1 Atmospheric methane: Comparison between methane's record in 2006-2022
2 and during glacial terminations.
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30 *The air is getting hotter. There's a rumbling in the skies.*
31 *I've been wading through the high muddy water, With the heat rising in my eyes.*
32 Bob Dylan: Trying to get to Heaven before they close the door.
33

Key points

35 The rapid growth in the atmospheric methane burden that began in late 2006 is very
36 different from methane's past observational record. Recent studies point to strongly
37 increased emissions from wetlands, especially in the tropics. This increase is comparable in
38 scale and speed to glacial/interglacial terminations when the global climate system suddenly
39 reorganised.
40
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Abstract

Atmospheric methane's rapid growth from late 2006 is unprecedented in the observational record. Analyses of atmospheric methane data attribute a large fraction of this atmospheric growth to increased natural emissions over the tropics, which appear to be responding to changes in anthropogenic climate forcing. Isotopically lighter measurements of $\delta^{13}C_{CH4}$ are consistent with the recent atmospheric methane growth being mainly driven by an increase in emissions from microbial sources, particularly wetlands. The global methane budget is currently in disequilibrium and new inputs are as yet poorly quantified. Although microbial emissions from agriculture and waste sources have increased between 2006-2022 by perhaps 35-40 Tg/yr, approximately another 35-45 Tg/yr of the recent net growth in methane emissions may have been driven by natural biogenic processes, especially wetland feedbacks to climate change. A model comparison shows that recent changes may be comparable or greater in scale and speed than methane's growth and isotopic shift during past glacial/interglacial termination events. It remains possible that methane's current growth is within the range of Holocene variability, but it is also possible that methane's recent growth and isotopic shift may indicate a large-scale reorganisation of the natural climate and biosphere is under way.

Plain language summary

Atmospheric methane's unprecedented current growth, which in part may be driven by surging wetland emissions, has strong similarities to ice core methane records during glacial-interglacial 'termination' events during global reorganisations of the planetary climate system. Here we compare current and termination-event methane records to test the hypothesis that a termination-scale change may currently be in progress.

Keywords

Atmospheric methane growth driven by biogenic sources. Sudden global climate change. Glacial/interglacial comparison.

Main Text

1. Introduction

In the past, rapid changes in atmospheric methane have signalled rapid global climate shifts. Does atmospheric methane's recent growth, sustained from the end of 2006 through 2022 and continuing, similarly signal a major global climate shift?

In the modern air, the global methane burden – the total amount of methane in the air – includes both emissions from human activities such as methane from fossil fuel use, agriculture and waste, as well as natural biogenic inputs. Both agricultural and natural emissions are subject to feedbacks from the sensitivity of the biosphere to changes in climate. Summing global biospheric change from measurement data across the planet is a complex task with large uncertainties, but provided direct anthropogenic forcing can be deducted (a difficult and complex task), the remaining non-anthropogenic growth in biogenic methane emissions provides a direct measure of change.

Unlike CO_2, whose annual cycle is strongly influenced by the spring growth and autumn leaf fall of deciduous plants in the temperate northern hemisphere, the natural methane cycle

87 reflects change across a much wider latitudinal spectrum, tropical, temperate and Arctic.
88 Natural biogenic sources include tropical and boreal wetlands, ruminants, termites, Arctic
89 bogs and permafrost, as well as forest and grassland fires, while anthropogenic biogenic
90 methane comes from agriculture and waste, especially food waste disposal. Aquatic
91 ecosystems, both natural and anthropogenic, contribute up to half the total emission
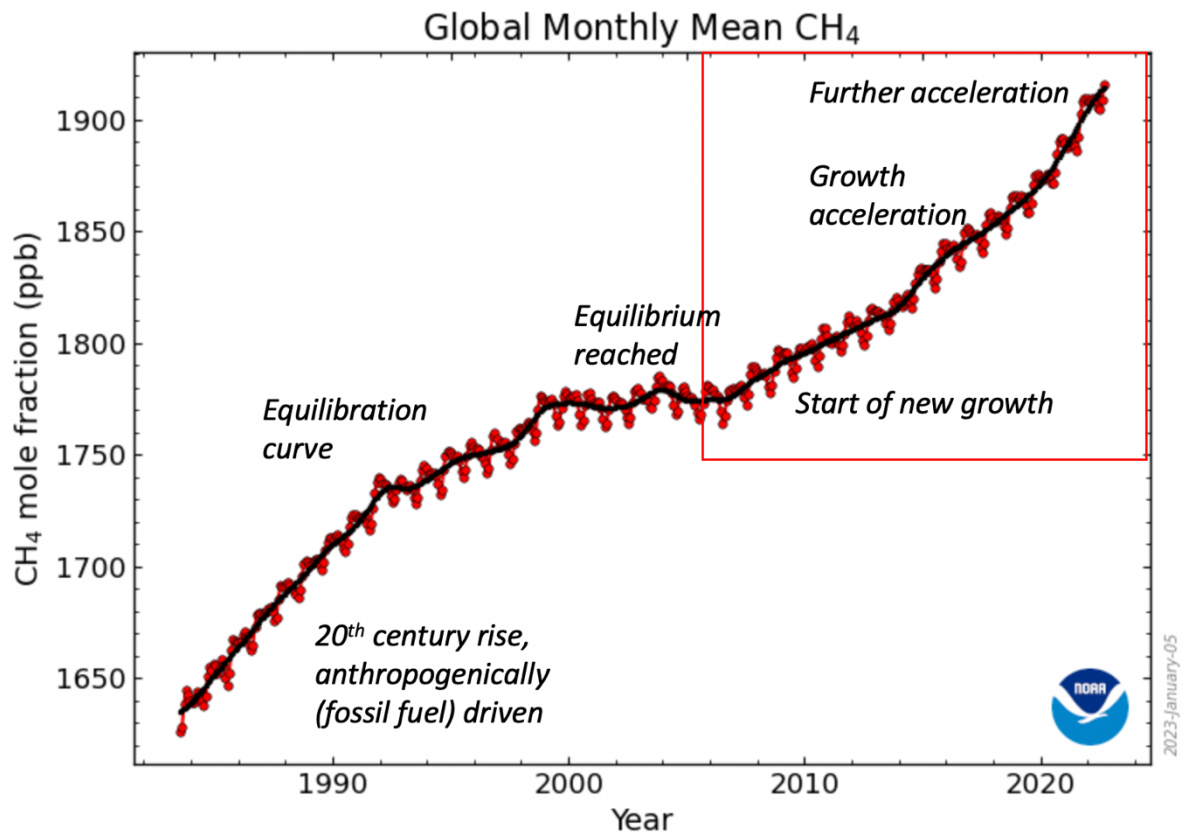92 (Rosentreter et al. 2021).

93 Starting in 2006 the atmospheric methane burden has grown strongly (Dlugokencky et al.
94 2011, Nisbet et al., 2014, Schaefer et al., 2016, Mikaloff-Fletcher and Schaefer 2019),
95 accompanied by a sustained negative shift in the carbon isotope delta value ($\delta^{13}C_{CH4}$). This
96 shift indicates present-day atmospheric growth is primarily driven by biogenic emissions
97 (Nisbet et al. 2016, 2019; Lan et al. 2021a,b, 2022; Basu et al 2022) and not primarily from
98 increased fossil fuel emissions, nor by greatly stronger sink processes. Note that we
99 distinguish between the atmospheric '*burden*' – the total mass of methane in the air
100 expressed in Tg; '*emissions*' or fluxes, in Tg/yr; and *emissions growth* in Tg/yr per year. 1 ppb
101 of methane, as an average mass fraction of the global atmosphere, has a mass of about
102 2.77Tg.

103 Methane's dominant sink is the atmospheric hydroxyl radical [OH], especially in the tropical
104 mid-troposphere, with minor sinks including reaction with atomic chlorine in the marine
105 boundary layer and bacterial methanotrophy in upland and forest soils. The formation and
106 distribution of [OH] is changing as the climatological tropics widen with expansion of the
107 Hadley cells (Nicely et al. 2018). While it remains unclear how much of the observed tropical
108 expansion is within the range of natural variability (Grise et al. 2019) the present rate of
109 increase is exceptional in the long-term record.

110 The following sections review recent work on the complex and often contradictory puzzle of
111 methane's post-2006 growth. That synthesis is then compared with past events in the
112 glacial paleoclimatological record, where is strong evidence (Möller et al. 2013) that fast
113 methane rises during rapid glacial to interglacial shifts in the global climate are driven by
114 feedbacks involving tropical wetlands that respond rapidly to warming.

115 *Figure 1. Global monthly mean of atmospheric CH₄, NOAA network. Note convex*
116 *equilibration curve to 2006; concave acceleration curve from 2007. The convex curve from*
117 *the 1980s to early 2000s is consistent with relaxation to a source-sink steady state*
118 *(Dlugokencky et al., 2003), but then the start of a renewed growth became apparent in*
119 *2007, and the slope of the new concave curve steepened in 2013 (acceleration of growth),*
120 *followed by further acceleration in 2020. Modified from Lan et al. (2022).*

121

Global Monthly Mean CH$_4$

122

1.1 Feedbacks

Anthropogenic methane emissions have dramatically added to the primary forcing of the climate (Saunois et al., 2020), but the extent of the feedback response of methane emissions as climate has become warmer and wetter remains uncertain (Dean et al, 2018). For methane in particular, it is difficult to separate primary emissions (e.g. gas industry and coal mine leaks), natural feedbacks (e.g. increased wetland emissions) and changing anthropogenic biogenic emissions from farming, sewage, and landfills. As fertiliser production, especially fixed nitrogen, has grown, the productivity of neighbouring wetlands may have risen, driven by nitrogen runoff. Rising CO_2 also acts as a fertiliser, globally promoting C3 plant growth (trees and bushes) (Haverd et al. 2020, Graven et al. 2013, Matthews, 2007, Möller et al. 2013), though this impact is eventually limited by supply of other nutrients such as fixed nitrogen and phosphorous (Wang et al, 2020).

Considering the interlinkages between climate and methane productivity, Dean et al. (2018) concluded that wetlands will form the majority of the methane climate feedback up to the year 2100. Higher primary productivity, in response to warmth, precipitation and inundation, supplies and enhances microbial activity in anaerobic environments. Methanogenic processes may respond more quickly to change than methanotrophic processes (Wen *et al*, 2018). We may have entered a new era of increased natural methane emissions from wetlands (Rosentreter et al. 2021), driven by multiple feedback factors, including increased rainfall and temperatures, higher rainfall in key areas (Lunt et al 2021), and higher ecosystem production, aided by agricultural impacts. If present-day feedback responses are indeed strong, then the biogenic component of methane's very strong current

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145 growth may be an integrative signal responding to, indicative of, and feeding global-scale
146 change.

147 Any modern global-scale climate change, by cause and starting point, must be
148 fundamentally different from past changes in the palaeoclimate record. Nevertheless, there
149 are strong analogies between methane's current growth and ice core methane records
150 during glacial-interglacial 'terminations'. In these events, the methane record tracked
151 planetary-scale meteorological reorganisations of the climate system (Broecker & Denton,
152 1990; Cheng et al. 2009; Denton et al. 2010). Thus, the question arises (Nisbet 2022, 2023):
153 Is methane's modern growth (Fig. 2) also a signal that a planetary-scale climate
154 reorganisation is underway?

155 *Figure 2. Annual mean growth (blue bars; ppb/yr) and acceleration in half-year intervals*
156 *(red,black bars; ppb/yr^2) of atmospheric methane inferred from NOAA data, 1984-2022*
157 *(NOAA 2023a). Red bars denote the gradient of the growth rate calculated using second-*
158 *order accurate central differences of the interior points and first-order accurate one-side*
159 *differences of the end points. Black bars denote the difference in atmospheric growth*
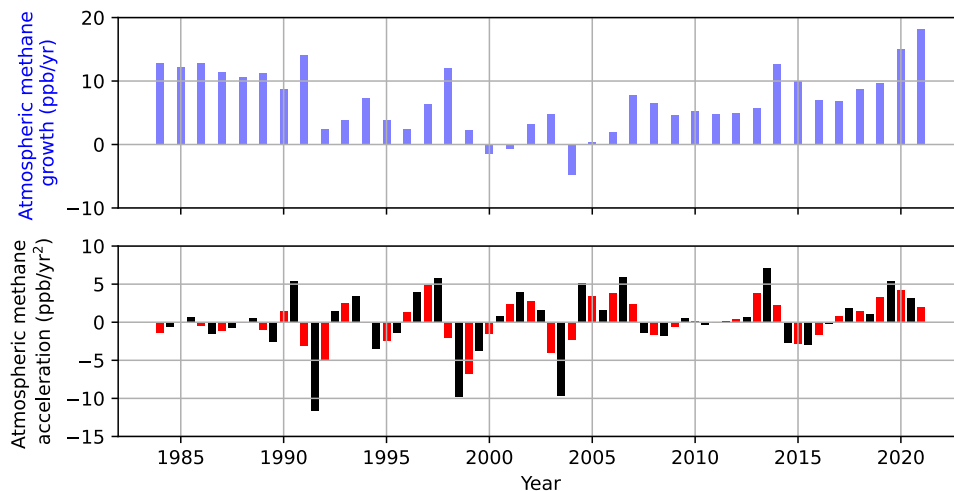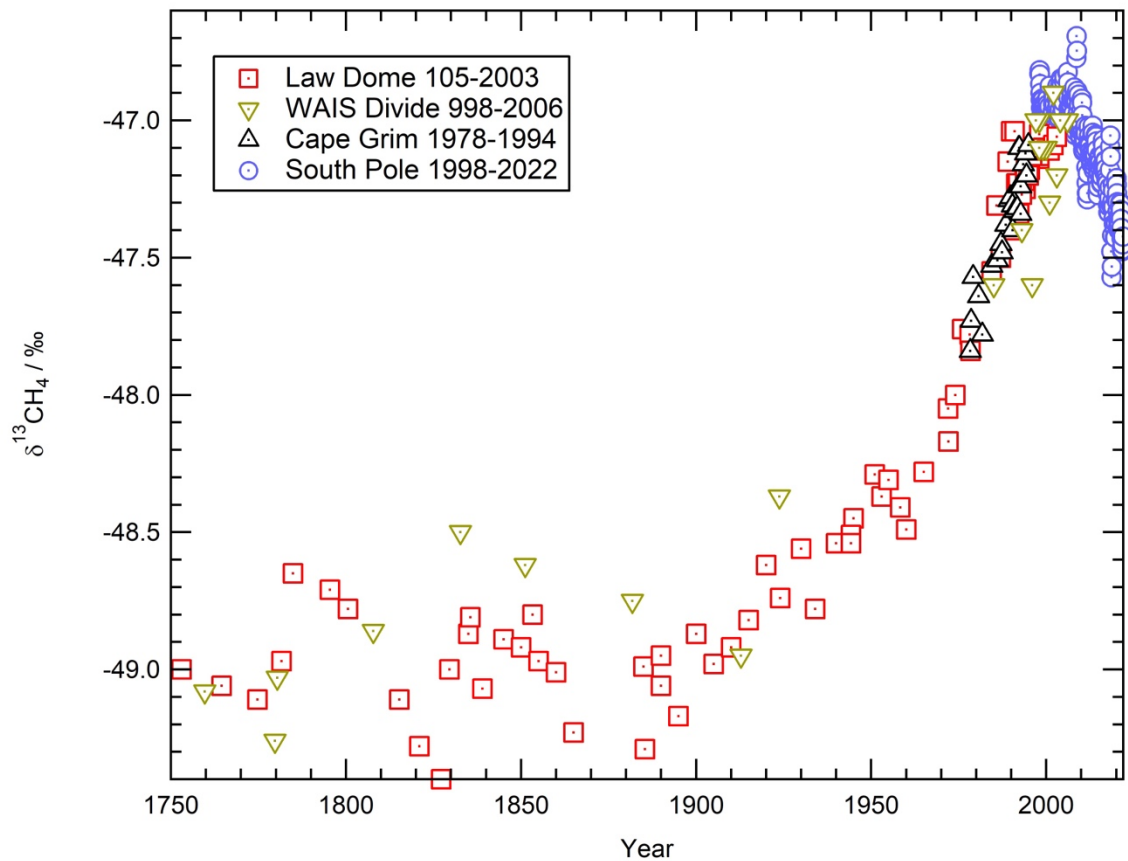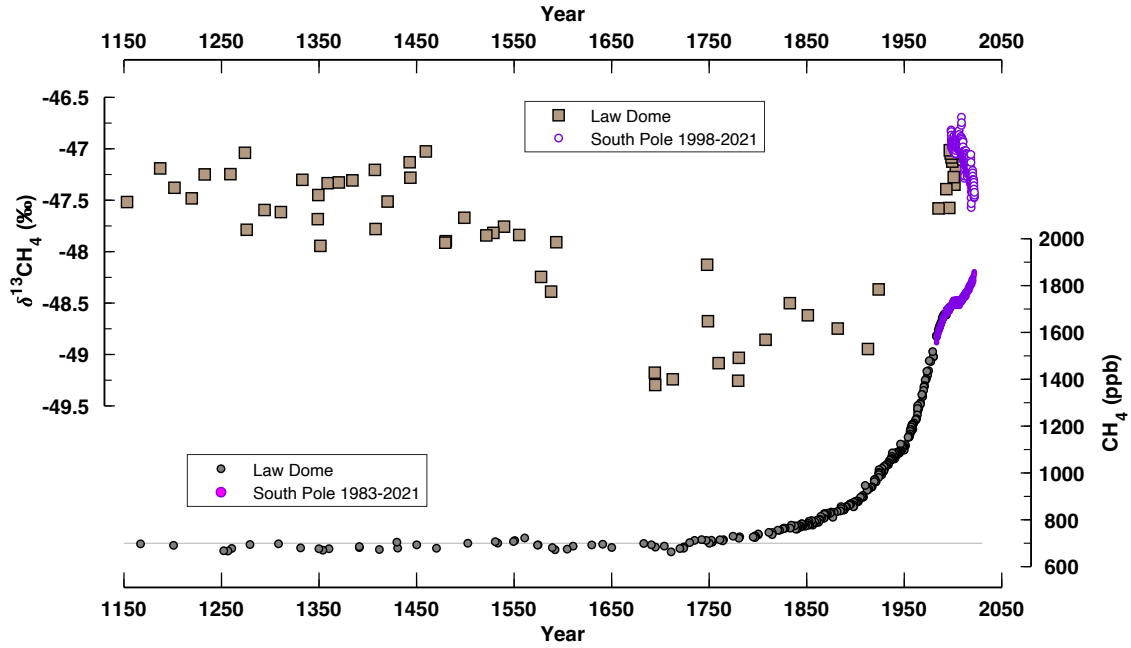160 *between successive years.*

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162

163 *Figure 3. Past records of $\delta^{13}C_{CH4}$.*

164 *3a. Methane and $\delta^{13}C_{CH4}$ record back to the year 1150 CE,* showing the background evolution
165 of both CH4 and $\delta^{13}C_{CH4}$ before *the budget was disturbed by human interferences (i.e.*
166 *before ca. 1500 -1600 AD), to indicate historic variability due to changes in climate and*
167 *wetland emissions on multidecadal or longer time scales. Note the CH$_4$ background is*
168 *essentially flat over pre-industrial time, but there is a notable negative trend of about 2‰*
169 *between 1500-1650 that is gradually reversed as coal-fired industrialisation begins. For*
170 *longer record see Sapart et al. (2012).*

171 *3b. Post-1750 $\delta^{13}C_{CH4}$ record from South Pole and ice core measurements, showing recent*
172 *record in more detail. Note long +ve trend in $\delta^{13}C_{CH4}$, driven by fossil fuel emissions, and*
173 *sustained reversal of trend since 2007.*

174 *Data from Law Dome: Ferretti et al. 2005; see also Rubino et al. 2019; WAIS Divide:*
175 *Mischeler et al 2009; Sapart et al. 2012 and from NOAA*
176 *https://gml.noaa.gov/aftp/data/trace_gases/ch4c13/flask/surface/).*

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178

2. Methane growth, pre-industrial period to present

180   There has been strong centennial-scale variation in methane's recent historic record (Fig. 3).
181   From Antarctic ice core measurements, Ferretti et al. (2005), Sapart et al. (2012) and
182   Mischler et al (2009) found that $\delta^{13}C_{CH4}$ was about -47‰ around 800 CE, but then showed a

183   strong depletion trend from about 900 CE to 1700 CE, until $\delta^{13}C_{CH4}$ was about -49‰. Prior to
184   the onset of industrialisation, in the medieval years from the 12th to the 19th centuries CE,
185   methane rose by around 100 ppb, accompanied by a negative trend in $\delta^{13}C_{CH4}$ from -47.5‰
186   to -49‰ (Fig. 3). Ferretti et al. (2005) interpreted this medieval 2‰ depletion as evidence
187   for a major drop in anthropogenic biomass burning emissions between 800-1700 CE, for
188   example a reduction in deliberate and intense North American grassland burning. CH₄ was
189   rising during this period, implying the reduction in biomass burning emissions must have
190   been more than balanced by other sources. This interpretation is supported by CO evidence
191   from ice cores. Agricultural methane emissions may have helped strengthen the negative
192   trend (Mischler et al. 2009). But that historic depletion rate was about 0.0025‰ per year,
193   totalling less than 0.04‰ over 15 years, very different from what has taken place in the 15
194   years 2007-2022.

