



The US COVID-19 and Influenza Scenario Modeling Hubs: Delivering long-term projections to guide policy[☆]

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ABSTRACT

Between December 2020 and April 2023, the COVID-19 Scenario Modeling Hub (SMH) generated operational multi-month projections of COVID-19 burden in the US to guide pandemic planning and decision-making in the context of high uncertainty. This effort was born out of an attempt to coordinate, synthesize and effectively use the unprecedented amount of predictive modeling that emerged throughout the COVID-19 pandemic. Here we describe the history of this massive collective research effort, the process of convening and maintaining an open modeling hub active over multiple years, and attempt to provide a blueprint for future efforts. We detail the process of generating 17 rounds of scenarios and projections at different stages of the COVID-19 pandemic, and disseminating results to the public health community and lay public. We also highlight how SMH was expanded to generate influenza projections during the 2022–23 season. We identify key impacts of SMH results on public health and draw lessons to improve future collaborative modeling efforts, research on scenario projections, and the interface between models and policy.

1. Scenario Modeling Hub prehistory

A diversity of prospective modeling efforts emerged in the first months of the COVID-19 pandemic to increase situational awareness and guide mitigation efforts. Periodic calls were organized as early as January 2020 by various public health agencies to increase information sharing among modelers, avoid redundancies, and gain a more comprehensive overview of emerging guidance (U.S. Centers for Disease Control and Prevention (CDC), United Kingdom Scientific Pandemic

Influenza Group on Modelling, World Health Organisation (WHO)). Modeling teams that had contributed to the modeling response to multiple prior outbreaks worked alongside new groups that often came from different disciplines, fostering a diversity of methodological approaches throughout the early dissemination phase and establishment of COVID-19. Nevertheless, many modeling teams addressed different interventions and assumptions, making it difficult to compare and synthesize projections across models during the first wave of the pandemic. This lack of coordination meant that important policy decisions

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regarding lockdown interventions had to be made without collective modeling evidence.

Eventually, COVID-19 modeling hubs were established to support the pandemic response, building on a growing body of evidence demonstrating the synergistic benefits of collating and aggregating outputs from different models (Reich et al., 2022). The US COVID-19 Forecast Hub (Cramer et al., 2022a) was launched in April 2020 to generate 1–4 week ahead forecasts of incident cases and deaths in each state and nationally and later expanded to include hospitalizations. Through April 2023, over 120 teams had contributed real-time forecasts over 160 weeks (Cramer et al., 2022a). In May 2020, the Multiple Models for Outbreak Decision Support (MMODS) study was launched to demonstrate the feasibility of generating 6-month ahead projections of COVID-19 for decision making (Shea et al., 2023). The results combined outputs from 17 models and projected the effects of several different re-opening strategies on disease burden in the post-lockdown period. Results of this proof-of-concept study were released in fall 2020 (Shea et al., 2020). These efforts provided important data to guide the pandemic response, and demonstrated the utility and potential impact of multi-model efforts during public health emergencies. While COVID-19 forecasts were useful for situational awareness and short-term decisions, MMODS demonstrated the robustness of long-term ensemble projections to provide insight into interventions (Shea et al., 2020).

2. Establishment of the COVID-19 Scenario Modeling Hub (SMH)

In late fall 2020 the landscape of the COVID-19 response radically changed with the pending release of new vaccines. Uncertainty regarding the availability and effectiveness of these vaccines, and the continuing need for non-pharmaceutical interventions (e.g., social distancing, mask mandates) heightened the need for decision-focused approaches and planning scenarios to complement existing short-term forecasts. The COVID-19 Scenario Modeling Hub (SMH, also referred to as the Hub) was launched in December 2020 to generate real-time, rigorous, and responsive long-term projections of COVID-19 and provide coordinated modeling evidence to guide decisions in the constantly evolving pandemic. To allow for comparison and aggregation of model outputs, independent modeling teams were tasked to work on the same set of key questions addressing disease burden over long-term horizons (6 months initially). To grapple with the substantial uncertainty in infectious disease trajectories over such horizons, projections were based on well-defined “what-if” scenarios focused on specific epidemiological, behavioral, and intervention conditions – a major difference from the structure of forecasts. National and state-level epidemic trajectories for cases, deaths, and hospitalizations were the focus of SMH projections.

Here, we aim to provide a detailed description of the context within which SMH operates, its partnerships and impacts, and importantly, its process, so as to provide a blueprint for future multi-model infectious disease efforts and their interactions with public health agencies.

3. Foundational principles of SMH

SMH was established under a set of foundational principles: employing an open-door policy to solicit projections from multiple modeling teams, aggregating individual model outputs to an ensemble, adopting concepts from expert judgment to manage interactions between hub collaborators, and maintaining a decision-focused objective with close partnership with public health stakeholders. In the following sections, we discuss how these principles have contributed to the operations and success of the SMH effort.

