Assessing differences in country-level estimates of maternal mortality: a comparison of GMatH, UN, and GBD model results for 2020

Zachary J. Ward,[a,b,] Rifat Atun,[b,c,d] Gary King,[e] Brenda Sequeira Dmello,[f] and Sue J. Goldie[a,b,d,g]*

[a]Center for Health Decision Science, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, USA
[b]Department of Health Policy and Management, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, USA
[c]Department of Global Health and Population, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, USA
[d]Department of Global Health and Social Medicine, Harvard Medical School, Harvard University, Boston, MA, USA
[e]Institute for Quantitative Social Science, Harvard University, Cambridge, MA, USA
[f]Maternal and Newborn Healthcare, Comprehensive Community Based Rehabilitation in Tanzania (CCBRT), Dar Es Salaam, Tanzania
[g]Global Health Education and Learning Incubator, Harvard University, Cambridge, MA, USA

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Summary

Background Estimates of maternal mortality are important for informing policy and resource allocation, both globally and for individual countries, and to track progress towards Sustainable Development Goals. The Global Maternal Health (GMatH) model was developed for policy analysis and produces global and country-level estimates of maternal mortality. Estimates are also produced by models from the United Nations (UN) and Global Burden of Disease (GBD).

Methods We compared country-level estimates for 2020 of maternal deaths and the maternal mortality ratio (MMR) across the UN (v2023), GBD (v2021), and GMatH (v2023) models. We summarized the differences, assessed model convergence, and characterized the available empirical mortality data for countries with large differences to shed light on potential reasons for these differences.

Findings On average, the GMatH estimates of country-level maternal deaths in 2020 were 272 larger (43% higher) than the UN estimates, and 728 larger (49% higher) than the GBD estimates. Country-level MMRs were on average 22.3 higher (19% higher) than the UN estimates and 48.1 higher (22% higher) than the GBD estimates. Overall, 87.9% of the UN country-level MMR estimates were convergent with the GMatH model, and 82.8% of the GBD MMR estimates were convergent, but large differences were found for some countries. Among countries with the largest differences across models, survey-based estimates of the pregnancy mortality ratio were usually the only empirical mortality data available.

Interpretation Although estimates of maternal mortality are similar across the GMatH, UN, and GBD models for most countries, there are also large differences. Our structural modelling approach leverages multiple types of data across the reproductive life course, including pregnancy mortality ratios, allowing for more robust estimation of maternal health indicators. Comparing results across models helps to build confidence in estimates where they are similar and sheds light on potential reasons for differences where they diverge to help refine estimates and guide policies to reduce maternal mortality.

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Introduction

Maternal mortality continues to be a major global health challenge, and is the focus of one of the United Nations' (UN) Sustainable Development Goals (SDG), with a target set to reduce the global maternal mortality ratio (MMR) to less than 70 maternal deaths per 100,000 live births by 2030, with no individual country above 140.[1] Although global maternal mortality has

*Corresponding author. Center for Health Decision Science, Harvard T.H. Chan School of Public Health, 718 Huntington Ave. 2nd Floor, Boston, MA 02115, USA.
E-mail address: zward@hsph.harvard.edu (Z.J. Ward).

Research in context

Evidence before this study

Aggregate regression models developed by the United Nations (UN) Maternal Mortality Estimation Inter-agency Group and the Global Burden of Disease (GBD) study have been used to estimate global, regional, and country-specific estimates of maternal health indicators, based on the cross-sectional associations between country-level factors and levels of maternal mortality. The Global Maternal Health (GMatH) microsimulation model was developed for policy analysis and uses a different modelling approach based on a defined system of causal components and their relationships to estimate maternal health indicators. A previous comparison of global estimates of total maternal deaths and MMR found that the GMatH (v2023) and UN (v2019) models had similar estimates (with GMatH estimates on average slightly higher), with GBD (v2019) having much lower estimates of global MMR and maternal deaths. In this analysis we compare updated model estimates for country-level maternal mortality indicators across the UN (v2023), GBD (v2021), and GMatH (v2023) models and identify areas of convergence and divergence, exploring possible reasons for divergence.

Added value of this study

This study provides the first comprehensive comparison of country-specific maternal mortality estimates from the UN, GBD, and GMatH models. By systematically identifying where and why model estimates diverge, we highlight important gaps in empirical data, differences in model assumptions, and implications for country-level policy and data collection. By leveraging multiple types of data in an internally consistent framework, our structural microsimulation model offers an alternative approach to statistical models for estimation, and provides a framework for policy analysis. In contrast to regression-based models, which are fitted to a limited set of outcomes (often a single outcome variable), the GMatH model, a structural model, was calibrated to empirical data from multiple sources on indicators all along the reproductive pathway, allowing us to leverage indicators that may be observed with more certainty to infer parameter values that are less certain or may be unobserved. Comparing our model results to estimates from the UN and GBD models, we identify a subset of countries with the largest differences across models, and find that among these countries with the largest discrepancies in estimated maternal deaths or MMR, the majority have empirical data available from DHS surveys for the pregnancy mortality ratio, identifying a potential reason for why model estimates may diverge for some countries.