195   Starting around the years 1750 to 1800 (Fig. 3b), with the onset of coal-fired and then oil
196   and gas-powered industrialisation, the $\delta^{13}C_{CH4}$ trend rapidly shifted positive (Etheridge et al.
197   1998, Ferretti et al. 2005, Mischeler et al 2009, Sapart et al. 2012). That exceptionally rapid
198   positive shift accompanying fossil-fuel industrialisation from the years 1800-2007 was +2‰
199   in 250 years, or about 0.01‰ per year, interpreted as evidence that the rise was primarily
200   driven by fossil fuel emissions, first mainly from coal, then with methane emissions as a by-
201   product of oil extraction and use, and more recently from the gas industry too.

202   In contrast, the ongoing 2007-2022 reverse negative shift in $\delta^{13}C_{CH4}$ has been -0.55‰ in 15
203   years: a rate of negative shift four times faster than the positive rise during industrialisation,
204   and more than tenfold the rate of the medieval depletion trend. However, it should be
205   noted that many biogenic sources, especially in extra-tropical wetlands, have greater
206   leverage on atmospheric $\delta^{13}C_{CH4}$ than fossil fuel emissions which are closer in source
207   signature to the bulk atmospheric value.

208   Sustained accurate methane measurement began in the late 1970s and by 1983 NOAA led a
209   co-operative global network collecting flask samples of air from remote sites. Between 1984
210   and 1990 the growth rate was over 10 ppb/yr, accompanied by a continuing positive shift in
211    $\delta^{13}C_{CH4}$ (Quay et al. 1988, Etheridge et al. 1998, Ferretti et al. 2005), but in the early 1990s
212   Steele et al. (1992) first recognised a slowing-down of growth and predicted stabilisation
213   around 2006. This was confirmed by Dlugokencky et al. (1994, 1998, 2003) and Lowe et al
214   (1994) as the budget equilibrated and the growth rate in fossil fuel emissions slowed. After
215   some years of equilibrium in the early 2000s, the return of growth in the atmospheric
216   methane burden became apparent from late 2006 and into 2007 (Figure 3).

217   Methane's recent growth is wholly different from the late 20th century pattern. Unlike the
218   convex, equilibrating trend of the late 20th century, growth since the end of 2006 has been
219   on a concave, accelerating trend with the highest growth rates on record in 2020 and 2021
220   (Dlugokencky et al. 2011, Nisbet et al., 2014, 2016, 2019, 2021, Lan et al. 2021a,b, 2022,
221   2023; Fig. 1). Moreover, methane's post-2006 isotopic record is isotopically quite unlike the
222   record of the 'fossil-fuel' industrial 19th and 20th centuries. The long trend towards more
223   positive $\delta^{13}C_{CH4}$, indicative of fossil fuel emissions, has unexpectedly reversed, replaced by
224   sustained strong trend to more negative $\delta^{13}C_{CH4}$. The trend is not a subtle statistical drift but
225   rather it is a strong planet-wide shift far outside any plausible statistical variability.

226   In 2006, the global mean of CH₄ in the marine background air was 1775 ppb, rising to 1912
227   ppb in 2022, a total rise of 137 ppb (about 379 Tg) in the methane burden. In 2021 alone,

228 growth was around 18 ppb or about 50 Tg. Rapid growth continues with an increase in 2022
229 of 14 ppb.

230 Synchronous with the onset of sustained sharp growth in CH_4 has been the isotopic reversal,
231 initiating a sustained strong negative trend in $\delta^{13}C_{CH4}$ (Fig. 3; also Nisbet et al. 2019, Lan et
232 al. 2021a,b). $\delta^{13}C_{CH4}$ values in Arctic air declined from -47.3‰ in 2006 towards -48‰ in mid-
233 2022. At the South Pole (Fig. 4), $\delta^{13}C_{CH4}$ values were about -46.9‰ in 2006, sinking towards -
234 47.4‰ in 2022 (Michel et al. 2022). These trends were constructed from detailed individual
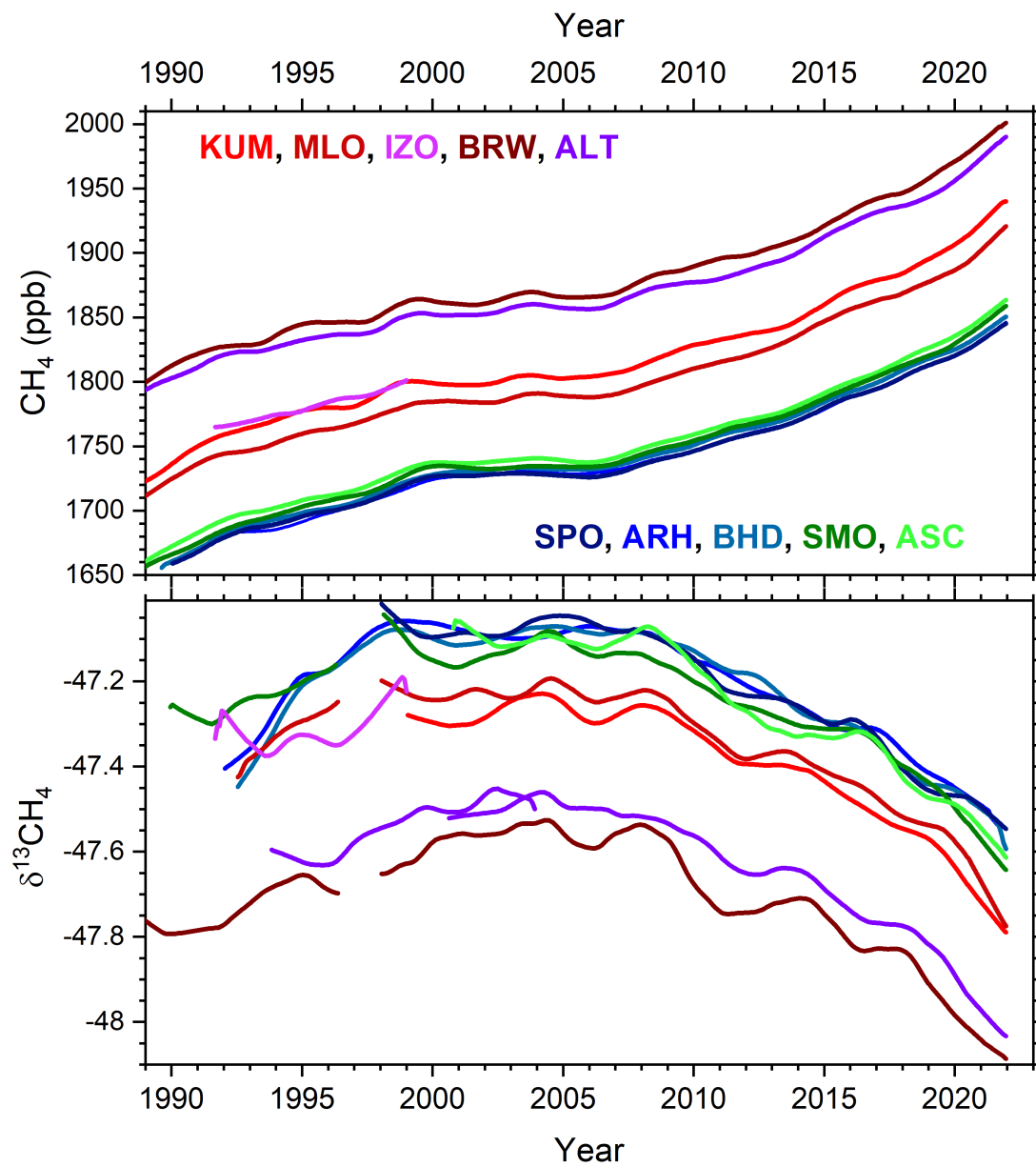235 flask records (e.g. see Figure SI 1 showing the flask-by-flask record from Ascension).

236 As seen in Figure 4, the last 30 years have had two phases for an increase in CH_4 mole
237 fraction but with these having strong opposite and global trends in $\delta^{13}C_{CH4}$. Longer term
238 records from ice-core and firn air show that this 'turnover' in $\delta^{13}C_{CH4}$, has reversed a
239 centuries-long trend towards 'heavier' (more 13C-rich) methane that ended around 1998,
240 then a few years of stability, and onset of the current trend towards 'lighter' (less 13C-rich)
241 values that began in late 2006 and has been sustained ever since. Globally, the negative
242 $\delta^{13}C_{CH4}$ shift over 2006-2022 has been about -0.55‰, from the maximum (most positive)
243 record in March 2008 to the more recent 2022 (Lan et al 2021a,b and update 2023).
244

245 *Figure 4. Trends in methane mixing ratio (top panels) and $\delta^{13}C_{CH4}$ (lower panels)*

246 *Figure 4a) Trends in methane mixing ratio (top panel) and $\delta^{13}C_{CH4}$ (lower panel) for five long*
247 *term monitoring sites in each hemisphere. In the Southern Hemisphere the measurement*
248 *stations are: NOAA's SPO – South Pole (90°S), SMO – Samoa (14°S), and ASC – Ascension*
249 *(8°S); and NIWA's ARH – Arrival Heights, McMurdo, Antarctica (78°S) and BHD – Baring*
250 *Head, NZ (41°S). In the Northern Hemisphere they are: NOAA's KUM – Cape Kumukahi*
251 *(20°N), MLO – Mauna Loa (20°N), BRW – Barrow, Alaska (71°N), ALT – Alert, Canada (83°N),*
252 *and University of Heidelberg's IZO – Izana (28°N). Early $\delta^{13}C_{CH4}$ data for SMO, MLO and BRW*
253 *are from Quay et al (1991) and for IZO from Levin et al., (2012).*

254 *Figure 4b) Detailed patterns showing seasonality for four selected sites, BRW and MLO in the*
255 *Northern Hemisphere, and ASC and SPO in the Southern Hemisphere. NOAA data.*

256 *NOAA data from https://gml.noaa.gov/aftp/data/trace_gases/ch4c13/flask/surface/).*
257 *NIWA data in the World Data Center for Greenhouse Gases https://gaw.kishou.go.jp/. For*
258 *further details see Supplementary Information. Intercomparison follows Umezawa et al.*
259 *(2018). SPO and MLO are at 2810 and 3397 m elevation respectively but the other points are*
260 *close to sea level. Details of the data from these sites are shown in supplementary material*
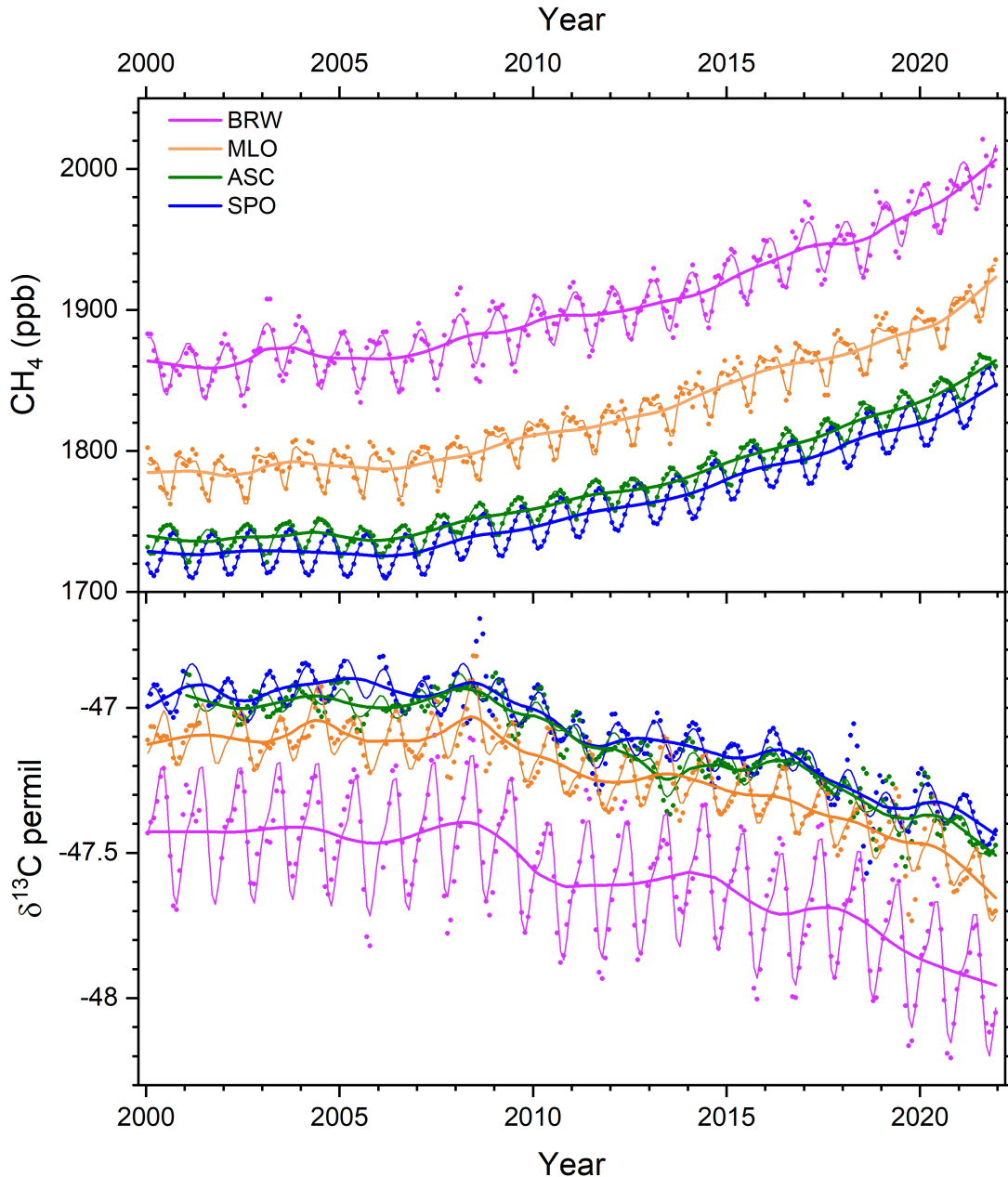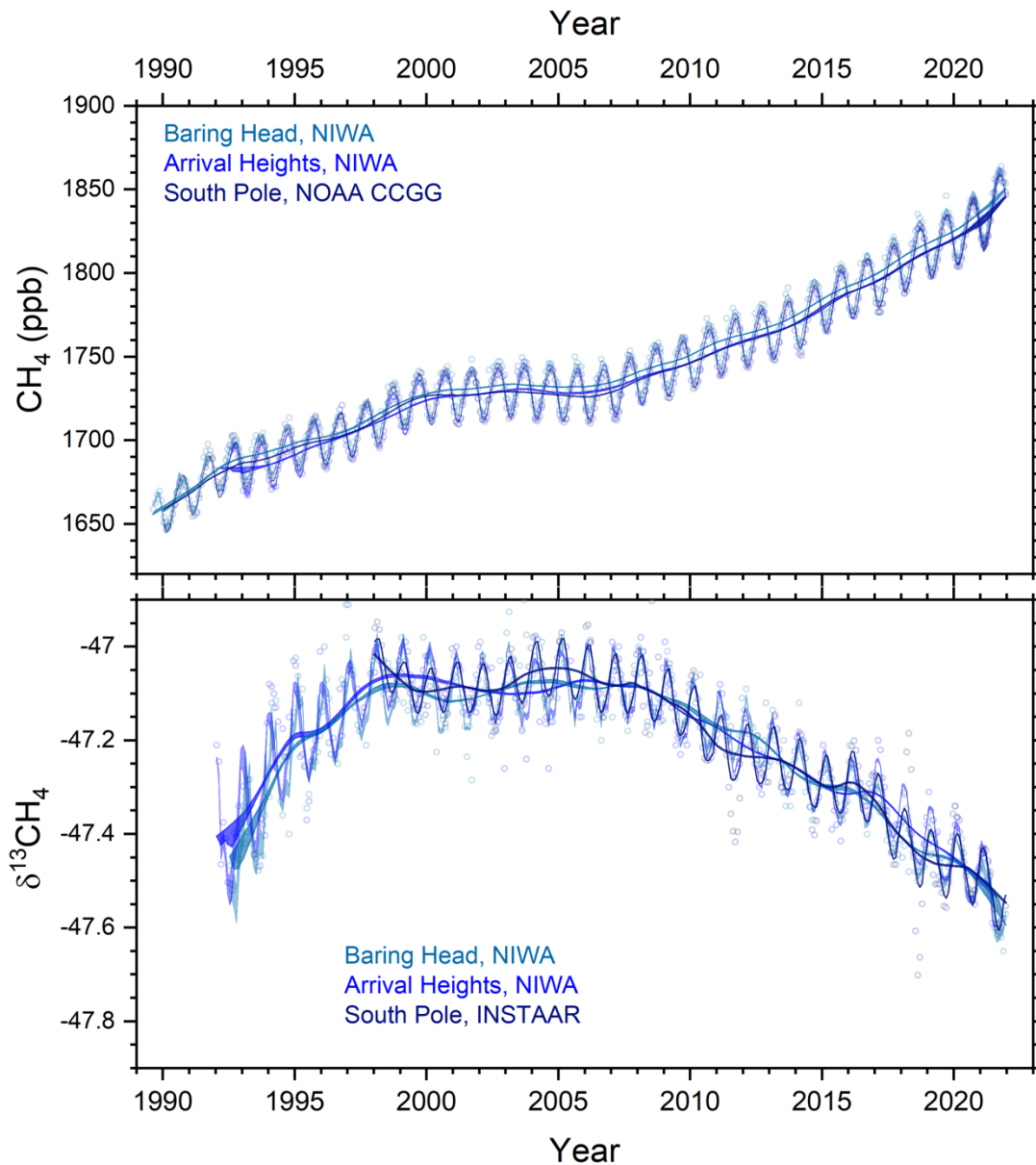261 *while this figure summarises the similar patterns seen globally.*

262

263

264   Figure 5 shows in detail the 'turnover' and seasonality in the remote (i.e. global) $\delta^{13}C_{CH4}$
265   trend. The centuries-long trend towards 'heavier' (more ^{13}C-rich) methane ended around
266   1998 (e.g. see Dlugokencky et al. 1994). Then came a few years of stability. The onset of the
267   trend towards 'lighter' (less ^{13}C-rich) values began in late 2006 and has been sustained ever
268   since. Globally, the negative $\delta^{13}C_{CH4}$ shift over 2006-2022 has been about -0.55‰, from the
269   maximum (most positive) record in March 2008 to 2022 (Lan et al 2021a,b and update
270   2023).