4. SMH collaborators

4.1. Open-door policy

SMH operates with an open-door policy, accepting any projections

that comply with SMH guidelines regarding scenario specification and projection format. This policy derives from the experience of prior infectious disease hubs (Cramer et al., 2022a; “FluSight,” 2023; Reich et al., 2022; Shea et al., 2020, 2023; Viboud et al., 2018) and from best practices from group decision making (Burgman, 2015). Teams are recruited through existing networks within the infectious disease dynamics and forecasting communities, and via word-of-mouth. To boost participation in SMH, the effort was advertised on various modeling channels and calls, especially at the onset of the collaboration and for each new round. With an open-door policy since its launch in December 2020, SMH grew from 5 participating modeling teams in 2020 to 17 in late 2022 as the scope of the work expanded to influenza and led to an influx of new teams. Between 4 and 12 teams participated in each round of disease-specific projections. SMH contributors have come from diverse backgrounds, most notably epidemiology, computer sciences, applied physics, network sciences, and expert judgment, and they represent a range of career stages and institutions (including academia, the government, and occasionally the private sector). The diversity of expertise represented in SMH has been invaluable for promoting cross-fertilization and new collaborations. Participation over rounds and a summary of model details is provided in Figure S1 and Table S1.

4.2. Public health partners

SMH has established a strong identity at the interface between public health, policy, and science. In particular, it has established a close connection with federal health authorities, most notably the CDC. These partnerships were initially engaged mainly through existing relationships within stakeholder groups, and have helped identify public health questions that should be addressed by the Hub (Biggerstaff et al., 2022; Borchering et al., 2023, 2021). CDC colleagues have also helped translate modeling outputs for a public health audience within the federal government (to other CDC or White House colleagues), and regularly participated in SMH activities, including scenario design and discussion of modeling outputs. Additional connections between SMH and public health stakeholders have expanded and strengthened over time (we return to this important point later).

4.3. Coordination group

In addition to the modeling teams contributing projections and public health partners, a coordination team of 8–15 researchers across 7 institutions manages the day-to-day life and scientific leadership of SMH. The SMH coordination team is responsible for guiding the larger group and creating a supportive and collaborative atmosphere where participation is encouraged. This is particularly important for the success of the Hub, so that all collaborators contribute to multiple aspects of the Hub process, including informing scenario design, generating projections, and disseminating useful and actionable results that impact policy, as detailed below.

5. Operating as a Hub (internal communication)

5.1. Weekly process

Frequent interactions between the SMH collaborators have been essential to facilitate the 5 main steps of the Hub operations: scenario development, generation of individual model projections for these scenarios, aggregation of model outputs into an ensemble, interpretation and limited release of results to stakeholders, and dissemination of projections and findings to the broader scientific community and the public (see Fig. 1 for a schematic of the day-to-day life of the hub).

The main interactions between SMH collaborators are via weekly hour-long hub-wide calls, which serve a variety of purposes, described in turn below. Firstly, a major part of these calls is dedicated to discussions about scenario design, a complex and iterative endeavor. SMH scenarios



Fig. 1. Flowchart of SMH round process, from scenario development through to result dissemination. The SMH process is an iterative process where rounds typically start at scenario development, moving to teams producing projections in the modeling step, submission of results, a period of integration and interpretation, before results are disseminated to stakeholders.

are structured on two axes, where typically one axis reflects uncertainty in the disease process (e.g., variant characteristics, duration of immunity), and the other axis represents an intervention (e.g., non-

pharmaceutical interventions, expansion of the vaccine program to a new age group, different levels of vaccine coverage) (see Fig. 2, and a separate paper on scenario design as part of this Special Issue (SI) (Runge et al., 2023)). At times, both axes have represented uncertainty (e.g., during the emergence of the Omicron variant), allowing a better representation of possible trajectories for situational awareness and horizon scanning. Weekly calls are used to design and agree on scenario axes and values, and then, once scenarios have been finalized, to clarify assumptions prior to the projection due-date. This process can take between 1 and 3 weeks and involves feedback between the coordination group, participating teams, and public health stakeholders (Figure S2).

Once scenarios have been finalized and projections have been produced by the teams, these hub-wide calls are used to review results from contributing models and the aggregate projections, and to identify key messages to include in reports delivered to interested parties after each round. These calls are also used to review website features and discuss broader scientific issues related to pathogen biology, human response to interventions, methodological development, and the observational process.

A designated facilitator leads the hub-wide calls to encourage sharing of insights and information; to avoid groupthink or the dominance of a small number of voices; and to reduce linguistic uncertainty in the scenario design and implementation. To achieve these purposes, the facilitators rely on methods from the fields of expert judgment and group decision-making. Notably, the process of generating SMH projections aligns with a 3-step modified Delphi approach with feedback loop (Dalkey and Helmer, 1963; Hanea et al., 2017), whereby a first round of teams' projections is followed by group discussion and a chance to modify projections, if warranted. The individual control in the first and last steps preserves autonomy of thought, guarding against groupthink, while the intervening discussion phase encourages exchange of insights and information, ensures consistent interpretation of scenarios

