January 2010

Train-borne measurements of tropical methane enhancements from ephemeral wetlands in Australia

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Recommended Citation

Deutscher, Nicholas M.; Griffith, David W. T; Paton-Walsh, Clare; and Borah, Rittick: Train-borne measurements of tropical methane enhancements from ephemeral wetlands in Australia 2010.
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Abstract

We report greenhouse gas concentrations measured on a train covering a north-south transect through central Australia from north to south coast. During the monsoonal wet season we found significant enhancements in methane that correlate well with changing area of wetland inundation in Australian tropical savanna regions. We used a meteorological and air pollution model to quantify the ephemeral wetland fluxes necessary to cause the observed enhancements and estimate the constant Australian tropical wetland emissions. Annual Australian tropical ephemeral wetland fluxes are estimated at 0.4 ± 0.2 Tg CH₄, with permanent wetlands contributing a similar amount, 0.5 ± 0.2 Tg CH₄.

Keywords

train, borne, measurements, tropical, methane, wetlands, enhancements, australia, ephemeral, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

Deutscher, N. M., Griffith, D. W. T., Paton-Walsh, C. & Borah, R. (2010). Train-borne measurements of tropical methane enhancements from ephemeral wetlands in Australia. *Journal of Geophysical Research*, 115 (N/A), D15304-1-D15304-8.

Train-borne measurements of tropical methane enhancements from ephemeral wetlands in Australia

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Received 7 September 2009; accepted 2 February 2010; published 6 August 2010.

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Citation: Deutscher, N. M., D. W. T. Griffith, C. Paton-Walsh, and R. Borah (2010), Train-borne measurements of tropical methane enhancements from ephemeral wetlands in Australia, *J. Geophys. Res.*, 115, D15304, doi:10.1029/2009JD013151.

1. Introduction

[2] Methane is the second most important anthropogenic greenhouse gas, responsible for around 18% of anthropogenic radiative forcing [Forster *et al.*, 2007]. Since the industrial revolution, its atmospheric dry-air mole fraction has increased from around 700 nmol mol⁻¹ to around 1775 nmol mol⁻¹. A recent unexpected leveling off occurred between 1999 and 2006 [Dlugokencky *et al.*, 2003; Rigby *et al.*, 2008], breaking the consistent upward trend observed since around 1800. A positive annual growth rate has been observed again since early 2007 [Dlugokencky *et al.*, 2009; Rigby *et al.*, 2008]. Despite its importance to climate forcing, the global methane budget is still highly uncertain [Dlugokencky *et al.*, 2003], with recent estimates [Denman *et al.*, 2007] diverging by more than 20% in some components. Wetlands and termites are significant natural sources, while energy production, farmed ruminant animals, landfills, rice agriculture, coal mining, and biomass burning are important anthropogenic sources. Biomass burning has natural, as well as anthropogenic, causes. The main recognized sinks of methane are reaction with the OH radical in the troposphere and uptake by soils.

[3] The largest single methane source to the atmosphere is from natural wetlands, which constitute approximately 100–231 Tg CH₄ yr⁻¹ of the total annual global methane source budget of 50–610 Tg CH₄ [Denman *et al.*, 2007]. Wetlands cover approximately 5–7% of the global surface area, and about half of these are located in the tropics [Neue *et al.*, 1997]. Bousquet *et al.* [2006] showed via inverse modeling that the 1999–2006 leveling off was due to decreased

wetland methane emissions, compensating increased anthropogenic emissions, at least up until 2003. Indeed, wetlands dominate the interannual variability in methane sources, being responsible for around 70% of global anomalies and varying by ± 12 Tg CH₄ yr⁻¹ [Bousquet *et al.*, 2006]. Most of the year-to-year variability occurs within the tropics, both in wetland emissions and the photochemical sink strength. Around 15% of interannual variability in methane sources is due to biomass burning, with estimates of the annual biomass burning source ranging from 14 to 88 Tg CH₄ [Denman *et al.*, 2007].