271   *Fig. 5 Remote Southern Hemisphere Isotopic Trend since the 1980s. Data from NIWA New*
272   *Zealand (Baring Head (41°S), Arrival Heights (78°S) and NOAA/INSTAAR measurements (SPO*
273   *90°S). See Fig. 4 for data sources; intercomparison after Umezawa et al. (2018).*
274   *https://gml.noaa.gov/aftp/data/trace_gases/ch4c13/flask/surface/).*

3. Methane sources and sinks; isotopic impacts.

The bulk source of global methane emissions has $\delta^{13}C_{CH4} \cong$ -53‰ for all sources
(Dlugokencky et al. 2011, Nisbet et al. 2019, Sherwood et al. 2017). Oh et al. (2022)
estimated a mean global wetland $\delta^{13}C_{CH4}$ signature of −61.3 ± 0.7‰. This reflects a mix
between northern high-latitude C3 plant wetlands (mean -67.8‰) and tropical C4-rich
wetlands (mean -56.7‰)(Quay et al, 1988, Dlugokencky et al. 2011; Sherwood et al. 2017,
2021, Ganesan et al. 2018, MOYA/ZWAMPS Team (2021), Menoud et al., 2022). Note the
means and precisions cited here are from partial and perhaps unrepresentative sampling:
real world averages may be several ‰ different. In addition to the global C3/C4 plant
distribution, the distribution of hydrogenotrophic / acetoclastic methanogens and
vegetation-specific CH_4 transport all contribute to the $\delta^{13}C_{CH4}$ variability of wetland
emissions (Ganesan et al. 2018). France et al. (2021) found methane from South American

288 and African southern outer tropical (seasonal) wetlands had $\delta^{13}C_{CH4}$ −60 ± 5‰ while
289 equatorial wetlands emitted methane with $\delta^{13}C_{CH4}$ -52±2‰. Similarly, Oh et al. (2022) found
290 tropical wetland emissions are enriched by about 11‰ relative to boreal wetlands.

291 Agricultural emissions, like wetland emissions, vary with latitude and C3/C4 proportions in
292 ruminant diets (Menoud et al. 2022, and tropical measurements are scarce. For rice fields,
293 France et al. (2021) found $\delta^{13}C_{CH4}$ -61±4‰. Farmed ruminant emissions vary with diet, with
294 a global average $\delta^{13}C_{CH4}$ perhaps around -65‰ (e.g. Chang et al. 2019), but data are scarce
295 from tropical ruminants where C4 fodder can dominate; for example, for Kenyan pastured
296 cattle, $\delta^{13}C_{CH4}$ is around -57‰ (MOYA/ZWAMPS Team 2021). Fossil fuel emissions have
297 $\delta^{13}C_{CH4}$ globally roughly between -43‰ and -45‰ (Lan et al. 2021a). However, $\delta^{13}C_{CH4}$
298 values range widely from highly positive values (e.g. -25‰ for some gasfields) to very
299 negative (as light as -70‰ in some cases). Howarth (2019) suggested that about a third of
300 growth in methane emissions from all sources globally over the past decade came from
301 shale gas production in North America. Nevertheless, Milkov et al. (2020), Basu et al. (2022)
302 and Zhang et al. (2023) showed this to be unlikely.

303 The steady-state lifetime for atmospheric methane is between 9 and 10 years (Ehhalt 1974;
304 Dlugokencky et al. 2011; Nisbet et al. 2019; Lan et al. 2021a). Methane's perturbation
305 lifetime, which accounts for atmospheric chemistry relaxation times and is more relevant for
306 climate impacts of emission reductions, is approximately 12 years (Prather et al. 2012,
307 Myhre et al. 2013). Methane's main sinks, atmospheric hydroxyl [OH], Cl, and soil
308 methanotrophy, are all subject to interannual variability as well as to the growth in the
309 methane burden. Nicely et al. (2018) found the expected decline in [OH] caused by methane
310 growth was largely offset by positive trends in tropospheric [OH] responding to changes in
311 water vapour, NO$_x$, and O$_3$. Methane's sinks all respond to climate change. Yin et al. (2021)
312 showed that the longer-term impact of [OH] changes was modest, a conclusion updated by
313 Basu et al (2022). Similarly, Thompson et al. (2018) and Drinkwater et al. (2023) also found
314 the impact of changes in the atmospheric sink did not appear to be a key driver of
315 methane's strong and sustained growth. However, in some years specific events can have
316 large impacts on methane growth. In particular, [OH] fluctuations can make a major
317 contribution to methane growth in hot El Niño years (Zhao et al. 2020), especially when
318 there are enhanced CO emissions from biomass burning. Such effects smooth out during a
319 full El Niño /Southern Oscillation (ENSO) cycle, as CO emissions from biomass burning
320 decrease again in subsequent cool, regionally-wet La Niña years.

321 Sources and sinks show interannual variability and may have been affected by covid lock-
322 downs in 2020 (Laughner et al. 2021), though that transient impact is unlikely to have been
323 sustained significantly into 2021 and 2022. For the unusual year 2020, when anthropogenic
324 emissions of air pollution were much affected by COVID lockdowns (e.g. Cooper et al.
325 2022), the growth in methane was driven both by a decline in [OH], and by increased wetland
326 emissions (Peng et al. 2022), especially in the tropical and sub-tropical Northern Hemisphere
327 and in western Siberia and central Canada. Using analysis of GOSAT retrievals, Qu et al
328 (2022) concluded 14% of growth was from [OH] changes. Likewise, Feng et al (2023) also
329 found an [OH] reduction comparable to Peng et al.'s results, but concluded that most of the
330 observed increase in atmospheric methane during 2020 and 2021 was caused by increased
331 emissions, especially in Eastern Africa. The full causes of methane's remarkable growth in
332 2021 and 2022, when covid lockdowns were less severe, are still being debated but it is

333   notable that over the period 2020-2022 the methane growth histogram matches the very
334   unusual 'triple-dip' 3-year La Niña event (NOAA 2023b).

335   Methane's minor sinks are destruction by atmospheric chlorine (Hossaini et al. 2016),
336   oxidation by soil methanotrophs, and upward transport into the stratosphere where
337   methane is destroyed (and isotopically fractionated) by photooxidation. Methane
338   destruction by chlorine is particularly interesting: although it only accounts for ~2.5% of the
339   total methane sink (but with larger regional-scale effects (Hossiani et al. 2016)), it is highly
340   fractionating for C and H isotopes (Strode et al. 2020).   All these sinks will have interannual
341   variability, especially in the ENSO cycle, and will also be subject to changing feedbacks to
342   long-term climate warming.

343   All biological methane sources, both purely 'natural' and anthropogenic, respond to climate
344   change and the rapid strong positive feedbacks make methane an excellent integrating
345   indicator of large-scale wetland ecosystem change. Increased warmth and moisture in the
346   'wet tropics' are likely to increase plant growth and thus ruminant productivity, and also
347   microbial activity in manure and wetlands. In the boreal and Arctic realms warmth is also
348   likely to increase wetland emissions. Moreover, as mentioned above (section 1.1), CO_2 acts
349   as a potent fertiliser for C3 plants, increasing plant productivity (Lobell and Field, 2008;
350   Uddin et al. 2018; Haverd et al 2020) and thus supply of organic matter to eventual
351   anaerobic decay, though it is possible this impact is eventually limited by supply of other
352   nutrients, primarily fixed nitrogen and phosphorus (Wang et al. 2020).

353   **Table 1: Simplified comparison of some recent assessments of wetland emissions and**
354   **their growth.**

355   **a) Examples of some estimated outer tropical wetland emissions**

Location	Latitude, area	Emissions Tg/yr	Reference
Bangweulu, Upper Congo basin, Zambia	11°S, >10000 km^2	1 to 3	Shaw et al, 2021
Pantanal, Brazil	Around 17°S, around 150000 km^2	2 to 3.3	Gloor et al., 2021
Llanos de Moxos, Bolivia	Around 12-15°S, Around 70000 km^2	3.6	France et al, 2022
Freshwater wetlands	*Global*	138-165	Rosentreter et al 2021
East Africa	*Regional*	Mar-May 2018 6Tg Oct-Dec 2019 9Tg	Lunt et al. 2021
South Sudan	*Regional*	7.4 ± 3.2 Tg	Pandey et al. 2021

356   **b) Global emissions growth (all sources) in the single years 2020 and 2021**

Period	Emissions growth in year (Tg)	Reference
2020	27	Feng et al. 2023
2021	21	Feng et al. 2023
2020	25-37 (48% from Africa)	Qu et al.

357   **c) Global wetland-only emissions growth in the single years 2020 and 2021**

Period	Emissions growth in year (Tg)	Reference
2020	14-26	Zhang et al. 2023
2021	13-23	Zhang et al. 2023
2020	6 - 7	Peng et al. 2022
2019-2020	22-32 (of which 15 in Africa)	Qu et al. 2022

358 **d) Global emissions in the years from the onset of growth prior to 2020**

Reference	Period	Growth in biogenic emissions Tg/yr	Estimated emissions growth acceleration Tg/yr/yr
Basu et al. 2021	2007-2012	26	4
Basu et al. 2021	2013-2017	32	
Zhang et al. 2023	2007-2021	8 - 10	1.3 -1.4
Oh et al. 2022	2006-2016	28 assumed scenario	

359

360 *Table 1 Note: numbers given here are for comparison purposes only. See cited sources for*
361 *original details. Numbers here highly simplified, rounded off from the disparate results in the*
362 *many cited studies, and are very approximate with large uncertainties.*

363 ## 4. The wetland hypothesis

364 The wetland hypothesis is that biogenic emissions, particularly from wetlands, are growing
365 rapidly and are the dominant cause of recent growth (Lunt et al. 2019, Nisbet et al. 2016,
366 2019, Lan et al. 2021a,b, Basu et al. 2022, Oh et al, 2022, Zhang et al. 2023). Aquatic
367 ecosystems are enormously important in the global methane budget (Rosentreter et al.
368 2021). Dean et al. (2018) found wetland emission growth can be primarily ascribed to
369 climate change feedbacks. Table 1 provides a highly simplified comparison of results from
370 recent studies in a very active and complex field.

371 The 'wetland hypothesis' has been supported by powerful evidence that increased wetland
372 emissions, especially in the tropics, drove methane's exceptional growth in 2020 (Lunt et al.
373 2019, 2021, Qu et al. 2022, Feng et al. 2022, 2023; Peng et al. 2022). The isotopic evidence is
374 strong. Using a process-based biogeochemistry model, Oh et al. (2022) concluded the spatial
375 distribution of wetland $\delta^{13}C_{CH4}$ emissions is consistent with the observed latitudinal gradient
376 in $\delta^{13}C_{CH4}$, implying the growth in microbial emissions has been the dominant driver for
377 methane's post-2006 rise and concurrent negative trend in $\delta^{13}C_{CH4}$. The causes of increased
378 wetland emissions likely include increased rainfall and inundation in drainage basins
379 (Pandey et al. 2017, Lunt et al. 2019, 2021, Feng et al. 2022), and also overall warm
380 temperatures in the post-2006 period, as plant and microbial productivities rise with
381 temperature, provided water and nutrients are available.

382 Methane's remarkable growth in 2020-2022 has been synchronous with an unusual La
383 Niña event (Hasan et al. 2022) with a 'triple-dip' 3-year period (McPhaden et al. 2023) that
384 has brought sustained seasons of exceptional rainfall to the important regions in the moist
385 tropics. However, emissions from aquatic systems are highly variable (Rosentreter et al.
386 2021), and inherently difficult to parameterize (Ringeval et al., 2014).

387 Because cloud cover is typically deep and persistent during wet seasons over key emitting
388 regions, it is difficult to study tropical wetland emissions in rainy season using satellite
389 remote sensing directly overhead, but the long atmospheric lifetime of methane allows for
390 these emissions to be quantified via observations collected downwind. Feng et al. (2022)
391 used satellite observations to infer that over 80% of the observed growth in the global
392 methane burden between 2010-2019 came from tropical terrestrial emissions. Separately,
393 Feng et al. (2023) estimated that 66 % of methane's global increase in 2020 was due to
394 increased emissions, particularly from the tropics. They found evidence for growing
395 microbial sources over the tropics with a very large increase (14±3 Tg) in recent (2020)

396 emissions from northern hemisphere Eastern Africa (e.g. the Nile Sudd – see Lunt et al.
397 2019), while emissions decreased in China and India.

398 These results are supported by the findings of Qu et al. (2022) from GOSAT retrievals, that
399 82% of methane growth from 2019 to 2020 was driven by increased emissions, with a large
400 contribution from African wetlands. Similarly, Drinkwater et al. (preprint submitted 2023)
401 found methane recent growth (2004-2020) has been driven by a progressive increase in
402 emissions, with emissions from tropical and sub-tropical sources (30°N to 30°S, i.e. including
403 the monsoonal climate belt) accelerating by 3.8 Tg/yr/yr. They concluded methane's growth
404 was primarily driven by biogenic emissions, especially from regions with large wetlands,
405 with increases in annual emissions over the period of about 17 Tg from Northern
406 Hemisphere Africa, and 21 Tg from Tropical South America, though Chinese annual
407 emissions also increased very strongly (27 Tg).

408 Anthropogenic impacts can also increase wetland emissions. Although widespread drainage
409 of wetlands is also taking place, tropical wetlands in Africa can host large cattle populations
410 (own observations). Indirect anthropogenic forcing factors include CO_2 fertilisation (Holden
411 et al. 2013, Haverd et al 2020), run-off to wetlands from nitrogen fertiliser application
412 (Ackerman et al 2018), sulphate deposition (Gauci et al. 2005) in regions like southern Africa
413 and China with large coal-industry emissions, and perhaps also the complex impacts of
414 human predation on wetland fauna. The fertilising impact of run-off from arable croplands
415 into nearby wetlands by nitrogen fertilisers (Fowler et al. 2013) may be important. However,
416 most boreal wetlands are far from farming drainage, while in many parts of the tropics,
417 although fertiliser application in arable lands around wetlands is increasing rapidly (e.g.
418 Uganda), the use of fertilisers is still very low compared to farming in northern temperate
419 regions (Dangal et al, 2019; FAO 2017, IFAstat 2022).

420 In particular, CO_2 fertilisation of C3 plants may be important. There is evidence (Möller et al.
421 2013) for CO_2 fertilisation impact in past transitions: the strong correlation between $\delta^{13}C_{CH4}$
422 and CO_2 in the ice core record of the past 160 ka is much better than the correlation
423 between $\delta^{13}C_{CH4}$ and CH_4. This suggests CO_2 fertilisation was an active feedback in past
424 changes by increasing plant productivity and hence microbial methane emissions during the
425 initiation of interglacial episodes, with isotopic impacts favouring C3 plants (more negative
426 $\delta^{13}C_{CH4}$) over C4 grasses. Thus the glacial/interglacial $\delta^{13}C_{CH4}$ record may reflect *in situ* shifts
427 in plant populations and productivity as well as shifts in the geographic loci of emission.
428 However, on the modern planet this impact is difficult to assess. It is also likely that nitrogen
429 cycle constraints and phosphorus availability may be progressively limiting the effect of CO_2
430 fertilisation (Wang, S. et al. 2020, Huntingford et al, 2022).

431 Wetland models have large uncertainties (Chang et al. 2023) and tropical wetland emissions
432 may be much larger than hitherto inferred in land surface models of wetland methane
433 sources (Shaw et al. 2022; Zhang et al. 2023; Nisbet 2023). Recent tropical wetland field
434 campaigns that included both low-flying aircraft and on-ground sampling have shown that
435 emissions from some wetlands are very substantial indeed. For example, overflying the
436 Llanos de Moxos wetlands in Bolivian Amazonia in March 2019 (late wet season), France et
437 al. (2022) found extremely large methane enhancements (500 ppb over background). These
438 were inferred to have come from very high surface fluxes of methane. Annual emissions
439 were estimated around 3.6 Tg/yr from the Llanos de Moxos wetlands. Further south, in the
440 Pantanal wetlands of Brazil and Bolivia in the South American seasonal outer tropics, Gloor
441 et al. (2021) used a planetary boundary layer budgeting technique to estimate the

442 Pantanal's total regional emissions of 2.0 to 2.8 Tg/yr, while their Bayesian inversion using
443 an atmospheric transport model found even higher emissions of ~3.3 Tg/yr.

444 At about the same southern outer tropical (seasonal) latitude in Africa, from an aircraft
445 campaign in February 2019 (mid-wet season) in the Upper Congo Bangweulu wetlands of
446 Zambia, Shaw et al. (2022) derived very large emissions of 1.2 to 3.0 Tg/yr. Bangweulu is
447 only part of the Upper Congo's extensive suite of wetlands. Emissions from Zambezi basin
448 wetlands were also significant (Shaw et al. 2022). This work suggests total emissions from
449 wetlands in the Congo and Zambezi basins may be very large. Interestingly the regional
450 $\delta^{13}C_{CH4}$ isotopic signatures of emissions of outer (single rainy season) tropical C4/C3
451 wetlands in Zambia and Bolivian Amazonia were very similar, around -59‰ to -60‰ (France
452 et al. 2021, MOYA team et al. 2021), presumably reflecting the similarity of the seasonal
453 outer tropical C4/C3 vegetation mix.

454 Unfortunately, on-ground or low-level aircraft/UAV *in situ* monitoring of major tropical
455 wetlands is inadequate (Ringeval et al. 2014, Nisbet 2023), so it is not possible to use *in-situ*
456 monitoring to confirm year-on-year changes. From satellite observations, Lunt et al. (2021)
457 found strong XCH4 enhancements in East Africa consistent with large positive seasonal
458 precipitation anomalies. Zonal observations from remote stations of the NOAA network
459 (Nisbet et al. 2016, 2019) broadly support the findings of increased wetland emissions.
460 Interannual rainfall and temperature variability can be very large (Lunt et al 2021, Peng et
461 al., 2022, Palmer et al. 2023), depending on shifts in the position and intensity of the Inter-
462 Tropical Convergence Zone (ITCZ). Thus expansion and intensification of the tropical Hadley
463 cell circulation can have dramatic impacts on methane emissions.

464 To turn to bottom-up assessments, Zhang et al. (2023), applying climate data from
465 meteorological stations and reanalysis in a land surface wetland model, found that climate
466 change impacts increased annual wetland emissions by 8-10 Tg/yr in 2007-2021 compared
467 to the 2000-2006 level. Specifically, they also found huge positive anomalies of 14-26 Tg in
468 2020 and 13-23 Tg in 2021, and that tropical methane emissions contributed a large part of
469 methane's growth in those two years. For the single year between 2019 and 2020, the
470 bottom-up estimate of Peng et al. (2022) found an increase in wetland emissions of 6.0 ±2.3
471 Tg. Their top-down 3D atmospheric inversion gave a global increase in surface emissions of
472 6.9 ±2.1 Tg/yr between 2019 and 2020, which they also mostly attributed to increased
473 wetland emissions. These very large increments are consistent with the hypothesis that
474 growth has been supercharged by precipitation in the unusual 2020-2022 La Niña "triple
475 dip" event (NOAA 2023b, McPhaden et al. 2023), though it should be noted that earlier
476 intense La Niña events did not coincide with years of especially extreme methane growth.