See detailed notes on each scenario below	No new variant: • No new variant • Protection from natural immunity and VE against infection decrease over time due to waning, but not due to variant mix • Risk of severe disease conditional on infection remains unchanged	High immune escape variant X: • 50 infections with new variant X seeded weekly from Sep 4th-Dec 24th (16 weeks) • 40% immune escape against infection (applies to VE and to protection from natural immunity) • There is a 20% increased risk of hospitalization and death with variant X, relative to Omicron, conditional on infection and immune status.
Reformulated vaccines available Sep-11, 2022 for all adults • Coverage of boosters progresses throughout fall 2022 in different age groups at a 10% reduced coverage (x0.9) compared to historical seasonal flu vaccination; whether individuals get a 2nd or 3rd booster is at teams discretion. • Boosters are recommended regardless of time since previous receipt of a booster.	Scenario A	Scenario B
Reformulated vaccines available Nov-13, 2022 for all adults • Coverage of boosters progresses throughout fall 2022 in different age groups at a 10% reduced coverage (x0.9) compared to historical seasonal flu vaccination; whether individuals get a 2nd or 3rd booster is at teams discretion. • Boosters are recommended regardless of time since previous receipt of a booster.	Scenario C	Scenario D

Fig. 2. An example of typical scenario structure from COVID Round 16. Scenarios are typically chosen based on a 2 × 2 structure. For more details on scenario design see a companion paper (Runge et al., 2023).

and resolution of linguistic uncertainty (Shea et al., 2020), and allows teams to improve their projections. Teams often share sources of relevant data and ideas, as well as resolve any potential difficulties in implementing scenarios. Because of the multiple-round structure of the SMH, there is also ample opportunity to share insights between rounds, during the scenario design process, and during interpretation and dissemination of results. The facilitators actively encourage broad

participation, drawing out the quieter voices and watching for dominant voices.

In addition to the weekly hub-wide calls, smaller meetings of the coordination group occur twice weekly, first to prepare for the hub-wide calls and then to debrief after these main calls. Typical agendas include drafting scenario specifications, reviewing technical details of the SMH methodologies, website and GitHub repository (Scenario Modeling Hub,

