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LETTER

The global warming potential of near-surface emitted water vapour

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Abstract

Water vapour is the most abundant and powerful greenhouse gas in Earth's atmosphere, and is emitted by human activities. Yet the global warming potential (GWP) and radiative forcing (RF) of emitted water vapour have not been formally quantified in the literature. Here these quantities are estimated for surface emission using idealised experiments conducted with the CAM5 global atmospheric model at fixed ocean temperatures. Water is introduced in vapour form at rates matching total anthropogenic emissions (mainly from irrigation) but omitting the local evaporative cooling seen in irrigation simulations. A 100 year GWP for H_2O of -10^{-3} to 5×10^{-4} is found, and an effective radiative forcing of -0.1 to 0.05 W m^{-2} for the given emissions. Increases in water vapour greenhouse effect are small because additional vapour cannot reach the upper troposphere, and greenhouse-gas warming is outweighed by increases in reflectance from humidity-induced low cloud cover, leading to a near-zero or small cooling effect. Near-surface temperature decreases over land are implied even without evaporative cooling at the surface, due to cooling by low clouds and vapour-induced changes to the moist lapse rate. These results indicate that even large increases in anthropogenic water vapour emissions would have negligible warming effects on climate, but that possible negative RF may deserve more attention.

1. Introduction

Water vapour is the most powerful greenhouse gas in Earth's atmosphere, accounting for roughly half of the present-day greenhouse effect (Schmidt *et al* 2010). Human activities lead to water vapour emissions through irrigation, power plant cooling, aviation, and domestic water use. Such emissions would be expected to increase atmospheric humidity and the water vapour greenhouse effect, and could also lead to knock-on effects on cloud cover which could either add or subtract from the 'direct' effect of the emissions. Although anthropogenic emissions of water vapour are small compared to evaporation from the oceans, and are not normally considered to be a significant climate forcing agent, the amounts generated are large compared to emissions of other greenhouse gases including CO_2. Therefore, in principle it would seem important to quantify the effect of H_2O emissions—and if they are indeed negligible, be sure a clear explanation is at hand as to why that is the case.

Radiative forcing (RF) has hitherto been a problematic concept for H_2O because traditionally RF is computed holding the tropospheric state (including humidity) fixed and only allowing for stratospheric adjustment. Clearly this does not work for H_2O which is part of the tropospheric state. However, the IPCC (Myhre and Coauthors 2013) has since adopted 'effective radiative forcing' (ERF), which includes rapid tropospheric adjustments to the forcing, as a new default due to the fact that tropospheric adjustments can be important even for CO_2 (Gregory and Webb 2008) and certainly for aerosol forcers (Boucher *et al* 2013). This change in perspective seems to overcome any conceptual objection to quantifying an (effective) forcing and global warming potential (GWP) for water vapour. For example, both H_2O and CO_2 can be altered by human emissions and both participate in natural feedbacks, so distinctions between them are only a matter of degree.

Near-surface water vapour shares characteristics with other forcers including aerosols and ozone. The

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heterogeneous distribution of short-lived forcers leads to heterogeneous heating patterns, which can provoke diverse responses for the same initial global-mean radiative impact (Hansen *et al* 2005, Baker *et al* 2015). Modelled responses to black carbon emissions, in particular, are strongly influenced by rapid adjustments including cloud changes, giving them a smaller ERF than would be expected based on a traditional forcing calculation (Stjern *et al* 2017). Stratospheric water vapour emissions from aircraft similarly have both a direct greenhouse effect (e.g., Wilcox *et al* 2012) and an indirect effect via contrail production (e.g. Bock and Burkhardt 2016), though both are small (Myhre and Coauthors 2013).

The standard metric for quantifying the importance of emissions of a greenhouse gas species is the GWP. This is the cumulative ERF over time caused by unit pulse of emissions of that species, relative that of CO_2, over a prescribed time horizon. The GWP has been quantified for all major greenhouse gases except H_2O (Myhre and Coauthors 2013). It is determined by the gases radiative efficiency and lifetime. To our knowledge, the only study to quantify the impact of emitted water vapour on the global radiation budget is Boucher *et al* (2004) (B04), who estimated a RF for present emissions of vapour from irrigation but pointed out that because the classical forcing concept required that the tropospheric state be held constant, it was difficult to apply to H_2O.