[4] Wetlands include soils that are periodically or permanently flooded with water. When flooding occurs, O₂ availability to the soil is decreased by up to a factor of 10⁵ [Neue *et al.*, 1997]. In flooded anoxic soils, methane is produced largely by methanogenic bacteria. Once oxygen is depleted, anaerobic organisms use oxidized substrates as oxidizing agents for respiration. In order, nitrate, Mn(IV), Fe (III), and then sulfate are reduced. Methane formation is the terminal step in anaerobic breakdown of organic matter, on a timescale of 2 weeks to several months after flooding occurs [Neue *et al.*, 1997].

[5] Wetland methane emissions have both seasonal and diel patterns, with fluxes highest in the early afternoon and lowest late at night [Neue *et al.*, 1997]. Seasonally, emissions are highest in the summer and in the tropical wet season. Measurements of tropical methane mixing ratios have shown 50–60 nmol mol⁻¹ enhancements during the wet season at Seychelles (5°S), but only 10–15 nmol mol⁻¹ at American Samoa (14°S) [Hein *et al.*, 1997]. Emission rates of around 1 g CH₄ m⁻² day⁻¹ have been measured from inundated tropical wetlands, dropping to no measurable values with falling water table position [Keller, 1990; Walter and Heimann, 2000].

[6] In subtropical Australia it has been estimated that ephemeral wetlands have net methane emissions similar to those from permanent wetlands [Boon *et al.*, 1997; Dalal

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et al., 2008]. The extent of these temporary wetlands has been quantified from satellite imagery in arid Australian regions [Roshier and Rumbachs, 2004; Roshier *et al.*, 2001], but not in the potentially significant tropical regions that may have fluxes greater than three times higher than from the wetlands in arid Australia [Dalal *et al.*, 2008]. A global satellite study of inundation area has failed to see significant tropical Australian wetlands, apart from some small coastal regions [Prigent *et al.*, 2007].

[7] Wetlands play an important role in global warming because of the magnitude of their methane emissions and the positive feedback caused by the temperature dependence. Shindell *et al.* [2004] find that a doubling of CO₂ would be likely to cause an annual increase of 156–277 Tg yr⁻¹ in methane emissions from existing wetlands, largely in the tropics. This would result in an atmospheric increase of 430 nmol mol⁻¹ based on an atmospheric methane lifetime of 8.4 years.

[8] Termites are also a significant natural source of methane to the atmosphere. Termite methane emissions are estimated to be in the range of 20–30 Tg yr⁻¹ [Denman *et al.*, 2007]. Termites, like wetlands, produce more methane at higher temperatures and higher humidity. Martius *et al.* [1993] found that termite emissions in the Amazon could reach 4.9 mg CH₄ h⁻¹ for each kilogram of termite biomass. Two species of Australian savannah termites are particularly large methane emitters, with each kilogram of termite biomass capable of emitting more than 7 mg CH₄ h⁻¹ [Fraser *et al.*, 1986]. The Oceania savannah has termite methane fluxes in the range of 0.027 to 0.108 Tg CH₄ yr⁻¹ [Sugimoto *et al.*, 1998].

[9] Quantifying spatial and temporal variation of greenhouse gas amounts is important for understanding and mitigating emissions. Temporal variations are well quantified on seasonal to long-term scales, aided by the fact that the majority of existing greenhouse gas measurements occur at fixed locations. Spatial variations are less well quantified because of the gaps present in the measurement coverage. Satellite measurements (e.g., from SCIAMACHY) [Frankenberg *et al.*, 2008, 2005] increasingly provide some spatial constraints, but often these measurements are not sensitive to the boundary layer, where most variability occurs and sources are located. Because they measure an integrated (total column) amount, any boundary layer signals can be relatively dilute.

[10] Much of northern Australia is located within the tropics. This region has very distinct climate, with mid-year dry season and monsoonal wet season from approximately late December/January through to March. The monsoonal season is generally characterized by WNW flow, while the dry season sees predominantly SE winds in the morning, switching to a northerly sea breeze in the afternoon.

