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Global Nitrogen and Sulfur Budgets Using a Measurement-Model Fusion Approach

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Abstract

Global reactive nitrogen (N) deposition has more than tripled since 1860 and is expected to remain high due to land use changes and fossil fuel consumption. We update the 2010 global deposition budget for nitrogen and sulfur with new regional wet deposition measurements from Asia, improving the ensemble results of eleven global chemistry transport models from the second phase of the United Nation's Task Force on Hemispheric Transport of Air Pollution (HTAP-II). The observationally adjusted global N deposition budget is 130 Tg-N, representing a 10% increase and the adjusted global sulfur deposition budget is 80 Tg-S, representing no change. Our study demonstrates that a global measurement-model fusion approach can substantially improve N and S deposition model estimates at a regional scale and represents a step forward toward the World Meteorological Organization's goal of global fusion products for accurately mapping harmful air pollution.

1. Introduction

Atmospheric nitrogen and sulfur deposition from human activities related to the use of fossils and land use have significant implications for ecosystem and human health (Bobbink et al., 2010). Elevated levels of nitrogen and sulfur can lead to eutrophication (Anderson et al., 2008; Heisler et al., 2008), changes in carbon sequestration (Kicklighter et al., 2019; de Vries et al., 2009; Zhu et al., 2020), loss of biodiversity (Clark et al., 2013; Dise and Stevens, 2005), and acidification (Bowman et al., 2008). While sulfur deposition is expected to decrease over the next 80 years (Lamarque et al., 2013), it will remain a serious hazard in many emerging economies. For instance, sulfur deposition in East Asia peaked in 2006 (Lu et al., 2010) but is still high enough to be concerning, especially in natural and semi-natural regions (Doney et al., 2007; Luo et al., 2014).

Oxidized nitrogen (NO_y) and reduced nitrogen (NH_x), together called reactive nitrogen (Nr), and oxidized sulfur (SO_x) deposition occur as wet and dry processes (Dentener et al., 2006). Wet deposition is measured at hundreds of locations in Europe, North America, and Asia, but dry deposition is harder to measure and is often instead derived from ambient concentrations and modeled deposition velocities (Xu et al., 2015). It is measured continuously at a few locations in

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North America (Clean Air Status and Trends Network (CASTNET), 2021) and Asia (Acid Deposition Monitoring Network in East Asia (EANET), 2021).

The United Nations Economic Commission for Europe's Task Force on Hemispheric Transport of Air Pollution (HTAP) is an international effort to improve the understanding of air pollution transport science with emissions models. The second phase of HTAP was launched in 2012. Tan et al. (Tan et al., 2018) used the multi-model mean (MMM) of 11 HTAP II chemistry transport models to estimate the sulfur and nitrogen deposition budgets for 2010. Significant uncertainty remained due to a lack of station measurements, especially in East Asia, a large contributor to the overall budget. Tan et al. (Tan et al., 2018) compared Acid Deposition Monitoring Network in East Asia (EANET (Acid Deposition Monitoring Network in East Asia (EANET), 2021)) measurements to the MMM output but there were very few measurements in East Asia and all were located along the southeastern coast. In contrast, the highest emissions and modeled deposition were inland and north, making it challenging to evaluate model performance.

Combining measurements and model estimates in a "measurement-model fusion" (MMF) approach has the advantage of retaining the broad spatial coverage of models while accurately matching observations. Generally speaking, MMF takes model estimates for a region and modifies them based on in-situ point measurements of the phenomenon to "nudge" the model towards the observed values (Labrador et al., 2020). One global MMF approach for wet deposition combined measurements with HTAP I ensemble model values for 2000-2002 (Vet et al., 2014) where model estimates filled empty grid cells lacking a 3-year observed mean. Another MMF approach in North America (Atmospheric Deposition Analysis Generated from optimal Interpolation from Observations, "ADAGIO") used observed concentrations to adjust predicted concentrations from the Global Environmental Multiscale-Modelling Air Quality and Chemistry (GEM-MACH) model (Schwede et al., 2019). Recent work in the US (Schwede and Lear, 2014; Zhang et al., 2019) incorporates Community Multiscale Air Quality (CMAQ) model output and precipitation data generated by the Parameter-elevation Regressions on Independent Slopes Model (PRISM, https://prism.oregonstate.edu/, Accessed: 10/01/22), as well as observations using inverse distance weighting to create total deposition ("TDep", https://nadp.slh.wisc.edu/committees/tdep/#tdep-maps) maps that are publicly available.

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More details of the MMF approach are described in Fu et al. (Fu et al., 2022) as they lay out a roadmap for future work, following the World Meteorological Organization's Global Atmosphere Watch Program (WMO GAW) and the intended role of the MMF Global Total Atmospheric Deposition (MMF-GTAD) project. This study updates Tan et al.'s (Tan et al., 2018) global S and N deposition budgets using a variation of the TDep methodology (Schwede and Lear, 2014) to merge NH_x, NO_y, and SO_x gridded surfaces from modeled results with observations of NO_3^-, NH_4^+, and SO_4^{2-} in precipitation and as an aerosol. We demonstrate the viability of a straightforward but globally applicable MMF approach while remaining consistent with previous work that provides impact assessments for various communities. This approach is an essential step towards the WMO's goal of reliable deposition products to aid decision-making.