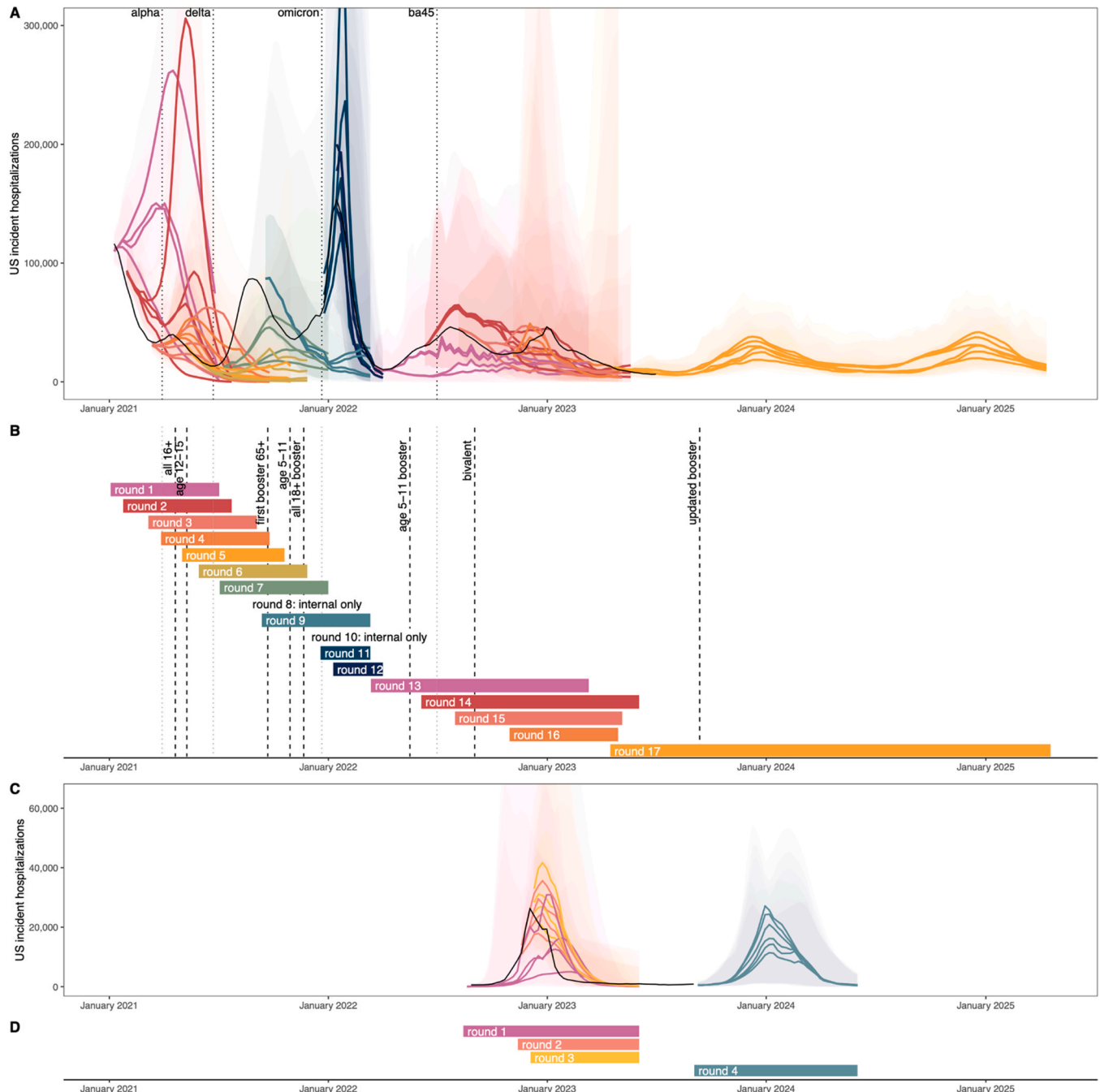


Fig. 3. Projections from the Scenario Modeling Hub over the course of the COVID-19 pandemic and the 2022–23 influenza season. (A) COVID-19 SMH ensemble projections for all four scenarios for each round (given in separate colors). The median line is shown in bold, as well as the corresponding 95 % prediction intervals (colored ribbon). Rounds 1–4 show the Vincent average ensemble, rounds 5–12 and 17 show the trimmed LOP, and 13–16 show the untrimmed LOP; these were the aggregation methods at the time of release of results. Observed weekly incident hospitalizations for the US are also shown (solid black line), as well as the timing of the emergence of new variants (dotted lines). (B) The projection period for each round (start and end date of each bar). Also shown are the timepoints vaccination was rolled out for different age groups, and vaccine formulations (dashed lines). (C) Flu SMH ensemble projections for all four scenarios for each round (given in separate colors), with median line shown in bold, and corresponding 95 % prediction intervals as in panel A. Observed weekly incident hospitalizations in the US are also shown (solid black line). Rounds 1 and 4 show the untrimmed LOP, and rounds 2 and 3 the trimmed LOP (method of choice at time of release of results). (D) The projection period for each round of Flu SMH (start and end date of each bar).

2023a; “Scenario Modeling Hub, 2023b), and discussing coordination with public health agencies, media, and international partners (e.g., European Covid-19, 2023, WHO).

Finally, to facilitate communication within the coordination group, and between the coordination group and participating teams, an active Slack workspace has been in place since early 2021. These frequent virtual interactions have been immensely valuable to the day-to-day life of SMH. Through more than 50,000 messages, Slack has enabled rapid coordination, result sharing, brainstorming, and scientific development. Overall, a high level of internal communication has been particularly important to enable a smooth process and ensure high quality projections are produced (see MMODS process model described in Shea et al., 2023), but perhaps most importantly to foster a collaborative spirit among teams.

5.2. In-person workshop to allow scientific thinking and nascent research ideas to flourish

A 3-day in-person workshop was held in September 2022 (21 months after SMH launch) to take stock of the Hub’s accomplishments and to plan future activities. The meeting convened 61 participants (47 in person and 14 online). This opportunity for face-to-face interactions strengthened the collaborative spirit of SMH, as many participants had been contributing projections for over a year without ever meeting in person. Workshop participants were particularly appreciative of the opportunity to discuss research, as operational aspects had dominated many of the Hub interactions since its inception.

Several useful outputs of the workshop are worth noting. The first is the creation of four working subgroups that meet regularly to discuss various research topics including methodologies for evaluation and aggregation of projections, modeling of the early stages of a pandemic, addressing health inequities, and optimization of scenario design. During the workshop, it was also decided to convene the present special issue of the journal *Epidemics* to review various aspects of SMH and its components, and provide a template for the modeling response for future pandemics. Another notable output includes a ‘peer-review’ session of each SMH model. The overall goal of this endeavor was for participants to obtain a deeper understanding of the component models and their performance, make suggestions in a constructive manner where relevant, and in turn improve the ensemble projections and the group. Details of the process are outlined in the GitHub.

6. Hub outputs

6.1. Projections generated

Facilitated by weekly interactions and a structured operating process, SMH collaborators generated 17 rounds of COVID-19 projections between December 2020 and September 2023, spanning multiple stages of the pandemic, variant circulation, and types of interventions (Fig. 3). Fourteen rounds were released publicly; one was a training round, and another one became obsolete before release due to the emergence of the Omicron variant. New rounds of projections were generated with an average cadence of 2–3 months, with a 5 week turn-around on average from scenario design to public release of projections (Figure S2). In the case of emergencies, SMH projections were released on a compressed timescale. For instance, to address the threat of the Omicron variant, a first set of projections were published on Dec 31, 2021, and these projections were revised 11 days later with updated scenarios (Rounds 11 and 12, respectively). In August 2022, the scope of the Hub was expanded to include influenza, with 3 rounds of projections delivered between September 2022 and January 2023, and a new round prior to the start of the 2023–2024 season. Overall, as of September 2023, the SMH has released 60,000 national and state-level ensemble projections, with 12 independent COVID-19 models and 13 influenza models contributing projections independently and as part of the ensemble.