[11] Here we describe latitudinal transect measurements of key anthropogenic greenhouse gases across the Australian continent from a train-borne trace-gas analyzer. Trace gas measurements have previously been made from a mobile lab on the trans-Siberian railway [Oberlander *et al.*, 2002]. These measurements have been used, for example, to estimate and verify Russian emissions of ozone-depleting substances [Hurst *et al.*, 2004]. The Australian latitudinal transect from tropics to mid latitude, 12–34°S, is influenced by a variety of vegetation types, including agricultural land,

desert, and tropical savanna, across an area that has few or no previously reported measurements. We report measurements from the first three transects in both tropical wet and dry seasons. We particularly focus on the latitudinal variation in methane concentrations and their implications for tropical wetland fluxes. Using a regional-scale model, we provide a preliminary estimate of the scale of Australian wetland fluxes necessary to explain the measured spatial and temporal patterns.

2. Methods

[12] All measurements were made with a versatile in situ FTIR gas analyzer, capable of simultaneous high-precision measurements of CO₂, CH₄, N₂O, CO, and δ¹³CO₂. In brief, the analyzer consists of a 22 m path length multipass White cell coupled to a 1 cm⁻¹ Bruker IRCube FTIR spectrometer (BrukerOptics, Ettlingen, Germany). The FTIR and cell are mounted on a vibration-stabilized platform, and enclosed in a thermostated case. Fully automated gas handling is controlled by a solenoid valve manifold. A continuously flowing air sample is dried and drawn from an inlet through the White cell, and spectra are coadded for the required time interval, typically 5 min. The entire analyzer is controlled by in-house developed software.

[13] We deployed the analyzer on the Ghan railway, which runs north-south across central Australia, from Adelaide (34.9°S, 138.6°E) to Darwin (12.5°S, 130.9°E) and back. The analyzer was located in the train's luggage van, with an inlet protruding from the train at approximately mid-carriage height. All tubing is Synflex, chosen to eliminate wall effects that can compromise trace gas measurements. To date, three trips have been taken, from 24–29 February 2008, 30 March–4 April 2008, and 28 September–1 October 2008. Each trip consists of a 53 h northbound journey, a 17 h stopover in Darwin, and a 51 h southbound voyage. On both north- and southbound fractions of the trip the train stops for four hours at both Alice Springs (23.7°S, 133.9°E) and Katherine (14.5°S, 132.3°E). On trip 3 the instrument was removed at Katherine. During the voyages, the instrument operated continuously, averaging 600 coadded spectra over 5 min periods, with calibrations against a reference gas of known concentrations traceable to the World Meteorological Organization (WMO) scale performed twice daily. A GPS provided latitude and longitude information for each 5 min measurement, though this information was not available south of Alice Springs for the northbound fraction of the first transect.

[14] The Ghan operates with a diesel-electric motor, so the mid-carriage inlet height is chosen to reduce interference from exhaust emissions, which can track above depending on cross-wind conditions. During the northbound voyage, the luggage van is located near the rear of the 710 m long train; however, because the locomotives swap ends for the return trip, the sampling inlet is only 100 m behind the locomotives while traveling southbound.

3. Spectral Analysis

[15] Analysis of the IR spectra is performed using the Multiple Atmospheric Layer Transmission (MALT) non-linear least squares-fitting software [Griffith, 1996, 2002].

Figure 1. The latitudinal gradients on methane as measured on the Ghan for (top) trip 1, (middle) trip 2, and (bottom) trip 3. The shaded vertical bars indicate Alice Springs and Darwin, where the train stops and variations in CH_4 due to local effects are evident. The color scales show the date of each measurement.

MALT generates a modeled spectrum from initial estimates of gas concentrations and instrument line shape (ILS). The partial derivatives of the root mean square (RMS) residual are calculated with respect to the concentration and ILS parameters, and the Levenberg-Marquart algorithm [Press *et al.*, 1992] used to iteratively reduce the RMS residual difference between the measured and calculated spectra until a predefined criterion is satisfied. The best-fit calculation provides concentrations of the species present in the spectrum.

4. Results

[16] Figure 1 shows the dry-air mole fractions of methane as a function of latitude measured on the three transects. During all journeys, a background latitudinal gradient is apparent, on the order of $1.2 \pm 0.2 \text{ nmol mol}^{-1} \text{ deg}^{-1}$. This can be seen throughout the southern part of all trips. During trip 2 and particularly in trip 1 during the northern half of the transect, there is an increase in methane above the latitudinal gradient. This fraction of the journey occurs in the tropics. In all transects, the concentrations are consistent between the northbound and southbound journeys. In trip 1, the concentrations drop off at the northern end of the transect to a level that is consistent with the gradient measured south of the Tropic of Capricorn (23.5°S).