Implications of all the available evidence

We find that maternal mortality estimates from the UN and GBD are convergent with the GMatH model for most countries, but there are large differences for some countries, which has implications for global resource allocation and efforts aimed at reaching Sustainable Development Goals. The countries with the largest differences across models generally have data for indicators other than MMR—instead estimates of the pregnancy-related mortality ratio are available, which are directly used as one of the data sources to calibrate the GMatH model, but which must be transformed into proportional mortality estimates via a series of assumptions and calculations for use in the UN and GBD models. This has implications for the design of future data collection efforts (e.g., choice of indicators), modelling approaches (e.g., pre-processing assumptions), and interpretation of estimates (e.g., comparison of results across models for divergent countries). Models should integrate all reliable data sources across the reproductive life course—not only for calibration and validation, but also to identify inconsistencies that may signal data quality or reporting issues. Further efforts are needed to strengthen data systems to provide robust empirical data that can be used for various types of modelling, and comparisons across modelling approaches can help to refine estimates and identify the highest priorities areas where better data are needed to accelerate reductions in maternal deaths.

declined over the years, progress has stalled in many countries, and the SDG maternal mortality target is unlikely to be met on current trends.[2,3]

Evaluating the effectiveness of strategies and assessing progress is particularly challenging because of difficulties surrounding the measurement of maternal mortality. In addition to inadequate data collection and incomplete vital registration systems in many low- and middle-income countries (LMICs), maternal deaths are often underreported across the pregnancy continuum,[4] or are misclassified, as maternal mortality is a composite of many distinct conditions.[5]

To address these data limitations, statistical methods have been developed to produce estimates of maternal mortality using what data are available. For example, aggregate regression models developed by the UN Maternal Mortality Estimation Inter-agency Group[6,7] and the Global Burden of Disease (GBD) study[8,9] estimate the cross-sectional associations between country-level factors and levels of maternal mortality, with gross domestic product (GDP) the largest driver of trends.[10] These models have been used to produce global, regional, and country-specific estimates of maternal health indicators, and have been influential for policymakers at various levels. Although these models can provide insight into relative trends, the maternal mortality estimates (both global and country-level) from these models often differ (sometimes substantially), which can result in confusion, mistrust in reported results, and uncertainty about the effects of policies.[10]

We developed the Global Maternal Health (GMatH) microsimulation model to simulate the reproductive lifecourse of individual women in each country, with the primary goal of performing policy analysis which can guide strategy prioritisation and planning.[3,11] In addition to policy analysis, the GMatH model can also be used to estimate maternal health indicators. In contrast to aggregate statistical models, which are based only on trends in the outcome of interest, the GMatH structural model is based on a defined system of causal components and their relationships, and can synthesize evidence (both theory and empirical data) on many factors from multiple sources to offer more robust predictions.[12]

A previous comparison of global estimates of total maternal deaths and MMR found that the GMatH (v2023) and UN (v2019) models had similar estimates (with GMatH estimates on average slightly higher), with GBD (v2019) having much lower estimates of global MMR and maternal deaths.[3] In this analysis we compare updated model estimates for country-level maternal mortality indicators across the UN (v2023), GBD (v2021), and GMatH (v2023) models and identify areas of convergence and divergence, exploring possible reasons for divergence in the estimates.

Methods

GMatH model overview

The Global Maternal Health (GMatH) microsimulation model simulates the reproductive histories of individual women in 200 countries and territories between 1990 and 2050.[3] Microsimulation modelling is based on graphical causal models and can estimate the effects of complex interventions over long time periods, and is increasingly recognized as another approach for epidemiologic causal inference.[13] In addition for the potential for more robust estimation, this structural approach is also better suited to perform counterfactual policy analyses to estimate the impact of various strategies to improve maternal health.[11,14] The GMatH model has been used to estimate global, regional, and country-level trends from 1990-2050,[3] for context-specific comparative effectiveness analysis of policies,[11] to estimate maternal health indicators for subgroups within countries,[15] and to develop a country typology framework to guide policy.[16]

Building on a previous conceptual model,[17] the GMatH model was developed using the most reliable and comprehensive demographic, epidemiologic, and clinical publicly available data, including data from over 4.6 million individual Demographic and Health Survey (DHS) respondents.[18] Individual women in each country are assigned an urban/rural location, and a level of education conditional on their location, accounting for subgroup differences in factors such as family planning preferences and access to care.[15]

The model simulates the reproductive lifecycle for each woman, beginning with her age of sexual debut, and models monthly probabilities of conception based on maternal age, breastfeeding status, and patterns of contraceptive use. Modelling these factors allows us to estimate fertility trends and ensures that all maternal health indicators (e.g., births, total fertility rate, causes of death, etc.) are internally consistent within the model. The risks of ectopic pregnancy and miscarriage are simulated for each pregnancy, and unintended pregnancies (modelled with respect to each individual woman's fertility preferences) may be terminated by induced abortion which may be 'safe' (e.g., by trained personnel in a medical setting) or 'unsafe' (e.g., by untrained personnel or by traditional methods), with differential risks of morbidity and mortality.

Complications during pregnancy and childbirth are modelled based on both individual-level risk factors (e.g., anemia) and health system factors, such as access to care and the availability of specific clinical interventions. The risks of indirect maternal death (e.g., deaths associated with other causes such as HIV or malaria that are aggravated by pregnancy), and competing mortality (i.e., deaths from all other causes) are also simulated (separately) for each woman. As part of the modeled data-generating process, we also simulate the (setting- and time-dependent) probability that each maternal death will be accurately reported, allowing us to account for substantial underreporting of maternal deaths that often occurs in Civil Registration Vital Statistics (CRVS) data.[19]

GMatH model calibration

The model was calibrated to empirical data for various fertility, process, and mortality indicators related to maternal health. Although country-specific data are often missing (or may be of poor quality), calibrating the model to empirical data from multiple sources on indicators all along the reproductive pathway allows us to leverage indicators that may be observed with more certainty to infer parameter values that are less certain or may be unobserved. We fitted the model parameters so that the model predictions were consistent with country-specific empirical data on: total fertility rate (TFR), contraceptive prevalence rate, twinning rate, anemia prevalence (by severity), stillbirth rate, proportion of births which occur in health facilities, caesarean-section rate, proportion of births which occur via spontaneous/operative vaginal delivery, total maternal deaths (CRVS data), maternal deaths by 8 causes (abortion, ectopic pregnancy, miscarriage; hypertensive disorders; hemorrhage; sepsis and other infections; obstructed labor; other direct death; late maternal deaths; indirect maternal deaths), pregnancy-related mortality ratio, and maternal mortality ratio.