We update the 2010 deposition budgets using MMF to combine the broad spatial coverage of a model with accurate in-situ measurements. The total nitrogen deposition budget is recalculated to 130 Tg-N and the sulfur budget is 80 Tg-N, representing about a 10% increase and no change, respectively, from the modeled values.

2. Data Availability

All data are from 2010, collected monthly. Wet deposition measurements (NO_3^-, NH_4^+, and SO_4^{2}) from the US's National Trends Network (NTN) and Atmospheric Integrated Research Monitoring Network (AIRMoN) are available through the National Atmospheric Deposition Program (NADP (National Atmospheric Deposition Program, 2021), http://nadp.slh.wisc.edu/NTN/). Measurements were filtered for completeness and quality, following Schwede and Lear (Schwede and Lear, 2014). Sites without a full year of measurements or with quality tags indicating collection issues were not included, resulting in 247 observations. Dry deposition generated values are available from the Clean Air Status and Trends Network (CASTNET (Clean Air Status and Trends Network (CASTNET), 2021)) at 84 locations. CASTNET uses an inferential method to calculate dry deposition fluxes as a product of surface concentration and modeled dry deposition velocity.

Nitrogen and sulfur wet deposition measurements and dry deposition estimates throughout Canada are recorded by the Canadian Air and Precipitation Monitoring Network (CAPMoN (Canadian Air and Precipitation Monitoring Network, 2021)) and are available through the National Atmospheric Chemistry (NAtChem) database (https://donnees.ec.gc.ca/data/air/monitor/). Dry deposition estimates from CAPMoN are

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calculated by multiplying atmospheric concentration and deposition velocity. There were 27 sites with a full year of data.

The European Monitoring and Evaluation Programme (EMEP (European Monitoring and Evaluation Prgrarmme (EMEP), 2021; Tørseth et al., 2012), http://ebas-data.nilu.no/) has records of precipitation chemistry (NO_3^-, NH_4^+, and SO_4^{2-}) for Europe. There were 86 sites with a full year of data.

A promising data set of wet deposition measurements (NO_3^-, NH_4^+, and SO_4^{2-}) in China is available through the National Nitrogen Deposition Monitoring Network (NNDMN (Xu et al., 2019)). It is comparable to other regional measurements (Wen et al., 2020). However, these data only exist for a fraction of 2010 (from September onwards) for a few sites; rather than use partial data to represent an entire year, these sites were not included. A prior multi-year nationwide field study, including some of these NNDMN data, was compiled by Li et al. (Li et al., 2019), which was used in this work as a good proxy for use of NNDMN data in the future studies. Daily NO_3^-, NH_4^+, and SO_4^{2-} site measurements (in mg/L) were averaged over the year for each of the 407 site locations with complete records by multiplying the concentration by the precipitation recorded at that same site (in mm) and then aggregating to produce annual precipitation-weighted deposition (Sirois, 1990). EANET (Asia Center for Air Pollution Research, 2021, https://www.eanet.asia/) wet and dry deposition and precipitation data are available at 47 sites.

The International Global Atmospheric Chemistry (IGAC) Deposition of Biogeochemically Important Trace Species (DEBITS) Africa (IDAF) program (Adon et al., 2010; Galy-Lacaux et al., 2014) has NH_4^+ and NO_3^- precipitation concentrations on the International Network to Study Deposition and Atmospheric Chemistry in Africa (INDAAF (INDAAF – International Network to study Deposition and Atmospheric chemistry in AFrica, 2021)) website (https://indaaf.obs-mip.fr/) for one site in Niger.

All measurements were converted to mg-N (or S) /m^2.

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3. Procedure

Global yearly wet and dry NO_3^-, NH_4^+, and SO_4^{2-} deposition observations (for wet deposition) or estimates (for dry deposition) were combined with the respective HTAP II model average grid cell estimates, using common 1 degree x 1 degree (1^0 x 1^0) grid cells (Figure 1). For example, wet NO_3^- deposition observations are combined with the wet NO_3^- modeled deposition in the nearest HTAP II MMM grid cell to the observation, where observations exist. Dry deposition values (NO_3^-, NH_4^+, and SO_4^{2-}) from CASTNET and n inverse-distance weighted 1^0 x 1^0 gridded dataset was created based on the distance from each observation to the center of the nearest HTAP II model grid cell. Inverse-distance weighting (IDW) was selected as the most implementable method to introduce MMF on a global scale while remaining consistent with previous work (Schwede and Lear, 2014).

The weighting function was calculated as

$$\left(1 - \frac{distance}{max\ distance}\right)^2 \tag{1}$$

following Schwede and Lear's (Schwede and Lear, 2014) approach for the TDep product, where "distance" is the distance between the site location and the center of the HTAP II model grid cell nearest to that sampling site location, within a maximum distance of 1^0 (approximately 111 km at middle latitudes). This maximum distance was chosen because that is the resolution of the HTAP II grids, not because that is the distance a species might travel in the atmosphere before it is deposited. The output values of the weighting function at each observation location are then multiplied by the observed deposition. For the center of every HTAP II model grid cell near that site, the modeled deposition is multiplied by 1 minus the value of the weighting function. As a consequence, if there are no observations near a model grid cell, the cell value remains the same. The two grids ([weighting function times observed deposition] and [1-weighting function times modeled deposition]) are added together. This has the effect of modifying the HTAP II grid only in locations where there are observations nearby.