[17] CO_2 and CO are measured simultaneously with CH_4 . Ratios of carbon monoxide to carbon dioxide excesses over background increase dramatically, clearly showing when the sampled air has been affected by the diesel exhaust. There is no correlation between either of these gases and CH_4 , implying that the diesel engines are producing undetectable amounts of methane, and therefore no methane data were removed due to this effect. Surface water was visible in the tropical savannah region during daylight hours north of 16°S during trip 1, and to a lesser extent during trip 2, but not during the third trip. We hypothesize that the increased tropical methane measured during the first two transects is due to ephemeral tropical wetlands. Previously defined wetlands in the Northern Territory cover a relatively small area, and certainly do not include the ephemeral savannah wetlands observed during the first two trips. Previous work on quantifying temporary wetland coverage and fluxes has occurred in Australia's southeast, but not in the tropics, which are our current area of interest. An existing study on global inundation areas failed to recognize any over the area of interest [Prigent *et al.*, 2007].

[18] Ten day back trajectory analyses were performed using Hybrid Single-Particle Lagrangian Integrated Trajectory (HY-SPLIT) [Draxler and Hess, 1997] for Katherine and Darwin for the dates of all three trips. These analyses (Figure 2) show that the air sampled at this time is largely from the west to northwest for trip 1 (peak monsoon), the south to southeast for trip 2 (late monsoon), and the east and southeast for trip 3 (dry season). The ocean origin of the air sampled during trip 1, coupled with the fact that we see lower concentrations at the very northern end of this transect, suggests that it is not a simple latitudinal gradient, such as might be caused by Inter-Tropical Convergence Zone (ITCZ) movement transporting Northern Hemisphere air into northern Australia. The ITCZ is at its southernmost at close to that time of year, reaching to $\sim 23^\circ\text{S}$, but Hamilton *et al.* [2008] showed that despite this, a chemical equator forms north from Darwin, meaning that northern Australia is not chemically part of the Northern Hemisphere. The similar back trajectories, but differing concentrations, of the air sampled at both Katherine and Darwin during this trip point to a local effect being responsible for the enhancements. The enhanced methane appears to be picked up over the land crossed by the air masses before reaching Katherine.

[19] Other possible sources and sinks that could possibly contribute to the latitudinal increase are the sources from biomass burning, ruminant animals, and energy consumption and sinks from reaction with the OH radical and soil uptake. Of these, populations of ruminant animals and humans are less dense in tropical Australia, resulting in lower emissions from farming and energy production than in the south of the country. Biomass burning is largest in the savannas in the dry season, out of phase with the seasonality of the observed enhancements. A natural gas facility is present in Darwin, according to the Australian National Greenhouse Gas Inventory [Department of Climate Change, 2009b] and may be responsible for some of the methane buildup observed during the layover in Darwin. In addition, gas is transported to this station via pipeline running roughly parallel to the Ghan.

[20] Production of OH radical is at a maximum in summer, resulting in a corresponding CH_4 minimum in the Southern

Figure 2. Daily back trajectory analyses for (left) Darwin and (right) Katherine for midday of the dates of the transect measurements with 6 h time steps—(a) trip 1, (b) trip 2, and (c) trip 3.

Hemisphere in February. This seasonality is apparent in the mixing ratios observed at Adelaide, which are a maximum in September. Conversely, there is no apparent seasonality in the concentrations at the northern end of the transect. OH

concentrations have a larger seasonal cycle, but lower concentrations at southern mid-latitudes than in the tropics due to greater photolysis and H_2O availability in the tropics [Spivakovsky *et al.*, 2000], resulting in observations of

methane mole fractions at Cape Grim (41°S) and Cape Ferguson (19°S) exhibiting distinct and similar seasonality, while those at Samoa (14°S) are much less variable [Cunnold *et al.*, 2002; Rigby *et al.*, 2008]. OH concentrations are higher over land, due to higher surface albedo and concentrations of precursors NO and O₃ [Spivakovsky *et al.*, 1990]. The oceanic air sampled at the northernmost end of trip 1 should therefore have a higher CH₄ mole fraction if reaction with OH is the driving factor for the latitudinal gradient, but the concentrations are in fact lower, implying that the enhancements at lower latitudes are due to a local source. The OH radical sink would be unlikely to cause the spatial variability in measured CH₄ concentrations because it acts throughout the entire volume of the troposphere, thus resulting in smoother spatial changes. Methane loss via soil uptake is driven by soil moisture and is at a minimum after rainfall events [Kiese *et al.*, 2008]; however, this can essentially be viewed as a wetland effect.