We fitted the model to empirical data (i.e., no modelled estimates) from 1990 to 2015, reserving estimates from 2016 to 2020 as a test set to assess the predictive accuracy of the model, and found that it performs well, with coverage probabilities (i.e., proportion of times the empirical point estimate was contained within the model 95% uncertainty intervals [UI]) of 96.0% for maternal mortality indicators and a mean error of 2.6 deaths (SE 8.9) for total maternal deaths.[3] Bayesian hierarchical models were used for all model parameters, and 1000 simulations were performed with the final calibrated model sampling from the best-fitting 100 parameter sets, accounting for uncertainty (and missing data) for all model parameters. Our 95% uncertainty intervals thus include both first-order (stochastic) and second-order (parameter) uncertainty, and account for how changes in parameter values affect all modelled outcomes. More details on the model parameters and calibration are available in the Appendix (section 1.1) and online (www.gmath-model.org).

United Nations (UN) modelling approach

The UN Maternal Mortality Estimation Inter-Agency Group (MMEIG) recently (in 2023) produced estimates of maternal mortality from 2000 to 2020 using a hierarchical Bayesian regression model.[2,20,21] Input data are adjusted for underreporting and converted to the desired outcome variable of "proportional mortality" (PM), defined as the proportion of all deaths among women of reproductive age due to maternal causes, except for estimates of maternal deaths from CRVS data and specialized studies which are used directly in the likelihood function. The model uses 3 predictor variables (per capita GDP, general fertility rate, and skilled birth attendant [SBA] coverage) to estimate PM values for each country-year, and all other maternal mortality indicators (e.g., number of maternal deaths, MMR) are calculated from the predicted PM. The UN model does not produce estimates by cause of death, and late maternal deaths are not included in the total estimates. See Appendix 1.2 for more details.

Global Burden of Disease (GBD) modelling approach

The most recent version of the Global Burden of Disease (GBD 2021, published in 2024) has estimates from 1980 to 2021, and includes late maternal deaths in the definition of maternal mortality.[22,23] Similar to the UN model, overall maternal mortality indicators were calculated using PM as the outcome variable, using the Cause of Death Ensemble modelling (CODEm) tool (described in detail elsewhere) to adjust for under-reporting/misclassification. Spatiotemporal Gaussian process regression (ST-GPR) models were used to estimate PM values based on 3 levels of predictor values, such as fertility rate, SBA coverage, ANC coverage, healthcare access and quality, female body weight, and socio-demographic indicators (see Appendix 1.3 for more details). A similar approach was used to model each cause of maternal death, with some variation in the specific predictor variables included.[22]

Maternal mortality definitions

The WHO defines a maternal death as a "death from any cause related to or aggravated by pregnancy or its management (excluding accidental or incidental causes) during pregnancy and childbirth or within 42 days of termination of pregnancy, irrespective of the duration and site of the pregnancy."[24] Maternal deaths can be due to "direct" causes, or may be "indirect" (i.e., deaths due to other causes that are aggravated by pregnancy). A "late maternal death" is defined as the "death of a woman from direct or indirect obstetric causes, more than 42 days but less than one year after termination of pregnancy".[24] A "pregnancy-related death" is defined as the death of a woman while pregnant or within 42 days of termination of pregnancy, regardless of the cause of death (The exact follow-up period after pregnancy may vary by source. For example, the DHS sisterhood method has sometimes used 60 days [2 months] postpartum,[25] while other countries such as the US extend the period up to one year[26]). Pregnancy-related deaths thus include all maternal deaths, and also deaths from accidental or incidental causes, and are often estimated from survey data using sibling-based mortality recall (e.g., "sisterhood method").[27]

Note that there are differences in the definitions for these indicators across models with respect to age range and the inclusion of late maternal deaths. GMatH (v2023) considers maternal deaths at all ages, and includes late maternal deaths in estimates of total maternal deaths but not in the MMR (consistent with the WHO definition of "maternal death").[3] UN (v2023) generally considers women of reproductive age as 15–49, and does not include late maternal deaths in any estimates.[2] In contrast, GBD (v2021) includes late maternal deaths in all maternal mortality estimates and considers ages 10–54 years.[22]

Model comparison

We compared estimates across the GMatH (v2023),[3] UN (v2023),[2] and GBD (v2021)[23] models for maternal deaths and MMR (maternal deaths per 100,00 live births) in 2020, the latest year estimated by all models. Among countries included in the GMatH model, UN estimates were available for 185 countries and GBD estimates were available for 197 countries. We calculated differences across model estimates in three ways: signed difference (i.e., GMatH estimates minus other model estimates, the result of which can be positive or negative), relative difference (i.e., the percentage difference between model estimates, calculated as GMatH minus other model estimates divided by GMatH estimates), and absolute difference (i.e., distance between model estimates, which is greater than or equal to 0). We summarized the mean and distribution for each difference metric. We also calculated the correlation (Pearson's r) of estimates across models, and classified UN and GBD estimates as 'convergent' with the GMatH estimates if our 95% UIs contained the other modelled point estimates. We also compared estimates of the total fertility rate (TFR) in 2020 across models to assess the potential impact of differences in fertility estimates.[3,28,29] Lastly, we compared causes of maternal death in 2020 across the GMatH and GBD models (Estimates of maternal death by cause were not available from the UN model).

We then compared the 10 countries with the largest absolute mean difference for maternal deaths and the 10 countries with the largest absolute mean difference for MMR. For countries in either top 10 list, we compared the type of empirical maternal mortality data available, categorizing the data as CRVS-based total maternal deaths (from the WHO mortality database), survey-based pregnancy mortality ratio (from DHS data), survey-based MMR (from DHS data), or CRVS-based MMR. We also compared which countries were included in the top 10 countries globally by burden (i.e., MMR and maternal deaths) using the mean estimates from each model.