There are indeed several reasons why GWP has not been calculated for water vapour, as it behaves differently from other greenhouse gases like CO_2. Water can condense and precipitate, and the vapour has a mean lifetime of less than two weeks, compared to years or more for other greenhouse gases. It is also not well mixed in the atmosphere, ranging in concentration by several orders of magnitude. It mostly arises from natural sources, and we do not have accurate measurements of the preindustrial distribution so the impact of human emissions on the ambient water vapour distribution cannot be inferred from observations.

Moreover, observed variations of atmospheric water vapour are controlled by natural variability much more than by anthropogenic sources. In particular, water vapour concentrations are very strongly controlled by temperature, especially in the middle and upper troposphere (see Sherwood *et al* 2010) which is also where they contribute most to the greenhouse effect (Held and Soden 2000). They exert a strong and fast positive feedback that amplifies any initial forcing on global temperature: if the temperature increases, the water vapour concentration increases (shown by many studies including recently Liu *et al* 2018), which leads to a stronger greenhouse effect. The feedback role of water vapour overshadows any role it might have as a climate forcer, but does not negate such a role.

A corollary of tight temperature control is that water vapour does not have a well-defined lifetime. It is not removed by a linear constant-rate process like a simple chemical reaction, but by condensation processes which depend nonlinearly on the temperature and the vapour concentration. This means that the effective lifetime of an added mass of vapour depends on many factors including the background humidity itself. H_2O emitted into a dry atmosphere could remain a very long time, while emission into water vapour saturated air would condense instantly. In order to reach the high altitudes where H_2O exerts a significant greenhouse effect, it must rise in saturated rain-generating updrafts, which implies a very short effective lifetime for H_2O emissions near the surface and implies that water vapour amounts reaching the upper troposphere are unaffected by humidity near the surface. To our knowledge the effective lifetime of such emissions has not been estimated.

While it is not possible to distinguish anthropogenic versus naturally produced water vapour in observations, it is possible to compute the effect of emissions in a model. Here we use a recent-generation atmospheric general circulation model (GCM) to simulate the impact of an idealised source of water vapour near the Earth's surface in order to obtain rough estimates of the ERF and GWP. GCMs are able to simulate the background water vapour distribution reasonably well, and include convective processes for rapidly transporting water vapour upward in convective drafts. These processes remain crude in models, but past studies have shown that the water vapour distribution is not sensitive to them (Sherwood *et al* 2010). GCMs also simulate clouds, changes in which could constitute an important indirect forcing mechanism for water vapour emissions. While this aspect is much less certain, the same is true for calculations of ERF for other forcers.

A complicating factor unique to near-surface water vapour is its high latent heat of condensation. Most anthropogenic sources of water vapour are via irrigation, which is applied as a liquid. When this water evaporates, this evaporation cools the surface; when the water rains out later, it heats the troposphere by the same amount. This upward transfer of latent heat has been inferred in past model irrigation studies (e.g. Sacks *et al* 2009, Cook *et al* 2015) to have caused localised decreases seen in land surface temperature, regardless of the top-of-atmosphere radiative effect. We take a unique approach to this problem as described in section 2, in order to distinguish water vapour's role as a greenhouse gas from the local impact of added liquid water on the land surface heat balance.

2. Data and approach

The evaporation rate from irrigation was estimated by B04 as 32 500 m^3s^{-1} of liquid water, and is the greatest anthropogenic water vapour source. The second most important anthropogenic emission, from combustion

in cooling towers, is much smaller (estimated in 1970 at 450 $m^3 s^{-1}$; Huff *et al* 1971). We scale our calculation using these numbers.

For our computations we use the Community Earth System Model (CESM 1.2.2). This model provides numerical simulations of the Earth system: the atmosphere, ocean, ice, land surface, carbon cycle, and other components. We specifically included only the atmosphere (see Neale *et al* 2010 for more details) and land (see Oleson *et al* 2010 for more details) components in our simulations (FC5 compset). This configuration does not include dynamic vegetation or a carbon–nitrogen cycle. The fixed climatological SST and sea-ice concentration were used as the boundary conditions (Hurrell *et al* 2008). The default initial conditions that accompany this CESM compset were used, including a CO_2 concentration of 367 ppmv. This model is currently the most recent version of Community Atmosphere Model (CAM5) and includes detailed representations of shallow and deep convection, and cloud microphysics with prognostic liquid and ice phases (Liu *et al* 2012). All the experiments use the finite volume dynamical core at 1.9° by 2.5° horizontal resolution and 31 vertical levels with hybrid coordinates.