477

478 **Table 2: Anthropogenic methane emissions in the years 2000, 2010 and 2020 and decadal**
479 **growth rate in the last two decades.** Data from EDGARv7.0 (EDGAR, 2023, Crippa et al.,
480 2021)

481

IPCC sector		Emission Tg yr⁻¹ CH₄			Growth rate (Tg CH₄ yr⁻²)	
Year		2000	2010	2020	2000_2010	2010_2020
1 Energy		103.51	123.98	137.42	2.05	1.34
2 Industrial processes and product use		0.19	0.33	0.49	0.01	0.02
3 Agriculture, forestry and other land use		137.41	151.93	162.47	1.45	1.05
3A1 Enteric Fermentation		91.70	101.69	111.03	1.00	0.93
3A2 Manure Management		10.87	11.69	12.54	0.08	0.08

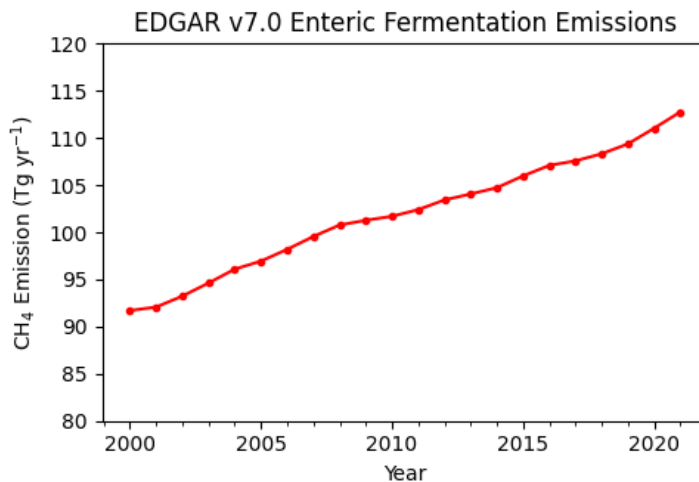|					
3C1 Biomass Burning	1.35	1.71	1.96	0.04	0.03
3C7 Rice Cultivations	33.49	36.84	36.94	0.33	0.01
4 Waste	62.72	70.60	83.58	0.79	1.30
4A Solid Waste Disposal	29.64	30.65	35.65	0.10	0.50
4B Biological Treatment of Solid Waste	0.17	0.23	0.28	0.01	0.01
4C Incineration and Open Burning of Waste	1.14	1.32	1.55	0.02	0.02
4D Wastewater Treatment and Discharge	31.76	38.40	46.10	0.66	0.77
5 Other	0.15	0.15	0.15	0.00	0.00
Total anthropogenic	303.98	346.99	384.11	4.30	3.71
Total 'microbial anthropogenic' (excluding FF etc)[*]	197.98	219.98	243.18	**2.2**	**2.3**

482 * excludes Energy (1), Biomass burning (3C1), and Incineration and open burning of waste (4C).

483

5. Agricultural, biomass burning, and waste emissions

485 Agriculture is a major source of biogenic methane emissions, from cattle breath ($\delta^{13}C_{CH4}$
486 slightly more negative than the bulk methane burden), wetland rice cultivation, and biomass
487 burning ($\delta^{13}C_{CH4}$ much more positive than the burden)(for isotopic signatures of sources see
488 Dlugokencky et al., 2011, Nisbet et al. 2016, 2019, MOYA/ZWAMPS Team 2021).

489 Livestock emissions are growing but the rate of growth is difficult to quantify. Zhang et al.
490 (2022) estimated, with uncertainty around 20%, that methane emissions from global
491 livestock populations were around 105 Tg in 2000, 121 Tg in 2011, and 132 Tg in 2019,
492 growing by 27 Tg from 2000-2019, or 1.4 Tg/yr/yr. Using an inversion framework to verify
493 methane emissions from satellite-based observations, Worden et al. (2023) reported a
494 growth rate of livestock emissions of 0.25 to 1.3 Tg/yr/yr. The growth rate they estimated
495 was similar to EDGAR results, although Worden et al. (2023) considered the EDGAR
496 assessment had underestimated livestock emissions. From 2000-2020, the EDGAR (2023)
497 assessment finds an increase in emissions from enteric fermentation of 20 to 21 Tg, (Fig. 6),
498 with another 2 Tg increase from animal manure (EDGAR 2023) but no significant
499 acceleration in the rate of increase in the past decade. Our assessment (Fig. 6) of growth in
500 ruminant emissions from enteric fermentation, estimated from the EDGAR (2023) database,
501 is nearly 1 Tg/yr/yr for 2000-2020 (Table 2), somewhat less than the Zhang et al. (2022)
502 estimate but within the very wide uncertainties.

503 *Figure 6. Estimated growth in methane emissions from enteric fermentation (ruminants),*
504 *from EDGAR (2023). See Table 2. Recent (2010-2021) growth rate about 1 Tg/yr/yr.*

505

506   The densest cattle populations are in South Asia, tropical Africa and tropical South America.
507   Livestock population growth will be facilitated by increased grazing and browsing
508   productivity in a warmer wetter climate. However, it is not clear how much agricultural
509   expansion in the tropics has increased total land surface methane emission. Africa and more
510   recently South America are undergoing a widespread transition from a complex 'natural'
511   ecology of diverse ruminants and pseudo-ruminants to a now human-dominated pastoral
512   system of cattle, goats and sheep (e.g. see Zhang et al. 2022).

513   In the 'natural' African ecology, ruminants from browsing giraffe to grazing buffalo exploit all
514   parts of the floral variety. In contrast, in cattle-dominated monocultures, where most or all
515   natural ruminants are eliminated, food production specifically for the very rapidly growing
516   human populations will have increased, but the total body mass per unit area of the
517   ruminants that are producing methane may not be larger (e.g. see data in Taylor and Walker
518   (1978). Moreover, much tropical cattle manure falls on dry pastures in aerobic conditions
519   not supportive of methanogens, although it should be noted that in some parts of Africa
520   cattle are kept overnight in 'bomas' (corrals) where manure collects under urine and
521   methane emissions can be significant (Leitner et al. 2023). Thus the overall net change in
522   methane emissions from replacing an original productive and diverse natural ecology with
523   anthropogenic cattle or maize monocultures is unclear.

524   Biomass burning emissions come from incomplete combustion. The amount of
525   burning varies from year to year, which has significant impact on emissions (Worden et al.
526   2017). In the tropics, biomass fires are closely linked to changes in the Inter-Tropical
527   Convergence Zone and the ENSO cycle. Grassland fires (mainly C4 plants in the tropics) are
528   widespread in dry winters after good rainy seasons, often covering very large areas. Crop
529   waste fires also occur mainly in dry season, varying with precipitation in the previous wet
530   season. These fires, particularly of ^{13}C-rich tropical C4 crop plants like maize, sugarcane, and
531   millet, emit isotopically heavy methane.

532   Burning of tropical C3 woodland and forest also occurs, especially in clearing land. Tracking
533   biomass burning is difficult: satellite observation quantifies burnt area but it is more difficult
534   to assess fuel load and intensity of fire (especially important in crop waste fires). Barker et
535   al. (2020) found high variability in emissions measured in flights over active fires, with
536   methane emissions of 1.8 ± 0.19 g/kg of fuel over outer-tropical Senegal, but 3.1±0.35 g/kg
537   over equatorial Uganda. Boreal biomass burning, in contrast, is mainly wildfire in northern
538   C3 forests, highly dependent on summer temperatures, and more easily assessed by remote
539   sensing.

540   'Biogenic' CO is mainly produced by biomass burning, but the CO record in the 2000-2010
541   decade is affected by Europe's decade of 'dieselisation' favouring diesel-fuel passenger cars,
542   which are low emitters of CO. Contrasting the period 2001–2007 to the 2008–2014, Worden
543   et al (2017) concluded biomass burning emissions of methane decreased by 3.7 (±1.4) Tg
544   CH$_4$ per year, and this drop may have contributed to the standstill in methane growth in the
545   early years of the 21st century. For the periods 2007-2012 and 2013-2017, inversions of both
546   mixing ratio and isotopic data suggest overall global pyrogenic emissions dropped slightly or
547   showed little change, (Zhang et al. 2021, comparison in Basu et al. 2022).

548   Much agricultural growth comes from expansion of farmed land area, displacing natural
549   ruminants from grasslands or cutting forest and draining wetlands and burning peatlands.
550   Thus, for tropical agricultural emissions it is difficult to allocate proportions of 'feedback-

551   driven' and 'technology-driven' emissions growth. The impact on crop yields and ruminant
552   fodder supply of indirect factors such as CO_2 fertilisation and sulphate deposition, is not
553   easily quantified.

554   Bottom-up (EDGAR 2023) inventories suggest anthropogenic emissions from wastewater,
555   solid waste, and landfills are increasing worldwide. Despite successful efforts to reduce
556   waste emissions in Europe and other regions, the rapid growth of tropical cities is driving
557   increased urban waste disposal and these emissions are very poorly quantified (Nisbet et al.
558   2020). Waste disposal in tropical cities is increasing in large poorly-managed landfills (Nisbet
559   et al. 2020), but food waste comes from local agriculture, so waste emissions are linked to
560   local agricultural productivity. In the EDGAR v7.0 inventory (EDGAR 2023) the estimated
561   growth of annual solid waste and landfill emissions from 2006 to 2021 is about 5.7 Tg, while
562   methane from wastewater has increased by about 11 Tg/yr over the same period.

563   The 'climate feedback' proportion of growth in emissions of methane from tropical
564   agricultural and waste disposal is uncertain. Growth in ruminant and landfill biogenic
565   emissions depends both on global change feedbacks (more productivity in a warmer,
566   wetter, CO_2-rich environment) and also on 'direct-action' factors increasing agricultural
567   productivity such as nitrogen fertiliser application and genetic modification of seeds.

568   Overall, including solid and liquid waste, manure handling and enteric fermentation in
569   agricultural ruminants, EDGAR inventory data (Table 2) suggest microbial methane
570   emissions from anthropogenic activities rose each year by about 2.3 Tg/yr, or an increase of
571   about 35 Tg from the end of 2006 to 2020. Although there is wide uncertainty on these
572   bottom-up estimates, they appear broadly consistent with top-down estimates.
573   Importantly, there is no evidence in the data for a sudden acceleration in the growth of
574   agricultural and waste emissions post-2006.

575   **6. Inference: increased natural emissions are a major cause of recent**
576   **methane growth**.

577   Quantifying emissions from 'natural' sources as they respond to climate change is difficult.
578   Ongoing experimental measurement of methane fluxes from wetlands is minimal, especially
579   in Africa. An alternative is to use isotopic information to assess global total (i.e. natural and
580   anthropogenic) biogenic emissions and then subtract bottom-up estimates of emissions
581   from biogenic sources under anthropogenic control, with the caveat that these too respond
582   to climate warming.

583   Studying the period 1999-2016, Basu et al. (2022) estimated methane's 2008-2014 rise was
584   driven by global emissions growth of 27.1 ± 0.6 Tg yr^{-1} or, nearly 4 Tg/yr/yr. They found the
585   negative shift in $\delta^{13}C_{CH4}$ can be balanced by assuming about 15%, or 50 Tg, of the recent rise
586   is from growth in fossil fuel emissions (i.e. with $\delta^{13}C_{CH4}$ more positive than the methane
587   already in the air). Comparing the period 2007-2012 with the period 2013-2017, Basu et al.
588   (2022) found an increase in biogenic emissions of 32.3 ± 3.2Tg/yr. After 2017 and especially
589   in 2020-2023, the burden grew more rapidly.

590   Similarly, looking at the surge in growth in 2019-2020, using a global inverse analysis of
591   GOSAT satellite observations, Qu et al. (2022) found the imbalance between sources and
592   sinks of methane increased by 31 Tg in the year 2019-20. They found that half the growth in
593   methane emissions in 2019-2020 took place in Africa, especially East Africa, most likely from
594   wetlands, with strong emissions growth in Canada also. For the year 2020, Qu et al. (2022)
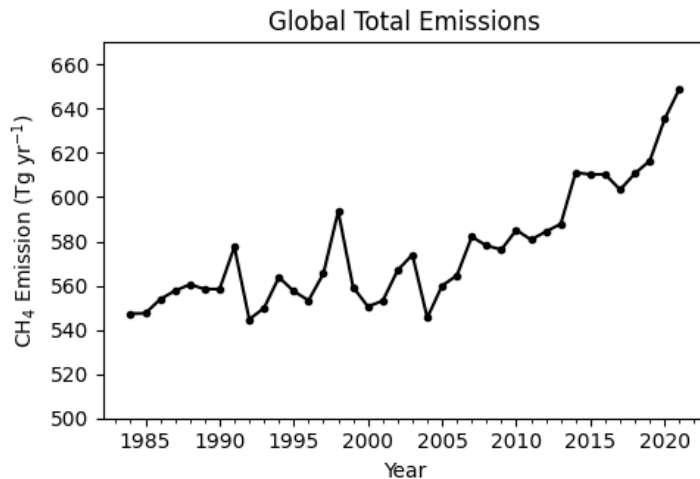
595 attributed 86±18% of the growth surge to increased emissions, especially from wetlands in
596 Africa (15 Tg/yr) and Canada and Alaska (4.8 Tg/yr), although there was also evidence for
597 14% of the growth coming from a decrease in methane's [OH] sink, to which also Stevenson
598 et al. (2022) attribute part of methane's growth in 2020. Overall, Qu et al. (2022) found total
599 emissions grew by 25–37 Tg/yr in 2019-2020. If their estimate that about 86% of growth
600 was biogenic is accepted, then the growth in biogenic emissions in 2019-2020 was as large
601 as 22-32 Tg.

602 Drinkwater et al. (2023), over the period 2004-2020, used *in situ* data to estimate a global
603 annual emission increase of 93 Tg/yr over the period (620 Tg/yr minus 527 Tg/yr), with 83%
604 of that increase occurring since 2011 when the global growth first began to accelerate.
605 Assuming 2.3 Tg/yr/yr of growth is from anthropogenic microbial sources, increased
606 wetland emissions will be responsible for the balance of emissions growth, of 2 to 2.5
607 Tg/yr/yr (with very wide uncertainty). Note also that the acceleration of methane's rise from
608 2020 implies the growth rate of emissions was much higher in 2020-2022.

609 More broadly, accepting the estimates of Basu et al. (2021) and Qu et al. (2022), and
610 extrapolating to end-2022, a very rough guess is that about 70-80 Tg/yr of the global
611 emission increase between 2006 and end-2022 came from specifically microbial sources,
612 both natural and anthropogenic. As detailed above, microbial emissions from anthropogenic
613 agricultural and waste sources have probably increased between 2006-2020 by about 35
614 Tg/yr (assuming linear growth, Fig. 6 and Table 2). If this is correct, the remaining recent net
615 growth in methane emissions is not likely to be primarily attributable to agricultural
616 expansion but has been driven by 'natural' biogenic processes, especially wetland feedbacks
617 to climate change.

618 Fig. 7 updates estimated emissions into the 2020s, using the methodology of Lan et al
619 (2021a) and Basu et al. (2022). Subtracting (say) 35 Tg for growth over this period in
620 anthropogenic emissions from agriculture and waste, the growth in 'natural' biogenic
621 emissions may have been 35-45 Tg. More generally, if total biogenic emissions continue to
622 accelerate at the same rate as in the period 2006-2022 (a very large assumption), then by
623 the year 2037, 30 years after the start of growth, specifically biogenic emissions might have
624 grown by perhaps 150 Tg/yr.

625 *Figure 7. Global methane emissions, estimated and updated using the top-down*
626 *methodology of Lan et al. (2021a) and Basu et al. (2022). For further details, see*
627 *supplementary information in Lan et al. 2021a, Fig S2b, red curve, updated.*

628

7. Glacial Terminations

630 During the past half-million years, several "termination" events have marked rapid changes
631 of global climate from cold glacial to warmer inter-glacial conditions. Terminations were
632 rapid major reorganisations of the Earth's climate systems, with degassing of upwelling
633 oceans and revival of a warmer biosphere (Broecker and van Donk, 1970; Raymo 1997;
634 Cheng et al. 2009; Denton et al. 2010; Lang and Wolff 2011, Schmitt et al. 2012). They are
635 characterised by very large-scale shifts of global and regional weather circulation patterns,
636 for example from glacial climates toward a more La Niña-like state (Cheng et al 2020).

637 Broecker and Denton (1990) interpreted 'terminations' in the broadest terms, as global-
638 scale climate reorganisations, which were synchronous with sharp changes in the methane
639 burden. likely driven by wetland emissions (Nisbet 1990, Nisbet and Chappellaz 2009). The
640 modern palaeoclimate understanding of a recognised 'Termination', named in Roman
641 numerals from I (youngest) to IX (nearly 800 ka ago) refers to specific transitions from glacial
642 to interglacial periods that took place about every 100 ka. In the finer detail of the glacial
643 record are Dansgaard-Oeschger (D-O) events, which were abrupt warming events, with
644 sharp temperature rises over decadal timescales, followed by slow relaxation over
645 millennia. These D-O events were very rapid, with decadal progression (Erhardt et al. 2019).
646 While Dansgaard-Oeschger events occurred within glacials and were likely linked to rapid
647 changes in sea ice cover (Boers et al. 2018), the numbered Terminations marked global-
648 scale climate changes.

649 Although full terminations took several millennia before the new warmer interglacial
650 climate was established, the transitions typically included brief abrupt phases when
651 methane growth and climate warming was very rapid indeed. It is likely that the new
652 warmer weather patterns became established within a few centuries or less (Severinghaus
653 et al. 1998), although it took millennia for the great ice domes to melt and, by their
654 shrinking, to change boreal albedo and replace ice with wetlands and forest, thus
655 completing the full climate transition of the termination.

656 Sudden methane growth is the bellwether of these changes (Möller et al. 2013, Bock et al.
657 2017). Methane emissions are very responsive to climate (Nisbet 1990, Petrenko et al. 2009,
658 Nisbet & Chappellaz 2009). Methane's growth record during glacial-interglacial Terminations
659 V to I (Fig. 8 and Table 3) is preserved in bubbles in ice cores (Spahni et al. 2005, Wolff et al.

660 2009, Möller et al. 2013, Bock et al. 2017). The methane record correlates with monsoonal
661 patterns as observed in oxygen isotope records in stalagmites (Cheng et al. 2009).

662 During Termination IA ending the Younger Dryas, methane rose abruptly by ~250ppb, with
663 essentially synchronous high-latitude and low-latitude climate change (Capron et al. 2021).
664 Ice core data imply emissions increases as large as 6 to 21 Tg/year
665 causing methane growth rates as high as 6 ppb/yr (Rhodes et al. 2015). It is likely methane's
666 rapid growth was primarily driven by rising tropical emissions, responding to abrupt changes
667 in tropical rainfall (Schaefer et al., 2006; Möller et al. 2013, Bock et al. 2017, Riddell-Young
668 et al. 2023).

669 Feedback loops in the methane budget rapidly respond to global-scale climate change. It is
670 likely that both warming and climate shifts such as intensification of ENSO events would
671 have especially driven emissions in the tropics where both wetlands and regional land
672 vegetation respond quickly to increased warmth and rainfall, wetland productivity
673 increasing synchronously with parallel expansion of methane-emitting (Clauss et al. 2020)
674 populations of ruminants (buffalo, antelope) and pseudo-ruminants (hippoipotamoi).

675 Figure 8 shows the changes in methane and $\delta^{13}C_{CH4}$ in selected past terminations, showing
676 data updated from Bock et al. 2017; see also Möller et al. (2013). Initially, at the start of a
677 typical termination, there was a gradual rise in methane and CO_2. This rise was accompanied
678 by a negative shift in $\delta^{13}C_{CH4,}$ which covaried with CO_2, as was characteristic during glacials,
679 and with CH_4. This gradual phase lasted a few thousand years.

680 In typical terminations the brief abrupt phase, with sharp growth in methane, In typical
681 terminations the brief abrupt phase with its sharp growth in methane by several 100 ppb
682 did not leave a significant imprint in the $\delta^{13}C_{CH4}$ record (Schaefer et al. 2006; Möller et al.
683 2013, Bock et al. 2017) indicated with arrows in Fig. 8. This pattern is consistent with the
684 interpretation that methane emissions growth was dominated by equatorial wetland which
685 has $\delta^{13}C_{CH4}$ close to the global bulk source (Brownlow et al. 2017, Ganesan et al, 2019,
686 Nisbet et al. 2021a,b, France et al. 2021, Oh et al. 2022). Methane's sharp growth in the
687 abrupt phase is thus best explained by a rapid increase in emissions from tropical wetlands
688 emitting methane with $\delta^{13}C_{CH4}$ close to that of the bulk atmosphere (i.e. especially in the
689 equatorial zone) (Bock et al. 2017).

690 Switching on tropical wetlands was likely associated with a rapid shift in the ITCZ that
691 coincided with resumption of a strong Atlantic Meridional Overturning Circulation (AMOC)
692 at the start of interglacial climate conditions, initiating a warmer northern hemisphere and
693 generally stable climate with subdued millennial-scale variability. The AMOC 'flip' is denoted
694 in Fig. 8 by vertical dashed lines, and essentially marked the crux of the termination,
695 although it took millennia for sea level to rise as the great ice domes in Canada and
696 Scandinavia melted. During the 'flip' phase, there was typically a rapid increase of about 200
697 ppb in methane mixing ratio, but only a relatively small change in $\delta^{13}C_{CH4}$.