Role of the funding source
The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. All authors had access to the data in the study and had final responsibility for the decision to submit for publication. Ethical approval was not required for this modelling study based on publicly available data.

GMatH comparison	Maternal deaths		MMR	
	UN (v2023)	GBD (v2021)	UN (v2023)	GBD (v2021)
Difference				
Mean	272	728	22.3	48.1
Min	−33,519	−1814	−545.5	−238.5
25th percentile	5	7	−9.4	−3.3
Median	36	38	16.7	20.1
75th percentile	179	260	43.0	64.3
Max	24,748	27,402	655.6	960.1
Relative difference				
Mean	43%	49%	19%	22%
Min	−265%	−93%	−431%	−389%
25th percentile	19%	28%	−6%	−6%
Median	51%	54%	25%	37%
75th percentile	82%	83%	70%	71%
Max	98%	97%	97%	96%
Absolute difference				
Mean	771	778	60.2	68.6
Min	0	0	0.3	0.1
25th percentile	16	13	14.5	15.6
Median	65	56	32.3	30.9
75th percentile	281	295	66.0	76.5
Max	33,519	27,402	655.6	960.1
Correlation/Convergence				
Correlation	0.866	0.901	0.879	0.828
Convergent %	76.8%	71.6%	88.1%	85.8%

GMatH = Global Maternal Health model, UN = United Nations, GBD = Global Burden of Disease. Difference = GMatH—other model; Relative difference = (GMatH-other model)/GMatH; Absolute difference = absolute value (GMatH—other model).

Table 1: **Summary of model comparisons (estimates for 2020).**

Results

Globally, the GMatH (v2023) model estimated there were 337,585 (95% UI 307,944–364,094) maternal deaths in 2020, compared with 301,216 (80% UI 272,718–343,429) estimated by the UN (v2023) and 194,251 (95% UI 164,813–229,211) estimated by the GBD (v2021). On average, the GMatH estimates of country-level maternal deaths in 2020 were 272 larger (43% higher) than the UN estimates, and 728 larger (49% higher) compared to GBD estimates (see Table 1). Absolute differences in maternal deaths ranged from 0 to 33,519 (mean of 771) for GMatH vs. UN, and ranged from 0 to 27,402 (mean of 778) for GMatH vs. GBD. Estimates of country-level maternal deaths were highly correlated across models (0.866 for GMatH vs. UN, 0.901 for GMatH vs. GBD), and 76.8% of the UN estimates and 71.6% of the GBD estimates of maternal deaths were convergent (i.e., within the GMatH 95% UIs) with the GMatH model (see Fig. 1).

The GMatH (v2023) model estimated a global MMR of 194 (95% UI 174–210) in 2020, compared with 224 (80% UI 202–255) estimated by the UN (v2023) and 148 (95% UI 126–174) estimated by the GBD (v2021). Estimates of country-level MMR from the GMatH model were on average 22.3 higher (19% higher) than UN estimates (mean absolute difference of 60.2), and 48.1 higher (22% higher) than GBD estimates (mean absolute difference of 68.6) (see Table 1). Estimates of country-level MMR were highly correlated for UN vs. GMatH models (0.879) and for GBD vs. GMatH (0.828). Overall, 88.1% of the UN country-level MMR estimates were convergent with the GMatH model, and 85.8% of the GBD MMR estimates were convergent (see Fig. 1).

Estimates of TFR were similar across all models (correlations of 0.946 for UN vs. GMatH, and 0.913 for GBD vs. GMath, see Appendix 2.1), while causes of maternal death varied substantially across the GMatH and GBD estimates (see Fig. 2, Appendix 2.2). Although estimates of maternal deaths from abortive causes, hypertensive disorders, and hemorrhage were similar, other causes of death were much lower in the GBD estimates.

The 10 countries with the largest discrepancies in estimated maternal deaths are shown in Fig. 3A, with

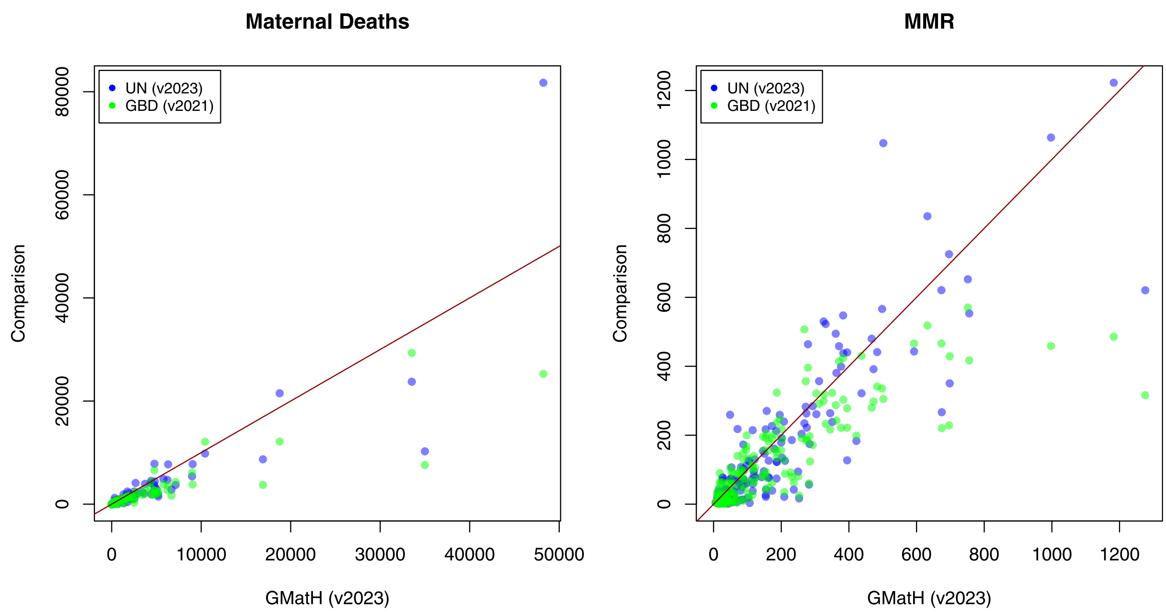

Fig. 1: Country-specific estimated means by model, 2020. Points indicate mean estimates from the UN (v2023) and GBD (v2021) models (y-axis) compared to the GMatH (v2023) estimates (x-axis). The red diagonal line indicates the GMatH predictions along the y-axis.