The MMF gridded surfaces were then summed by species along with the remaining unchanged HTAP II gridded surfaces that lacked in-situ measurements to create total N and S deposition gridded surfaces (e.g., the MMF wet and dry SO_4^- gridded surfaces were added to the HTAP II wet and dry SO_2 gridded surfaces to get total S deposition). The MMF wet deposition surfaces

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include measurements from Europe, Asia, and North America, but the dry deposition MMF surface only includes measurements from the USA and Asia, due to a lack of measurements elsewhere.

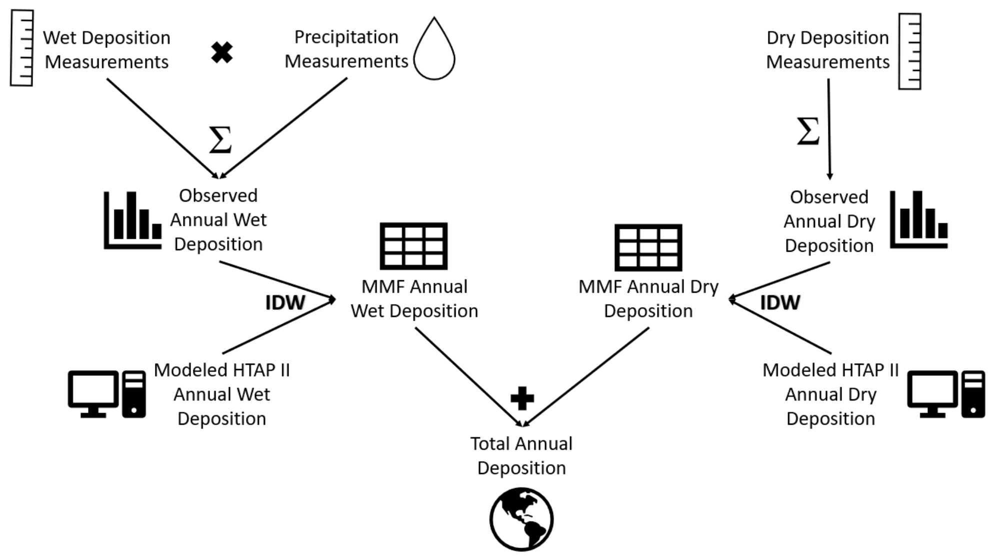

Figure 1. A flowchart describes the MMF methodology implemented in this paper.

4. Results

The total global NH_x deposition in 2010 is adjusted from 54 Tg-N (from HTAP II models) to 70.65 Tg-N (Table 1). Combined with a NO_y deposition of 59.4 Tg-N (from a modeled HTAP II 59.3 Tg-N), the total global deposition is adjusted to 130 Tg-N (from 113 Tg-N). Most of this increase comes from a model underestimation in East Asia (Figure 2A). Total S deposition is adjusted to 80 Tg-S (Table 1), a slight decrease from the HTAP II model prediction of 83.5 Tg-S (Figure 2B).

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Table 1: 2010 adjusted global wet and dry deposition in Tg, MMM indicates Tan et al.'s 2018 multi-model mean and MMF is this measurement-model fusion work. Coastal means within 1 degree of the coastline. RBU is an abbreviation for Russia, Belarus, and Ukraine.

	Non-Coastal		Coastal		Non-Coastal		Coastal		Non-Coastal		Coastal	
	MMM	MMF	MMM	MMF	MMM	MMF	MMM	MMF	MMM	MMF	MMM	MMF
Region	**Total NH_x**				**Total NO_y**				**Total S**			
North America	3.40	4.56	0.40	1.02	4.40	4.34	0.80	1.50	4.70	3.35	1.30	1.60
Europe	2.50	1.97	0.80	1.74	2.60	1.61	1.20	1.76	2.70	1.21	1.50	1.99
South Asia	8.60	8.60	1.00	1.00	3.60	3.60	0.70	0.70	3.70	3.70	1.00	1.00
East Asia	6.70	5.93	1.00	1.84	8.30	4.85	2.20	3.47	11.20	8.04	2.90	3.69
Southeast Asia	3.20	1.13	1.60	2.87	1.90	0.74	1.40	1.67	2.40	0.71	2.80	3.51
Australia	0.40	0.40	0.40	0.40	0.60	0.60	0.40	0.40	1.00	1.00	1.50	1.50
North Africa	0.70	0.70	0.20	0.20	1.40	1.40	0.40	0.40	1.00	1.00	0.50	0.50
Sub-Saharan Africa	3.40	3.40	0.40	0.40	4.70	4.70	0.60	0.60	2.70	2.70	0.70	0.70
Middle East	0.50	0.70	0.10	0.30	1.40	1.40	0.30	0.30	1.70	1.70	0.60	0.60
Central America	1.40	1.40	0.60	0.60	1.20	1.20	0.80	0.80	1.40	1.40	1.40	1.40
South America	3.80	3.80	0.30	0.30	3.40	3.40	0.30	0.30	2.40	2.40	0.60	0.60
RBU	1.80	3.48	0.30	0.68	2.40	2.50	0.50	0.68	3.60	2.81	0.90	0.78
Central Asia	0.50	0.50	0.00	0.00	0.60	0.60	0.00	0.00	1.20	1.20	0.10	0.10
Antarctica	0.10	0.10	0.00	0.00	0.10	0.10	0.00	0.00	1.40	1.40	0.00	0.00
Continental	37.00	36.70	7.10	11.67	36.70	29.81	9.70	11.81	41.00	32.62	15.60	18.28
Open Oceans	9.90	22.28			12.90	17.80			26.90	29.10		
Global	46.90	58.98	7.10	11.67	49.60	47.61	9.70	11.81	67.90	61.72	15.60	18.28

