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Additional information

Supplementary information is available in the online version of the paper.

COMMENTARY:

Clearing clouds of uncertainty

Mark D. Zelinka*, David A. Randall, Mark J. Webb and Stephen A. Klein

Since 1990, the wide range in model-based estimates of equilibrium climate warming has been attributed to disparate cloud responses to warming. However, major progress in our ability to understand, observe, and simulate clouds has led to the conclusion that global cloud feedback is likely positive.

Clouds play a crucial role in Earth's climate, perhaps most importantly by modulating the radiation balance. Averaged globally and annually, clouds cause ~18 W m^{-2} of cooling relative to a hypothetical cloud-free Earth[1] (Fig. 1). This is the net result of a 46 W m^{-2} cooling from reflecting sunlight back to space (an albedo effect) partly offset by a 28 W m^{-2} heating due to reduced terrestrial radiation emitted to space (a greenhouse effect). The net planetary cooling provided by clouds is roughly five times as large as the planetary heating from a doubling of CO$_2$. Subtle changes in cloud properties that accompany anthropogenic warming — cloud feedbacks — can therefore strongly amplify or dampen that warming.

The overall cloud feedback is actually the aggregate effect of several individual cloud feedbacks, commonly separated into three components[2]: cloud amount, cloud altitude, and cloud opacity feedbacks. 'Cloud amount' feedbacks describe changes in the spatial coverage of clouds, the sign of which strongly depends on cloud type. Warming-induced increases in the amount of high, thin clouds would constitute a positive feedback because these cloud types have a stronger greenhouse effect than albedo effect. In contrast, warming-induced increases in the amount of low, opaque cloud would constitute a negative feedback. 'Cloud altitude' feedbacks represent changes in the height of cloud tops, and are positive if warming causes high clouds to rise, impeding Earth's ability to radiate additional heat to space. Finally, changes in cloud water content, phase (ice versus liquid), and size and number of droplets or ice crystals within clouds constitute 'cloud opacity' feedbacks; if the enhanced albedo effect dominates over the greenhouse effect, these feedbacks are negative.

Nearly all current climate models simulate an overall positive cloud feedback, amplifying warming. However, they differ as to the strength of the individual feedback components, and as a result, model estimates of the overall cloud feedback strength vary. These inter-model differences in cloud feedback are the dominant driver of inter-model differences in equilibrium climate sensitivity — the steady-state global warming

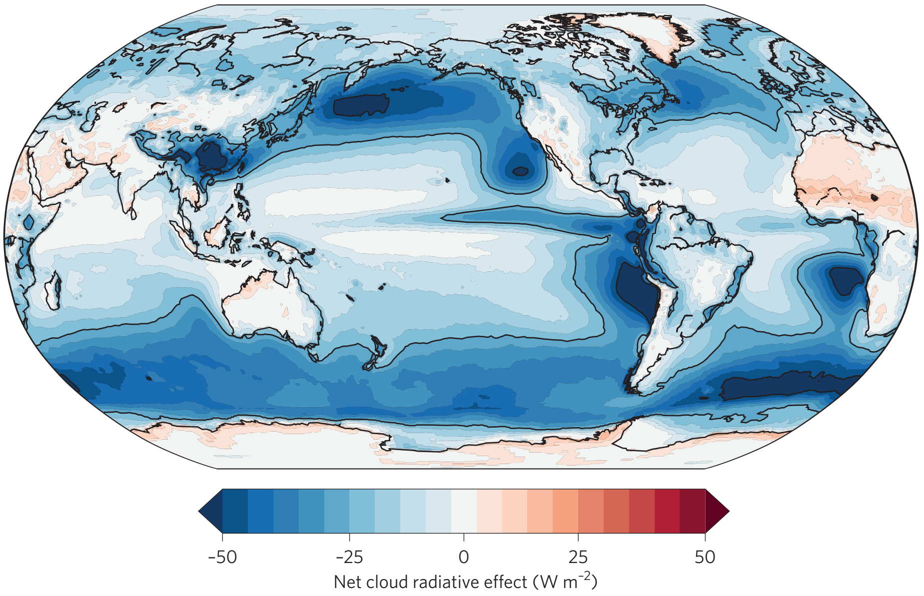

Figure 1 | Geographical distribution of the annually averaged net cloud radiative effect at the top of the atmosphere, computed over 2001–2016 from CERES EBAF Ed4.0 (ref. 1). Cloud radiative effect is computed as the difference between all-sky and clear-sky net radiative flux at the top of the atmosphere. Black contour lines are displayed for the −50 W m^{-2} and −25 W m^{-2} values.

