Response to Anonymous Referee #2

Overall response: We would like to thank reviewer 2 for these critical and useful comments. These help improve the manuscript. Here we outline the point-by-point responses below in blue, and the relevant figures are attached.

Comment: The manuscript presents AMCLIM, a process-based, dynamic model for estimating NH_3 emissions from livestock. The model comprehensively accounts for NH_3 emission processes and nitrogen flow across housing, manure management, and land application. Figures 1–3 clearly show these processes, and the model simulations successfully capture NH_3 emissions observed from individual animal houses. AMCLIM represents a significant improvement in the estimation of NH_3 emissions from livestock. I believe the manuscript should be published, with only a few comments for the authors to address:

Reply: We appreciate that the reviewer recognizes the value of our study. We thank the reviewer for spending time reviewing the manuscript.

1. In the Introduction, the authors highlight challenges in previous process-based models when representing various management practices. I recommend a direct comparison between the processes considered in AMCLIM and those in previous studies to better illustrate the differences.

Reply: We added the following text to highlight the state-of-art of AMCLIM for simulating agricultural NH_3 emissions compared with other process-based models. From L60,

"A process-based, dynamical emission model, AMmonia–CLIMate (AMCLIM) has been specifically designed that incorporates the effect of both environmental conditions and management practice to simulate agricultural NH_3 emissions. Compared with existing process-based models, AMCLIM is thought to be the first model that simulates NH_3 emission from both synthetic fertilizer use and livestock farming using a consistent process-based modelling approach, with high levels of detail of the representation of agricultural practices. There are other process-based models, such as the 'Flow of Agricultural Nitrogen' model, version 2' (FANv2; Vira et al. 2020) that simulates agricultural NH_3 emissions interactively within the Community Earth System Model (CESM) with detailed soil processes for land application of fertilizers and ruminant grazing. Another is the 'Calculation of AMmonia Emissions' model (CAMEO), which includes several management modules for livestock feed, manure management and agricultural handling practices within the global land surface model ORCHIDEE (Beaudor et al., 2023). While these models still largely rely on emission factors (EFs) for estimating NH_3 emissions from livestock sectors, AMCLIM explicitly models the N flows within the systems and includes several major N processes. AMCLIM uses an integrated approach to simulate how various N species are influenced by environmental factors in a sequence of the practices in the livestock sector, from livestock housing to manure management and ultimate application of manure to fields, as well as ruminant grazing. By following this sequence in AMCLIM, changes in emissions at an early stage of livestock agriculture influence the simulated N pools, and can thereby affect emission at a later stage of these activities. The simulations for global synthetic fertilizer use have been presented in the companion paper (Jiang et al, 2024)."

2. Equations (1)–(19) provide a detailed description of how the model calculates NH3 concentrations inside animal houses and nitrogen flow. However, it remains unclear how these nitrogen pools or NH_3 concentrations are ultimately converted into NH3 emissions. Could the authors clarify?

Reply: The volatilization of NH_3 from the land surface to the atmosphere is driven by the concentration difference at two heights and is constrained by a set of resistances. For indoor simulations such as livestock housing and indoor manure storage, the calculation of NH_3 is given by the first half on the right hand side of Eq. (2) in the manuscript. We updated the equation to explicitly show how NH_3 emission is calculated as follows:

$$\begin{cases} V_{\mathrm{house}} \frac{\mathrm{d}\chi_{\mathrm{in}}}{\mathrm{d}t} = \frac{(\chi_{\mathrm{srf}} - \chi_{\mathrm{in}})}{R_{\mathrm{G,house}}} \cdot S_{\mathrm{house}} - Q_{\mathrm{in}} \left(\chi_{\mathrm{in}} - \chi_{\mathrm{out}} \right) \\ \qquad\qquad F_{\mathrm{NH_3}} = \frac{(\chi_{\mathrm{srf}} - \chi_{\mathrm{in}})}{R_{\mathrm{G,house}}} \end{cases}, \qquad (2)$$

For the NH_3 volatilization processes of outdoor simulations like manure application to field, we refer to the paper that describes the first part of AMCLIM by Jiang et al. (2024), in "Volatilization of NH3" under Sect 2.2.1.