698 AMOC changes and consequential meridional heat transport anomalies have been a feature
699 of past episodes of abrupt global climate shifts (Cheng et al. (2007). For example, Riveiros et
700 al. (2013), and Rhodes et al. (2015) showed that AMOC slowdown is capable of producing
701 atmospheric responses that extend throughout the Northern Hemisphere and into the
702 tropics, with strong coupling between the two regions. Though very different from today's
703 changes, the 32 ppb rise in atmospheric methane during the HS 1 event reported by Rhodes

704 et al. (2015) has interesting parallels with modern shifts, including both weakening of AMOC
705 and southern expansion of the ITCZ and Hadley cell. However, there are also large
706 differences: in HS1 there was boreal cooling as the ITCZ moved southward; in the present
707 event the north is warming strongly.

708 Although there are many possible explanations of this sequence of events, the pattern is
709 consistent with a wider scenario beginning with initial modest Hadley cell expansion during
710 interdecadal variation, bringing about more methane emission from wetter outer tropical
711 swamps ($\delta^{13}C_{CH4}$ perhaps very roughly -60‰ in cool conditions). Then in response, changes
712 in AMOC, the Walker circulation and the Indian Ocean Dipole (Abram et al. 2020, Brierley et
713 al. 2023), may have brought about intensification of equatorial rainfall and consequent
714 rapid growth in equatorial wetland emissions, initiating methane's abrupt rise.

715 Thus in this scenario of the abrupt phase of a glacial termination, the growth of wetlands
716 under strong equatorial rainfall will rapidly increase the atmospheric methane burden but
717 be accompanied by only subdued initial leverage on $\delta^{13}C_{CH4}$. Then, as the boreal realm
718 warms, northern methane sources with more negative $\delta^{13}C_{CH4}$ begin to contribute. Note
719 that in an end-glacial scenario the presence of large ice domes over Canada and Scandinavia
720 inhibited development of boreal vegetation: in these areas boreal wetlands were not
721 functioning until millennia later when the ice melted. Today, the boreal and Arctic wetlands,
722 which emit methane with markedly negative $\delta^{13}C_{CH4}$, are very productive and are
723 experiencing strong warming (Previdi, et al. 2021).

724 *Figure 8. Ice core records from Terminations I, II and V. Modified from Bock et al. 2017 and*
725 *updated. Note synchroneity of CH$_4$ rise with negative shift in $\delta^{13}C_{CH4}$ (plotted upwards on y-*
726 *axis). Solid arrows denote the CH$_4$ from the start of a Termination to the point of the growth*
727 *flip. Dashed arrows mark the corresponding CH4 change in the abrupt flip. CO$_2$ record is*
728 *from Bereiter et al. (2015) and CH$_4$ from Loulergue et al. (2008) with updates from Bock et*
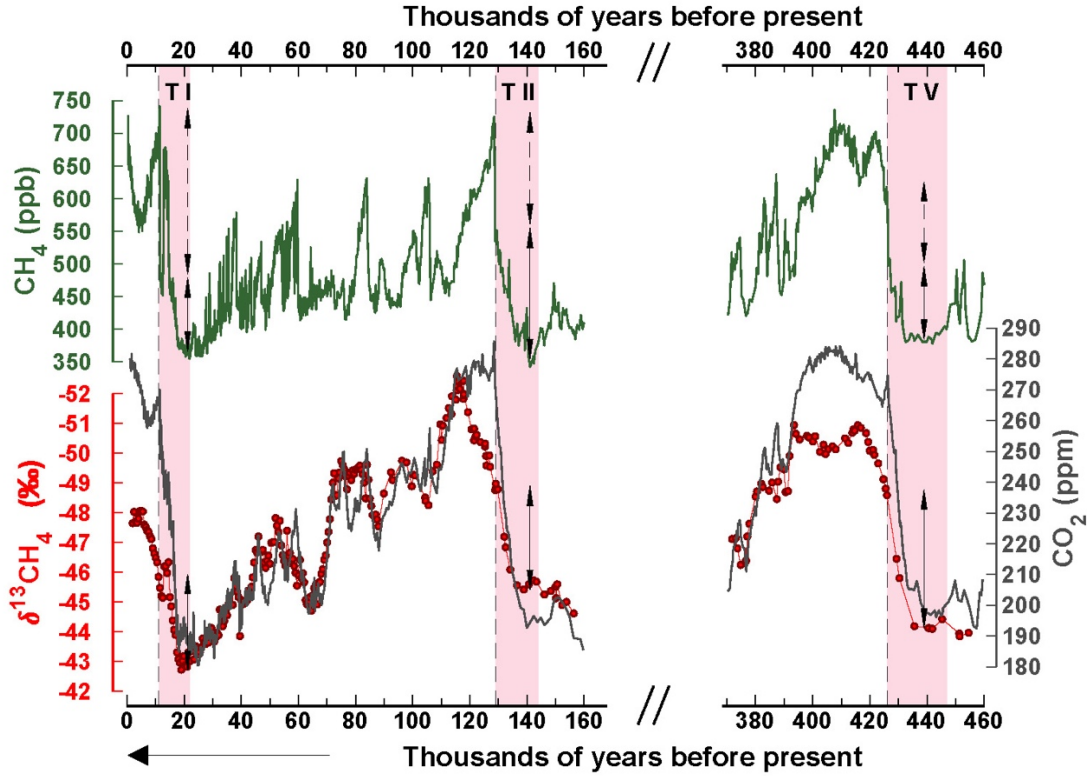729 *al. (2017).*

730

731

732 **Table 3: Synopsis of Termination changes**
733 *Summarised here from methane records detailed in Section 7, particularly Bock et al. 2017.*
734 *Assumes 1 ppb is equivalent to 2.77 Tg methane.*

735

Event	Approximate Date (ka BP) of abrupt phase	Change over whole termination ppb (approx.)	CH₄ Change over whole termination Tg (approx.)	Maximum Growth rate ppb/yr (approximate)	δ¹³C_CH4 shift over whole termination (approximate)
PAST					
Termination IA **Termination IB**	11.64 14.65	250 150	700- 400-450	> 2.5 > 2	-3.5‰
Termination II	131	350	900-1000	> 2.5	-4.5‰
Termination III	250	300	800-850		
Termination IV	345	400	1100		
Termination V	430	350	900-1000		-5‰
MODERN					
Modern	2006-2022-?	135	374 318 (biogenic 85% component)	~ 9 (Between 6 and 18 ppb)	-0.7‰
Model to 2035	2006 to 2035	573	1584	10	-1.1‰ (roughly equivalent to -4.4‰ if injected into much smaller glacial burden)

736

737   Over full terminations, negative drops in $\delta^{13}C_{CH4}$ ranged between -5‰ to -3‰ (Bock et al.
738   2017). For example, in Termination V, $d^{13}C_{CH4}$ dropped from about -44‰ to -49‰, while in
739   Termination II there was a similar negative shift (Bock et al. 2017). Again, at the start of the
740   Preboreal Holocene $\delta^{13}C_{CH4}$ shifted from about -43‰ in full glacial conditions, to about -
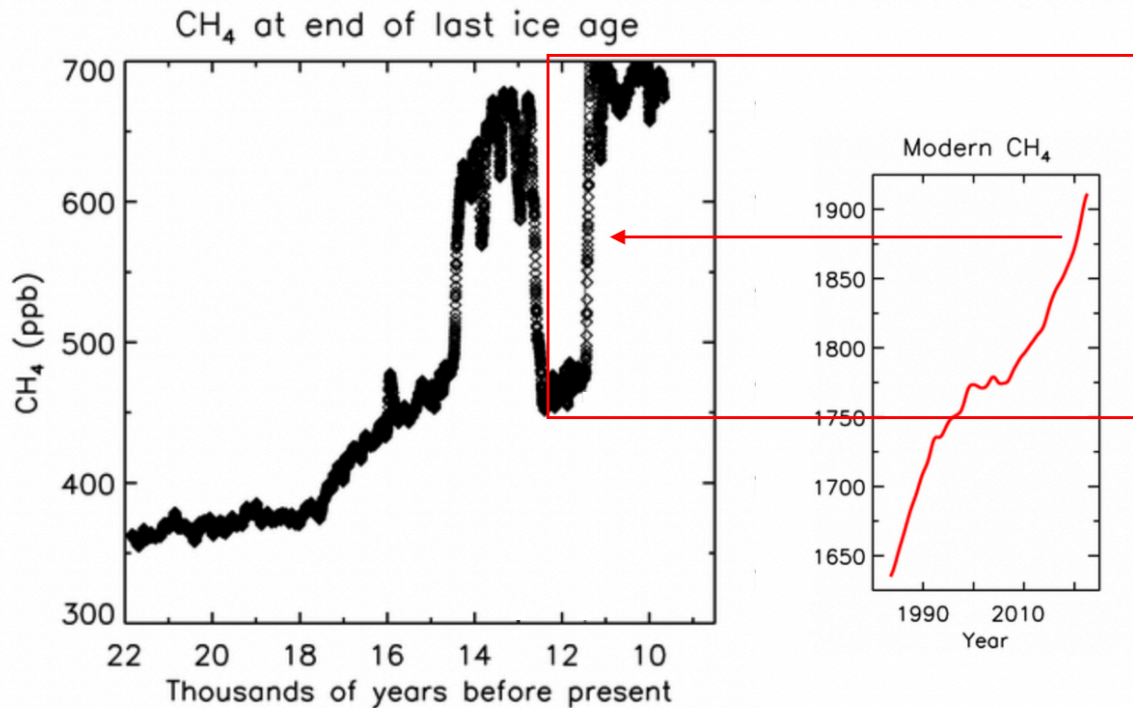741   46.3‰ (Fischer et al. 2008, Melton et al. 2012; Bock et al. 2017).

742   To consider the older events first, the abrupt phase of Termination II took place between
743   130.9 ± 0.9 and 130.7 ± 0.9 ka ago (Moseley et al., 2015), with contemporary strengthening
744   of the monsoon. In Terminations II and III the methane burden rose by roughly 500-600Tg in
745   sudden growth events. During similar abrupt rises in Terminations IV and V, methane rose
746   from about 400ppb to 700ppb, or more, increasing the methane burden by 800-900Tg.

747   The most recent termination was in multiple phases (Fig.9 left panel). In the abrupt part of
748   Termination 1B, which ended the last major glaciation, the Greenland Summit climate
749   rapidly warmed by 9±3°C, and 20-30 years later methane rose abruptly (Severinghaus and
750   Brook, 1999). Methane rose quickly over the sixty years between 14,655 and 14,595 BP,
751   with especially rapid growth in the decade from 14,655 - 14,645 BP (Severinghaus and Brook
752   1999). This change initiated the Bølling–Allerød interstadial, until 12.87 thousand years BP,
753   when the Younger Dryas began, with sudden cooling of the North Atlantic realm linked to a
754   drop in methane to 450-500 ppb. Then, ending the Younger Dryas, the abrupt warming
755   event of Termination 1A took place between ~11,700 and 11,610 B.P, with the fastest
756   change about 11.64 thousand years ago (indicated by vertical line in Fig. 8). About 0-30
757   years after this warming began, methane rose sharply to above 700 ppb (Severinghaus et al
758   1998; Cheng et al. 2020). In all, methane rose as much as 250 ppb in little over a century, an
759   increase of about 700 Tg in the burden.

760   *Figure 9. Comparison between Methane's record during Termination 1 and methane's*
761   *growth since 1980s. Note – these plots are not to the same time scale.*
762   *Left panel: Methane record during Termination 1. Prior to about 17ka before the present,*
763   *methane was below 400 ppb (from various sources: see text). Methane rose in Termination*
764   *IB, especially in the abrupt phase about 14.65 kyr ago. The Younger Dryas. 12 ka ago, saw a*
765   *return to cold conditions, especially in the northern North Atlantic, abruptly ended in*
766   *Termination IA, 11.64 kyr ago, date shown by vertical line.*
767   *Right panel: modern methane record. Growth prior to 2006 shows convex equilibration*
768   *trend; growth from 2006 shows concave (accelerating) trend (NOAA data). Note time scales*
769   *not the same.*

770

771 There is evidence for strong growth in tropical (30ºS to 30ºN) methane emissions during
772 Termination 1 (Riddell-Young et al. submitted 2023, Baumgartner et al 2012), as tropical
773 wetlands responded to an abrupt expansion of tropical rain belts. Methane output may
774 have risen from perhaps 60 Tg/yr during glaciation to 120 Tg/yr or more in the post-
775 termination Holocene. That global increase of 60 Tg across the whole event can be
776 compared to the present-day estimate derived above that 'natural emissions' have
777 increased by about 35-45 Tg since 2006.   Riddell-Young et al. (submitted 2023) and
778 Baumgartner et al. (2012) also found evidence for a supplementary role of emissions from
779 boreal methane sources, findings prescient of the present-day results of Qu et al. (2022).
780 Similar patterns are also inferred from the weak interpolar gradient for methane in
781 Termination 1B which suggests methane growth was driven by a major tropical input
782 (Severinghaus and Brook 1999).

783 In addition to termination events, examples of rapid changes in atmospheric methane, in
784 which methane rose by 32-53 ppb, are also recorded in Heinrich events during glacial
785 periods. Though not analogous to present-day conditions, the rapid methane changes are
786 instructive as they show how responsive methane emissions are to climate shifts. Heinrich
787 events are marked by layers of ice-rafted debris in the North Atlantic seabed record, that
788 must have been dropped by armadas of icebergs breaking off the ice sheets over Greenland
789 and North America. Studying the HS1 event (16.15 kyr BP), which occurred near the end of
790 the last major glacial period, Rhodes et al. (2015) inferred a marked southerly shift in the
791 Inter-Tropical Convergence Zone had taken place in response to Northern Hemisphere
792 cooling and greater sea-ice cover, causing a major expansion in southern hemisphere
793 wetlands, which in turn drove a rapid increase in methane emissions by 29 Tg/yr.

794 To conclude, the methane and $\delta^{13}C_{CH4}$ records of glacial/interglacial events are consistent
795 with the hypothesis that the abrupt phase of methane growth was driven by a very rapid
796 biogenic response, mainly from tropical wetlands.

797 ## 8. Meteorological Changes

798   Meteorologically, past termination events may have originated in specific regional locations
799   and then spread globally. For example, in the North Atlantic realm, the rapid meteorological
800   changes in the most studied abrupt termination event, the end of the Younger Dryas (T1A),
801   may have been a consequence of a set of changes originating in the tropics and then
802   spreading to include the North Atlantic, the Asian Monsoon and the Westerlies (Cheng et al.
803   2020). Moreover, model experiments typically show a spin-up time before any change has
804   impact on the global methane budget: thus for a methane signal to have become
805   identifiable in the period 2007-2022, the changes triggering the necessary spin up would
806   have been perhaps a decade or more ago.

807   If the post-2006 methane growth represents more than multi-decadal variability and is
808   indeed the start of a major long-term reorganisation of the planetary climate system, then
809   two questions arise: Can such global-scale modern meteorological changes be identified,
810   given that both short-term change and sustained regional multi-decadal variability are
811   characteristic of the Holocene climate (Wanner et al, 2008)? Are there today any direct signs
812   of incipient global-scale meteorological reorganisation?

813   Recent meteorological changes, though different in style and regional impact, may indeed
814   be similar in speed and planetary scale to global changes during termination events. During
815   2006-2020 the total Earth system has experienced a remarkable heating of $0.76\pm0.2Wm^{-2}$
816   with about 89% of the heat stored in the ocean, 6% on land, 4% in the cryosphere and 1% in
817   the atmosphere (von Schuckmann et al. 2023). Even a small increase in the partitioning of
818   this heat into the air will have dramatic impact on global weather.

819   Arguably the most profound global-scale evidence for present-day climate warming comes
820   from the heat content of the upper part of the oceans (von Schuckmann et al. 2023), which
821   not only has a sustained and strong warming trend, but the rate of warming is accelerating
822   (Cheng et al 2023). Warming has been particularly anomalous in the South Atlantic, in the
823   North Atlantic offshore North America and in the Indian Ocean offshore Southern Africa.
824   Ocean heat produces evaporation and thus precipitation: wetlands will respond. The 'triple-
825   dip' La Niña of the first years of this decade must be a factor (McPhaden et al. 2023), while
826   multi-centennial variability of internal origin may also be important.

827   In recent years, there has been marked weakening of the Atlantic Meridional Overturning
828   Circulation (AMOC), in particular since 2005 (WMO 2023, Bonnet et al, 2021). Concurrently,
829   changes in the Walker circulation (El Niño /Southern Oscillation, ENSO) and the Indian
830   Ocean dipole have had profound impacts on tropical precipitation and temperature on land.
831   Hadley cell expansion has shifted the zone of tropical cyclones (Sharmila and Walsh 2018),
832   with poleward shifts in extra-tropical storm tracks and jets, and upper tropospheric
833   warming. As during glacial/interglacial transitions, and particularly in the abrupt 'flip' phase,
834   the Hadley circulation is expanding again today and the extension of the subtropical edge of
835   the Hadley circulation has already had impact on a wide range of extratropical biological
836   productivity (e.g. Pandey et al. 2017, Osland et al 2021). The poleward shifts of the
837   planetary circulation and the concurrent expansion of tropical weather systems are now
838   becoming well-documented (Staten et al. 2020, Grise et al. 2019, Voight et al. 2021,
839   Studholme et al. 2022).

840   Tropical weather systems are tightly interlinked (Cai et al. 2019, McPhaden et al. 2023), with
841   widespread major recent changes. Geng et al (2022) have suggested that increased ENSO
842   changes may emerge much sooner than hitherto expected, while Wang et al. (2019)

843 presented evidence for major shifts in the origination and strength of El Niño events, finding
844 more frequent occurrence of extreme events since the 1970s and changes in ENSO onset
845 from originating in the eastern Pacific to the western Pacific. McPhaden et al. (2023), Hasan
846 et al. (2022) and Jo et al. (2021) suggested linkage between the Indian Ocean Dipole and
847 Atlantic and Pacific conditions. Sun et al. (2022) present evidence for substantial increases in
848 early onset of monsoon weather and positive Indian Ocean Dipole events, with dramatic
849 impacts on regional flooding. For example, catastrophic rains and floods in East Africa in
850 2019 came from a remarkable concatenation of meteorological factors, including record
851 levels of the Dipole Mode Index, ENSO effects, anomalous zonal winds over the central
852 Indian Ocean, very warm sea surface temperatures in the eastern Atlantic and Indian
853 Oceans, and unusual zonal circulation (Nicholson et al 2022).

854 There have been recent large-scale shifts in the Indian Ocean Dipole (IOD) and unusual
855 ENSO changes (Pandey et al. 2017). These weather changes have profound impacts on
856 methane emissions. Feng et al. (2022) attributed much of the change in methane emissions
857 over tropical South America and tropical Africa to IOD and ENSO shifts. Dramatic changes
858 may be affecting the Indian Ocean Dipole, which plays a major role in controlling rainfall
859 over the wetlands of east sub-Saharan Africa (Feng et al, 2022), with recent trends towards
860 more frequent and intense positive events (Abram et al. 2020). During strong La Niña
861 episodes, rainfall can deeply fill wetlands, while during El Niño episodes various parts of
862 Amazonia and East Africa have experienced changes likely related to climate warming, with
863 longer dry- and shorter wet-seasons in some places, and fires spreading to areas that have
864 not burned for millennia; the opposite taking place in other regions. In particular, rains in
865 Eastern Africa have strong links to the ENSO cycle and are dependent on changes in the
866 Walker circulation (Nicholson 2015) and Indian Ocean dipole, together with the strength of
867 pulses of the Madden-Julien oscillation.

868 Polar climates are also changing rapidly (Łupikasza & Cielecka-Nowak, 2020) especially with
869 Arctic amplification of warming (Previdi et al. 2021). Arctic sea ice is in very rapid retreat
870 (Kim et al. 2023). Arctic amplification may be linked to a negative Northern Hemisphere
871 Annular Mode, large scale circulation changes, and increased durations of weather patterns
872 and extreme precipitation over the Northern Hemisphere (Liu et al. 2021). Weather patterns
873 are shifting in continental interiors (IPCC 2021 their Fig. 8.11), with regional warming across
874 Siberia (Wang et al 2022). Regional climate warming has had significant impact on plant
875 productivity, promoting the greening of the tundra (Berner et al. 2020). Boreal and Arctic
876 warming have had marked effects on temperature and precipitation over large swampy
877 areas, for example in western Siberia (Gorbatenko et al 2020), presumably by increasing
878 supplies of organic detritus and thus methanogen productivity.