5. CH₄ Flux Modeling

[21] The Air Pollution Model (TAPM) [Hurley *et al.*, 2005] is a prognostic meteorological and air pollution model. In this study we used TAPM to estimate the enhancement of CH₄ over background levels that would be observed from the Ghan given existing estimates of termite and cattle emissions from literature and cattle populations, and to quantify the tropical wetland methane source required to match the observed enhancements. In the model, CH₄ is treated as a nonreactive tracer since it is effectively inert within the modeled time scale. The model was run in the Eulerian grid module, with resolution of 25 vertical levels and 10 km × 10 km horizontal grid spacing, and has one hour time resolution, over a 1500 km × 1500 km domain. TAPM is driven by synoptic weather analyses on a 100 km grid, using fluid dynamical equations to predict local scale meteorology on the 10 km scale. TAPM was chosen based on its availability and ability to model on a relatively small spatial scale [Hurley *et al.*, 2005]. For each transect, we ran TAPM four times, with scenarios depicting termite, cattle, natural gas leakage, and wetland emissions. We assume that there is no contribution to the measured methane variability from outside the model domain.

5.1. Cattle and Termite Modeled Fluxes

[22] Cattle numbers and densities were estimated from regional Northern Territory Pastoral Industry Surveys. Each head of cattle was assumed to have an average CH₄ emission of 300 ± 30 g day⁻¹, estimated from the 2007 Australian National Greenhouse Gas Inventory [Department of Climate Change, 2009b], and total regional fluxes were estimated for four regions. The total Northern Territory cattle emission is of the order of 0.17 Tg CH₄ yr⁻¹. The termite methane fluxes are assumed to be spatially constant over the region shown in Figure 2b. The range of estimates of Sugimoto *et al.* [1998] gives us a window of expectation for the net termite flux of 0.027–0.108 Tg CH₄ yr⁻¹.

[23] For each of the twelve model runs (four tracers and three transects) we ran the model for 1 week spin-up time with the given emissions, and then over the duration of the campaign. For the spatial scale in which we are interested, 1 week provides ample lead-in time. We sampled the model

output at a number of locations along the train route and compared that output to the measured concentration enhancements. The measured enhancement is calculated by assuming that the methane latitudinal gradient is constant, and that any variation from that is due to local sources and sinks. The latitudinal gradient is calculated from the transect measurements south of the Tropic of Capricorn (23.5°S).

[24] For the cattle runs we see a modeled CH₄ enhancement of 3–4 nmol mol⁻¹, about an order of magnitude less than the measured increases. Similarly even using the maximum from the range of estimates for termite emissions results in a maximum modeled increase of 3 nmol mol⁻¹, again an order of magnitude smaller than the measured enhancement. Thus, neither cattle nor termite emissions produce a modeled concentration enhancement close to that measured. Combined cattle and termite emissions, would need to produce fluxes of 0.9–2.6 Tg CH₄ yr⁻¹, from three to ten times larger than the estimated fluxes, and are therefore not sufficient to explain the magnitude of the observed enhancement.

5.2. Potential Natural Gas Leakage Fluxes

[25] The Australian National Greenhouse Gas Inventory and the corresponding state and territory report [Department of Climate Change, 2009a, 2009b] are used to estimate natural gas leakage, or fugitive emissions, along the gas pipelines. Assuming that all Northern Territory fugitive emissions come from the pipeline in question at a constant rate throughout the year yields a potential leakage rate of 2.7 gCH₄ s⁻¹ km⁻¹. TAPM is run with an emission four times this amount to allow for possible underestimation in this reporting and yields modeled CH₄ enhancements on a sub nmol mol⁻¹ level for the time of all campaigns. Based on these assumptions, the gas pipelines therefore contribute undetectable amounts to the measured methane enhancements.