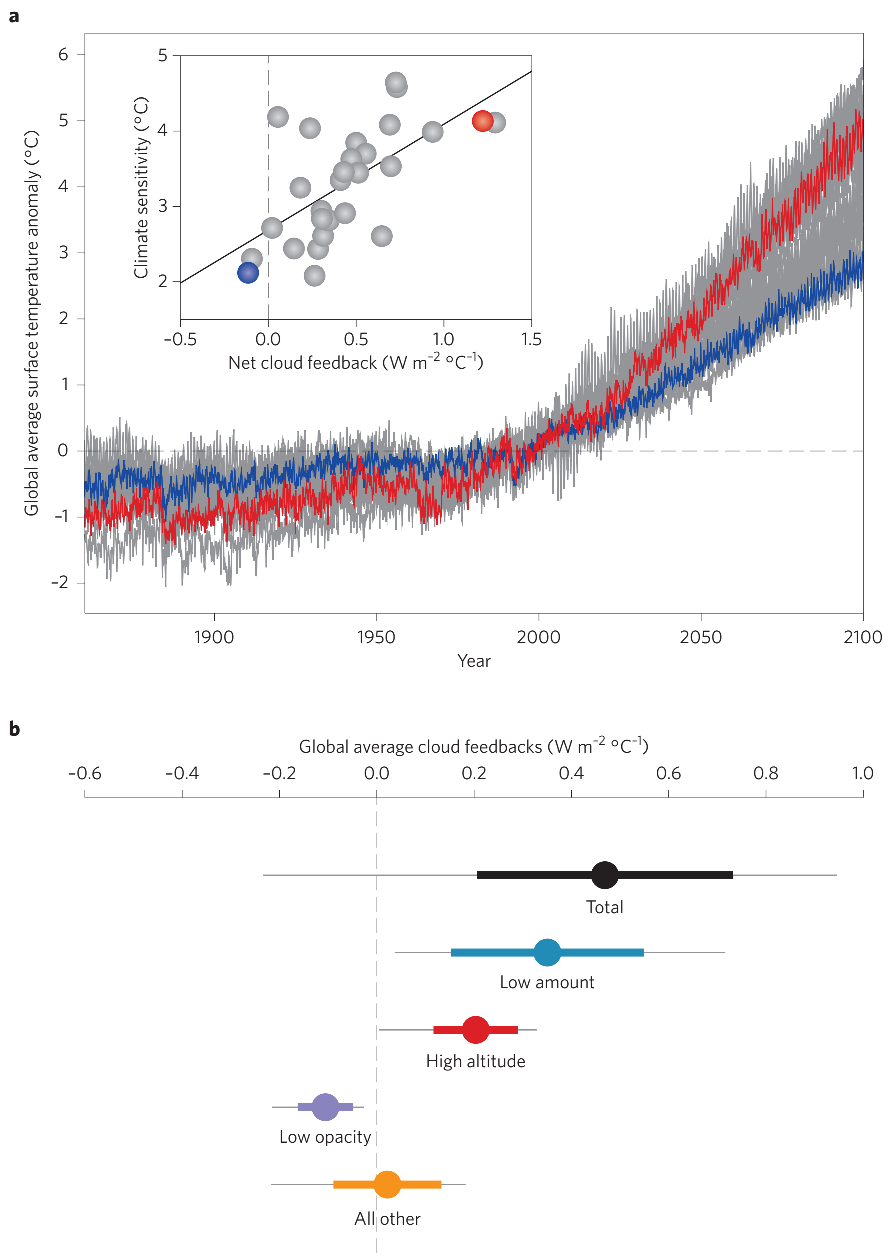

Figure 2 | Global average cloud feedbacks and their impact on climate sensitivity. **a**, Global mean surface temperature anomalies with respect to the 1986–2005 mean in historical (1860–2005) and RCP8.5 (2006–2100) simulations for 23 CMIP5 models, each represented with grey lines. In the inset, equilibrium climate sensitivity (ECS) estimates are plotted against global mean net cloud feedback estimates from 28 CMIP5 models (grey). Cloud feedback is computed by regressing cloud-induced radiation anomalies on global mean surface air temperature anomalies from 150-year 'abrupt4xCO_2' simulations, in which atmospheric CO_2 is instantaneously quadrupled from its pre-industrial concentration and then held fixed. ECS refers to the change in global mean surface temperature in response to a doubling of CO_2 and is computed as the effective forcing divided by the net feedback from 150-year abrupt4xCO_2 simulations. Blue lines and symbols refer to an illustrative low sensitivity model (GISS-E2-R, with an ECS of 2.1 °C) and red lines and symbols refer to an illustrative high sensitivity model (IPSL-CM5A-LR, with an ECS of 4.1 °C). **b**, Distribution of global average net cloud feedback (black) among 18 models analysed by ref. 2, and its breakdown into feedback components due to the change in low cloud amount (blue), high cloud altitude (red), low cloud opacity (purple), and all other cloud feedback components (orange). Low and high clouds refer to those with cloud top pressures greater than and less than 680 hPa, respectively. Circles indicate the multi-model average feedback values, with coloured lines spanning the across-model standard deviation. Thin grey lines extend to the model extrema.

that would result from a doubling of CO_2 (Fig. 2).

Understanding cloud feedback is a truly humbling challenge, in part because of the diversity of cloud types in the Earth system, each affecting radiation differently, and each being controlled by distinct processes operating on scales ranging from microns to thousands of kilometres. The importance of cloud feedbacks has long been identified[3], but despite major advances on theoretical, observational, and modelling