6.2. Target data and generation of probabilistic distributions

In each COVID-19 round, teams are asked to generate projections for several weekly targets of epidemiological relevance, including cases, hospitalizations and deaths. These targets were generally based on data from the Johns Hopkins Center for Systems Science and Engineering (CSSE) effort (cases and deaths) (Dong et al., 2020) and U.S. Department of Health and Human Services (HHS) Protect (hospitalizations) (HHS Protect, 2023), though we have had to evolve with changes in data availability and reliability. As of March 2023, the CSSE effort was discontinued, so that case and death data became unavailable. As a result, all case targets were dropped in COVID-19 Round 17, and an alternative source of COVID-19 death data was sought (National Center for Health Statistics, 2023; FluView, 2023). The switch in surveillance practice from facility-based testing to unreported at-home rapid tests in early 2022 had already made the COVID-19 case data a less reliable metric in later rounds.

As SMH expanded to form the Flu Scenario Modeling Hub and address the effects of limited influenza circulating during the COVID-19 pandemic on the 2022–23 influenza season, new targets and ground truth datasets had to be identified. Influenza targets were limited to hospitalizations and deaths (HHS Protect, 2023; CDC Flu Burden, 2023), as no ground-truth data was available for influenza cases. New targets for peak size and timing were added as these quantities are an important public health consideration for influenza control. Further, projections of peak timing and size can better reflect the potential asynchrony between individual model simulations (which includes variability in individual simulations of a given model, and between models), as these asynchronies can be ‘averaged out’ when outputs are summarized as weekly quantiles.

For each scenario, location and target in a given round, modeling teams generate probabilistic projections. Teams are required to submit 23 quantiles, although in more recent rounds we have also called for teams to submit a sample of 100 trajectories. This may enable us to better capture heterogeneities in incident outcomes between and within models, heterogeneities that may be minimized or lost during the aggregation process, such as magnitude and timing of peaks (Sherratt et al., 2023).

6.3. Multiple-model ensemble

The strength of SMH has come in part from the ability to use projections from multiple models to better represent uncertainty about future dynamics, including by aggregating individual model projections into an ensemble, with prediction intervals. Repeatedly, multi-model ensembles have been shown to produce more accurate and better calibrated forecasts than single models, in infectious disease settings (Cramer et al., 2022b; Johansson et al., 2019; Paireau et al., 2022; Reich et al., 2019; Viboud et al., 2018) and other fields (Clemen, 1989; Timmermann, 2006). The goal of aggregation is to capture the insights of individual models while gaining from the wisdom of the crowd. We include multi-model aggregations and individual model outputs in reports and presentations, as discrepancies between models (and between scenarios) are important in capturing future uncertainties.

Over the lifecourse of SMH, we have used several aggregation approaches as our primary ensemble. SMH’s initial aggregation method followed that used by the COVID-19 Forecast Hub, and was used for SMH COVID-19 Rounds 1–4. This method takes a median of each submitted quantile, a variation of the Vincent average (Ratcliff, 1979; Vincent, 1912). The Vincent average approach stands in contrast to an alternative method called the Linear Opinion Pool (LOP) (Stone, 1961). Unlike the Vincent average, LOP approaches treat individual model predictions like alternate hypotheses about how the future could unfold and therefore preserves variation between those predictions in the aggregate (Howerton et al., 2023b). It is important to preserve variation across models in the SMH context, as individual models are unlikely to

capture all the uncertainties about the future and these uncertainties increase with longer projection horizons. Thus, in Round 5, the aggregation method switched to a variation of the Linear Opinion Pool method (Howerton et al., 2023b; Jose et al., 2014; Stone, 1961). A known limitation of the standard LOP approach is that outliers can cause the aggregate prediction intervals to become excessively wide (resulting in underconfident projections). Therefore, a trimmed LOP was chosen as our primary aggregation method because it narrows the prediction intervals (Jose et al., 2014), where the two most extreme probabilities at each value are excluded when aggregating. Since Round 9, both the trimmed and untrimmed-LOP have been shown on the website (Scenario Modeling Hub, 2023a). Which of these aggregation methods to highlight as the default approach is decided by the SMH coordination team on a round-by-round basis; typically the untrimmed LOP is favored in periods of particularly high uncertainty (e.g., COVID rounds 13–16, with hypothetical variants and flu round 1) or when fewer models participate. Performance-wise, the trimmed LOP generally produces the highest performing ensemble model for COVID-19 and outperforms the individual models on average (Howerton et al., 2023a). While much progress has been made in ensembling and performance evaluation of infectious disease projections in recent years (Bay et al., 2023; Bracher et al., 2021; Cramer et al., 2022b; Keeling et al., 2022; Sherratt et al., 2023), more work is needed to further improve these multi-model efforts.

7. Output visualization and external communication

A major goal of SMH from its inception has been to disseminate disease projections in the public domain to provide policy makers and the lay public with the most complete modeling evidence. Careful consideration has been paid to the release of projections and communications with external stakeholders and interested parties.

7.1. Presenting and visualizing results effectively for the lay public

A public-facing SMH website is the major dissemination channel for projections, particularly for the lay audience (see Figure S3 and Scenario Modeling Hub, 2023a); in addition, raw projections are released on a public GitHub (Scenario Modeling Hub GitHub, 2023). The SMH website is interactive, allowing users to explore the projections for every state, scenario, and round. Different tabs display weekly incident and cumulative targets for component models and the aggregated ensemble, and summary statistics compare projections between scenarios. For context, later rounds display thresholds for cases, hospitalizations and deaths based on levels experienced in prior COVID-19 variant waves or past influenza seasons.

