

Collaborative forecasting of influenza-like illness in Italy: The Influcast experience

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## Collaborative forecasting of influenza-like illness in Italy: The Influcast experience

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### ABSTRACT

Collaborative hubs that integrate multiple teams to generate ensemble projections and forecasts for shared targets are now regarded as state-of-the-art in epidemic predictive modeling. In this paper, we introduce Influcast, Italy's first epidemic forecasting hub for influenza-like illness. During the 2023/2024 winter season, Influcast provided 20 rounds of forecasts, involving five teams and eight models to predict influenza-like illness incidence up to four weeks in advance at the national and regional administrative level. The individual forecasts were synthesized into an ensemble and benchmarked against a baseline model. Across all models, the ensemble most frequently ranks among the top performers at the national level considering different metrics and forecasting rounds. Additionally, the ensemble outperforms the baseline and most individual models across all regions. Despite a decline in absolute performance over longer horizons, the ensemble model outperformed the baseline in all considered horizons. These findings show the importance of multimodel forecasting hubs in producing reliable short-term influenza-like illnesses forecasts that can inform public health preparedness and mitigation strategies.

### 1. Introduction

In modern public health, infectious disease forecasting and scenario modeling play a crucial role. These approaches provide stakeholders and policymakers with essential tools to anticipate and respond to infectious diseases by integrating mathematical models, advanced analytics, and data (Desai et al., 2019; James et al., 2021; Lutz et al., 2019). Over the past decade, inspired by best practices in disciplines like meteorology (Gneiting and Raftery, 2005), collaborative hubs have emerged as an innovative tool for epidemiological forecasts (Reich et al., 2022;

Shea et al., 2020). More in detail, a forecasting hub is a consortium of several modeling teams that contribute their forecasts to a common set of targets. These forecasts are typically aggregated into an ensemble, which combines predictions from individual models to produce a consensus forecast representing the hub's collective outlook. In previous efforts, ensemble forecasts have demonstrated greater accuracy and reliability over time compared to the contributions of individual models (Sherratt et al., 2023; Cramer et al., 2022). In the context of epidemiological forecasts, this approach was pioneered by the Centers

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for Disease Control and Prevention with the 2013–2014 Influenza Season Challenge (Biggerstaff et al., 2016) and later expanded to support the response to several health threats including Ebola (Viboud et al., 2018), West Nile Virus (Holcomb et al., 2023) Dengue (Johansson et al., 2019), Chikungunya (Del Valle et al., 2018), Influenza (McGowan et al., 2019; Reich et al., 2019), and more recently, COVID-19 (Sherratt et al., 2023; Cramer et al., 2022; Wolffram et al., 2023). In various instances, different targets have been considered, ranging from cases to hospitalizations and disease-related mortality.

Here, we present *Influcast*, the first Italian epidemic forecasting hub on influenza-like illness (ILI). Influenza and other respiratory diseases impose a significant burden on healthcare and hospital systems worldwide and constitute one of the primary economic costs for public health systems (World Health Organization, 2019; Putri et al., 2018). Forecasting the impact of respiratory diseases has the potential to provide a wealth of actionable information to optimize the allocation of resources (e.g., hospital beds, medical staff, vaccines) and help fine-tune communication campaigns to raise public awareness and promote preventive measures.

In Italy, the epidemiological surveillance of respiratory diseases typically runs every winter season, from week 42 (mid-October) to week 17 of the following year (late April). Sentinel physicians diagnose potential cases of ILI based on specific symptoms and report them to the Istituto Superiore di Sanità (ISS, the Italian National Institute of Health). This data is then aggregated by the ISS, which releases weekly estimates of ILI incidence at both national and sub-national (19 regions and 2 autonomous provinces) levels (Istituto Superiore di Sanità, 2020). Due to the time required for reporting and aggregation, the provided report pertains to the week preceding its release date.