879 These profound ongoing global-scale changes in the modern ocean and atmospheric
880 circulation patterns have many parallels in past termination events (see Section 7 and Fig.
881 8), though with the caveat that the modern world is profoundly different, especially in the
882 absence of the major meteorological impacts of the large ice domes over Canada and
883 Scandinavia. Thus any global-scale meteorological changes that occur in the next few
884 decades will clearly be very different from the glacial/interglacial transitions. Yet perhaps
885 there are analogies too, particularly in the paleoclimatological evidence that the global
886 climate system can reorganise very rapidly indeed, over as short a time period as a few
887 decades.

888 A further caveat: although the present-day meteorological changes are widespread and
889 profound, clearly on an inter-hemispheric scale, and likely involving multiple interlinked
890 teleconnections, they may yet still be within the multi-decadal or centennial spectrum of
891 Holocene variability. Many major meteorological circulation patterns have only recently
892 been identified and their record of change compared to the recent historic past remains
893 poorly documented, although the IPCC (2021) Summary for Policymakers commented that
894 evidence of observed change has strengthened since the previous assessment report. It is
895 not clear that current climate extremes, though large, abrupt, and ongoing, and with potent
896 impact on methane emissions (Feng et al 2022), are great enough in sum to be evidence for
897 an ongoing global-scale meteorological reorganisation. A grand-scale meteorological
898 progression of the type identified by Cheng et al. (2020) would be hard to identify from
899 weather data while it took place, and likely only recognisable in retrospect. The evidence
900 remains unclear.

901 Moreover, apart from the measurement of heat stored in the oceans (Cheng et al. 2023, von
902 Schuckmann et al. 2023), it is difficult to quantify the total sum of change, nor to quantify
903 the collective impact on global climate. But equally it is plausible that the multiplicity of
904 recent events, their abruptness, and their power are circumstantial signs a major
905 reorganisation of the global climate system has already begun. Like the heat of the oceans,
906 the biogenic methane signal may be a telling summation, a bellwether that signals the onset
907 of permanent global change, the end of the Holocene.

908 To summarise the results in Sections 1-8: In the period 2007-2022, methane's growth rate
909 has bee very high, with as overall concave (accelerating) trend and a significant negative
910 shift in $\delta^{13}C_{CH4}$. If the estimates given above of the growth in agricultural emission are
911 accepted, then much of the new emissions that are driving this growth come from wetlands
912 and other natural sources, as found by Basu et al (2022), Qu et al. (2022), Feng et al. (2022,
913 2023), Peng et al (2022) and Rosentreter et al. (2021). If the "85% biogenic" estimate (Basu
914 et al. 2022) continues to apply in the year 2022, growth from specifically biogenic emissions
915 alone (i.e. growth from climate change feedbacks, both wetland and agricultural and waste)
916 may have been 15 ppb, implying the present-day 'non-fossil fuel' growth trend by itself is
917 significantly faster than the maximum growth rates in the ice core records (Table 2).

918 ## 9. Modelling

919 **9.1 Modelling Methodology**

920 Is methane's growth since late 2006 now becoming comparable in scale and in cause to
921 methane's growth during a termination event?

922 To address this question, modelling focussed on the question: what would happen to the
923 methane burden and its $\delta^{13}C_{CH4}$ during the abrupt phase of a termination event, if the
924 abrupt growth took place today? This is not a model to replicate the palaeoclimate record
925 but to elucidate modern trends. Thus the model is set up with a modern distribution of
926 wetlands, including both tropical and boreal wetlands (which were largely absent in glacial
927 periods). The model is designed to match century-scale trends over a conceptual abrupt
928 growth phase and to follow major emission variations.

929 A modified version of the model used in Nisbet et al. (2019) was used. The model is a
930 running budget model with 4 semi-hemispheres and exchange rates between them
931 consistent with the observed interhemispheric rate of mixing. Methane removal uses [OH]

932 destruction from Spivakovsky et al. (2000) with kinetic isotope exchange from Cantrell et al
933 (1990), Cl removal from Hossaini et al. (2016), and soil removal from Curry (2007). The
934 model was designed to examine changes in methane mole fraction and in methane's
935 isotopic content, averaged over four semi-hemispheric regions (30–90°S, 0–30°S, 0–30°N,
936 and 30–90°N), with exchange rates between them consistent with the interhemispheric
937 transport time. Fitting methane's carbon isotopic record is central to the modelling because
938 of the powerful insights $\delta^{13}C_{CH4}$ provides into changing methane sources (Craig et al. 1988).

939 We first modelled an abrupt ('flip') phase patterned on a the abrupt phase of a 'typical'
940 termination event, to understand its dynamics. Then, having characterized the abrupt phase
941 of a typical event, we used the model to match the current (21st century) growth record. The
942 model tracks the impact of a sharp increase in biogenic methane, to test whether it is
943 comparable to the sudden changes in a typical termination.

9.1.1 – Termination event model – changes in methane burden and $\delta^{13}C_{CH4}$

944
945 We simulated modern-type emissions growing over a time period of 30 years, into a
946 putative model of methane's glacial-like atmospheric burden to see if a 'termination-like'
947 pattern developed, not just replicating the growth in methane burden but also to
948 investigate the $\delta^{13}C_{CH4}$ isotopic consequences.

949 Biogenic sources used in each semi-hemisphere for the "Ice-age" and "Termination 1"
950 periods are scaled down from a modern scenario fitting recent CH_4 and $\delta^{13}C_{CH4}$ data (Nisbet
951 et al 2019) and are not from glacial-period biosphere reconstructions, but the fossil fuel
952 contribution, taken as 30% of the total source at present (Lowe et al. 1988; Lassey et al.
953 2007), was omitted. Relative to the total, the distribution of CH_4 sources by semi-
954 hemisphere was: 12.4% in 30-90°S (HSH); 27.7% in 0-30°S (LSH); 31.1% in 0-30°N (LNH) and
955 28.8% in 30-90°N (HNH). The analysis of geographic spread was not expected to be very
956 sensitive to the latitudinal distribution of fossil methane sources but the omitted recent
957 fossil fraction was taken as being distributed 20% : 40% : 40% in LSH : LNH : HNH. Omitting
958 the fossil fuel emissions source leaves a distribution for the other sources as: 17.7% in HSH;
959 31.0% in LSH; 27.3% in LNH; and 24.0% in HNH.

960 These proportions according to latitudinal zone applied to a global total source consistent
961 with sources scaled to give a global mean CH_4 mixing ratio of 700 ppb for "post-transition"
962 and 400 ppb for 'initial' conditions. The initial scenario also reduced the 30-90°N (HNH)
963 region source further because cold temperatures restricted land plants and especially
964 wetland areas. Global average results are not particularly sensitive to how much the HNH
965 region is reduced relative to the global total source, but results are shown for the HNH
966 region source being reduced from 24% to 16% of the total with the other 8% distributed
967 equally over LNH and LSH.

968 The isotopic signatures of the "Initial" (i.e. pre-transition) sources (S), here termed $\delta^{13}C_S$, are
969 taken as having $\delta^{13}C_S$ 4‰ heavier than present sources, and the source pulse of increased
970 emission leading into the transition is taken as having $\delta^{13}C_S$ = -59‰, a value typical of
971 modern outer (seasonal) tropical wetlands (France et al. 2021, MOYA/ZWAMPS Team 2021).
972 The transition between the "interglacial" and "glacial" states of the global methane budget
973 is done with a constant rate of change in the source, and its $\delta^{13}C_{CH4}$, over 30 years. Mixing
974 ratio, source emissions, *Src* (Tg/yr), source signatures for $\delta^{13}C_S$, and atmospheric $\delta^{13}C_{CH4}$,
975 here termed $\delta^{13}C_M$, are summarised in Table 4.

976 **Table 4: Source emissions, $\delta^{13}C_S$, mixing ratios and atmospheric $\delta^{13}C_M$ in modelled 'Initial'**
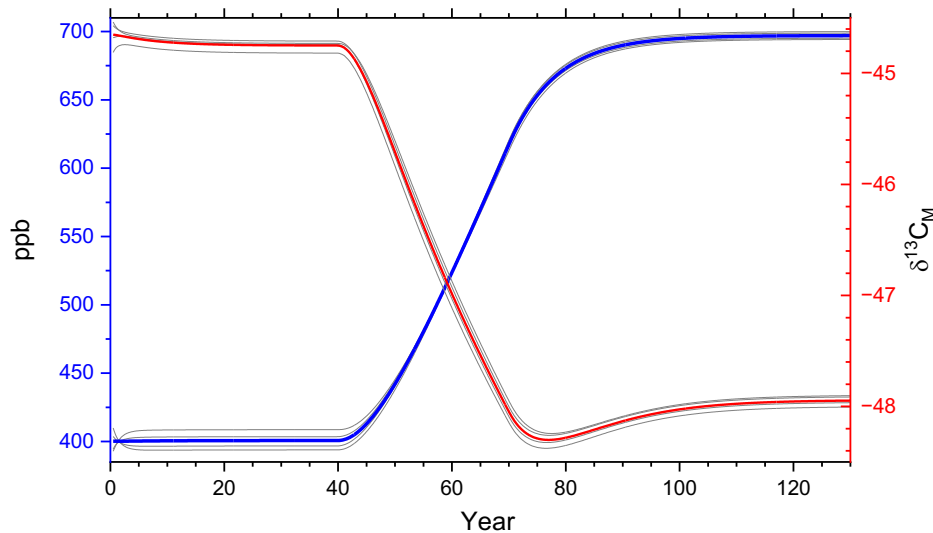977 **(pre-transition) to post-transition ('Post') values**

	Source Tg/yr (running annual average)					Source $\delta^{13}C_S$ ‰				
	30-90°S	0-30°S	0-30°N	30-90°N	Global	30-90°S	0-30°S	0-30°N	30-90°N	Global
Initial	23.6	46.7	41.8	21.4	133.5	-49.8	-50.8	-51.7	-56.4	-51.8
Post	30.9	78.2	79.6	45.1	233.7	-53.8	-54.3	-54.8	-57.5	-55.0
	Mixing ratio ppb (running annual average)					Atmospheric $\delta^{13}C_M$ ‰				
	30-90°S	0-30°S	0-30°N	30-90°N	Global	30-90°S	0-30°S	0-30°N	30-90°N	Global
Initial	408.6	403.5	396.7	393.8	400.7	-44.7	-44.7	-44.7	-44.82	-44.75
Post	694.2	695.1	698.9	699.9	697.0	-47.9	-47.9	-48.0	-48.0	-48.0

978

9.1.2 Modelling Results.

980 Plots of the changes in methane mixing ratio and $\delta^{13}C_{CH4}$ in the modelled *'Source-jump'*
981 *Scenario* (Table 4), are shown in Figures 10a and 10b. This sequence of events is broadly
982 similar to the real records of the methane burden in typical glacial terminations. The
983 isotopic results reflect the very rapid growth of emissions from all latitude zones, both
984 tropical and boreal. The isotopic results show the 'Tans effect' (Tans 1997), with changes in
985 $\delta^{13}C_M$ overshooting followed by a slow recovery – i.e. with $\delta^{13}C_M$ taking longer to equilibrate
986 than the mixing ratio. Inter-hemispheric spatial gradients take time to adjust after major
987 changes in emissions and Tans (1997) pointed out that the timescale for the $\delta^{13}C_{CH4}$ ratio is
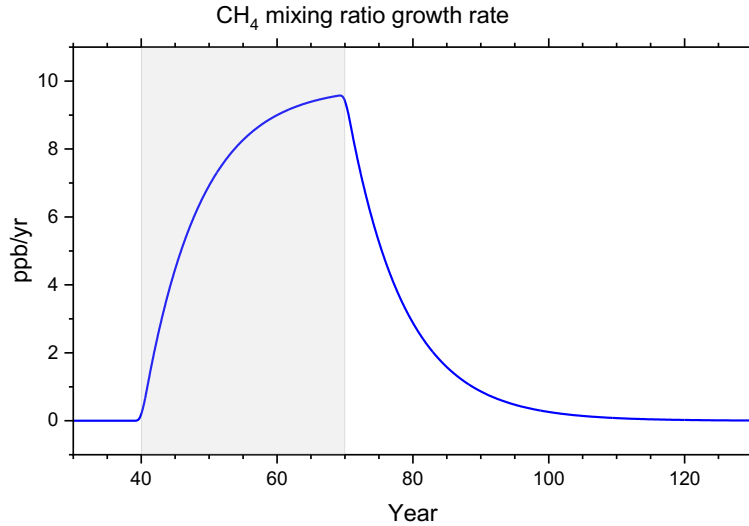988 also longer than for methane's abundance so provides complementary information.

989 In glacial terminations, the boreal wetlands took longer to deglaciate and hence the
990 dominance of tropical emissions with $\delta^{13}C_{CH4}$ close to the bulk atmospheric source led to a
991 brief hiatus in $\delta^{13}C_{CH4}$ while the burden grew. In the model, unlike the real past record, the
992 abrupt growth of boreal sources produces a significant negative shift in $\delta^{13}C_{CH4}$.

993 *Figure 10a. Methane mole fraction ($\delta^{13}C_M$) in ppb and $\delta^{13}C_{CH4}$ from the 4-box running budget*
994 *analysis with a 30-yr transition from 'Initial' to 'Post' sources. Blue is the global average mole*

995   *fraction and thin lines are for the four semihemispheres. The latitudinal distribution of the*
996   *CH₄ mole fraction reverses from being lowest in 30-90°N to being the highest there. Red is*
997   *the global average $\delta^{13}C_M$ and thin lines show values for each semihemisphere and this*
998   *change in $\delta^{13}C_{CH4}$ is uniform across all semihemispheres.*

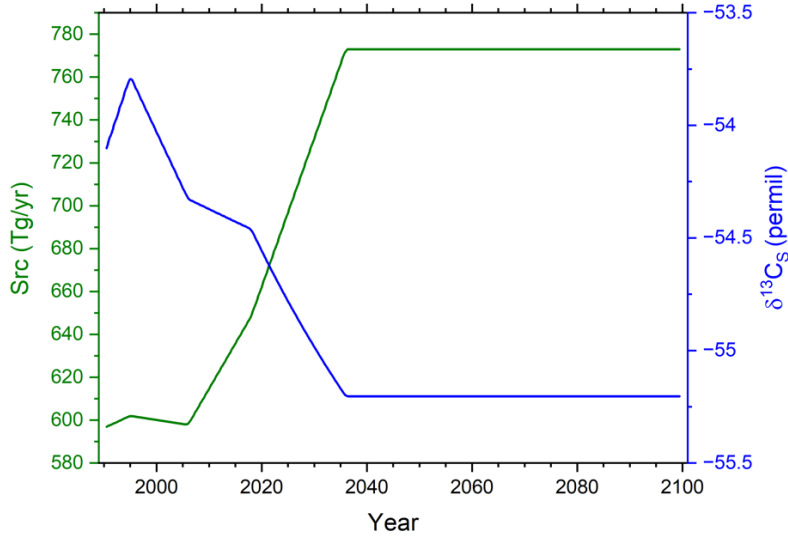999   *Figure 10b. Growth rate (ppb/yr) of the global average CH₄ mixing ratio in Fig. 8a.*

CH₄ mixing ratio growth rate

1000   **9.2. Present-day scenario: Modelling methane's modern growth and predicting the**
1001   **near future**
1002   To predict the impact if current trends continue for a full span of 30 years, from end-2006 to
1003   2037. the second model experiment focussed on matching the current growth in methane
1004   emissions and then projecting into the future until the change is assumed to be completed
1005   after 2036. This is an optimistic scenario that assumes good progress in the Global Methane
1006   Pledge to reduce methane emissions from purely abiogenic (fossil fuel) sources, and that
1007   biogenic emission growth then slows in a stable future climate.

1008   ***9.2.1 – Modern event methane growth model – changes in methane burden and $\delta^{13}C_{CH4}$***
1009   The 'modern-day' model run is for a 30-year period 2007-2037, together with initialising
1010   years and years of post-change stability in emissions budgets. After the 30-year period,
1011   emissions stabilise. In this model, sources are fitted to observations with a simple piecewise
1012   linear fit of both source emissions, *Src* (Tg/yr) and $\delta^{13}C_S$ up to 2022 (Fig. 11). Then the
1013   projections in Figs 11a and 11b that go beyond 2022 extend the source flux growth that was
1014   fitted to the most recent data, and continue for the rest of a 30 year transition period. The
1015   isotopic signature $\delta^{13}C_S$ is determined by assigning a constant $\delta^{13}C$ lighter than the current
1016   average $\delta^{13}C_S$ to the *Src* increase.

1017   *Fig. 11. 'Modern-day' model for a 30 year transition period 2007-2037 assuming a change*
1018   *from earlier global climate state ending in late 2006 to new stable climate state beginning in*
1019   *2037. Source flux (Src) and source isotopic signature $\delta^{13}C_S$ modelled to fit to measurement*
1020   *data (see Fig. 11a) up to 2022, thereafter projected to end of 30 year period, after which Src*
1021   *and $\delta^{13}C_S$ remain constant.*

For the *Present-day Scenario*, Figure 12a shows NOAA methane mixing ratio and atmospheric $\delta^{13}C_{CH4}$ data together with an extrapolated extension of the running budget analysis in Nisbet et al. (2019). The fit-to-data follows a smoothed version of the observed mixing ratio, shown in Figure 12a, with a maximum growth of 14.5 ppb/yr in 2022 (Figure 12b), when the observed rate was actually about 14 ppb, following an 18 ppb rise in 2021. This fit-to-data is up to August 2022 for the observed mixing ratio and $\delta^{13}C_{CH4}$ measurements, and then extrapolated to 2037, for a full 30-year period of emissions growth. The scenario has an overall mean growth rate over 30 years of 10.5 ppb/yr.

