climate regions under the East Asian monsoon system and suggested that the air temperature increases could lead to a significant decrease in rice grain yield by 22.1–35.0%50. In this study, rice grain yield was significantly lower in the ‘warm and dry’ season (2013) than in the normal season (2014) ($P < 0.001$, Table 3). The yield decreased by 13–19% for Huayou14 and 7–12% for Hanyou8 in 2013 compared to the yield in 2014 and this was probably due to higher air temperature and reduced precipitation. In another case study conducted in the same region, Liu et al. reported that although the average rice grain yield increased by 46% from the 1980s to 2000s due to the soil improvement, rice variety updating and agricultural management advances, the climate conditions (e.g. higher air temperature, less precipitation) had a negative effect on rice grain yield41. Generally, air temperature enrichment in rice growing seasons could shorten rice development and increases in CO$_2$-eq emissions caused by higher respiration demand25. Moreover, there was a significant interaction between rice variety and year ($P < 0.001$, Table 3). This suggests that the CO$_2$-eq emissions vary considerably with rice growing season or rice variety. Furthermore, CO$_2$-eq emissions from the NA70% and NA30% plots of both rice varieties (excluding H8-NA30% in the 2014 normal season) were potentially depressed when compared to the NA100% plot (Table 3). The decreases in CH$_4$ emissions from the NA70% and NA30% plots were the main cause of the effective depression in CO$_2$-eq emissions, especially during the ‘warm and dry’ season. However, in the normal season, due to the higher N$_2$O emissions, reductions in the amount of irrigation had little effect on CO$_2$-eq emissions.

In conclusion, CH$_4$ and N$_2$O emissions strongly differed according to rice variety and irrigation management between the two rice growing seasons under contrasting climate conditions. The amount of irrigation water was significantly higher in the ‘warm and dry’ season than that in the normal season. Although the same amount of irrigation water was applied to the two rice varieties, the SSWDs in the plots planted with Hanyou8 were higher than Huayou14, due to lower water demand from Hanyou8. The CH$_4$ emissions by Huayou14 and Hanyou8 increased 93% and 161% in the ‘warm and dry’ season (2013), respectively, compared with that in normal season (2014). Moreover, the CH$_4$ emissions from Hanyou8 were higher than from Huayou14 in both seasons. Reducing the amount of irrigation water can effectively reduce the CH$_4$ emissions, regardless of the rice variety and climate conditions. However, less irrigation during the ‘warm and dry’ season greatly decreased the Huayou14 grain yield, but had little impact on Hanyou8 yield. In contrast, compared to the effect of rice variety, N$_2$O emission depended

### Table 3. Rice grain yield and CO$_2$-eq emissions in the 2013 and 2014 rice growing seasons. Numbers in the table represent means ± standard errors. H8 = Hanyou8, H14 = Huayou14, NA100% = normal amount of irrigation, NA70% = 70% of normal irrigation, NA30% = 30% of normal irrigation, IM = Irrigation management, RV = Rice Variety. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ns = not significance at 0.05 level.

| Treatments       | Rice grain yield (t ha$^{-1}$) | CO$_2$-eq emission (kg CO$_2$-eq t$^{-1}$) |
|------------------|--------------------------------|------------------------------------------|
|                  | 2013                           | 2014                                     |
|                  | 2013                           | 2014                                     |
| H14-NA100%       | $8.8 \pm 0.1$                 | $10.1 \pm 0.2$                          |
| H14-NA70%        | $8.3 \pm 0.2$                 | $10.0 \pm 0.2$                          |
| H14-NA30%        | $7.9 \pm 0.0$                 | $9.8 \pm 0.1$                           |
| H8-NA100%        | $8.7 \pm 0.1$                 | $9.4 \pm 0.1$                           |
| H8-NA70%         | $8.6 \pm 0.3$                 | $9.3 \pm 0.1$                           |
| H8-NA30%         | $8.2 \pm 0.4$                 | $9.3 \pm 0.1$                           |