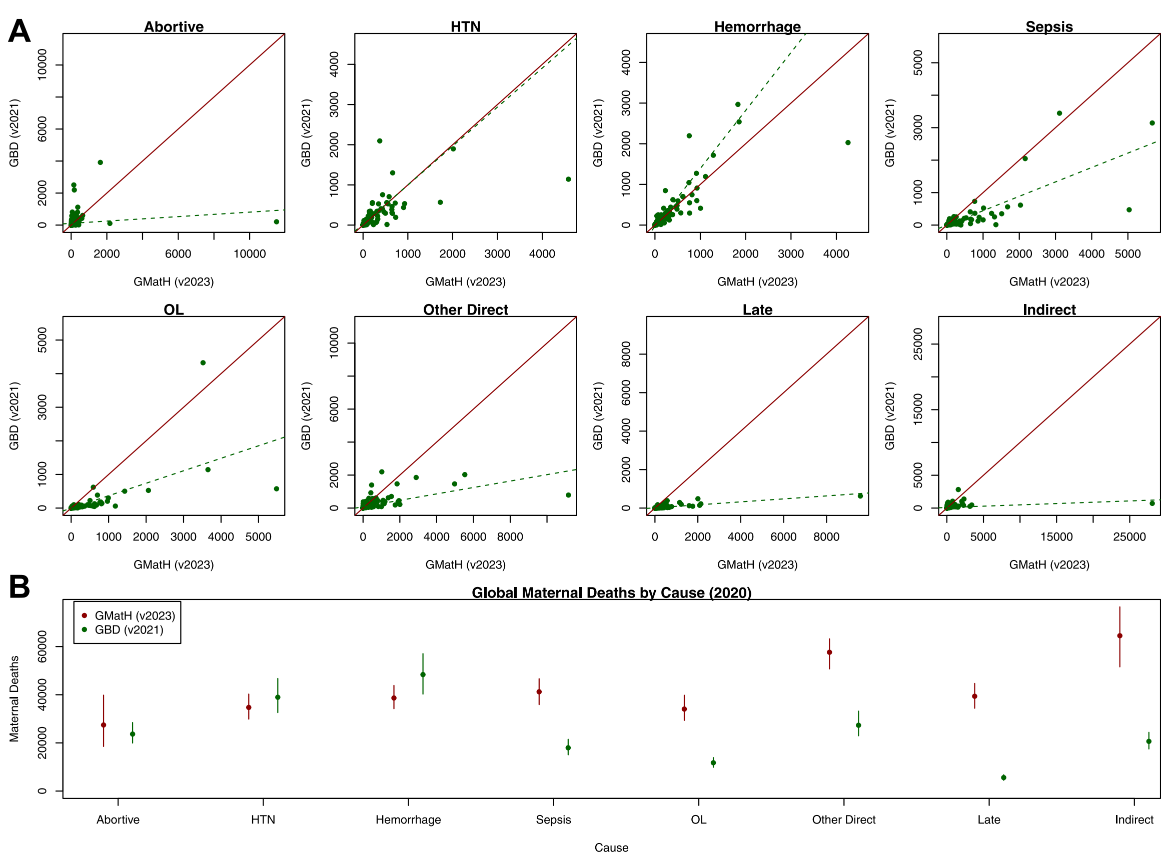

Fig. 2: Country-specific A) and global B) estimated maternal deaths by cause in 2020, GMatH (v2023) vs. GBD (v2021). Points indicate mean estimates from the GBD (v2021) model (y-axis) compared to the GMatH (v2023) estimates (x-axis). The red diagonal line indicates the GMatH predictions along the y-axis. The green dotted line indicates the (linear) line of best fit of the GBD vs. GMatH country-level estimates.