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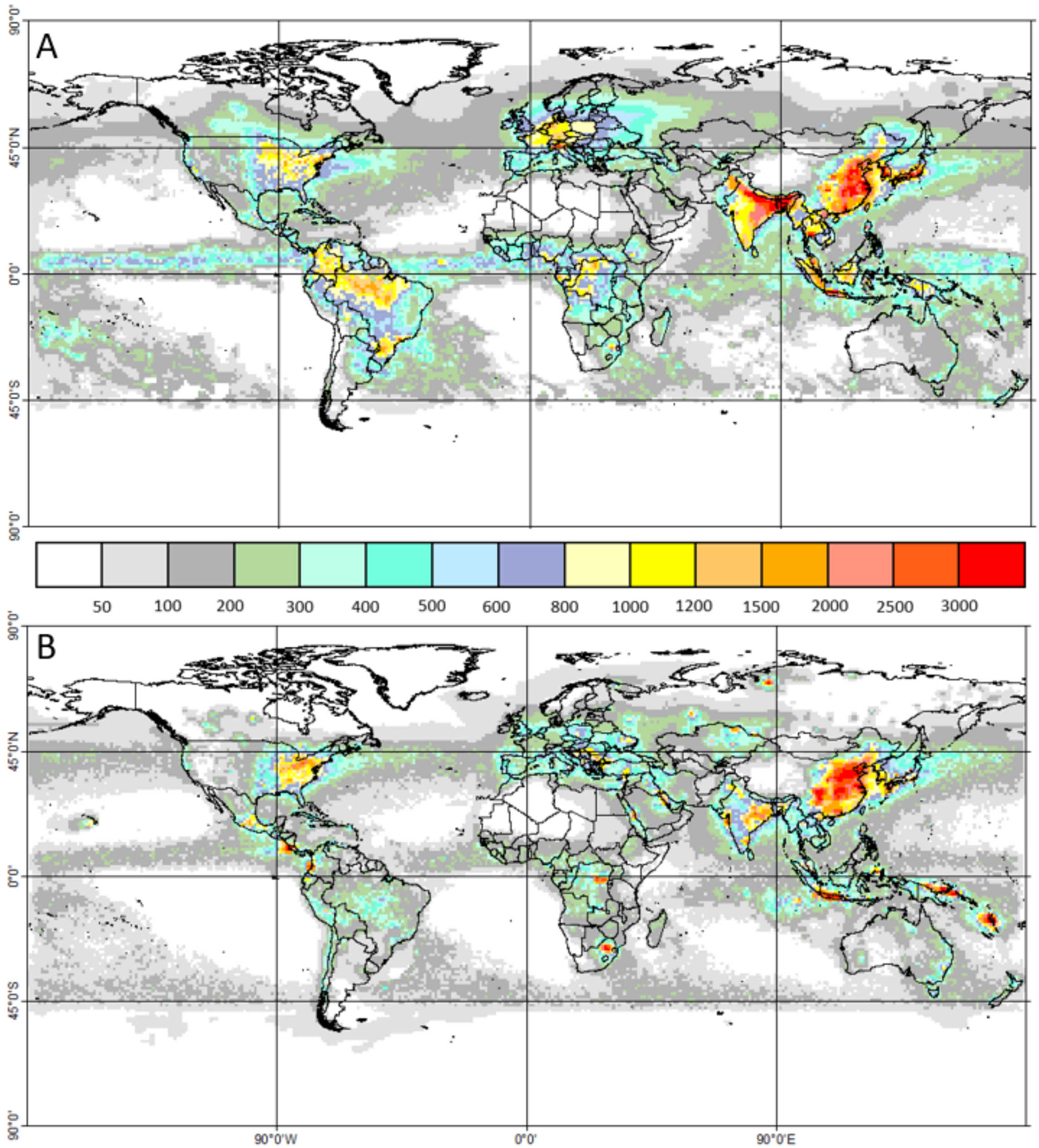

Figure 2: Total N and S deposition in 2010 using the MMF approach. A) Total N deposition (mg N/m^2), the sum of wet and dry NO_3^- and NH_4^+ after applying the MMF approach, as well as HTAP II gridded surfaces of wet and dry NH_3, HNO_3, and NO_2 with no MMF approach due to the lack of measurements. **B)** Total S deposition (mg S /m^2), the sum of wet and dry MMF SO_4^{2-} and wet and dry HTAP II SO_2.