For simplicity we conduct our experiments by adding a horizontally uniform and steady water vapour source to the lowest atmospheric model level at every grid point. We conduct two experiments, one with vapour emitted uniformly over the globe and one with emissions uniformly over land only. The total global mass source M is set to correspond to the anthropogenic emission of water cited above, 32 500 $m^3 s^{-1}$ liquid equivalent (1,020 GT yr^{-1}). Past studies (e.g. B04) have usually specified anthropogenic water sources with a realistic geographic dependence. However, for defining a general concept such as GWP it would be preferable if results could be found that were robust to the specific source or location of the emissions. We thus choose a horizontally uniform source of vapour but are careful to compare results with past studies.

The control run and two experiments have been run for 35 years each. We estimate the ERF by comparing the net top-of-atmosphere radiative budget in the perturbed versus control runs, i.e. the 'Cess Method' (see Sherwood *et al* 2015). As mentioned, this effective forcing includes various tropospheric adjustments, including humidity and cloudiness changes and slight changes in land temperature (B04).

Unlike previous studies we add the H_2O in vapour form rather than as liquid on the surface. This means that effectively we are adding a latent heat source to the atmosphere, without adding the corresponding evaporative cooling source at the (land) surface. This will lead to more warming than would occur otherwise (estimated in section 3). The addition of a vapour source in this way mimics emissions from steam generators, e.g., traditional power plants, and isolates the anticipated enhancement of the greenhouse effect from the localised cooling effect at the surface that arises from irrigation.

Table 1. Responses (experiment minus control) in W m^{-2}.

	Global	Land only
TOA SW	−0.058	−0.070
TOA LW	+0.032	−0.032
Total forcing	−0.026	−0.102
Clear sky only	+0.012	−0.043
Precipitation	+0.065	+0.180
Evaporation	−0.095	+0.018

The GWP is defined as the ratio R_X/R_{CO2} of the integrated radiative effect of a gas X to that of CO_2, where R is given by

$$R(t_0) = \int_{t_0}^{t_0+N} F'(t,\ t_0)\,dt. \tag{1}$$

Here, $F'(t,t_0)$ is the increment in RF caused at time t by a unit pulse emission at t_0, and N is the specified GWP time horizon (20 or 100 years). The forcing increment F' decays with t due to the finite gas lifetime, but can also change due to changes in state or background opacity of the atmosphere that affect the gases radiative efficiency. In the case of a continuing mass source $M(t_0)$, the RF $\Delta F(t)$ is

$$\Delta F(t) = \int_{-\infty}^{t} F'(t,\ t_0)M(t_0)\,dt_0. \tag{2}$$

Since the lifetime of H_2O is much less than one year, F' decays rapidly to zero and the integrands in (1), (2) are significant only near the lower and upper limits respectively; and since M is time-invariant in our experiments, the system quickly reaches a statistically steady state. Therefore, in (2) we can take $M(t_0)$ out from under the integral and move to the LHS; $F'(t,\ t_0)$ depends only on $t - t_0$; and the RHS of (2) becomes equal to that of (1). Thus, the GWP of H_2O is

$$\mathrm{GWP} = (\Delta F/M)/R_{CO2}. \tag{3}$$

This formula could be used for any short-lived species in steady state. R_{CO2} is 2.5×10^{-14} W m^{-2} yr kg^{-1} for $N = 20$ years, and 9.2×10^{-14} W m^{-2} yr kg^{-1} for $N = 100$ years (Myhre and Coauthors 2013).

3. Results

The results are summarised in table 1. The total ERF averaged over the 35 years of simulation is found to be -0.026 ± 0.036 W m^{-2} for the global-emission case, thus insignificantly different from zero, but -0.10 ± 0.04 W m^{-2} for the land-only case. These negative values are in the opposite direction to that expected from an increased water vapour greenhouse effect. Note that our range does not include the +0.03 W m^{-2} obtained by B04 in their most realistic irrigation scenario, and surprisingly, their result is closer to our global-emission one than either is to our