5.3. Modeling Wetland Emissions

[26] MODIS 8 day composite 250 m images (MOD09Q1) acquired in January and May 2008 were used for wetland classification of the study area. This MODIS surface reflectance product is computed from MODIS level-1B 250 m bands 1 and 2 and provides an estimate of the surface spectral reflectance for these bands. The MOD09Q1 data are provided every 8 days as a gridded Level-3 product in the sinusoidal projection. The product uncertainties are well defined over a range of representative conditions and are ready for use in scientific studies. Atmospheric, cloud, sensor, and other characteristics are used to quality control each pixel, and only the best quality pixels were selected for our analysis.

[27] MODIS band 2 was used for rule-based classification. The spectral range of band 2 is 841–876 nm, which belongs to NIR spectra region. Water vapor absorbs radiation at this wavelength. This absorption characteristic of water was used to set the reflectance threshold for band 2 to delineate wetlands. The reflectance of clear water is very low in the near-infrared (NIR) region. However, due to the presence of sediment, living biota within the water column bottom increase the reflectance of wetlands slightly. Investigating the spectral profile of wetlands in the MODIS scene of the study area and visually comparing low-resolution

Figure 3. The area surveyed (a) for wetland coverage from composite MODIS satellite images. The quantified wetlands areas are shaded and shown in blue for (b) January 2008 and (c) May 2008. The red dots represent the Ghan train route.

MODIS wetlands to high-resolution 30 M Landsat wetland scenes yielded a threshold for wetland demarcation. A series of decision rules were also tested by varying the thresholds and comparing the results with the Landsat wetlands before determining this threshold. Not all wetlands are captured by the set threshold; however, increasing the threshold greatly increases misclassification, therefore leading to its selection as the optimal threshold for the wetland classification for the study area.

[28] Previously, satellite observations have been used to characterize inundation on a global scale [Prigent *et al.*,

2007], but that study appears not to see any inundation over the tropical north of Australia, such as that observed from the train in February and March 2008. A 630,000 km² area was surveyed using MODIS data and is shown in Figure 3, corresponding in latitude to the savannah area of the Northern Territory surrounding the Ghan train route. The resulting vectorized maps are shown in Figures 3b and 3c, with the wetland areas shown in shades of blue and the Ghan train route shown in red. The wetland extent is approximately 205,000 km² in January and around 55,000 km² in May. The uncertainties on these areas are approximately 10%. Thus, nearly three-quarters of the area of January wetlands are not detected during May. We find that in savannah regions of Australia, up to 25% of the area constitutes ephemeral wetlands, with approximately 10% of the total area being permanent wetlands. In January, there is a considerable density of wetlands to the north of the surveyed area, with the wetland coverage decreasing toward the south with the rainfall gradient. The total savannah area in Australia is approximately 1.9 million km².

[29] TAPM was run with input source areas corresponding to the wetland extent characterized via satellite, and a constant CH₄ flux. For trips 1 and 2 the wetland distribution shown in Figure 3b is used, and that in Figure 3c is used for trip 3. The input flux is scaled over the entire model time series to match the modeled and measured concentrations, thereby giving an estimate of the wetland flux. An ensemble

Figure 4. Measured (open diamonds) and modeled (closed squares) CH₄ with latitude for each of the three campaigns for the northernmost latitudes, corresponding to the area modeled.

Figure 5. Hourly average measured (open diamonds) and modeled (closed squares) CH_4 time series for each campaign. The data presented here correspond with that presented in Figure 4.