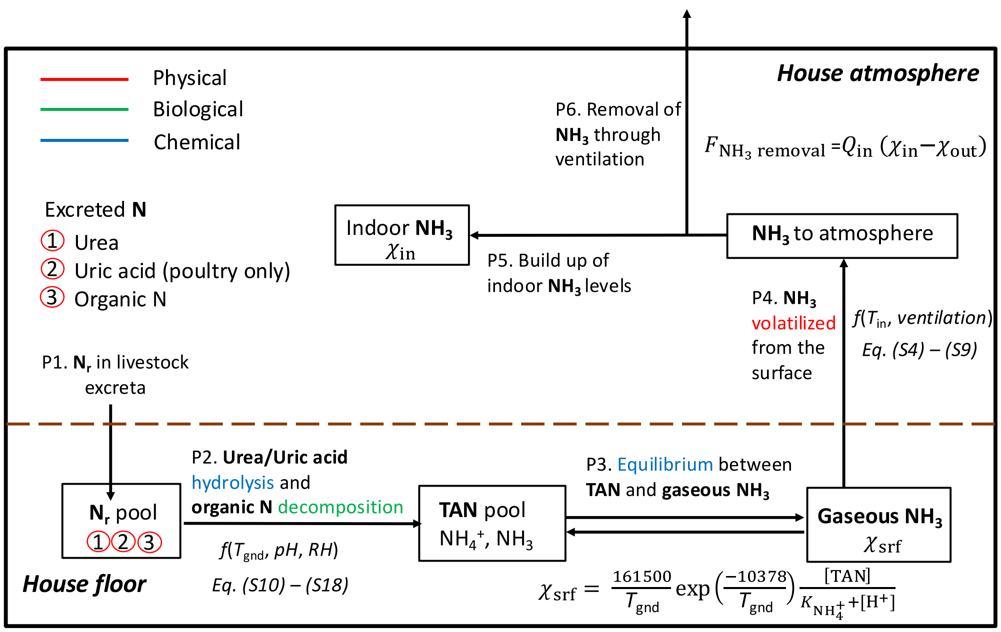
We have drawn attention to this cross reference in the present manuscript by adding the following sentence from L351

"Specifically, the volatilization processes of NH_3 have been described in Sect.2.2.1 in Jiang et al. (2024)."

3. In Figure 2, I suggest including the explicit equations for *f(Tgnd, pH, RH)* and *f(Tgnd, pH)* since the influence of pH on the calculations is discussed in the manuscript.

Reply: We found it quite difficult to explicitly include all the equations in Figure 2 as requested due to limited space in the figure. However, we have added key relationships in a revised version of Figure 2. When it is not feasible to add an equation, we refer to the equation numbers of the manuscript.

Here is the updated Figure 2, including added equations and references to specific equation numbers of the manuscript:



4. In Section 3.1, the indoor temperature, airflow, and RH for individual animal houses are derived from observations, which likely contribute to the good agreement between modeled and observed NH3 emissions. How are these indoor parameters determined when estimating NH3 emissions at the global scale?

Reply: We refer to Sect.S6 in the Supplementary Material, which describes the generalization of housing environments applied to the global simulations.

In AMCLIM–Housing, the indoor temperature and ventilation of animal houses are modelled using a set of empirically derived relationships in relation to the outdoor temperature. These relationships are based on data from the Animal Feeding Operations (AFOs) dataset of the US Environmental Protection Agency (EPA, 2012) and theoretical parameterizations of indoor environments by Gyldenkærne et al. (2005). These relationships can vary between livestock sectors and production systems as each production system of livestock has a corresponding housing system and house type in the global simulations. More details and equations that present the relationships between indoor temperature, ventilation and outdoor temperature for different housing systems are given in Sect.S6.1. The RH of indoor environments is assumed to be equivalent to outdoor RH.

To help better guide readers to these points in the revised manuscript, we have added a summary of the above points to expand the existing mention of Section S6 in Section 2.5.2 from L487

"To estimate the environmental conditions in livestock houses, we applied empirical relationships between indoor temperature and ventilation of animal houses based on data from the Animal Feeding Operations (EPA, 2012) and theoretical parameterizations of indoor environments by Gyldenkærne et al. (2005). Equations that present the relationships between indoor temperature, ventilation and outdoor temperature for different housing systems are given in Sect.S6.1. The RH of indoor environments is assumed to be equivalent to outdoor RH."

5. The global livestock population data is based on FAOSTAT for 2010. How is this dataset extended to other years? Are the calculations for 2010 and 2018 based on the same livestock population and distribution, or do they incorporate changes over time?