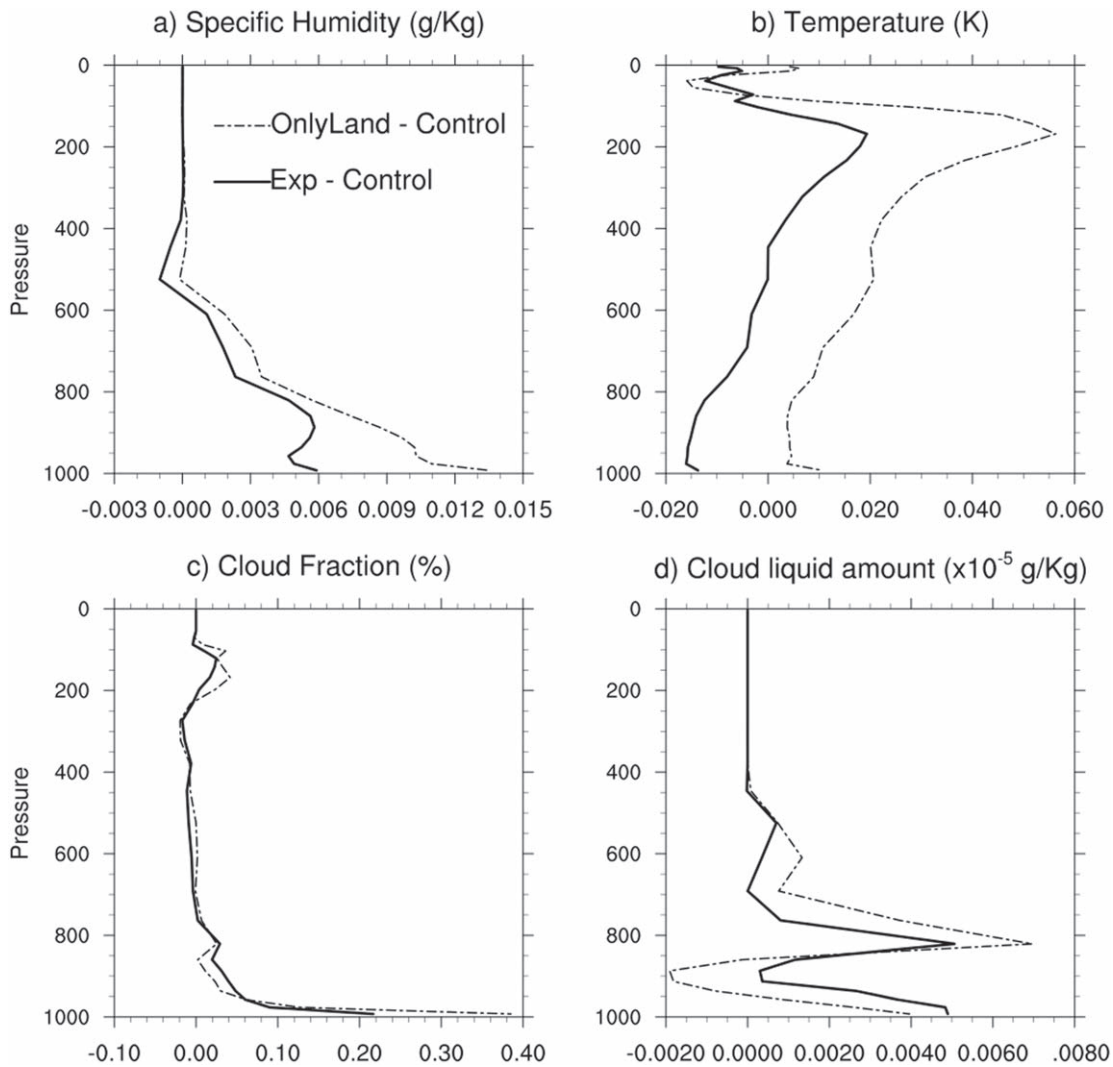

Figure 1. Change (experiment minus control) in (a) specific humidity, (b) temperature, (c) cloud fraction and (d) cloud liquid water concentration. Two experiments shown by solid and dot-dashed traces.

land-only one. These results suggest an overall likely range of [−0.1, +0.05] W m^{-2} to the ERF.

This range equates to a 20 year GWP of [−0.004, +0.002] and a 100 year GWP of [−0.001, +0.0005]. These numbers reinforce how weak an influence a unit mass of emitted water vapour has on climate. The linearity of the results was checked with a shorter global-emissions run at 10x the emissions, which produced roughly 10x the net TOA radiative response, confirming a roughly linear response.