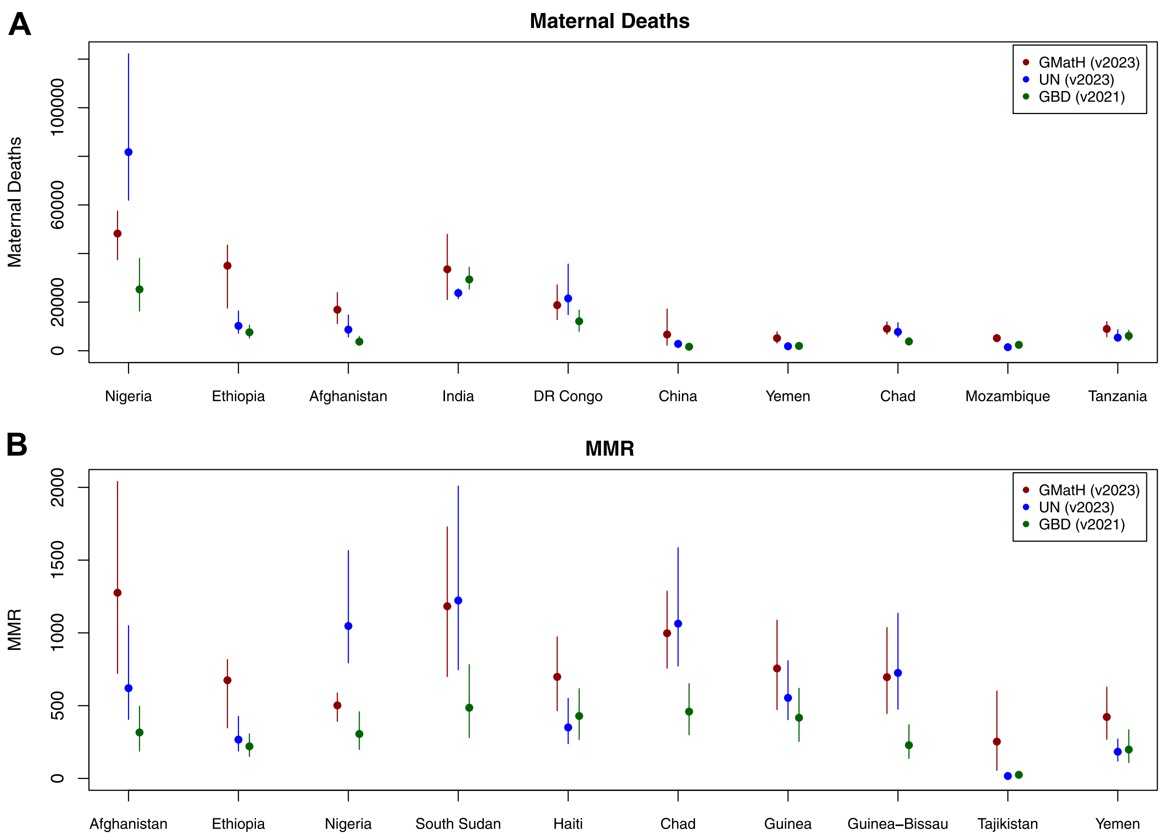

Fig. 3: Top 10 countries by mean absolute difference for A) Maternal Deaths and B) MMR. Vertical lines indicate 95% UIs for GMatH and GBD estimates, and 80% UIs for UN estimates.

large differences across all three models for Nigeria, ranging from below 30,000 in the GBD model to over 80,000 in the UN model, with the GMatH model estimates falling in the middle. The 10 countries with the largest differences in estimated MMR are shown in Fig. 3B, with large differences across all 3 models for Afghanistan and Nigeria, and the GBD estimates of MMR generally lower than the other models.

Table 2 lists countries that were in either of the top 10 largest differences for maternal deaths or MMR (n = 15), and characterizes which model estimates are convergent with the GMatH model. Among these countries, 6 of the UN estimates of maternal deaths are convergent with the GMatH model, compared to only 2 of the GBD estimates. For MMR, 7 country UN estimates are convergent with the GMatH model, compared to 3 GBD estimates.

Among countries with the largest differences in estimated maternal deaths or MMR, we find that the majority (10/15) have empirical data available from DHS surveys for the pregnancy mortality ratio (Table 2). Particularly for countries that are divergent across all models (e.g., Afghanistan, Ethiopia, Haiti, Mozambique, Nigeria, Yemen), survey-based pregnancy mortality

Country	Maternal deaths convergence		MMR convergence		Empirical mortality data
	UN (v2023)	GBD (v2021)	UN (v2023)	GBD (v2021)	
Afghanistan					Pregnancy Mortality Ratio (Survey)
Chad	X		X		Pregnancy Mortality Ratio (Survey)
China	X		X	X	Maternal Mortality Ratio (CRVS)
DR Congo	X		X	X	Pregnancy Mortality Ratio (Survey)
Ethiopia					Pregnancy Mortality Ratio (Survey)
Guinea			X		Pregnancy Mortality Ratio (Survey)
Guinea-Bissau	X		X		Maternal Mortality Ratio (Survey)
Haiti					Pregnancy Mortality Ratio (Survey)
India	X	X	X		Maternal Mortality Ratio (Survey)
Mozambique					Pregnancy Mortality Ratio (Survey)
Nigeria					Pregnancy Mortality Ratio (Survey)
South Sudan	X		X		Maternal Mortality Ratio (Survey)
Tajikistan					Maternal deaths (CRVS)
Tanzania		X		X	Pregnancy Mortality Ratio (Survey)
Yemen					Pregnancy Mortality Ratio (Survey)

Convergence is defined as the GMatH (v2023) 95% UI containing the point estimate from the UN or GBD model.

***Table 2:* Country comparison among top 10 differences for either maternal deaths or MMR.**

ratios are the only empirical data available. In contrast, for countries in this list with convergent estimates (e.g., China, Guinea-Bissau, India, South Sudan), empirical data on estimated MMR are available (See Appendix 2.5 for country comparisons of multiple indicators across models).

Comparing the top 10 countries with the highest burden of maternal mortality (measured by MMR or absolute number of maternal deaths) across models reveals notable differences (see Appendix 2,.3 and 2.4). Some countries (Nigeria, Ethiopia, India, DR Congo, Pakistan, and Tanzania) consistently appear among the highest number of maternal deaths, although the exact rankings and burden vary across models. In contrast, the top 10 countries by MMR show less consistency across models, with only a few (South Sudan, Chad, Liberia, Somalia, and Central African Republic) appearing across all three models.

Discussion

We developed the GMatH model to perform policy analyses of various strategies across the reproductive lifecourse. In addition to comparing the effectiveness of potential strategies, our structural microsimulation model offers a fundamentally different modelling approach to estimating maternal mortality that can be compared to aggregate statistical models used by the UN and GBD.

We find that our mean country-level estimates of maternal deaths and MMR are slightly higher than the UN estimates on average, and substantially higher than the GBD estimates, which is similar to our previous comparison of global (total) maternal deaths and MMR across models.[3] Overall, estimates of maternal deaths and MMR are convergent across models for most countries, but there are differences in the top 10 countries by MMR and maternal deaths, and large differences for some country-specific estimates, such as Nigeria, Ethiopia, Afghanistan, and South Sudan. Estimates of TFR are similar across all models, suggesting that potential differences in fertility estimates do not drive the differences in maternal mortality estimates.