For incident and cumulative targets, the default visualization is a multiple-quantile ribbon; this visualization shows multiple prediction intervals, focusing on outer intervals, and does not present the median. Users must engage with the website to select an alternate view of ensemble projections.

From Rounds 1–14, the website defaulted to visualization of national incident COVID-19 cases for the US, reflecting the target of emphasis at the time. As vaccination and rapid antigen testing was rolled out and the public health concern shifted to severe disease, the default target for visualization switched to incident hospitalizations. This became important as case (and to some extent death) reporting became more inconsistent across states in later stages of the pandemic.

A separate SMH website has been created for influenza (Scenario Modeling Hub, 2023b). Incident hospitalizations have been the default visualization as they are considered reliable. As concerns over the dual burden of COVID-19 and influenza rose during fall 2022, new plots showing the combined impact of these pathogens were debuted on the website for each pathogen, synthesizing hospitalization projections from COVID-19 and flu rounds (Figure S4). Users can select a particular scenario and quantile and explore the relative hospitalization burden of

each pathogen. These combined projections make the implicit assumption that there is no interaction between influenza and COVID-19, whether immunological or behavioral.

7.2. Generating reports to communicate with public health partners

In addition to releasing projections on the SMH website and on GitHub, which are open to everyone, the coordination team generates reports after each round to disseminate to interested parties, such as local, federal and international health authorities. These reports include an executive summary of key messages and results, scenario specifications, and analyses of ensemble and individual model projections. Results for incident and cumulative burden targets at the national and state level are presented. State-level heterogeneities in peak timing are shown and differences between scenario axes and between models are highlighted.

As the need arises, public facing technical reports and statements have also been produced that target questions of particular and urgent public health interest. These have included a statement about the potential magnitude of the impending Omicron wave, estimates of when the US would reach the milestone of 1 million COVID-19 deaths, and the potential combined burden of COVID-19 and influenza during the 2022–23 winter season.

7.3. Engagement with media

SMH does not produce press releases or proactively engage with the media, but SMH collaborators (both on the coordination team and contributing modelers) respond to media inquiries to ensure that projections are well used and understood. At key moments in the pandemic, there has been considerable scientific and general media attention; for example, at the emergence of new variants (Holtgrave, 2021; Stein, 2021; Stein and Simmons-Duffin, 2021), around key vaccination decisions (Associated Press, 2021; Christensen, 2022; Kozlov, 2021; Malapaty et al., 2021), leading up to winter seasons (Callaway, 2022; Wu, 2022), at possible downturns in the pandemic trajectory (Johnson, 2022; Stein and Wroth, 2021; Sullivan, 2022), and as a warning for possible upticks in cases (Guarino and Diamond, 2021).

8. Making an impact

SMH has produced multiple documented impacts, including quantifiable engagements with stakeholders, instances of direct influence on policy decisions, driving modeling practices and priorities for both COVID-19 and influenza, as well as broader influences on the future of modeling application and research (Biggerstaff et al., 2022; Borchering et al., 2023, 2022, 2021; Rosenblum, 2022). We also refer the reader to a companion paper on SMH's impact from the lens of the US CDC (Borchering et al., 2023).

8.1. Tangible impacts on public health and policy decisions

Though we cannot fully quantify all direct and indirect impacts of SMH, we can characterize some aspects of its interactions with public health officials, policy makers, healthcare practitioners, and other researchers (Fig. 4). The results of SMH rounds have been formally presented by members of SMH more than 22 times to more than 9 different organizations or groups. These have included recurrent and sporadic presentations to US federal agencies (e.g., CDC, National Institute of Allergy and Infectious Diseases, United States Food and Drug Administration), special purpose committees (e.g., US Advisory Committee on Immunization Practices (ACIP), US Vaccines and Related Biological Products Advisory Committee (VRBPAC)), international organizations (e.g., WHO, EU Hub), state and regional health agencies and groups (e.g., Council of State and Territorial Epidemiologists (CSTE), Region 6), and research working groups (e.g., CDC facilitated COVID-19