The weak effect may be understood by examining changes in hydrologic and state variables. Specific humidity increases in the lower troposphere by roughly 0.1% of its control values there (figure 1(a)), but changes little in the upper troposphere where most of the greenhouse effect is exerted. Temperature (figure 1(b)) averaged through the troposphere remains about the same with global-emissions and rises somewhat with land-only emissions, but in both experiments the lapse rate decreases. This decrease, which was also reported by B04, can be explained by increased humidity near the surface which would reduce the moist adiabatic lapse rate. The change in clear-sky greenhouse effect is slightly positive in the global experiment (0.012 W m^{-2}), but slightly negative in the land-only experiment. This indicates that moistening does increase the greenhouse effect, but only to a very small extent, and it can be negated by atmospheric warming.

The net TOA cooling effect is therefore explained by a decrease in the net cooling due to clouds, in particular the shortwave component, also reported by e.g. Sachs *et al* (2009). The profiles of cloud fraction (figure 1(c)) and liquid water (figure 1(d)) change show that cloud amount and opacity increased in the boundary layer. This is not surprising, as these same levels have higher specific humidity and lower temperature. Low-level cloud cover has a strong net cooling effect on climate because its reflection of shortwave radiation exceeds its small greenhouse effect. We thus conclude that the emission of water vapour near the Earth's surface triggers an increase in low cloud cover

that has a comparable, if not larger effect on climate than the small increase in water vapour, at least in our simulations. This cloud increase occurs in both experiments.

The natural hydrological cycle (i.e., surface evaporation) slowed by 0.095 W m^{-2} in the global-emission simulation, such that precipitation increased by only 0.065 W m^{-2}, but this did not happen in the land-only one where the increase in precipitation roughly matched the added vapour (equivalent to a latent heat flux of 0.159 W m^{-2}). Thus emissions over oceans are largely compensated by reduced natural evaporation due to higher humidity above the ocean surface, but emissions on land are not. The reduced latent heat transfer from ocean to atmosphere in the global-emissions experiment could explain why average atmosphere temperature dropped only in that experiment.

It is possible to estimate roughly the direct impact of the latent heat of the added water vapour. Kamae and Watanabe (2013) show that, under fixed SST, a CO_2 RF of roughly 8 W m^{-2} causes ~0.5 K global-mean warming in global models including the one used here; assuming a similar efficacy for latent heat forcing, our total (0.16 W m^{-2}) or net (0.065 W m^{-2} in the global experiment) inputs would contribute direct mean surface warming of ~0.01 K or ~0.004 K respectively. While not negligible, these contributions are 2–4 times smaller than the range seen in the experiments, so we conclude that the temperature changes are dominated by indirect responses to the vapour rather than the latent heat release.

4. Discussion

Except for the increase in albedo, our results are similar to those of B04 in spite of their prescription of surface latent cooling. In particular, both simulations show a decreased lapse rate, with lower temperature near the surface under global-emissions. While the land-only simulation did not produce lower near-surface temperature at fixed SST due to its warmer overall atmosphere, that mean warmth also produced a TOA flux imbalance (0.1 W m^{-2}) which, if the system were coupled, would lead to surface cooling (by up to 0.1 K assuming a typical climate sensitivity). This suggests that the mean land-surface cooling found in B04 and other studies (e.g., Sachs *et al* 2009, Cook *et al* 2015) may not be principally caused by the surface evaporative heat sink, but rather by a combination of invigorated convective heat transport away from the surface due to the increased low-level water vapour, and overall system cooling due to low-level cloud cover. This is consistent with other work showing that global-scale land surface moist enthalpy is strongly linked to the free troposphere via convection (Byrne and O'Gorman 2018), which requires a compensating cooling near the surface if the vapour mixing ratio increases (for a given free troposphere temperature). Further work could test this in a coupled or slab-ocean model.

Though the artificial source used here amounted to 0.2% of natural evaporation, simulated precipitable water only increased by about 0.1% in the global-source experiment. This means the effective lifetime of emitted vapour, $\tau_e \equiv dC/dC$ where C is concentration and C is source, is roughly half the mean lifetime $\tau = C/C$ of ambient vapour for emissions over oceans. This confirms that water vapour cannot necessarily be thought of as having a single lifetime, although the order of magnitude of its lifetime appears to be robust to reasonable changes in the system, and the lifetime change is found to be negligible for land emissions.