Analysis of variance

|                          | IM | RV | Year | IM × RV | IM × Year | RV × Year | IM × RV × Year |
|--------------------------|----|----|------|---------|-----------|-----------|----------------|
| ** ns                    | ns | ns | ns   | ns      | ns        | ns        | ns             |

The average CO$_2$-eq emissions in the NA100% plots was 378 kg CO$_2$-eq t$^{-1}$ with a range of 170 to 736 kg CO$_2$-eq t$^{-1}$ (Table 3), which was within the 33–557 kg CO$_2$-eq t$^{-1}$ range reported in previous studies conducted in the same region5,32–35. In most treatments, the detected CO$_2$-eq emissions were higher in the ‘warm and dry’ season than in the normal season. However, the difference between the two seasons was not significant (Table 3). Higher CH$_4$ emissions and lower rice grain yields from the treatments led to greater CO$_2$-eq emissions in the ‘warm and dry’ season relative to the normal season. Interestingly, there was a significant difference in CO$_2$-eq emissions between Huayou14 and Hanyou8 ($P < 0.05$, Table 3). This suggests that the CO$_2$-eq emissions vary considerably with rice growing season or rice variety. Furthermore, CO$_2$-eq emissions from the NA70% and NA30% plots of both rice varieties (excluding H8-NA30% in the 2014 normal season) were potentially depressed when compared to the NA100% plot (Table 3). The decreases in CH$_4$ emissions from the NA70% and NA30% plots were the main cause of the effective depression in CO$_2$-eq emissions, especially during the ‘warm and dry’ season. However, in the normal season, due to the higher N$_2$O emissions, reductions in the amount of irrigation had little effect on CO$_2$-eq emissions.
more on fertilization and surface water depth when the fertilizer was applied. Under the global warming
scenarios, feasible reductions in the amount of irrigation water applied and the suitable selection of rice varieties
would be a promising way to mitigate greenhouse gas emissions as well as maintain rice grain yield.

Materials and Methods

Study site and experimental design. The study was conducted in an experimental field at the Shanghai
Engineering Research Center of Low-carbon Agriculture, which is a part of the Zhuanghang Experimental
Station (30°52′N, 121°23′E). It is located in the Yangtze River delta zone in east China. A rice-wheat cropping
rotation system is the typical practice in this area. The paddy field soil was plowed to a depth of ~15 cm, and its
chemical and physical properties were as follows: soil organic C (SOC) 13.7 g·kg⁻¹, total N 1.4 g·kg⁻¹, bulk density
1.4 g·cm⁻³, and pH (H₂O) 7.6.

Each experimental plot was 60 m² and an impermeable membrane was buried vertically in the soil around
each plot at 1.1 m depth to prevent lateral seepage between the experimental plots. Then a concrete wall (30 cm
width × 60 cm height) was built around the experimental plots. It was half buried into the soil over the impermea-
ble membrane. A centrifugal pump (SW100-160, 100 m³·h⁻¹, Shanghai Sanxing Supply and Drainage Equipment
Co., Ltd., Shanghai, China) and polyethylene pipes were used to transport river water to each plot for irrigation. A
meteorological station was established nearby in 2012, which provided data about the air/soil temperature, dry/
wet precipitation, evaporation, solar radiation, wind speed/direction etc.

Two rice varieties (Oryza sativa L. Huayou14 and Hanyou8) and three types of irrigation management were
employed in this study. Each treatment was replicated three times, resulting in a total of 18 plots in this experi-
ment (i.e., 2 rice varieties × 3 irrigation levels × 3 replicates). Huayou14 is a high-yielding hybrid that is often cul-
tivated by local farmers and Hanyou8 was recently developed by the Shanghai Agrobiological Gene Center for its
water-saving and drought-resistant traits. The three types of irrigation management applied were normal amount
of traditional irrigation management (NA100%), 70% of normal (NA70%), and 30% of normal (NA30%). The
performance of NA100% was consistent with conventional irrigation practice for meeting rice growth demand.