In contrast, estimates of maternal death by cause vary substantially across the GMatH and GBD models, except for deaths from abortive causes, hypertensive disorders, and hemorrhage. Globally, the GMatH model estimates higher maternal deaths from sepsis, obstructed labour, other direct, indirect causes, and late maternal deaths. Women who experience these complications may be more likely to face delays in obstetric care, with resulting maternal deaths less likely to be accurately captured in traditional data sources, highlighting the importance of adjusting for underreporting by location of death (e.g., home vs. facility) in the GMatH model.

Maternal mortality estimates are critical indicators for priority-setting and assessing progress towards achieving universal health coverage and health-related SDG targets, especially for countries with large burdens. We find that countries with large differences across models generally only have empirical survey-based estimates of the pregnancy mortality ratio, which differs from the maternal mortality ratio in that it includes all causes of death. The prevalence of this particular indicator among countries with divergent estimates, and lack of other indicators such as the MMR, highlights an important feature of our structural modelling approach in that we calibrated the model to empirical data on a range of fertility, process, and mortality indicators. The causal relationships specified in our model also allow for realistic counterfactual simulations to be performed for policy analyses.[11]

Because we model the entire reproductive life course of individual women, we can integrate various data from multiple sources into the model. We also account for uncertainty around all model parameters across the reproductive life course, including accounting for uncertainty around underreporting of maternal deaths, which are reflected in our uncertainty intervals. This approach provides the potential for more robust estimates of maternal health outcomes as we can incorporate data for multiple indicators along the reproductive life course that are generally more accurately observed than maternal mortality outcomes. For example, we calibrated the model to empirical estimates for a variety of maternal mortality indicators, including the pregnancy mortality ratio, number of maternal deaths, and maternal mortality ratio, among others.

However, these types of data are not easily integrated into statistical regression models which only use a narrow set of data as outcome variables. For example, the UN and GBD models are fit to a limited set of outcomes, often the single outcome variable of proportion of deaths among women of reproductive age due to maternal causes (PM). Other types of data (e.g., MMR, pregnancy-related mortality) must first be converted (via a series of assumptions and calculations) to the PM, which introduces additional assumptions (and potential errors) outside of the modelling framework, and which may explain differences in model estimates for countries with only pregnancy-related mortality estimates. In contrast, structural models such as the GMatH model can directly incorporate various types of indicators (without pre-processing assumptions/transformations) when calibrating to empirical data.

Although the GMatH model is a flexible, comprehensive framework for maternal health and can incorporate various types of data from multiple sources, every model has its own assumptions and limitations. For example, although we model cause-specific maternal deaths, we do not disaggregate indirect maternal deaths by underlying cause (e.g., HIV vs. malaria), which limits the model's ability to evaluate interventions to address specific causes of indirect maternal deaths. Further model developments would be needed to incorporate country-specific disease prevalence of contributing factors (e.g., HIV and malaria) to refine these estimates. The GMatH model could also be extended to estimate maternal morbidity outcomes within the same modelling framework. Statistical models, such as the regression-based models used by the UN and GBD to estimate maternal mortality also have their own set of assumptions, which are generally less flexible than simulation-based approaches. Comparing across models can help to explore the impact of various assumptions and limitations on global and country-specific estimates.

Maternal mortality remains a large challenge in global health, and the use of different types of modelling (e.g., estimation and counterfactual policy analysis) can help to guide policy efforts in this area.[14] Rigorous estimates based on robust empirical data will be needed regarding the impact, cost-effectiveness, and feasibility of potential interventions, and how these may vary by setting. Although estimates of maternal mortality have improved over time, further efforts are needed to strengthen data systems to provide robust empirical data that can be used for various types of modelling. In particular, the different assumptions used to convert estimates of pregnancy-related mortality to PM for use in regression models may explain the differences in model estimates for high burden countries. This has implications for the design of future data collection efforts (e.g., choice of indicators), modelling approaches (e.g., pre-processing assumptions), and interpretation of estimates (e.g., comparison of results across models for divergent countries).

Although more computationally intensive, by leveraging multiple types of data in an internally consistent framework, our structural microsimulation model provides a framework for policy analysis and offers a robust approach to estimation that could also be applied to other areas in global health.[14] Continued comparisons across modelling approaches can help to refine estimates and identify the highest priorities areas where better data are needed to inform resource allocation, policy, and practice to accelerate reductions in maternal deaths.

Contributors
ZJW acquired the data, performed the analyses, and developed the model based on a conceptual framework developed by SJG. ZJW and SJG accessed and verified the data. All authors designed the study, interpreted the results, and contributed to the writing of the report. All authors had access to the data and the final responsibility to submit for publication.

Data sharing statement
GMatH model results (means and 95% UIs) are available in a public data repository: https://doi.org/10.7910/DVN/UBGY9P. UN model results are available at: https://www.who.int/publications/i/item/9789240068759. GBD model results are available at: https://vizhub.healthdata.org/gbd-results/.

Declaration of interests
We declare no competing interests.

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Appendix A. Supplementary data
Supplementary data related to this article can be found at https://doi.org/10.1016/j.eclinm.2025.103505.