fronts, pinning down the cloud feedback remains one of the central goals of climate science. Here we trace the community's evolving assessment of cloud feedback across the five IPCC reports, highlighting key developments (Fig. 3). It is not possible here to do justice to the huge range of literature assessed by IPCC by citing individual studies. Readers should refer to the relevant IPCC reports for references to the relevant primary research papers.

At the time of the First Assessment Report[4] (FAR; 1990), there was already extensive literature on cloud feedbacks. Changes in cloud amount, altitude, water content, and phase had been identified as potential feedback mechanisms during the 1970s and 1980s. The climate models in use at the time were, by today's standards, rudimentary. Most diagnosed cloud cover simply from relative humidity, although a few had started to diagnose cloud radiative properties from water content. The FAR assessed the cloud altitude feedback to be positive, but there was little sense of the relative strengths of individual feedbacks. Perhaps the FAR's most important conclusion was that cloud feedback represented the largest source of uncertainty in climate sensitivity among atmospheric models.

By the Second Assessment Report[5] (SAR; 1995), more climate models were predicting the mass of cloud liquid and ice, and generally finding negative cloud opacity feedbacks, albeit of widely differing strengths. Warming-induced increases in cloud liquid water relative to ice, and responses of anvil clouds, were identified as potentially powerful cloud feedbacks. The SAR described the increasing understanding of the meteorological factors that control low clouds (for example, a more stable lower atmosphere favours greater low cloud cover), and a possible positive feedback between sea-surface temperature and decreases in low cloud cover. Evidence for countervailing negative cloud feedback processes remained lacking. Weaknesses in the parameterization of small-scale processes that lead to cloud formation and dissipation were however highlighted. The report concluded that it was not possible at that time to judge the sign of the net cloud feedback, but it was assessed as unlikely either