Figure 12a. Change in global mean mixing ratio (blue) and $\delta^{13}C_{CH4}$ (red) together with NOAA data to August 2022 and $\delta^{13}C_M$ data (green) to 2018. Compare with Fig. 10a.
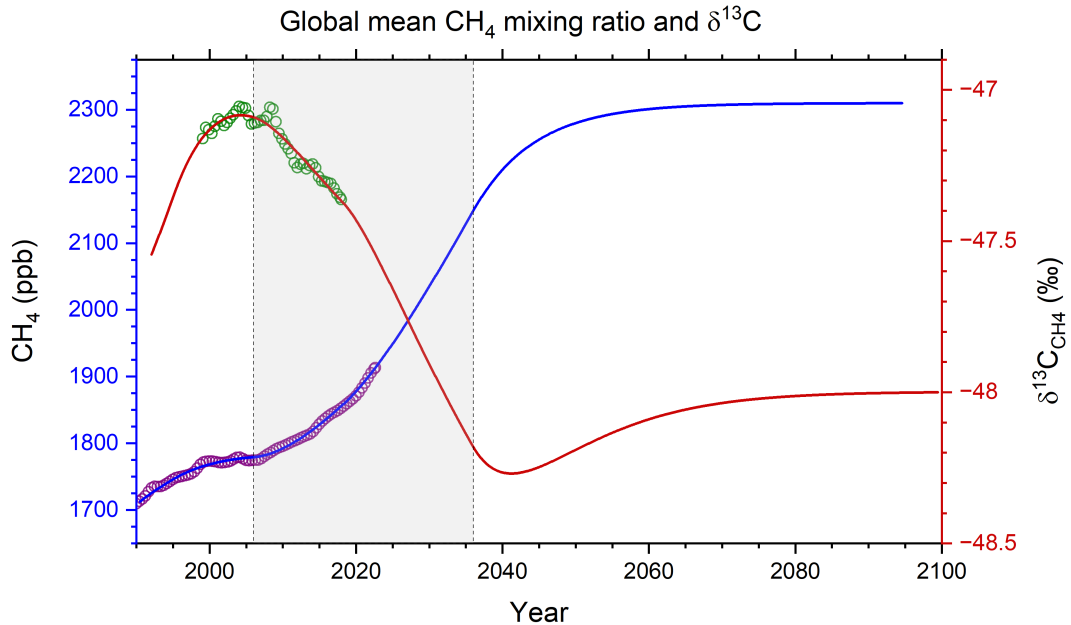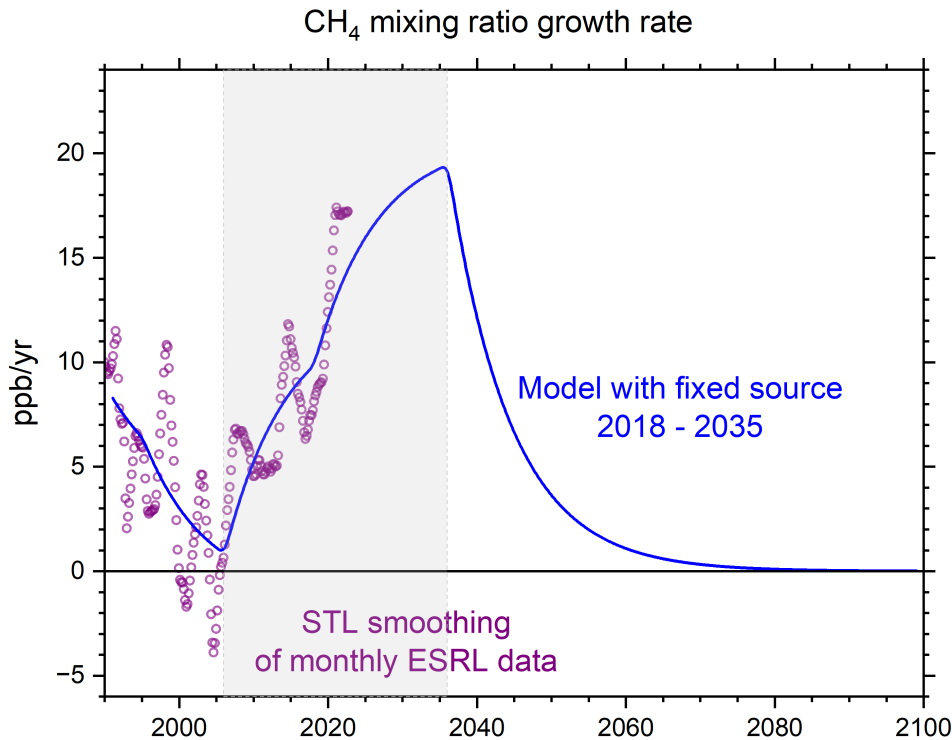

Figure 12b. Observed methane growth rate in ppb/yr from the ESRL data and from the model using a fixed source strength up to 2037, as shown in Fig 11. The measurement-based

1037 *growth rate determination uses the Seasonal Trend Loess (STL) analysis of Cleveland et al*
1038 *(1990) to separate a changing seasonal cycle from a changing trend. Compare with Fig. 10b.*
1039

CH$_4$ mixing ratio growth rate

1040 This analysis successfully tracks the observed inflexion and then decrease in atmospheric
1041 $\delta^{13}C_{CH4}$ (see Fig. 4 and green circles on red curve in Fig 12a), observed until 2022. In the
1042 projection part of the model analysis, the global mean CH$_4$ mixing ratio reaches 2348 ppb
1043 and stabilises around the year 2055. The budget analysis also follows the observed decrease
1044 in $\delta^{13}C_M$, which reaches a minimum in the year 2040 followed by some recovery.
1045 Stabilisation of $\delta^{13}C_M$ takes longer than for the mixing ratio because of the Tans effect, with
1046 $\delta^{13}C_{CH4}$ eventually reaching a minimum in 2040, followed by some limited recovery as the
1047 burden equilibrates, while the global mean $\delta^{13}C_s$ of source emissions decreases from -
1048 54.3‰ in 2006 to -55.2‰ in 2099.

1049 Our modelling suggests that the modern pulse of new biogenic methane, despite ongoing
1050 anthropogenic fossil fuel inputs with relatively positive $\delta^{13}C_{CH4}$, is capable of shifting the
1051 $\delta^{13}C_{CH4}$ of the much larger whole modern atmospheric burden by, say, -1.1‰ over the full
1052 30 year period 2007-2037. That includes inputs of equatorial methane with little isotopic
1053 leverage, outer seasonal tropical methane with some isotopic leverage, and boreal/Arctic
1054 methane with strong isotopic leverage. In the real record of the contemporary modern
1055 atmosphere, prior to the onset of growth in 2006, the mean atmospheric methane burden
1056 was slightly over 4900 Tg. In 2022, the mean burden had risen to 5300 Tg, a net increase of
1057 roughly 400 Tg during 2006-2022 inclusive. The accompanying $\delta^{13}C_{CH4}$ shift of about -0.55‰
1058 includes a 'positive' isotopic input from thermogenic sources such as anthropogenic fossil
1059 fuel emissions and biomass burning with isotopic signatures more ^{13}C rich than the bulk
1060 atmospheric source. Had there been no such positive leverage, the total biogenic-driven
1061 $\delta^{13}C_{CH4}$ shift over 2007-2022 that we would now be measuring would have been perhaps -

1062 0.7‰. Note that this shift has occurred despite the new emissions being diluted into a
1063 global burden five times larger than in glacial periods. A comparable pulse into the glacial air
1064 would shift $\delta^{13}C_{CH4}$ by 3 to 4‰ over a complete termination, including turn-on of boreal
1065 sources.

1066 To conclude: If methane emissions, primarily from biogenic methane sources, continue to
1067 rise at a rate similar to the one observed in recent years, the modern rise since 2006 would
1068 be large enough to be identified as the first part of a 'termination-scale' event in the ice core
1069 record of atmospheric methane. The conclusion also holds if only 85% of the current growth
1070 is considered, given that 15% of the ongoing rise is likely from fossil emissions that may be
1071 mitigated in the near future. Even if livestock emissions growth as fast as 1.4 Tg/yr/yr (Zhang
1072 et al., 2022: see above) is deducted, the remaining 'non-fossil fuel, non-livestock' growth
1073 rate still bears comparison with abrupt growth in a termination-scale event, the more so
1074 because the productivity of tropical livestock depends on vegetation growth that in turn
1075 follows climate-driven rain and warmth.
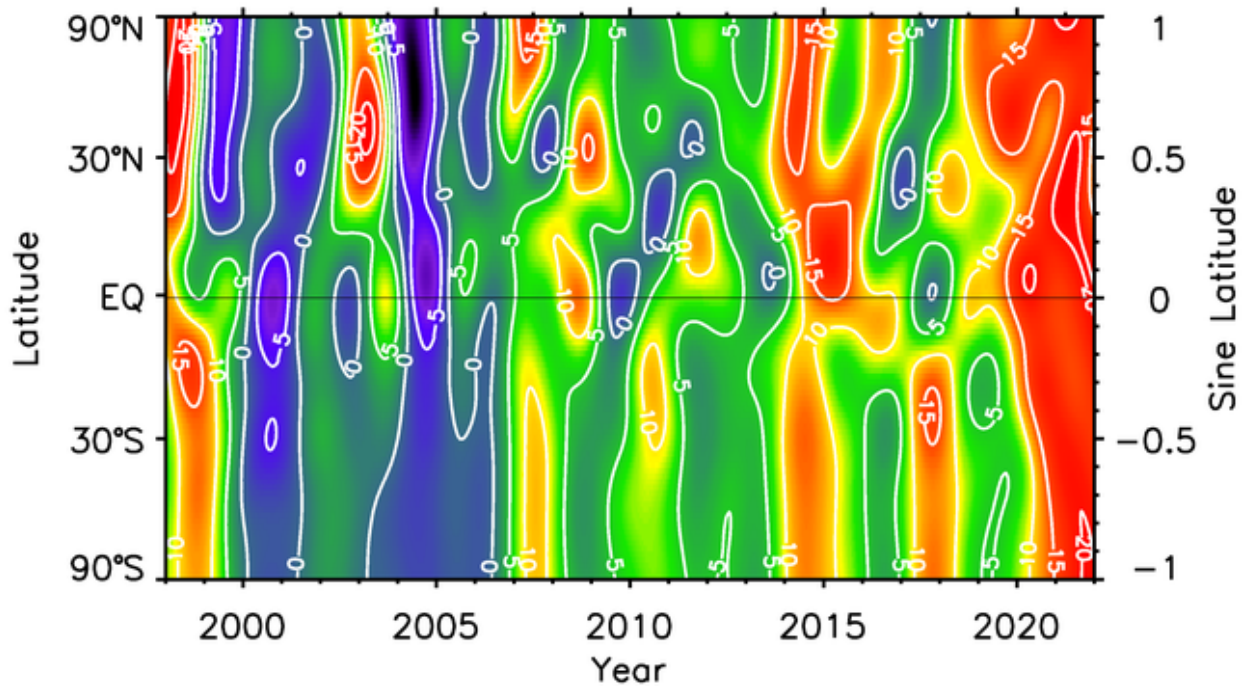
1076

1077   10. Discussion of Comparison

1078 To summarize, methane's mole fraction growth in the past 15 years is comparable to growth
1079 in termination events, and it is likely that ongoing changes in methane emissions from
1080 present day wetlands are comparable to feedbacks during the past global change events.
1081 Even if only 85% of modern methane growth is biogenic, and part of that biogenic growth is
1082 due to anthropogenic inputs like increased cattle populations and more use of nitrogen
1083 fertilisers, methane's non-anthropogenic growth in the past 15 years has been at least
1084 comparable to growth in past climate change events. Allowing for the difference in the mass
1085 of the pre-transition burden, the associated isotopic shift is also comparable to shifts
1086 recorded (Fig. 8) across whole termination events (i.e. after the boreal wetlands had
1087 become fully active).

1088 It remains unclear how much the biogenic changes to the methane budget in recent
1089 decades are within the natural range of responses to decadal or centennial-scale climate
1090 variability.

1091 The current methane growth event started in late 2006 in both northern and southern high
1092 latitudes (Fig. 13). In Arctic summer, southerly winds blew high-methane air poleward from
1093 boreal zones. From then on, the tropics became the main zone of methane growth,
1094 especially in 2014/5, but with marked growth in the northern temperate zone in 2014 and in
1095 the southern outer tropics around in 2018 (e.g. Pantanal wetland). Then came the
1096 extraordinary ongoing growth surge of 2019-2022. The sine-latitude-time methane map in
1097 Figure 13 (updated from Lan et al. 2021b) reflects this history, though with the obvious
1098 caveat that changes in natural sources and sinks are added to by changes in human
1099 emissions from the fossil fuel industry, agriculture and waste.

1100 *Figure 13 –Methane growth rate averaged by latitudinal zone, from 2000 through 2021,*
1101 *updated from NOAA data. Red 'warm' colours – growth. Blue 'cool' colours – decline. The*
1102 *vertical axis denotes the sine of latitude, which weights each latitude band by its*
1103 *atmospheric mass. The ITCZ migrates seasonally from roughly 30°N to 30°S (sine latitude 0.5*
1104 *to -0.5), while the Arctic zone is the band north of sine latitude 0.91. The current growth*
1105 *event began in late 2006. Note the remarkable growth since 2020.*

1106

1107

1108　Although the ongoing increase in global biogenic methane emission might be within the
1109　multi-century range of historic emissions variability (Fig. 3) (Ferretti et al. 2005, Mischler et
1110　al. 2009), the speed-of-change of the modern trend is extreme, much more rapid than
1111　methane's medieval changes or the post-1800 rise driven by fossil fuel use. The inference is
1112　that the biogenic component of methane's current (2007-2022) change is indeed likely
1113　outside the range of natural variability.

1114　Methane's modern growth, in ppb/yr, and isotopic shift are more rapid than in glacial-
1115　interglacial terminations (Table 3), though not necessarily faster than the maximum decadal
1116　change rates during some terminations. Thus there is evident similarity between the past
1117　increases in tropical biogenic sources that drove the glacial-interglacial terminations and the
1118　present-day biogenic inputs driving the current 2006-2022 rise in methane emissions.
1119　Though the events are very different, in the 15 years of growth to date the modern rise does
1120　indeed bear comparison with the scale and speed of the abrupt phase of a termination
1121　event.

1122　Previous orbitally driven natural transitions from cold glacial periods to warmer interglacial
1123　periods took place in the presence of large ice caps and widespread sea ice. In contrast, the
1124　modern climate change is from a warm Holocene (i.e. with widespread northern wetlands)
1125　to a new, presumably even warmer future. The comparison between modern growth and
1126　past analogues should not be taken too far. A modern 'termination-style' event marking the
1127　reorganisation from a Holocene warm climate to some new post-Holocene yet-warmer
1128　climate will be very different from any of the end-glacial events of the past half-million
1129　years.

1130　Moreover, today's transition is anthropogenically driven, in an atmosphere where CO_2 is
1131　much higher and rapidly growing, and where crop wastes and fertilizer run-off are

1132 widespread. Thus it is possible that the wetland response today has already surpassed the
1133 wetland response in past glacial interglacial terminations.

1134 Yet it is indeed possible to imagine a new, modern step-change reorganisation of the
1135 planetary climate in a global 'termination-scale' event – this could include marked ocean
1136 warming and expansion of the ITCZ, and changes in the behaviour of the Indian Ocean
1137 Dipole as the Hadley circulation expands coupled with alteration in the strength and
1138 frequency of ENSO variations. Such changes could be accompanied by rapid Arctic land-
1139 surface warming and sustained ocean circulation responses, including changes in the
1140 Atlantic Meridional Overturning Circulation, on centennial-level timescales (Matsumoto,
1141 2007).

1142 Compared to the 'natural' CO_2 budget, which has a major component in the deciduous
1143 vegetation of the temperate northern hemisphere, changes in the biogenic methane signal
1144 reflect more global distribution of sources and sinks. In past palaeo-climate transitions, large
1145 changes occurred in the CO_2 budget, in response to changing latitude distribution of
1146 insolation or meteorology and warming oceans. But such feedback-related changes in CO_2
1147 are hard to identify. In the present-day record there is not yet clear evidence for sustained
1148 changes in the CO_2 burden that directly relate to climate change feedbacks and which
1149 cannot be explained within the uncertainty of quantifying anthropogenic fossil fuel
1150 emissions and land use changes. In contrast, given methane's lifetime, it can serve as a
1151 'tallying-together' of ongoing climate change impacts, a representative bellwether.

1152 Methane is a good integrative signal of the state of global wetlands, and methane's global
1153 budget – its growth or decline when the burden in the air is not in equilibrium with the net
1154 flux from sources and sinks – sums the changing breath of the whole land biosphere. This
1155 includes not only changing outputs from biogenic sources (nearly all terrestrial or coastal,
1156 not oceanic) such as tropical and boreal wetlands, grass and tree growth for ruminants, and
1157 growth in biomass fire fuel loads, but also changes in the meteorologically sensitive
1158 oxidative capacity of the atmosphere involving [OH] Cl , and soil uptake. All natural sources
1159 and sinks are highly variable with climate fluctuation. Wetland and ruminant emissions vary
1160 with plant growth, rapidly changing as precipitation and temperature shift in ENSO and
1161 Indian Ocean Dipole cycles, and as CO_2 varies. Methane removal by [OH] (especially in the
1162 tropical mid-troposphere) and Cl fluctuates with the intensity of the Inter-Tropical
1163 Convergence and the trade winds in the ENSO cycles. Hydroxyl is also sensitive to
1164 atmospheric NO_x, that historically came from dry season fires, usually human-lit. Soil sinks in
1165 aerated soils, capable of breathing as pressure fluctuates under frontal passage are climate-
1166 dependent, as bacterial methanotrophy needs the right conditions, neither too dry nor too
1167 wet.

1168 If the climate is constant, then the methane burden equilibrates and is steady. When the
1169 climate changes, natural methane sources and sinks respond and there is consequent
1170 disequilibrium in the methane budget (i.e. growth or decline of the burden). Sustained
1171 disequilibrium in the methane burden thus signals ongoing change in the biological
1172 productivity of the entire planet's land surface. With the isotopic spin-up taking several
1173 decades, a long-sustained growth or decline indicates a multi-decade change that is outside
1174 decadal variability.

1175 The abruptness, power and global scale of past glacial/interglacial terminations provide
1176 palaeoclimatological standards for comparison with what is taking place today (Tzedakis et

1177 al. 2009). The Eemian interglacial (130-115 kaBP, Marine Isotopic Stage 5, initiated by
1178 Termination II) was warmest around 125,000 years ago, with sea level perhaps 6 to 9 m
1179 above present-day level, implying significant melting both in Greenland and Antarctica
1180 compared to today (Dutton and Lambeck, 2012). The Eemian 'green Sahara' had abundant
1181 wetlands and great lakes (Larrasoana et al. 2013), very different from the current climate.
1182 However, the Eemian may be a poor guide to the future. Such past records may give little
1183 predictive help: the driving force today is anthropogenic, the speed of growth in CO_2 and
1184 CH_4 burdens is unprecedented, as is global land use change, so what is to come may be
1185 warmer than recent interglacials, even the Eemian.

1186 The model growth curve in Figures 12 a,b assumes growth that may be below what will
1187 occur in the next decade if both natural and anthropogenic emissions rise strongly.
1188 However, assuming the emission growth rates in the model, the increased radiative forcing
1189 of the climate from this extra methane input from the years 2021-2036 can be estimated at
1190 roughly 0.17 W/m^2. To put this in context, that is about equivalent to five years of present-
1191 day growth in CO_2 forcing. There are important consequences for climate modellers. Using a
1192 methane-enabled Earth System Model, Kleinen et al. (2021) found methane mixing ratios
1193 and hence radiative forcing substantially higher than assumed in the scenarios used for the
1194 Coupled Model Intercomparison Project (CMIP6); assuming methane growth is only due to
1195 anthropogenic causes may lead to underestimation of future change.

1196 The question remains open. The observed post-2006 CH_4 growth (Fig. 1) is comparable to
1197 growth during the abrupt phase of a termination. Top-down and bottom-up estimates of
1198 modern emission growth rates are comparable to or greater than growth in termination
1199 events. Modelling shows that the modern record is comparable to termination events both
1200 for the change in CH_4 abundance driven by natural sources and that there are parallels
1201 between the observed modern $\delta^{13}C_{CH4}$ record and the isotopic records during full
1202 terminations.

1203 Methane's unexpected rise means achieving the Paris Agreement's targets will be very
1204 difficult (Mikaloff-Fletcher and Schaefer 2019, Nisbet et al. 2020) and will likely demand
1205 accelerated switching from fossil fuels to renewable energy sources, in addition to rapid
1206 elimination of methane emissions from fossil fuel use. Reducing the methane burden to its
1207 pre-industrial size would have beneficial impacts not only on climate, but also on air quality,
1208 increasing the oxidising capacity of the atmosphere (Staniaszek et al. 2022). Shooting the
1209 methane messenger will not eliminate methane's message. But it would help.

1210 A casual coincidence is not necessarily a causal connection. That we are in the midst of an
1211 rapid methane growth event, substantially driven by natural sources, does not necessarily
1212 mean the onset of global climate change. There is still the possibility that we are simply
1213 experiencing decadal- or centennial-scale variability. But past decadal- and centennial- scale
1214 Holocene variability, while significant, is smaller and much less abrupt than the typical
1215 abrupt climate change. Moreover, rapid growth in natural methane emissions does not
1216 happen unless climate is changing also: thus methane may indeed be the bellwether, the
1217 first indicator, the messenger of climate change.

1218 There are limits to comparison. Applying the designation 'termination' to current changes is
1219 not strictly correct in the modern usage of Terminations IX to I. Yet Broecker and Denton
1220 (1990) originally recognised terminations in the wider sense as "massive and abrupt
1221 reorganizations of the ocean-atmosphere system". In this sense, such an event may indeed

1222 be taking place. The remarkable shifts in the biogenic methane budget since the end of 2006
1223 may indeed be a first indicator of a large-scale reorganisation of the climate system on a
1224 scale that matches past great changes. Any current or near-future warming transition will
1225 differ greatly from the past glacial-interglacial Terminations IX to I. There is no Roman
1226 number zero. But then, zero is different from all other numbers. The question is valid: have
1227 we already entered Termination Zero?