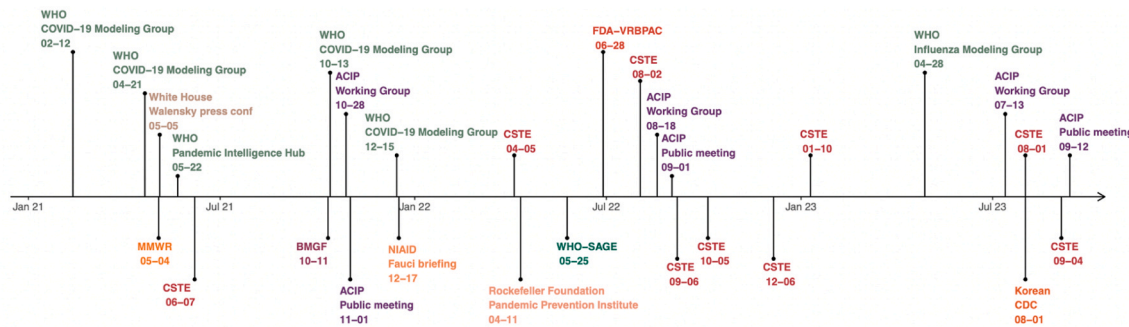


Fig. 4. A timeline of Scenario Modeling Hub public health impacts since establishment in December 2020 through to September 2023. Timeline shows key presentations members of the SMH coordination team have given to different public health groups and stakeholders. Abbreviations: WHO: World Health Organisation; MMWR: Morbidity and Mortality Weekly Report; CSTE: Council of State and Territorial Epidemiologists; BMGF: Bill and Melinda Gates Foundation; ACIP: Advisory Committee on Immunization Practices; NIAID: National Institute of Allergy and Infectious Diseases; WHO-SAGE: World Health Organisation - Strategic Advisory Group of Experts on Immunization; FDA-VRBPAC: Food and Drug Administration - Vaccines and Related Biological Products Advisory Committee.

Forecasting calls).

Through these engagements, SMH has had demonstrated impacts on at least two critical national-level policy decisions. First, results from COVID-19 Round 9 were directly used as evidence in the decision by ACIP to recommend expanding the vaccination program to include 5–11 year-olds in November 2021. This decision was supported by SMH results demonstrating that expanded vaccination was projected to avert 7–9 % of all-age COVID-19 cases, hospitalizations and deaths during Nov 2021 and mid-March 2022, even in the absence of a new variant (Borchering et al., 2022). Again in August 2022, SMH results from COVID-19 Rounds 14 and 15 provided explicit evidence to support ACIP's decision to recommend vaccine boosters to a broad swath of the population, rather than those at high-risk (Rosenblum, 2022). SMH Round 14 results found that expanded booster coverage in adults aged ≥ 18 years, similar to coverage for influenza vaccine, would lead to a reduction in hospitalizations and deaths of > 20 % and > 15 %, respectively, compared with a recommendation for adults aged ≥ 50 year (Rosenblum, 2022). Round 14 also provided evidence to support the White House's push for manufacturers to have bivalent vaccines ready sooner, moving up the availability of a COVID-19 vaccine booster by two months, from November 2022 to September 2022. Further, Round 17 projections demonstrated the potential of broad repeated booster vaccination to reduce the burden of disease at a two-year projection period (Jung et al., 2023).

8.2. Unquantified and future impacts on the modeling community and scientific community

Potentially one of the most important impacts of SMH has been the overall contribution to the practice and science of predictive modeling, both in the present and for the future. This contribution has been possible because of the community that SMH developed. Through close collaboration, SMH has driven continued scientific development within the Hub and among each of the infectious disease modeling teams. Several of these teams have had continual individual engagements with local, state, national, and international partners (Davis et al., 2023; Porebski et al., 2023). Additionally, several junior scientists have been able to emerge in the field of disease modeling through mentorship and engagement with more experienced SMH members from across institutions, building a stronger and more capable future workforce. SMH also provided a model to establish other scenario modeling hubs both domestically and internationally, including the long-term scenarios that are part of the California Communicable disease Assessment Tool and the European COVID-19 Scenario Modeling Hub (California Communicable diseases Assessment Tool, 2023; European Covid-19, 2023). There have been strong interactions between hubs, with two of the US SMH teams regularly participating in the European Hub, and members of the

California Hub contributing to SMH Flu projections.

The repeated rounds of SMH have driven scientific discovery, improvement in communication of scientific results, and model development. Participating models were gradually adapted over the course of multiple rounds, with more complexities added to reflect changing aspects of COVID-19 biology and scenario specifications (eg, waning immunity, immune escape, multiplicity of co-circulating variants). Eight SMH COVID-19 teams have also regularly contributed to the COVID-19 Forecast Hub, several of which are among the top performers (Cramer et al., 2022b). Six SMH COVID-19 teams also regularly contributed to CDC's FluSight Influenza forecasting collaboration and three completed rounds of SMH Flu. Much research work is on-going to evaluate scenario projections (Bay et al., 2023; Howerton et al., 2023a) and explore optimal methods for ensembling – we expect this to remain a very active field of research in coming years. This community-focused engagement on both COVID-19 and influenza epidemiology, evolution, and modeling will continue to drive advances and applications in the field for years to come.

In addition to driving scientific discovery, SMH efforts have contributed to improving the infrastructure of predictive modeling hubs. SMH's technical infrastructure relies on GitHub source-code control system for the publishing of scenarios, submissions of results, validation, and publication of results. Originally developed for the COVID-19 Forecast Hub (Cramer et al., 2022a), this model has been customized and enhanced by the SMH and the EU COVID-19 Scenario Hub. Realizing the value of a shared platform for these related efforts, representatives of these groups formed the Consortium of Infectious Disease Modeling Hubs to develop common conventions for specifying tasks and output formats, supported by a common software stack (Hubverse, 2023). SMH Round 17 was the first hub effort to use this infrastructure. The goal of these efforts is to develop a “plug and play” infrastructure that can be readily reused and adapted for future similar efforts, particularly for emergencies.