	FAR[4] (1990)	SAR[5] (1995)	TAR[6] (2001)	AR4[7] (2007)	AR5[8] (2013)
Assessed cloud feedback	Not provided	Not provided	Not provided	Not provided	0.6 (−0.2 to 2.0) $\mathrm{Wm^{-2}\,{}^{\circ}C^{-1}}$
Overall assessment	"There is... a nearly threefold variation in the global sensitivity parameter... this implies that most of the disagreements can be attributed to differences in cloud feedback"	"At present, it is not possible to judge even the sign of the sum of all cloud process feedbacks... but it is assessed that they are unlikely either to be very negative or to lead to much more than a doubling of the response that would occur in their absence"	In spite of model improvements "There has been no apparent narrowing of the uncertainty range associated with cloud feedbacks in current climate change simulations" "...the sign of [the cloud] feedback remains unknown"	"...it is not yet possible to assess which of the model estimates of cloud feedback is the most reliable"	"The sign of the net radiative feedback due to all cloud types is... likely positive" "No robust mechanisms contribute negative feedback"
Key statements	"There is no simple way of appraising the sign of [the cloud amount] feedback" "...if global warming displaces a given cloud layer to a higher and colder region of the atmosphere, this will produce a positive feedback because the colder cloud will emit less radiation and thus have an enhanced greenhouse effect" "Models disagree about the net effect [of cloud water content increases] which depends crucially on the radiative properties at solar and infrared wavelengths" "A further possible negative feedback due to increases in the proportion of water cloud at the expense of ice cloud has been identified"	Growing understanding of the environmental factors that favour low clouds, but feedback mechanisms controversial Models simulate positive tropical high cloud altitude feedbacks "...the sign of the cloud liquid–water feedback in the real climate system is still unknown"	"The sign of the cloud cover feedback is still a matter of uncertainty..." Positive high cloud altitude feedback seen in cloud-resolving models "Cloud optical feedbacks produced by these GCMs, however, differ both in sign and strength. The transition between water and ice may be a source of error, but even for a given water phase, the sign of the variation of cloud optical properties with temperature can be a matter of controversy"	"The shortwave impact of changes in boundary-layer clouds, and to a lesser extent mid-level clouds, constitutes the largest contributor to inter-model differences in global cloud feedbacks" "...understanding of the physical processes that control the response of boundary-layer clouds and their radiative properties to a change in climate remains very limited" Controversy exists regarding the response of anvil cloud fraction Theory presented for positive altitude feedback "Differences in the representation of mixed-phase clouds and in the degree of latitudinal shift of the storm tracks predicted by the models also contribute to inter-model differences in [cloud feedback], particularly in the extratropics..."	"Uncertainty in the sign and magnitude of the cloud feedback is due primarily to continuing uncertainty in the impact of warming on low clouds" "Low clouds contribute positive feedback in most models, but that behaviour is not well understood, nor effectively constrained by observations, so we are not confident that it is realistic" "...the consistency of GCM responses, basic understanding, strong support from process models, and weak further support from observations give us high confidence in a positive feedback contribution from increases in high-cloud altitude" Cloud opacity feedback "is highly uncertain"

Figure 3 | Assessed cloud feedbacks and key statements regarding cloud feedbacks from the five IPCC assessment reports. Statements regarding the overall cloud feedback are shown in black font. Statements regarding cloud amount, altitude, and opacity feedbacks are shown in blue, red, and purple font, respectively. The assessed cloud feedback in AR5 is the most likely value, with the 90% (very likely) range in parentheses.

to be very negative or to result in much more than a doubling of the warming response that would occur in its absence.

Parameterizations continued to improve between the SAR and Third Assessment Report[6] (TAR; 2001), treating cloud water, precipitation, and phase more consistently, and better representing unresolved cloud properties and microphysics. These improvements resulted in better simulations of clouds and their radiative properties, but added new sources of uncertainty. For example, the cloud opacity feedback in models was found to be sensitive to assumptions about how cloud phase varies with temperature. Even for a given cloud water phase, the change in cloud opacity with temperature was controversial. While a positive high cloud altitude feedback was seen in a variety of models, including cloud-resolving models, the uncertainty of the net cloud feedback remained unchanged from the SAR.

Arguably the largest improvements in cloud parameterizations occurred between the TAR and Fourth Assessment Report[7] (AR4; 2007). Model-satellite 'simulators' enabled like-with-like comparisons of models with satellite products, providing a more detailed evaluation of simulated clouds, including identification of compensating biases (for example, the 'too few, too bright' problem). An important conclusion of AR4 was that all climate models simulated positive cloud feedbacks overall. This conclusion was made possible by a common set of experiments and standards established by the Coupled Model Intercomparison Project (CMIP) and improved methodologies for systematically evaluating radiative feedbacks. Another advance that focused much subsequent research was the finding that low-level clouds were the primary cause of the inter-model spread in cloud feedback. There was growing awareness of various competing processes controlling low clouds, and that the strong dependence of low cloud cover on the stability in the lower atmosphere does not guarantee increased low cloud cover in response to warming as had been previously suggested. However, understanding of the physical processes controlling the low cloud response remained limited. Substantial uncertainty in the sign of feedbacks from mid-latitude cloud changes was also noted. While AR4 highlighted a number of advances in understanding, including a theory for the positive cloud altitude feedback, the report concluded that "It is not yet possible to assess which of the model estimates of cloud feedback is the most reliable."