of scalings are used to give a range of possible fluxes, thereby defining the flux magnitude and its uncertainty. Figure 4 shows the measured and modeled latitudinal CH_4 gradients north of 20°S , while Figure 5 shows the modeled and measured time series, with the measurements averaged to the model time grid, rather than presented as the raw 5 minutely values as in Figure 4. The modeled concentrations include the added background component of the $1.2 \pm 0.2 \text{ nmol mol}^{-1} \text{ deg}^{-1}$ gradient, with the modeled concentration matched to that measured at 20°S . In general, the hourly model values capture a good degree of the spatial and temporal variability. For trips 2 and 3, the flux magnitude of $0.10 \pm 0.03 \mu\text{g m}^{-2} \text{ s}^{-1}$ provided a good match, while for trip 1 a flux of $0.07 \pm 0.02 \mu\text{g m}^{-2} \text{ s}^{-1}$ obtains the best match between model and measurement values. The increased flux necessary for trip 2 compared to trip 1 fits well with the mechanism of methane production in wetlands, which sees maximum emissions delayed from the inundation event while other noncarbon substrates are preferentially reduced before methanogenesis commences, resulting in a delay on methane flux commencement ranging from 3 days to 6 months [Boon *et al.*, 1997]. The assumption of a constant background methane gradient introduces uncertainty to the fluxes estimated here, as does the assumption of a non-time-

varying wetland flux. In addition, there may be influence on the measured methane from outside the model domain; however, it is not possible to run boundary conditions through our current model framework.

[30] We used trip 3 to estimate the flux from permanent wetlands given a distribution detailed in Figure 3b. From this, assuming a constant flux rate across the year, a flux of $0.5 \pm 0.2 \text{ Tg yr}^{-1}$ is derived. From the first two trips an estimate of the ephemeral flux can be calculated, resulting in an estimated contribution of $0.4 \pm 0.2 \text{ Tg CH}_4 \text{ yr}^{-1}$, assuming that the ephemeral wetland fluxes are $0.10 \pm 0.03 \mu\text{g m}^{-2} \text{ s}^{-1}$ and contribute for 3 months of the year. Therefore permanent and transient tropical wetlands contribute approximately equally (a similar finding to Boon *et al.* [1997]), around 10% each of the total Australian methane budget. They are therefore significant, previously uncharacterized sources in the Australian methane budget. Together they constitute about 1% of global wetland methane emissions. Even if these ephemeral wetlands were present for 1 year only, this represents a significant methane source within that year's budget, about 5% of the interannual variability ($\pm 12 \text{ Tg yr}^{-1}$) of wetlands.

[31] The average modeled CH_4 flux over the defined wetland areas required to match measurements is $250\text{--}360 \mu\text{g CH}_4 \text{ m}^{-2} \text{ h}^{-1}$, well within the range of $3,000\text{--}44,000 \mu\text{g CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ [Dalal *et al.*, 2008] of reported emissions in Australia (none of which have been measured in the tropics). Other measurements of wetland fluxes in the tropics average at around $6.0 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$, ranging from 0.4 to $91.1 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ [Dalal *et al.*, 2008], higher than calculated here, probably because less than 100% of the areas that we have defined as wetland are actually emitting CH_4 . The calculated flux here does agree with values of $300 \pm 140 \mu\text{g m}^{-2} \text{ h}^{-1}$ measured in low-water-level flooded Amazon forests [Devol *et al.*, 1990] and diffusive fluxes of $420 \pm 710 \mu\text{g m}^{-2} \text{ h}^{-1}$ from Brazilian lakes and floodplains [Marani and Alvala, 2007].

6. Conclusions

[32] Australian ephemeral savanna wetlands are a significant source of methane, contributing up to about 10% of Australia's total annual methane emissions with an annual source strength of $0.4 \pm 0.2 \text{ Tg CH}_4$ in 2008. Ephemeral savanna wetlands are roughly equal in magnitude as a methane source on an annual scale to the colocated permanent wetlands, which have a source of $0.5 \pm 0.2 \text{ Tg CH}_4$. Both temporary and permanent wetlands are therefore significant contributors to Australia's methane emissions. Additional isotopic measurements could confirm the nature of the observed source. The implied diffuse fluxes from this study are similar to those previously measured in South America.

[33] **Acknowledgments.** The authors thank the Australian Research Council and the Department of Climate Change (formerly Australian Greenhouse Office) for funding under Linkage Project LP0562346. We would also like to gratefully acknowledge Rachel Law for fruitful and insightful discussions, and Great Southern Railways, especially Brian Duffy and Shaun Crowe, for their support. The assistance of Glenn Bryant, Martin Riggensbach, Graham Kettlewell, and Travis Naylor in experimental design and instrument development and operation is also greatly appreciated.

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