9. Limitations

9.1. Funding is key to sustaining modeling hubs

A project the size of SMH is only possible with significant dedicated funding, though, initially at least, many teams and the coordination team contributed unfunded. Several funding sources were activated to make the continuation of SMH possible, with the greatest amount of funding coming from CDC, including directly through mechanisms like the Safety and Healthcare Epidemiology Prevention Research Development (SHEPHERD) Program and cooperative agreements, National Science Foundation's Rapid Response Research (RAPID) grants, National Institute of Health grants, and CSTE. Funding is critical for an effort like

SMH because of the large time commitment and engagement required by both the coordinating team and the modeling teams. Each round requires substantial preliminary literature and data review, meetings with experts, analysis, and scenario development to prepare. Each team must modify their models to fit both the requirements of the scenarios and of the current context of the rapidly changing pandemic. Production of projections by the teams is often highly intensive, with numerous test runs, model updates, and computational developments to produce the final results. With each set of projections, substantial effort is needed to develop timely reports, manuscripts, and new methods to analyze and interpret the outputs of multiple models, and to then communicate these results to stakeholders. All of this requires substantial commitment from all those involved in SMH, and only through the financial support received by members of SMH has that been possible.

9.2. Maintaining engagement

As in any large group, it is not always straightforward to maintain engagement with teams, manage conflicts and personalities, and balance demands of the pandemic with the wellbeing of hub members. However, in our experience, these challenges are outshone by the influx of new teams, facilitated by the expansion of SMH to new pathogens and, perhaps more importantly, by the collective commitment of SMH colleagues to providing useful, decision-relevant information.

9.3. Evaluating scenarios

An additional limitation of the current SMH framework lies in how scenarios are evaluated (Howerton et al., 2023a). Unlike forecasts, SMH provides value beyond simply generating accurate predictions. It is often the comparison of scenario projections and burden averted under a given assumption that provides information from which decisions may be made; e.g., Round 6 and 7 COVID projections were helpful in planning for the emergence of the Delta variant (Truelove et al., 2022), despite poor performance under standard evaluation metrics (Howerton et al., 2023a). Further work in this area will be a fruitful avenue of further research.

10. Lessons learned

We have learned numerous lessons regarding the formulation, operations, and ongoing collaboration of scenario modeling hubs, throughout the more than three years of SMH operations. One of these was the importance of carefully defining scenarios, both when a specific intervention was in question, or when both axes of interest were uncertainty axes. We have developed a strong connection with public health stakeholders and decision makers, though there is more to be learned from how projections were used, to better inform future scenario modeling efforts.

Second, we demonstrated the need to maintain and continue developing these hubs, and the models contributing to them. It is important to build capacity for new diseases and hub infrastructure, to continue building capacity for new models, and to improve existing models. It has been particularly heartening to see the demand from both public health partners and the Hub itself to keep building these different capabilities.

Finally, perhaps one of the greatest lessons learned through this experience has been the importance of establishing and continuing to sustain an open, collaborative and supportive environment. The community of SMH is highly interpersonal and diverse, and partnerships have been developed and maintained between experts in the field, and with public health parties, with the collective goal of developing a community that has tangible public health impact. As a case in point, teams generally remained involved in weekly meetings and discussions, even if they were unable to produce projections for a given round. Our structure of the coordination team (that spans multiple institutions) and modeling teams has proven to be successful in establishing a shared

knowledge base across numerous disciplines, and maintaining communication, trust and a strong sense of purpose within SMH is a key part of establishing and sustaining this community towards its public health goals.

11. What next?

As the world transitions out of the acute pandemic response, maintaining efforts like SMH will likely involve a combination of operational tasks addressing new interventions to mitigate endemic pathogens, along with more research-oriented efforts to advance the science of disease prediction. While we have come a long way and learnt much since the first open predictive hub for infectious disease was launched in 2012 (*"FluSight,"* 2023), there is still a long road towards achieving a mature multi-model disease prediction system that would parallel that of weather and climate. Major improvements in predictive modeling capabilities will come from a better understanding of behavioral aspects and feedback from interventions, a complexity which does not arise in weather and climate modeling. Improvements in predictive models will also necessitate robust investments in data, including stable surveillance systems that provide granular observations of infections and severe outcomes, monitoring of populations' immunologic status, and robust genomic information on circulating strains. Changes to reporting in important COVID-19 data streams (e.g., HHS-Protect hospital admissions) with the end of the pandemic emergency phase (Silk, 2023) illustrates the fragility of long-term observational datasets for infectious disease. We also see major opportunities for further work in statistical methods to aggregate projections from individual models, optimize scenario design, and evaluate scenario projections, as exemplified by several articles in this special issue (Bay et al., 2023; Runge et al., 2023; Wade-Malone et al., 2023). Further, we cannot overemphasize the importance of keeping modeling hubs alive in inter-outbreak periods to facilitate the accelerated establishment of a concerted modeling response in future pandemics. Investments in computational infrastructure on which to build these modeling hubs can increase the scope and efficiency of methodological approaches, analytical end-products, and visualization options. There is also a need to expand modeling hubs to resource-limited settings, where resource optimization is particularly important. Building on the SMH experience, development of long-term modeling hubs will ensure that decision makers have access to the best-possible collective evidence in periods of high stakes and substantial uncertainty.

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Shaun Truelove: Conceptualization, Writing-original draft preparation, reviewing and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

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