The Fifth Assessment Report[8] (AR5; 2013) benefited substantially from advances in model diagnostic techniques and a greater diversity of model experiments in CMIP5, including those introduced as part of the Cloud Feedback Model Intercomparison Project (CFMIP). The role of cloud 'adjustments' in modifying forcing was better separated from their role as a feedback, and cloud amount and altitude feedbacks were shown to be systematically positive. AR5 marked the first time that the cloud feedback was assessed as 'likely positive', with a central estimate (90% range) of 0.6 W m^{-2} °C^{-1} (−0.2 to 2.0 W m^{-2} °C^{-1}). This was due not only to the fact that all global climate models (GCMs) continued to simulate a near-zero to moderately strong positive net cloud feedback, but also because progress had been made in understanding the physical mechanisms involved. Notably, the high cloud altitude feedback was deemed positive with high confidence due to supporting evidence from theory, observations, and high-resolution models. On the other hand, continuing low confidence was expressed in the sign of low cloud feedback because of a lack of strong observational constraints. However, the AR5 authors noted that high-resolution process models also tended to produce positive low cloud cover feedbacks. The cloud opacity feedback was deemed highly uncertain due to the poor representation of cloud phase and microphysics in models, limited observations with which to evaluate models, and lack of physical understanding. The authors noted that no robust mechanisms contribute a negative cloud feedback.

In the four years since AR5, evidence has increased that the overall cloud feedback is positive. This includes a number of high-resolution modelling studies of low cloud cover that have illuminated the competing processes that govern changes in low cloud coverage and thickness[9], and studies that constrain long-term cloud responses using observed short-term sensitivities of clouds to changes in their local environment[10]. Both types of analyses point toward positive low cloud feedbacks. There is currently no evidence for strong negative cloud feedbacks[11]. Even the relatively weak negative cloud opacity feedbacks simulated by models have recently been called into question, with errors in modelled cloud water phase identified as a likely culprit[12]. These high-resolution modelling and observational constraint studies provide strong and specific targets, which, if matched by models, would further increase our confidence in simulated cloud feedbacks.

As the community works to further constrain cloud feedbacks, there are new opportunities to capitalize on our increased understanding. An example is the realization that cloud feedback strength varies over time[13]. The fact that low clouds are strongly affected by stability, which depends on the spatial pattern of ocean surface warming, will be crucial to understanding and ultimately constraining their evolving feedback strength[14]. This has major implications for reconciling estimates of climate sensitivity from the historical record with estimates from GCMs[15,16]. Further progress on constraining cloud feedbacks will also help to narrow the range of future circulation and precipitation changes[17].

New experiments performed as part of the CFMIP contribution to CMIP6[18] will target these and other open questions at the frontiers of knowledge on cloud feedback. These include using idealised experimental frameworks (such as 'aquaplanets' with no land or seasonal cycle) to isolate the fundamental processes underlying climate model spread in cloud feedbacks. Experiments designed to understand the role of atmospheric convection and other processes in controlling cloud feedbacks will focus future model development activities into areas having the biggest impact on improving model projections[17–19].

Throughout the IPCC reports, observations have been indispensable for formulating theories, developing representations of clouds in models, and rigorously evaluating simulations. An unprecedented global view of cloud occurrence, water content, and phase is now being provided by space-based active sensors, complementing the much longer record from passive satellite sensors[20]. As new sensors enable ever more stringent tests of simulations and provide guidance for improving models' cloud representations, emerging trends in the long-term record are being used to verify model-predicted cloud changes[21]. Multi-platform observations of clouds and their meteorological environment in tropical trade-wind cumulus regimes[22] and over the stormy Southern Ocean[23], two regions where clouds are poorly simulated by climate models and where important cloud feedbacks occur[24,25], will provide much-needed information. Observations from satellites, ground-based platforms and field campaigns are the lifeblood of advances in cloud research and must be sustained.