The other two types were applied proportionately during every irrigation event when little or no surface-standing
water was observed in the NA100% plot for Huayou14. The irrigation was mainly carried out between 30 and 100
days after transplanting.

Climate conditions and agricultural practices. Seasonal changes in daily mean air temperature, daily
precipitation, and soil temperature at 5 cm depth in the 2013 and 2014 rice growing seasons are shown in Fig. 1.
The mean seasonal air temperature was 26.7 °C and ranged from 14.8 to 33.5 °C during the 2013 rice growing
season (Table 1 and Fig. 1a), whereas it was 24.4 °C (ranging from 14.7 to 30.2 °C) in 2014 (Table 1 and Fig. 1b).
The mean seasonal air temperature (24.4 °C) in 2014 was similar to the normal value (24.7 °C) reported by Su
in this region55. The mean seasonal air temperature in 2013 was 2.3 °C higher than that in 2014. Seasonal varia-
tions in soil temperature were similar to the daily mean air temperature (Fig. 1). Total precipitation in the 2013
and 2014 seasons was 492.1 and 762.7 mm, respectively (Table 1). In this region, annual precipitation is about
1200 mm, and about 60% of precipitation occurs between May and September56. In the 2013 season, precipitation
between June and September (i.e., a duration from transplanting to the grain-filling stage) was only 271.8 mm,
and this season was considered as a ‘warm and dry’ season. In contrast, in 2014, the total precipitation between
June and September was similar to the average for the area, and this season was regarded as normal season.

Rice plants were transplanted at a density of 20 hills per m² on June 14/16 and harvested on October 21/22
in 2013 and 2014, respectively. The N fertilizer application rate was 225 kg·ha⁻¹, which was applied at a ratio of
5:3:2 (w/w/w) as base, tillering and heading applications, respectively. The base fertilizer was applied in the form
of a compound fertilizer at 1–2 days before transplanting. The tillering and heading fertilizers were applied in the
form of urea at about 1 week and 7 weeks after transplanting, respectively. Phosphorous (P₂O₅) fertilizer was
applied as a base, compound fertilizer at a rate of 112.5 kg·ha⁻¹, and 44% potassium (K₂O) fertilizer was applied
as a base, compound fertilizer at a rate of 255 kg·ha⁻¹. The remaining of potassium (K₂O) fertilizer was applied as a
heading fertilizer in the form of commercial potassium chloride (KCl).

There were 12 and three irrigation events in the 2013 and 2014 seasons, respectively. Mid-season drainage
(MD) is a conventional agricultural practice during the rice growing season. The MD began on July 19/21 and
finished on July 29/August 4 in 2013 and 2014, respectively.

Measurements. The samples used to determine CH₄ and N₂O concentrations were taken using a static trans-
parent chamber consisting of a plexiglass base frame (50 cm length × 40 cm width × 20 cm height) and a plexiglass
lid (50 cm × 40 cm × 50 cm) equipped with a battery-driven 12 V fan at the center of its inner top. Other plexi-
glass frames were used to extend the lid height, by 20, 40, or 60 cm depending on the height of rice plants. The
base frames were inserted approximately 15 cm into the soil, and four hills of rice plants were transplanted. One
base frame was placed in each plot. Four gas samples were collected from each chamber at 6-min intervals using
an auto gas sampler attached to four aluminum foil gas bags (1 L, Dalian Delin Gas Packing Co., Ltd., Dalian,
China) at each sampling time. The auto gas sampler was composed of a 12 V rechargeable battery (NP7-12,
YUASA Battery (Guangdong) Co., Ltd, Guangzhou, China), a gas pump (FAY4002, 2 L min⁻¹, Chengdu Qihai
E&M Manufacturing Co., Ltd., Chengdu, China), a box containing a circuit board (Nanjing Weina Electronic
Co., Ltd., Nanjing, China), and a series of compact direct-operated 2-port solenoid valves (VDW23-6-G-1, SMC
Pneumatics Ltd., Tokyo, Japan).