References
1 EPMM Working Group. *Strategies toward ending preventable maternal mortality (EPMM)*. Geneva: World Health Organization; 2015.
2 United Nations. *Trends in maternal mortality 2000 to 2020: estimates by WHO, UNICEF, UNFPA, World Bank Group and UNDESA/Population Division*. Geneva: World Health Organization; 2023. Available from: https://www.who.int/publications/i/item/9789240068759.
3 Ward ZJ, Atun R, King G, Sequeira Dmello B, Goldie SJ. Simulation-based estimates and projections of global, regional and country-level maternal mortality by cause, 1990-2050. *Nat Med*. 2023;29(5):1253–1261.
4 Graham W. Now or never: the case for measuring maternal mortality. *Lancet*. 2002;359:701–704.
5 Main EK. Maternal mortality: new strategies for measurement and prevention. *Curr Opin Obstet Gynecol*. 2010;22:511–516.
6 Alkema L, Chou D, Hogan D, et al. Global, regional, and national levels and trends in maternal mortality between 1990 and 2015, with scenario-based projections to 2030: a systematic analysis by the UN maternal Mortality Estimation Inter-Agency Group. *Lancet*. 2016;387:462–474.
7 WHO, UNICEF, UNFPA, World Bank Group, United Nations Population Division. *Trends in maternal mortality 2000 to 2017*; 2019. https://www.who.int/reproductivehealth/publications/maternal-mortality-2000-2017/en/.
8 Kassebaum NJ, Bertozzi-Villa A, Coggeshall MS, et al. Global, regional, and national levels and causes of maternal mortality during 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. *Lancet*. 2014;384:980–1004.
9 GBD 2015 Maternal Mortality Collaborators. Global, regional, and national levels of maternal mortality, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet*. 2016;388:1775–1812.
10 Abouzahr C. New estimates of maternal mortality and how to interpret them: choice or confusion? *Reprod Health Matters*. 2011;19(37):117–128.
11 Ward ZJ, Atun R, King G, Sequeira Dmello B, Goldie SJ. A simulation-based comparative effectiveness analysis of policies to improve global maternal health outcomes. *Nat Med*. 2023;29(5):1262–1272.
12 Murray CJ, Ezzati M, Lopez AD, Rodgers A, Vander Hoorn S. Comparative quantification of health risks conceptual framework and methodological issues. *Popul Health Metr*. 2003;1:1.
13 Arnold KF, Harrison WJ, Heppenstall AJ, Gilthorpe MS. DAG-informed regression modelling, agent-based modelling and microsimulation modelling: a critical comparison of methods for causal inference. *Int J Epidemiol*. 2019;48:243–253.
14 Ward ZJ, Goldie SJ. Global Burden of Disease Study 2021 estimates: implications for health policy and research. *Lancet*. 2024;403(10440):1958–1959.
15 Ward ZJ, Atun R, King G, Dmello BS, Goldie SJ. Global maternal mortality projections by urban/rural location and education level: a simulation-based analysis. *eClinicalMedicine*. 2024;72:102653.
16 Ward ZJ, Atun R, King G, Sequeira DMello B, Goldie SJ. Global maternal health country typologies: a framework to guide policy. *PLoS Glob Public Health*. 2024;4(11):e0003867.
17 Goldie SJ, Sweet S, Carvalho N, Natchu UC, Hu D. Alternative strategies to reduce maternal mortality in India: a cost-effectiveness analysis. *PLoS Med*. 2010;7:e1000264.

18 ICF. Demographic and health surveys (various) [datasets]. Rockville, Maryland: ICF [Distributor]. Funded by USAID. Available from: https://dhsprogram.com/.
19 Wilmoth JR, Mizoguchi N, Oestergaard MZ, et al. A new method for deriving global estimates of maternal mortality. *Stat Politics Policy*. 2012;3(2).
20 Alkema L, Zhang S, Chou D, et al. A Bayesian approach to the global estimation of maternal mortality. *Ann Appl Stat*. 2017;11(3):1245–1274.
21 Peterson E, Chou D, Moller AB, Gemmill A, Say L, Alkema L. Estimating misclassification errors in the reporting of maternal mortality in national civil registration vital statistics systems: a Bayesian hierarchical bivariate random walk model to estimate sensitivity and specificity for multiple countries and years with missing data. *Stat Med*. 2022;41(14):2483–2496.
22 Global Burden of Disease Collaborative Network. *Global Burden of Disease study 2021 (GBD 2021) results*. Seattle, United States: Institute for Health Metrics and Evaluation (IHME); 2022. Available from: https://vizhub.healthdata.org/gbd-results/.
23 GBD 2021 Causes of Death Collaborators. Global burden of 288 causes of death and life expectancy decomposition in 204 countries and territories and 811 subnational locations, 1990-2021: a systematic analysis for the Global Burden of Disease study 2021. *Lancet*. 2024;403(10440):2100–2132.
24 World Health Organization. The global health observatory: maternal deaths - indicator metadata registry list. Available at: https://www.who.int/data/gho/indicator-metadata-registry/imr-details/4622.
25 Saifuddin A, Li Q, Scrafford C, Pullum TW. An assessment of DHS maternal mortality data and estimates. In: *DHS methodological reports no. 13*. Rockville, Maryland, USA: ICF International; 2014. Available at: https://dhsprogram.com/pubs/pdf/MR13/MR13.pdf.
26 Centers for Disease Control and Prevention. *Pregnancy mortality surveillance system*; 2024. Available at: https://www.cdc.gov/maternal-mortality/php/pregnancy-mortality-surveillance/index.html.
27 Mgawadere F, Kana T, van den Broek N. Measuring maternal mortality: a systematic review of methods used to obtain estimates of the maternal mortality ratio (MMR) in low- and middle-income countries. *Br Med Bull*. 2017;122(1):121–134.
28 United Nations, Department of Economic and Social Affairs, Population Division. *World population prospects 2022*. 2022 [Online Edition].
29 GBD 2021 Fertility and Forecasting Collaborators. Global fertility in 204 countries and territories, 1950-2021, with forecasts to 2100: a comprehensive demographic analysis for the Global Burden of Disease study 2021. *Lancet*. 2024;403(10440):2057–2099.