Since the FAR, substantial progress has been made in developing a nuanced and well-founded understanding of clouds and their feedbacks (Fig. 3). This has culminated in the 'likely positive' assessment of AR5, a conclusion that has subsequently been strengthened. Nevertheless, much work remains to observe and more fully understand the many relevant processes, to further improve cloud simulations, and to further narrow the range in estimates of cloud feedback. Meeting these challenges will require continued theoretical, observational, and modelling advances. Given that uncertainty in cloud feedback remains a dominant cause of uncertainty in projections of global warming and hence more societally relevant aspects of climate, such as sea-level rise and changes in precipitation, continued progress is necessary. Given how far we have come since 1990, and the recently accelerating developments noted above, increasing optimism is warranted. ❐

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COMMENTARY:

Whither methane in the IPCC process?

Patrick M. Crill and Brett F. Thornton

In anticipation of the IPCC's Sixth Assessment Report we look back at our evolving understanding of atmospheric CH_4. Though sources, sinks, and atmospheric burden are now well known, apportionment between the myriad sources and sinks, and forecasting natural emissions, remains a challenge.

Methane (CH_4) has been recognized as a climate forcing trace gas with strong anthropogenic components since well before the IPCC process began in the 1980s. It was first identified in the Earth's atmosphere with solar spectral maps of atmospheric column measurements by Migeotte[1]. The absorption wavelength regions used in its identification (3.4 µm and 7.7 µm), well within Earth's blackbody radiation, should have been an early indication of its role as a heat-trapping gas. There was also early interest in the role of CH_4 in the oxidation chemistry of the atmosphere, particularly as a source of carbon monoxide (CO) and a control on hydroxyl (OH) radical concentrations[2].

The recognition of the contribution of CH_4 to global warming, and its more rapid increase relative to CO_2 and other climate forcing gases in the troposphere, was labelled a "surprise" in the World Meteorological Organization's report of the World Climate Program conference in 1985 (ref. 3). This added a sense of urgency to understanding the biogeochemical and anthropogenic controls on trace gas composition of the atmosphere. The same report noted that our understanding of the biogeochemical cycles was inadequate to support policy decisions directed towards the management of CH_4 and other trace gas emissions.

The first reports of palaeo-atmospheric composition and the magnitude of the increase in the CH_4 burden since prehistoric times were included in the original 1990 IPCC report (the First Assessment Report, or FAR). The ice core gas analyses continued and by the 2013 Fifth Assessment Report (AR5) it was clear that the total 2011 atmospheric burden of about 5 Pg CH_4 had increased by 3 Pg from pre-industrial levels over the course of about 250 years. This is in stark contrast to a variation of less than 1 Pg between the 8 glacial and interglacial periods in the previous 800,000 years of Earth's history. This 1 Pg range probably represents the physical climate-driven biogeochemical CH_4 system, including freshwaters, wetlands, termites, geological sources (including hydrates) and fires, although what drove those fluctuations remains unclear[4]. It is important to understand which CH_4 sources and sinks have driven the observed increase of more than 150% above pre-industrial levels, a much greater relative increase than other major climate forcing gases (CO_2 and N_2O) that also have significant natural contributions to their cycles. This high rate of increase occurred in spite of the much shorter lifetime[5] of 9.1 ± 0.9 yr for CH_4 compared with 131 ± 10 yr for N_2O and an atmospheric lifetime for CO_2 that is next to impossible to determine precisely, but far longer[6].

Methane has both direct and indirect effects on the energy budget of the atmosphere. To that end, the FAR, Second Assessment Report (SAR), and Third Assessment Report (TAR) emphasized delineation of the specifics of the CH_4 budget: total sources and sinks, assembled from several reviews for various time periods. Overall emissions and sink estimates barely changed from the 1980s to 1998 (597 Tg of CH_4 per year to 598 Tg of CH_4 per year, with sinks of 560–576 Tg yr^{-1}.)

The basic elements of the global CH_4 budget had been identified and outlined before the FAR, by Ehhalt in 1974 (ref. 7). Each of the assessment reports (ARs) that followed has reported the CH_4 source budget to be within a relatively narrow range of 550–600 Tg yr^{-1}, towards the low end of the 550–1,100 Tg yr^{-1} estimate of Ehhalt. The most recent global budget estimate is 559 Tg yr^{-1} for the decade 2003–2012 (ref. 8), which is within the range reported in AR5. During that decade, 60% of the emissions were anthropogenic and it is likely that agricultural-related