Reply: Livestock inputs for 2010 and 2018 are different. Livestock and MMS data for the year 2010 were obtained from the FAO GLEAM model. We applied the interannual variability between 2005 to 2015 reported by Lu and Tian (2017) and extended to year 2018 by a linear interpolation. The meteorological inputs were from ERA5 reanalysis datasets for both years. We made the following changes for the revised manuscript, from from L455

"In the present paper, the combined AMCLIM model was applied for 2010 and 2018 to demonstrate full simulations for two different years, with activity data and meteorological variables varied between years, so that the inter-annual variability in both emissions and volatilization rates can be analysed."

and from L466

"...The reference year of these data is 2010. For simulations for the year 2018, livestock population and N excretion rates were extended by a linear interpolation based on the inter-annual variations between 2005 and 2015 suggested by Lu and Tian (2017). The MMS data that determines the fraction of a manure management system are assumed to be constant through the year."

6. Line 574: Do the volatilization rates refer to the ratio of NH3 emissions to total nitrogen excreted by livestock (Nr)? Please clarify.

Reply: We added the following text in the revised manuscript to improve clarity from L655

"For housing, the volatilization rates (P_V) are expressed as percentage of total N by excreted by livestock in the animal houses. For manure management and application to land, the volatilization rates are expressed as percentage of the total remaining N from the previous stage that is volatilized as NH_3."

7. In the comparison of NH_3 emissions between 2010 and 2018, could the authors directly show the spatial distribution of the difference? Current spatial maps make it difficult to distinguish the changes clearly.

Reply: We followed suggestions from both reviewers to make a new figure (included as Figure 15 in the revised manuscript) showing the NH_3 emissions from each livestock group by geographical regions for both simulated years, along with comparisons of the volatilization rates. We added the following text from L906

"As shown in Fig. 15, NH_3 emissions and volatilization rates vary across different geographical regions and between the two simulated years, i.e., 2010 and 2018. The highest NH_3 emissions from livestock agriculture are estimated to occur in East and South Asia. In general, the volatilization rates for livestock are lower in 2018 than 2010, except for poultry. This is because a large fraction of poultry which are broiler and layer production systems are assumed in the model to be kept in houses with controlled temperature and ventilation, so the P_V rates were less impacted by the differences in environmental conditions between years. By comparison, the P_V rates from sheep and goats show the largest inter-annual variability among all livestock groups because sheep and goats typically graze outside and are housed in naturally ventilated barns. As a result, NH_3 volatilization from sheep and goats is more dependent on the environmental conditions than poultry. The differences in housing and grazing management also explain why P_V rates from pigs showed the second smallest difference and cattle showed the second largest difference between the two simulated years."

We also generated six additional global maps to show the differences of NH_3 emissions and volatilization rates for the two simulated years, expressing as ratios between years. These maps are included as Figures A12 to A17, and we updated Sect.4.4. Please see the revised manuscript for changes.