The gas samples from all the plots were collected between 08:00 and 10:00 and immediately taken to the
laboratory. The concentrations of CH₄ and N₂O were determined by a gas chromatograph (7820 A, Agilent
Technologies, Inc., Santa Clara, CA, USA) equipped with a flame ionization detector and an electron capture
detector, respectively. The sampling frequency was once a week. However, whenever there was a fertilizer application, an MD, or irrigation after MD, a higher sampling frequency (once every 2 days) was used and daily sampling lasted for one week. CH$_4$ and N$_2$O flux were calculated by examining the linear increases of CH$_4$ and N$_2$O concentrations in the headspace of the chambers over time. The seasonal total CH$_4$ and N$_2$O emissions from all plots were calculated directly from the fluxes.

The surface-standing water depth (SSWD) was measured directly using a ruler after each gas-sampling event. Soil Eh (Oxidation-Reduction Potential) was detected at 5 cm soil depth with a pH/NO$_3$/Eh meter (PRN-41, DKK-TOA Co., Tokyo, Japan). Soil temperature was monitored at 5 cm soil depth using a moisture meter (HH2, Delta-T Devices Ltd, Cambridge, UK) during each gas-sampling event around the base frames. At the end of each rice growing season, the plants in each plot were manually harvested. The dry weight of the rice grains was determined using an oven at 75 ℃. Finally, the rice grain yield of each plot was calculated on a rice grain dry weight basis using the equation:

$$RY = DW/(1-14.5\%)$$

where RY is the rice grain yield (t·ha$^{-1}$), DW is the dry weight of rice grains (t·ha$^{-1}$), and 14.5% was used as the standard moisture content for storage of the rice varieties used in this study.

The equivalent CO$_2$ (CO$_2$-eq) emission for total CH$_4$ and N$_2$O emissions (greenhouse gas intensity) was calculated on a rice grain yield basis using the equation:

$$T_{CO2\text{-eq}} = \left(T_{CH4} \times 25 + T_{N2O} \times 298\right)/RY$$

where $T_{CO2\text{-eq}}$ is the total amount of equivalent CO$_2$ emission (kg CO$_2$-eq·t$^{-1}$), $T_{CH4}$ is the total amount of CH$_4$ emission (kg·ha$^{-1}$), $T_{N2O}$ is the total amount of N$_2$O emission (kg·ha$^{-1}$), 25 and 298 are the multiples of GWP (global warming potential) for CH$_4$ and N$_2$O versus CO$_2$ over 100 years$^3$, and RY is the rice grain yield (t·ha$^{-1}$).

**Statistical analysis.** The impacts of the three parameters (irrigation management, rice variety, and year) on CH$_4$ and N$_2$O emissions from rice paddies were examined. Their effects were analyzed using the general linear model for analysis of variance along with the least significant difference test. The significance level for both tests was 5%. SPSS 20.0 statistical software (IBM Co., New York, USA) was used to conduct the analysis. The figures were prepared using SigmaPlot 12.5 software (Systat Software Inc., San Jose, CA, USA).

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**Acknowledgements**

This study was financed by National Natural Science Foundation of China (No. 41375157), National Key Technology Support Program of the Ministry of Science and Technology of China (No. 2013BAD11B02) and the Shanghai Municipal Agriculture Commission (Hu Nong Ke Tui Zi (2013) No. 1-1). The language in this paper has been re-edited and polished by International Science Editing.
Author Contributions
X.S., G.Z. and S.Z. conceived and participated the experimental design. H.S., Z.F. and G.C. carried out the experiments. H.S. and S.Z. wrote the main manuscript text and H.S. prepared all the figures and tables. All authors reviewed the manuscript.

Additional Information
Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Sun, H. et al. A two-year field measurement of methane and nitrous oxide fluxes from rice paddies under contrasting climate conditions. Sci. Rep. 6, 28255; doi: 10.1038/srep28255 (2016).

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