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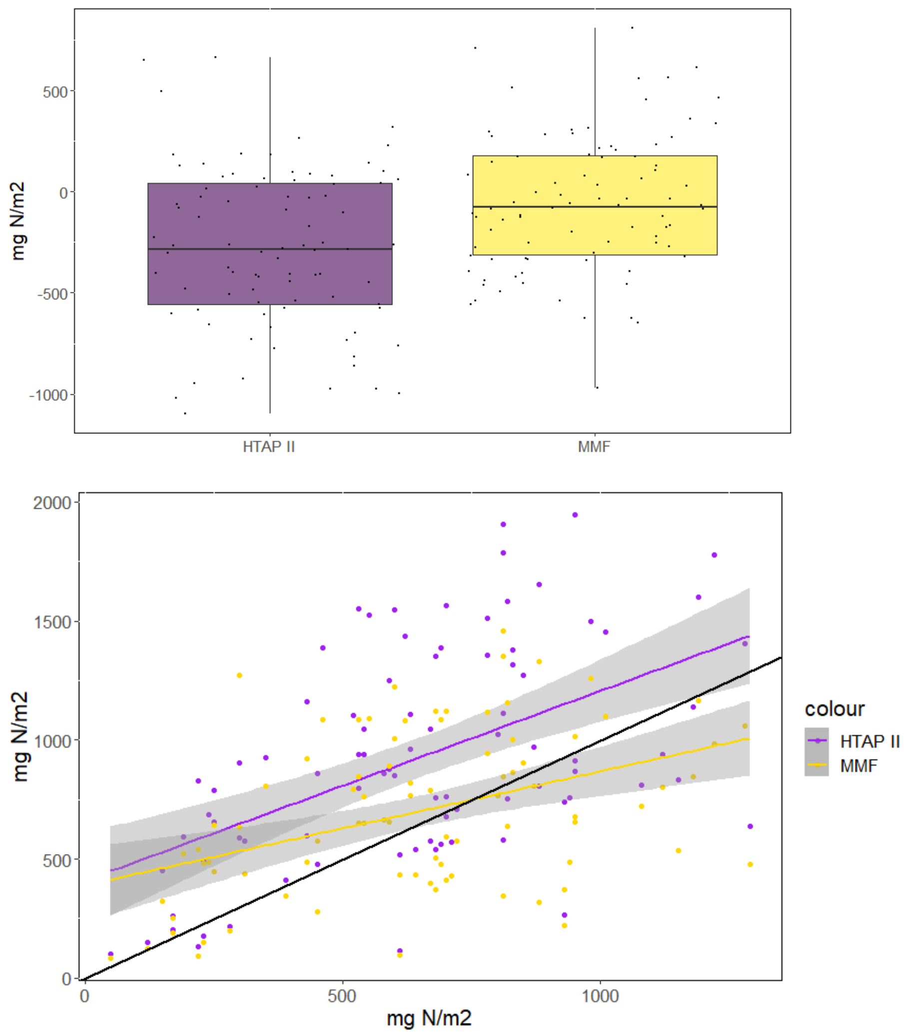

Figure 3: A comparison between HTAP II and MMF results at EMEP observation sites. A) A boxplot shows the distribution of difference between EMEP and HTAP II and EMEP and MMF modeled wet deposition results at each EMEP observation location. **B)** HTAP II and MMF values versus the respective EMEP wet deposition observation at each measurement location with standard error shown in gray. The 1:1 line is black.

Tan et al. (2018) report that their MMM is underestimating the high observations of total N deposition at some EMEP stations. We find that our value for European N deposition (7.08 Tg) is very similar to the MMM surface (7.10 Tg), though higher observations are better reproduced with MMF (Figure 3). Higher observations in East Asia are also better reproduced with MMF (Figure 4).

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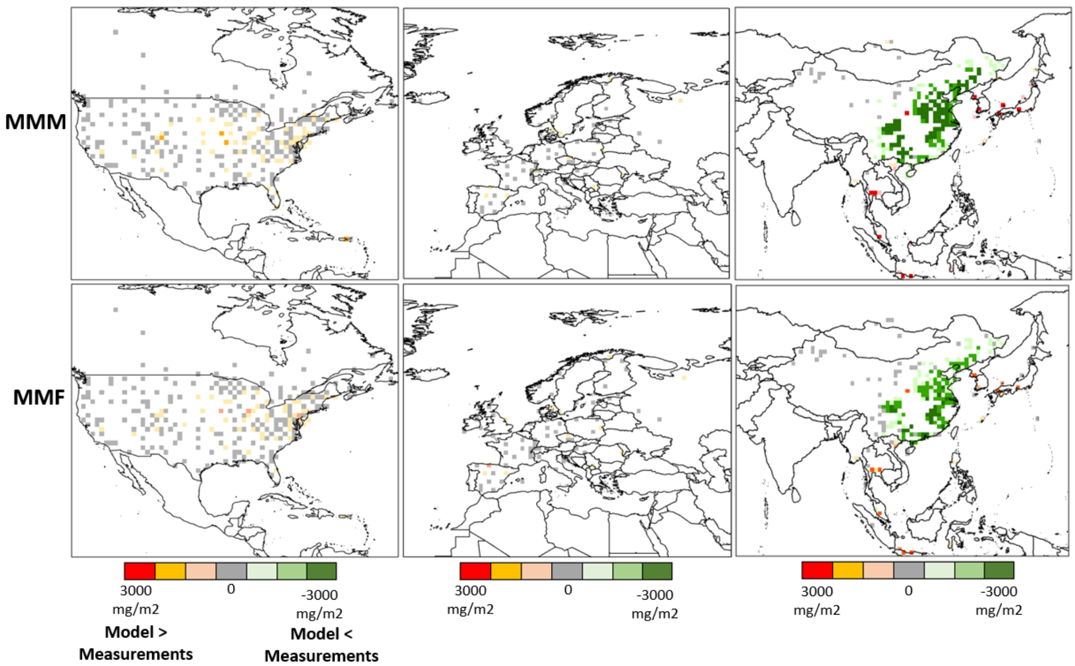