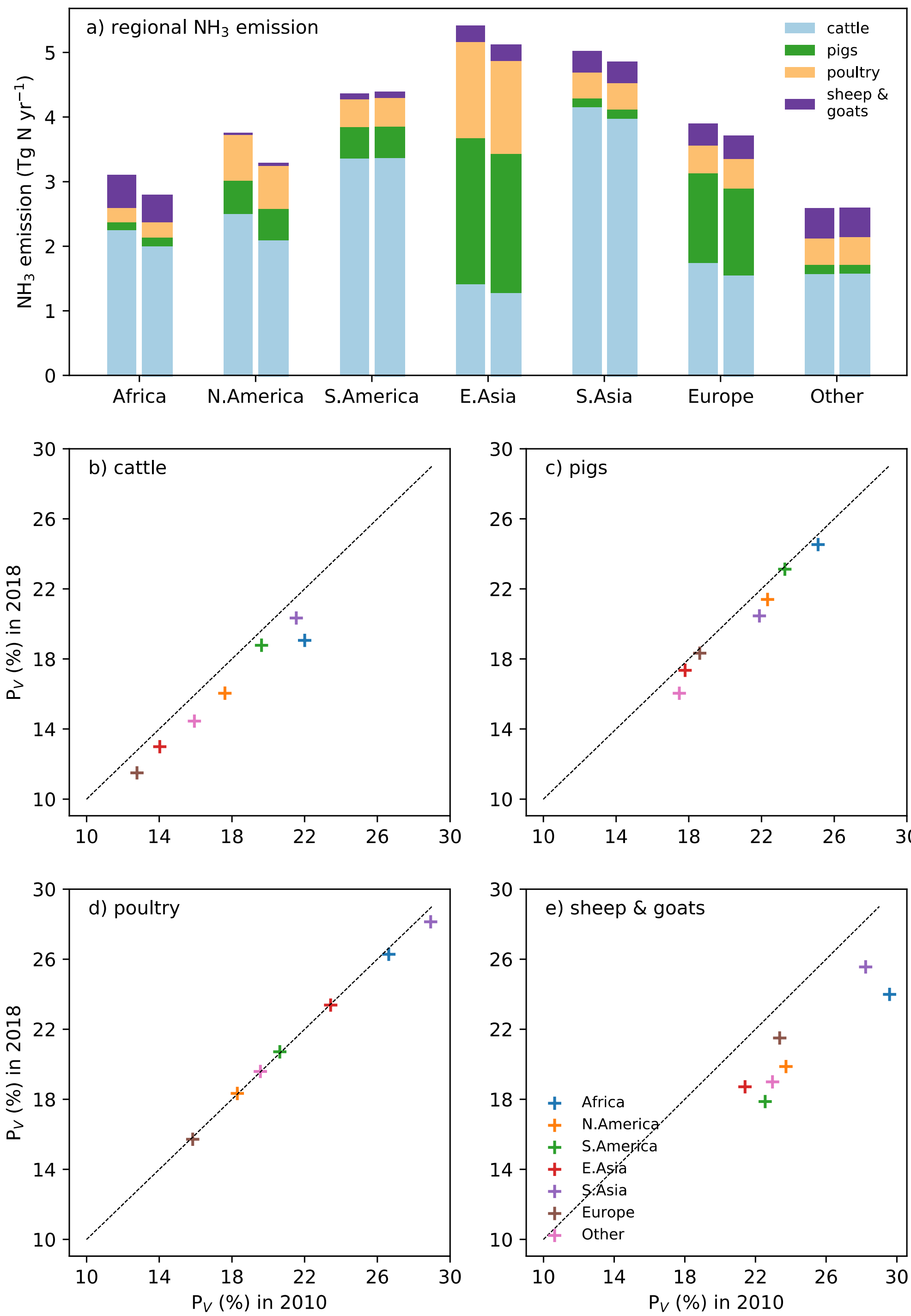


Figure R2-1. Estimated (a) NH_3 emissions from livestock farming in seven geographical regions for the two studied years, 2010 (left) and 2018 (right, hashed), and comparisons of volatilization rates P_V between the two years for (b) cattle, (c) pigs, (d) poultry and (e) sheep and goats.

8. Line 575: It would be helpful if the authors could explain the spatial variations in Pv.

Reply: Explanation of the major spatial differences in P_V is given in Section 4.3. We added the following text from L1023

"Among cattle and buffaloes, the overall simulated volatilization rates for buffaloes are higher than other types of cattle. This is because buffaloes are predominantly reared in hot regions such as southern China, South Asia and southeast Asia compared with other cattle, which are widely distributed across the globe, resulting in higher P_V for buffaloes due to generally hotter conditions. Also, the estimated volatilization rates for sheep and goat farming are higher than those of cattle farming, which is partly due to a higher N concentration in sheep and goat's urine compared with cattle. Another reason is that sheep and goat are more "concentrated" in the Middle East and South Asia where they tend to have higher volatilization rates due to warmer climates. In addition to temperature, soil pH plays an important role in NH_3 volatilization. As pointed out by Jiang et al. (2024), simulated high *P*v values have been found in regions with high soil pH, such as the western US, Namibia, Mongolia and part of northern China.

Various management practices can lead to very different volatilization rates. For housing, industrial pigs show higher volatilization compared to intermediate and backyard pigs because the industrial pigs are kept in buildings with heating systems and excreta are kept longer in the houses as in-situ storage is available. Moreover, the pits for manure storage provides an additional emitting surface of NH_3. The housing density assumed in AMCLIM is another factor that affects the volatilization rates. The volatilization rates of feedlot cattle housing are the second lowest among ruminants. This is partly because the feedlot cattle had the highest stocking density in the model. Increasing the stocking density results in a smaller source area for NH_3 emission, which leads to lower emissions.

For manure management, especially in warm climates, manure left on land without much management is identified to result in much higher NH_3 emissions than manure that is stored either as liquid or solid manure, leading to larger P_V values. Such practice is common in Africa and some countries in South Asia like India and Myanmar, and these regions have hot climate (as reflected in high P_V values). Conversely, manure storage under cover greatly reduces NH_3 emissions (Bittman et al., 2014). Although the effect of covering stored manure has not been the focus of the present study, the process-based nature of AMCLIM would lend itself to a future examination of such effects."