1228

Acknowledgements

1242

Contributions

1244 EJD, XL, SEM, DL, REF, JLF, TR, JS and EGN collected samples, made primary measurements,
1245 participated in development of the study and edited the manuscript. SEM performed $\delta^{13}C_{CH4}$
1246 measurements. MRM carried out the modelling in Section 9 and he and PP had input on
1247 meteorological and modelling discussion, especially in the tropics. XL and HDvdG estimated
1248 emissions growth from EDGAR data. JS and MND guided the input on ice core records and
1249 past terminations. Figures, including updates and modifications: 1 EJD,XL,(NOAA), EGN; 2
1250 PIP; 3 JS, MRM; 4 SEM,MRM,GD, TB; 5 SEM,MRM,GD, TB; 6 XL, HDvdG; 7 JS; 8 EJD; 9, 10,
1251 11 MRM; 12 JLF with input from TR and SEM; 13 EJD, XL; SI 1 SEM, EJD, SI 2,3,4 MRM, GB,TB
1252 SI 5 XL and HDvdG,. Table 1 EGN; Table 2 HDvdG; Table 3 EGN; Table 4 MRM.
1253 Conceptualisation and manuscript preparation mainly by EGN, MRM and EJD, with input
1254 from all authors. This paper and all methane papers depend on the impeccable quality of
1255 NOAA data (EJD, XL, SEM). Eric Wolff and Mark Lunt, and especially Vas Petrenko are
1256 thanked for their thoughtful, critical, and extremely helpful comments. We thank the most
1257 helpful anonymous reviewers and the editor for their kind and perceptive assistance over
1258 this very long and demanding study.

1259

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1810 **Supplementary information**

1811 *Figure SI 1. NOAA $\delta^{13}C_{CH4}$ record 2007-2022 from Ascension Island (8ºS in the equatorial*

1812 *zone). Note variability range of short-term weather changes and sustained negative shift.*

1813 *Ascension Island is the key monitoring station representing the southern hemisphere Atlantic*
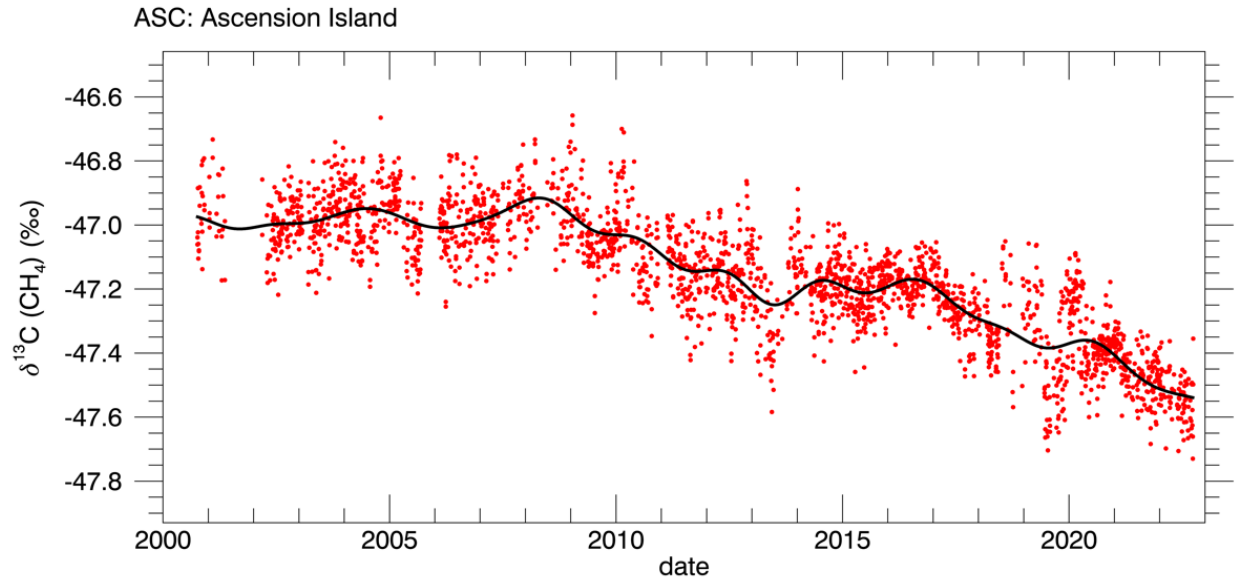
1814 *tropical and trade wind zones.*

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1817 *Figure SI 2 . Polar record for CH_4 and $\delta^{13}C_{CH4}$, Alert and Barrow. NOAA data. See Fig. 4*

1818 *caption in main text.*

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1821   *Figure SI 3 Northern mid-latitude record for CH₄ and δ¹³C_{CH4}. Data from World Data Center*
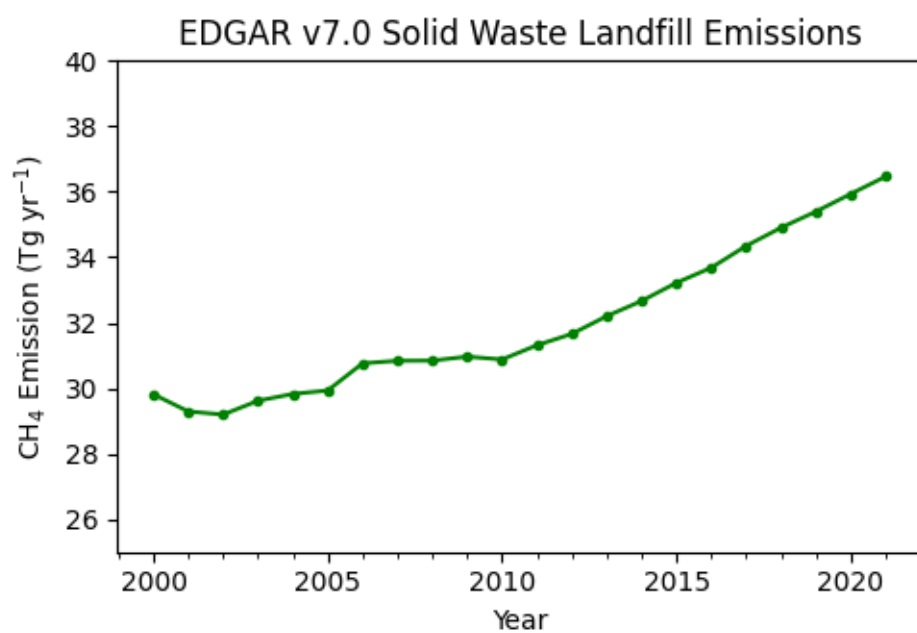1822   *for Greenhouse gases and NOAA (see Fig. 4 caption in main text).*

1823

1824   *Figure SI 4. Equatorial record for CH₄ and δ¹³C_CH4, Ascension and American Samoa. NOAA*
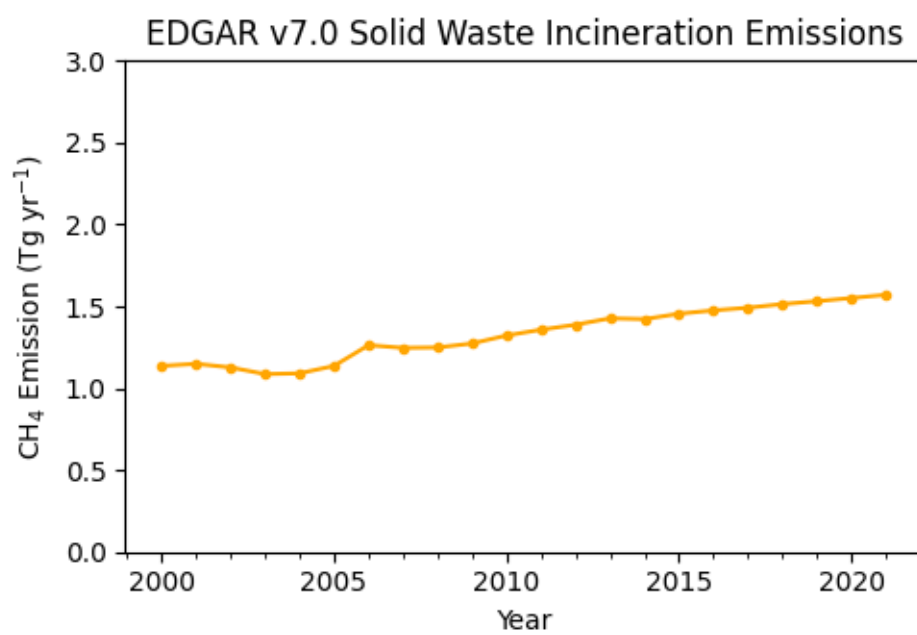1825   *data. See Fig. 4 caption in main text.*

1826
1827   *SI 5 EDGAR v. 7.0 (Emissions Database for Global Atmospheric Research) estimates of*
1828   *growth in emissions from a) solid waste and landfill; b) solid waste incineration; c) Manure*
1829   *management; d) Waste water; e) Ricefields.*
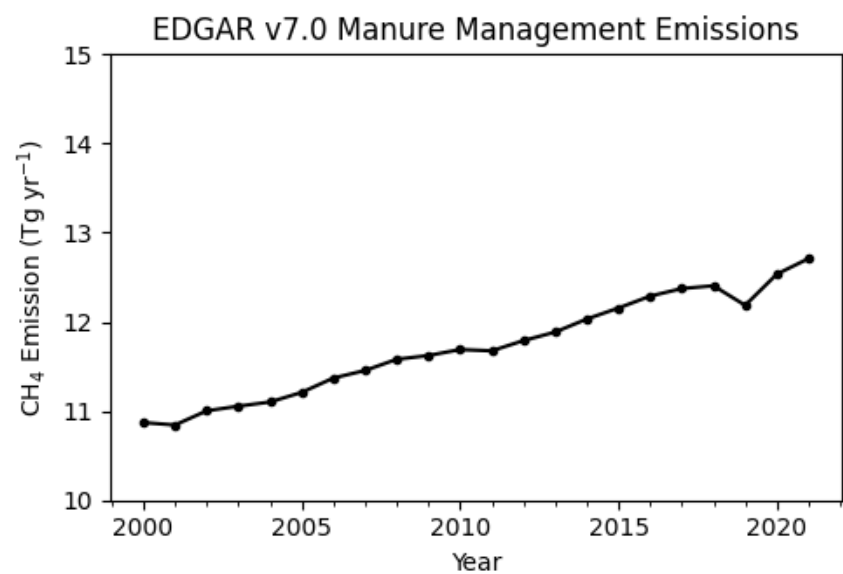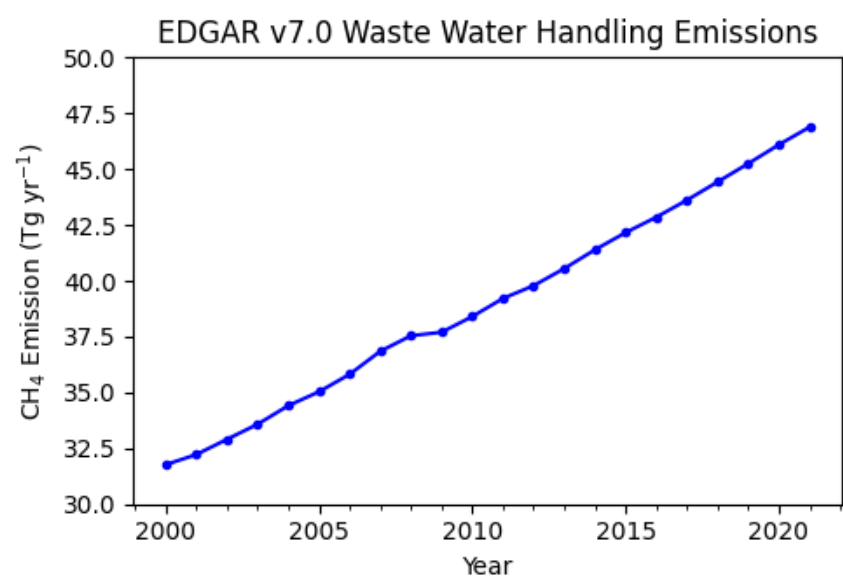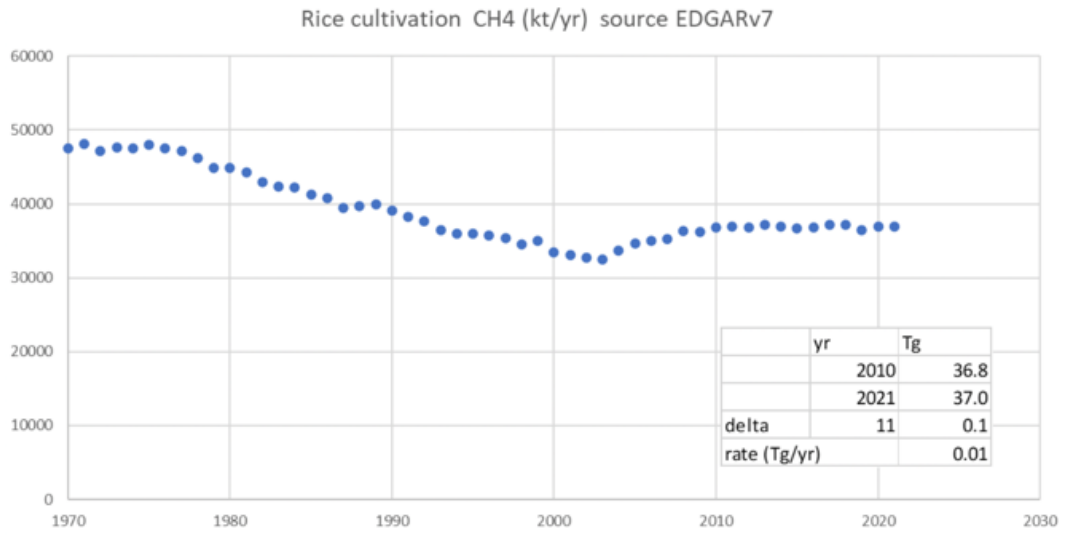1830   *From EDGAR (2023). https://edgar.jrc.ec.europa.eu/dataset_ghg70*
1831

EDGAR v7.0 Solid Waste Landfill Emissions

1832

EDGAR v7.0 Solid Waste Incineration Emissions

1833

EDGAR v7.0 Manure Management Emissions

1834

EDGAR v7.0 Waste Water Handling Emissions

1835
1836   *Fig. SI.5e Methane from rice cultivation: minimal recent (2010-2021) growth rate.*

Rice cultivation CH4 (kt/yr) source EDGARv7

	yr	Tg
	2010	36.8
	2021	37.0
delta	11	0.1
rate (Tg/yr)		0.01

1837
1838

1839   *Fig SI 6. CH$_4$ mole fraction values in ppb from the 4-box running budget model for sources*
1840   *that fit measured values to 2017 and then give 10 ppb/yr growth until 2035. Orange is 0-*
1841   *30°N. Black is the glob*al *average and overlays the 30-90°N case. Blue is 30-90°S and green 0-*
1842   *30°S. Jump in emissions takes place in 2007; equilibration is mostly complete by 2045. Note*
1843   *that CH$_4$ mixing ratio is higher in the 0-30°N semihemisphere before and after this transition.*
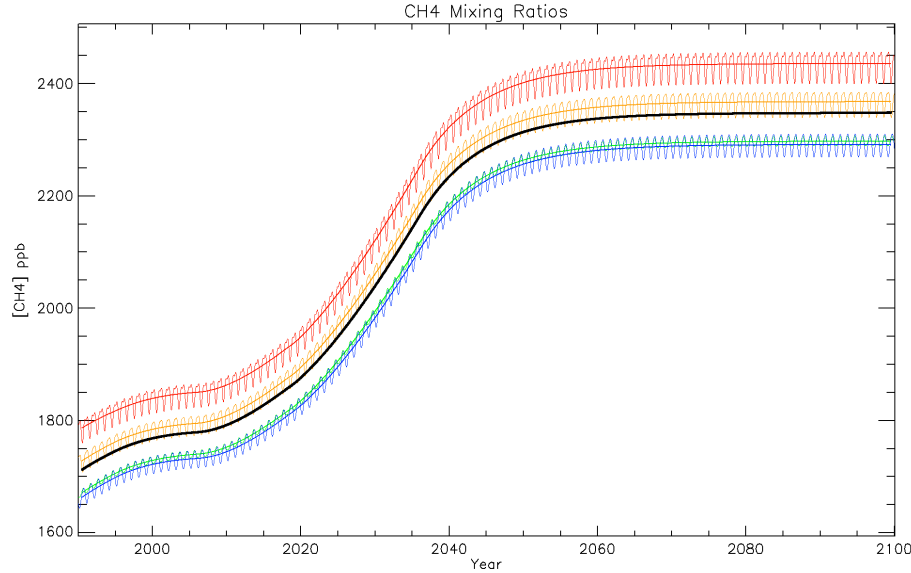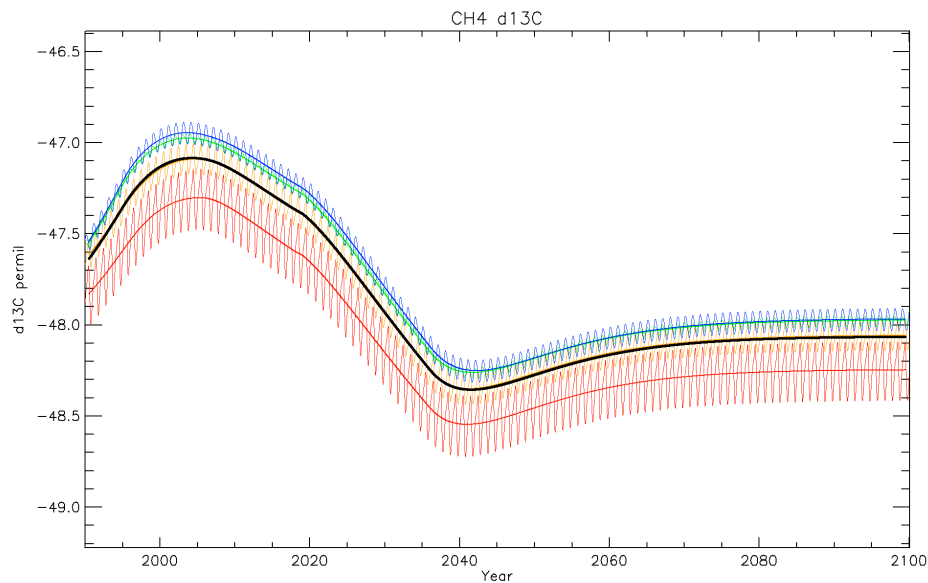

1844   *Fig SI 7. δ^{13}C$_{CH4}$ (‰) in the 4 semi-hemispheres for the inputs and colours shown in Fig SI2.*

1845

1846

1847   **Main Text Figures 4 and 5**
1848   Changes in CH$_4$ mole fraction and δ^{13}C have been taken from ten sites and data from the
1849   World Data Center for Greenhouse Gases (https://gaw.kishou.go.jp/), NOAA, INSTAAR,
1850   NIWA, University of Washington and University of Heidelberg (IZO from Levin et al., (2012).
1851   Changing trends in the data have used the Cleveland *et al* STL (Seasonal Trend Loess)
1852   method with monthly data for each site. This approach has been extended to deal with
1853   missing monthly data values by optimising these to produce a smooth STL fit. Periods where
1854   the number of months is not a multiple of 12 are dealt with by merging a series of STL fits

1855   that cover sub-periods that are a multiple of 12 months and retaining the full range of these
1856   partial fits across common months. The result is a spread in trends at the begin and end of
1857   the data series and around regions where there are significant groups of missing data.
1858   The same colour code is used in the following plots as in Figure 4 of the main text.
1859   The δ^{13}C values shown have used the recent intercomparison of $\delta^{13}C_{CH4}$ (Umezawa et al,
1860   2018) to adjust reported values and make them all consistent with the reference level used
1861   in that paper. Notably, the degree of agreement between different organisations that is
1862   shown here demonstrates the great and continuing value of that painstaking study by
1863   Umezawa *et al*. (2018).
1864
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1866