Figure 4. The difference between modeled and observed deposition. Observed annual wet nitrogen deposition is subtracted from MMM and MMF annual wet nitrogen deposition for North America, Europe, and Asia, respectively in mg/m^2.

The spatial distribution is slightly different, with more deposition in coastal areas in the MMF estimate (Table 1). Tan et al. (Tan et al., 2018) report that the HTAP II MMM overestimates NO_3^- wet deposition in North America, but underestimates NH_4^+ deposition. We find that the MMF interpolated deposition slightly improves these estimates, although the spatial distribution is very similar (Figures 2, 5). The largest change for N deposition (comparing MMM and MMF) is in grid cells classified as ocean because of an increase in East and Southeast Asia deposition which mostly occurs in areas classified as ocean due to the small island size and low spatial resolution. Ocean cells were classified as such if they were located further than 1 degree from the mainland; therefore, any islands smaller than 1 degree were counted as ocean. The largest change for S deposition is in continental grid cells due to a decrease in East Asia.

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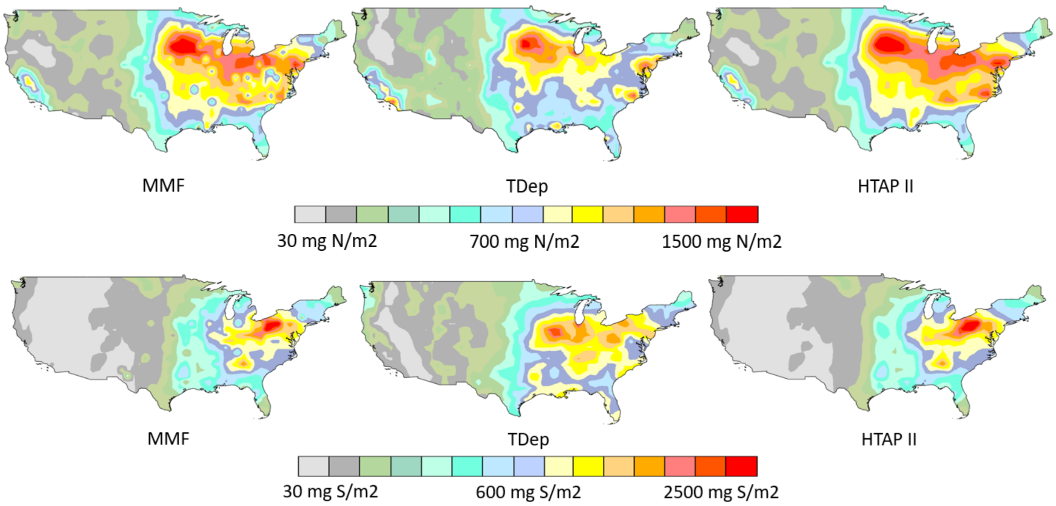

Figure 5: 2010 Total N deposition in the US. A) Total N is modeled with 1) MMF (this work), 2) TDep annual map available from the NADP and 3) Tan et al.'s 2018 MMM. **B)** 2010 SO_x wet deposition in the US as modeled with 1) MMF (this work), 2) TDep annual map available from the NADP, and 3) Tan et al.'s 2018 multi-model mean HTAP II output.

There are spatial differences between an aggregated 1^0 x 1^0 the original TDep map of nitrogen deposition for the United States as available from the NADP (Figure 5A), the HTAP II surface produced by Tan et al. (Tan et al., 2018) corresponding to the same area, and the deposition map produced in this work. A similar pattern is seen in the map of SO_4^{2-} (Figure 5B).

The R^2 value for the linear regression between MMF wet NH_4 and observed wet NH_4 in the US is 0.76 (Figure 6). The R^2 value for the linear regression between the HTAP II wet NH_4 and observed NH_4 is 0.66, and 0.92 for the linear regression between the TDep wet NH_4 and observed NH_4 (Figure 6). This means that TDep is better reproducing the NADP/NTN measurements, whereas the MMF methodology is more similar to the HTAP II model. The higher TDep R^2 value likely occurs because of the finer mesh (12 km) used in the TDep product, and the closer proximity to individual stations as compared to HTAP II used in the MMF approach. All three datasets produce similar values to the measured wet NH_x deposition at the NADP/NTN sites (Figure 6).