A few complications or caveats arise in interpreting our results. The relevance of our calculation is complicated by the fact that in practice nearly all water is introduced in liquid form on land surfaces. For one thing this leads the perturbation to be classified as a land-use change rather than as a greenhouse-gas emission. Moreover, irrigation clearly produces cooling at a regional level (e.g., Cook *et al* 2015) so it would be misleading to characterise the climate impacts of irrigation in terms of a top-of-atmosphere RF alone. Nonetheless it is useful to separate the TOA impact of emitted water vapour from direct impacts at the surface.

Another potential complication in interpreting our forcing result is that the ERF is often defined as the change in TOA energy budget for a zero global-mean temperature change, although some calculations define it under fixed SST as in the current study. This does not appear to be an issue for our study, since the average temperature change in the atmosphere was nearly zero (in the global experiment) or small compared to the anticipated coupled-system response to the calculated forcing (in the land-only experiment). An unanswered question is why the atmosphere warmed in the land-only experiment but not the global one.

Finally, we note that our calculation assumes a steady state at near-present-day conditions. The radiative impact per unit mass in a future, warmer climate would likely be even smaller due to the larger background concentrations, but this should be a small effect compared to the large uncertainty of our estimate.

5. Conclusions

Water vapour is a greenhouse gas which must exert a warming if emitted into the atmosphere, analogous to other greenhouse gases. We have attempted to isolate this effect. Although a number of modelling studies have simulated the effects of irrigation, none have looked at the question more generally or calculated the metrics used for other climate forcers. Specifically, we

added a uniform water vapour flux everywhere on the globe in the CAM5 atmosphere model, or only on land, and quantified the impact on Earth radiation balance and atmospheric state.

We find that vapour added at current irrigation rates would yield a net ERF of −0.1 to +0.05 W m^{-2}, and that the 100 year effective GWP for vapour emitted near the surface is −0.001 to +0.0005, making emitted water, at best, a thousand times less effective per kg at altering the heat budget of the Earth than emitted carbon dioxide. Moreover we find a top-of-atmosphere cooling, rather than a warming. The primary reason for this is that the added water vapour rains out before it can reach the altitudes required to significantly contribute to Earth's greenhouse effect. Moreover, humidity near the surface increases the low-level cloud cover (as seen in some previous studies e.g. Sachs *et al* 2009), which in our simulation dominates changes to the greenhouse effect.

It appears unlikely that the result would differ substantially in other models. It is well understood that humidity at radiatively important altitudes is controlled by air temperature and circulation (e.g. Sherwood *et al* 2010), and the key results echo those of previous studies using more realistic irrigation forcing. Not all studies have shown the cloud cover increase seen here, so this does depend on the model and/or the geographic distribution of emissions, but any significant *decrease* in low cloud seems very unlikely. This implies that a reasonable upper bound can be placed on the GWP of water vapour, even if modelling and scenario uncertainties remain as to the lower bound or exact value.

Interestingly, we also find a robust weakening of the lapse rate as found in previous irrigation studies, showing that this can occur regardless of how water is introduced or whether it evaporatively cools the surface. This change is consistent with a change in the moist-adiabatic lapse rate due to increased near-surface humidity and, along with the increased cloud cover, contributes to the decline in surface temperature.

The short lifetime of H_2O means that its ERF is proportional to current emissions with essentially no memory of past emissions. In this respect H_2O is different from CO_2 and more like aerosol which has a similar lifetime. However, unlike other species, H_2O cannot necessarily be thought of as having a single lifetime: the effective lifetime of emissions (change in atmospheric mass / emission rate) can be as little as half that of the ambient vapour (atmospheric mass / evaporation rate).

Our results come with some important qualifications. First, the impact of H_2O emissions will be very sensitive to the altitude of emission, so our numbers do not apply to aircraft emissions, where GWP would be much higher (though feasible rates of emission likely much lower). Second, the impact of H_2O consists mainly of 'rapid adjustments' of tropospheric state variables to the emissions, making it more uncertain and model-dependent than radiative effects of other greenhouse gases, although not dissimilar to other short-lived forcers. For this reason, a precise quantification of the forcing is unlikely in the near future, although our estimate could be improved by running the experiment in an ensemble of climate models.

While our estimates here are very approximate, it seems unlikely that future computations would change the basic conclusion that water vapour emissions are capable of little net warming of the global radiation budget, even at current irrigation scale which would vastly exceed the direct emissions of any greenhouse gas today. We do however find that a non-trivial cooling is possible, which deserves further investigation to see whether it is still possible with more realistic irrigation scenarios. We hope that this result will clarify future discussions of the radiative impact of water vapour in the climate system.

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