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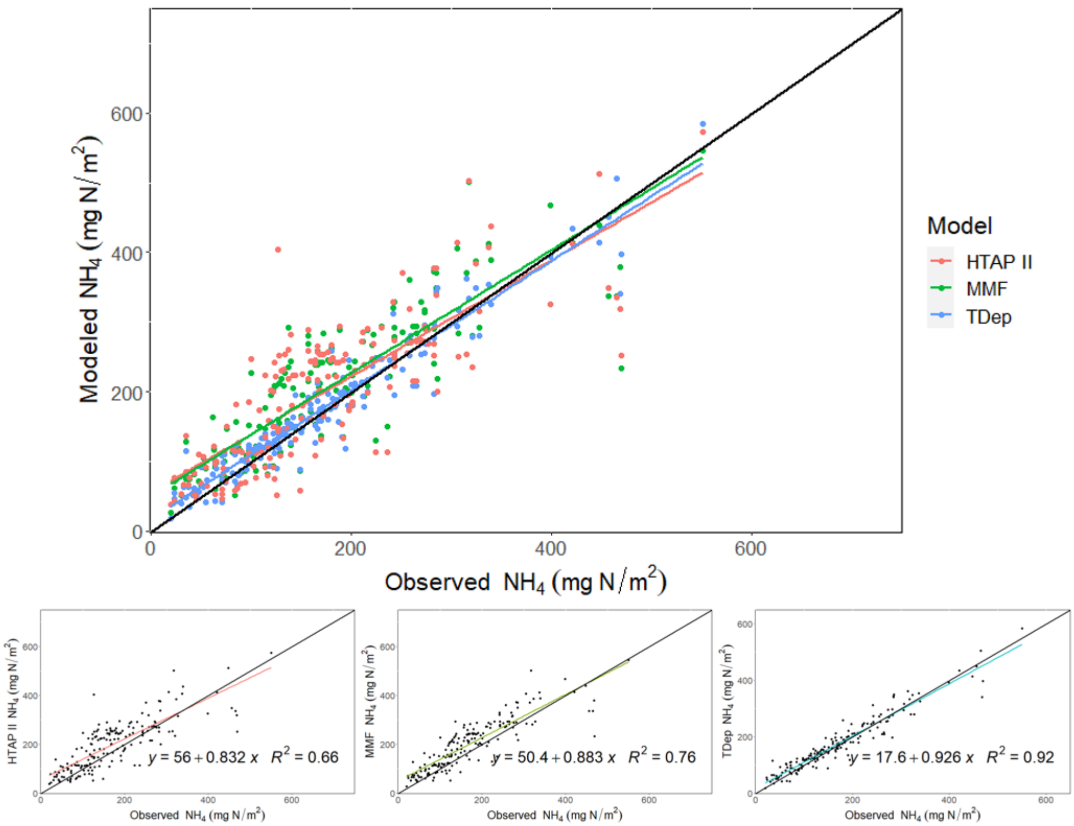

Figure 6: **Observed and modeled wet NH_4 deposition in the US in 2010**. Each NADP/NTN wet deposition measurement and the associated HTAP II, TDep, or MMF NH_x wet deposition value. The black line is the 1:1 line.

5. Discussion

Geddes et al. (Geddes and Martin, 2017) used satellite observations to report global NO_y emissions of 57.5 Tg-N/yr in 2010, similar to the 59.26 Tg-N emissions reported by HTAP II. This matches well with our total NO_y deposition (59.4 Tg-N). However, it suggests that either emissions for HTAP II models' simulations are too low, or deposition is too high since presumably deposition should be similar to or lower than emissions. HTAP II ammonia emissions were 51.93 Tg-N, lower than the MMF NH_3 and NH_4 deposition of 70.65 Tg-N, suggesting that emissions are too low, or deposition is too high. The total MMM sulfur emissions for 2010 were 90.7 Tg S, somewhat larger than the MMF sulfur deposition of 80 Tg-N.

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Research in China (Liu et al., 2020) explored the spatial pattern of N deposition by combining satellite observations with NNDMN observations (Xu et al., 2019); they found a 2012 average of 18.21 kg N ha^{-1}. Additional work combining the GEOS-Chem (http://acmg.seas.harvard.edu/geos/) model with satellite observations and surface measurements reports the average annual deposition from 2008-2012 as 16.4 Tg-N with 10.2 Tg-N from NH_x and 6.2 Tg-N from NO_y (Zhao et al., 2017). The averages reported by these studies are consistent with ours (16.6 kg · ha^{-1} · yr^{-1}) despite the slight difference in timeframe and resolution. The spatial pattern of N deposition in 2010 (Figure 2A) also remains similar to that of previous decades (Jia et al., 2014), with high deposition in eastern China and low deposition over the Tibetan Plateau. This pattern is confirmed in 2006 and 2013 (Qu et al., 2017).

As seen in Table 1, the largest difference between MMM and MMF is in the ocean. While MMF does give better deposition estimates by incorporating in-situ measurements, it is worth considering the scale of the model. Observations of deposition are probably not representative for a 1^0 resolution and observations of precipitation may not be homogenous in all directions at that scale, especially over varying terrain. So, for example, the coarse resolution of the model, even with added measurements is likely not accurately capturing the gradient between coastal and inland deposition. While higher resolution precipitation values are available in some regions (e.g. PRISM in the US), there is still a dearth of both wet and dry deposition measurements. Schwede et al.(Schwede et al., 2011) showed that dry deposition estimates from CASTNET and CAPMoN can be very different, despite using similar methodologies. This adds uncertainty to the dry deposition data (though there are very few dry deposition estimates included in this study) and emphasizes the importance of deposition velocity model methodology.

The differences between the TDep, MMM, and MMF gridded deposition in the US (Figure 5) are clear on the coasts. While the general patterns of deposition are similar for the three products, the magnitude of deposition in the aggregated TDep dataset (1^0 x 1^0) is higher in the eastern US and lower in the western US than either of the other two deposition fields. This difference is likely due to the precipitation dataset used to calculate wet deposition. MMF deposition is based on the MMM dataset; therefore, both utilize the same precipitation dataset, from a combination of 11 global models. However, TDep wet deposition is produced by multiplying PRISM precipitation data and an interpolated gridded surface dataset of wet NH_4^+ concentrations. PRISM is a reanalysis product designed to interpolate precipitation in particularly complex

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landscapes using weather radar and rainfall gauge observations, though it is not identical to observations because it used long-term averages as predictor grids (Zhang et al., 2018). It captures much more localized variation in precipitation due to geographical variations which are not captured in the lower resolution global precipitation models used in the HTAP II MMM (Tan et al., 2018). To illustrate this, we compare PRISM to the available Community Atmosphere Model with Chemistry (https://www2.acom.ucar.edu/gcm/cam-chem, "CAM-Chem"), which was one of the models in the HTAP II ensemble. Subtracting the CAM-Chem precipitation output over the US from aggregated PRISM precipitation shows that CAM-Chem greatly underestimates precipitation volume in the US in 2010 (Figure S1). We note, however, that this comparison does not take precipitation frequency into account. This matters because if the difference in volume comes from a few large magnitude storms, it will not influence the deposition values much. This is a good example of the differences that occur when comparing global and regional climate models and serves to emphasize the importance of resolving spatial and temporal scales. The total deposition within the US borders is similar for the MMF, HTAP II, and aggregated TDep gridded surfaces; however, the spatial distribution is different.

MMF and MMM deposition distributions are similar because MMF is based on HTAP II. Likewise, the MMF results are similar to the TDep values at observation locations because, despite the difference in precipitation, both utilize the same NADP/NTN measurements to constrain the models. The key difference between MMF, when compared to MMM, is that measurement locations are not centered in each 1^0 x 1^0 grid cell; therefore, the center of each grid cell (the value compared to the observation, by interpolation to the station location) will not exactly equal the measured deposition but will instead be equal to the measurements weighted proportionally to distance from the centroid. This means that the graphical comparison of Figure 6 is showing the actual measurement locations and 3 different model results with some meaningful influence from measurements that are nonetheless unique values, except in the very rare instance that the measurement corresponds exactly to the center of a grid cell.

TDep maps of North American nitrogen deposition created with Schwede and Lear's methodology (2014), using IDW, are widely in use and freely available from the NADP. However, there are limitations associated with IDW (Sahu et al., 2010), and other interpolation methods such as kriging or geographically weighted regression could provide smoother surfaces with fewer artifacts. IDW is a fast and flexible interpolation method, but it does not minimize

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error and can produce inaccurate results in regions with sparse measurements and large sub-grid variability. This problem is relevant to much of the world. The lack of measurement sites globally is a hindrance that can be alleviated by including remotely sensed observations (Walker et al., 2019). Future work should also investigate methods such as machine learning techniques with spatial information to avoid these limitations.

These results from measurement-model fusion are important because previous methods on a global scale have relied primarily on models (Vet et al., 2014; Tan et al., 2018). They compare their results with measurements, of course, in order to demonstrate the model capabilities but they do not explicitly incorporate point measurements into the final product. Our results serve to emphasize that the models are adequately simulating deposition (in terms of total deposition budgets) but that the regional discrepancies between models and measurements can still be quite large; and measurement-model fusion helps to ameliorate this without changing the fundamental model parameters and processes that actually capture the overall deposition reasonably well.

6. Conclusions

Sulfur and nitrogen depositions remain a serious concern for human and ecosystem health. We update the 2010 deposition budgets using measurement-model fusion to combine the broad spatial coverage of a model with accurate in-situ measurements. The total nitrogen deposition budget is recalculated to 130 Tg-N and the sulfur budget is 80 Tg-N, representing about a 10% increase and no change, respectively, from the modeled values. This work emphasizes the necessity of combining models with observations wherever possible to better capture regional patterns and to inform policy and decision-making. Future work to improve measurement-model fusion should investigate other methods of interpolation to avoid the limitations associated with IDW such as surface artifacts and high error in regions with sparse measurements. It should also incorporate satellite imagery to improve model estimates where in-situ measurements are not available.

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Author Contribution

HR carried out the methods and analyzed the results. JSF and FD designed the project. HR prepared the manuscript with contributions from JSF and FD. RL, KH, and HF provided data.

Competing Interests

The authors declare no competing interests.

Code Availability

Data analysis was done using ArcMap Desktop 10.8.1, ArcGIS Pro, and R (R Core Team, 2022).

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