Influcast was launched in the 2023/2024 winter season to forecast ILI incidence in Italy and its regions up to four weeks ahead. Over 20 forecasting rounds, 5 independent research teams contributed a total of 8 different models. Individual model's forecasts were combined into an ensemble forecast and evaluated in real-time against a baseline forecasting model which consistently predicts as median value the last data point within the calibration period and whose predictive intervals are estimated on past data. Across various evaluation metrics and spatial units, the ensemble model emerged as one of the best performers. When assessing aggregated performance metrics, the ensemble model frequently ranks in the upper half across different criteria. Although its absolute forecasting accuracy declines over longer horizons, the ensemble outperforms the baseline model at all considered forecasting horizons. At the sub-national level, the ensemble remains the leading model, surpassing the baseline in every region and outperforming individual models in most cases.

Overall, our findings confirm the effectiveness of collaborative forecasting and ensemble models in delivering reliable short-term forecasts of influenza-like illness incidence. The results demonstrate that pooling predictions from multiple modeling teams not only improves accuracy but also increases the robustness of forecasts. These results stress the value of multi-model approaches in public health, supporting better-informed decision-making for managing influenza-like illness.

## 2. Results

Influcast generated 20 forecasting rounds during the 2023/2024 influenza season, from week 2023-46 (mid-November 2023) to week 2024-13 (late March 2024). In each round, modeling teams were asked to submit forecasts on ILI incidence in Italy and its regions for the next four weeks. Incidence is calculated as reported cases per 1000 patients (i.e., the population covered by the network of sentinel physicians). Only probabilistic forecasts in the form of quantiles were accepted (more details on the submission format are provided in Section 4.1). Each week, individual forecasts were combined into an ensemble forecast and evaluated against a baseline model which consistently predicts as median value the last data point within the calibration period and whose prediction intervals are estimated on past data. Details on the calculations for both ensemble and baseline models are provided in Section 4.2.

### 2.1. Forecasting challenge and contributing models

By the end of the 2023/24 season, 5 modeling teams had submitted a total of 8 individual models. Forecasts were uploaded and visualized throughout the season on an interactive web platform, enabling users to examine both individual model forecasts and the ensemble output (<https://influcast.org/>). The platform also provided weekly bulletins that interpreted and communicated the latest insights from the forecasts. More details on the Influcast platform are reported in Section 4.1. Of the eight models submitted, four were mechanistic models, two were semi-mechanistic models, and the remaining two were statistical models. Among the four mechanistic models, two adopted a metapopulation approach, while the other two used a single-population approach. Besides historical data for fitting, the models incorporated additional data, including (i) mobility data, (ii) contact data, (iii) population distribution data, and (iv) participatory surveillance data. We refer the reader to the section S7 (*Models Description*) of the Supplementary Information for further details on the models, where we also provide a table reporting the correspondence between the model names used in this manuscript and those used on the Influcast platform (Table S3).

Fig. 1A shows an example of one-week-ahead ensemble forecasts (50% and 90% prediction intervals) for Italy and its regions in different forecasting rounds. In the Supplementary Information (Figures S11–S14), we also show two, three, and four weeks ahead ensemble forecasts in different spatial units. Fig. 1B illustrates the number of models submitted for each round. Despite small fluctuations, the number of submitted models remained fairly stable across rounds, with four out of eight total models submitting forecasts at the sub-national level as well.

### 2.2. Performance of submitted models

Defining what makes a model “good” is challenging, particularly because a model's performance depends on the target metric considered. In this context, we evaluate models' predictive performance based on the paradigm of *maximizing the sharpness of the predictive distributions subject to calibration* (Gneiting et al., 2007). In other words, we aim for prediction intervals to be as narrow as possible (and closely aligned with real data), while ensuring that forecasted probabilities match the observed frequencies.

**National forecasts.** Table 1 presents the aggregated performance of individual models using several metrics to evaluate the predicted ILI incidence at the national level. The first metric considered is the relative mean absolute error of the median forecast (relative MAE). The procedure to compute the relative MAE is detailed in Section 4.3. In general, aggregating forecasts from all rounds and horizons, each model is compared to the others submitted in the same round in terms of MAE, and the obtained value is then divided by the value for the baseline model. Consequently, values of relative MAE below 1 indicate better performance, while values above 1 indicate worse performance compared to the baseline. Among the models, *Mechanistic-1* shows the lowest relative MAE (0.56), followed closely by *Mechanistic-3* (0.58) and the ensemble (0.59). Notably, a relative MAE of around 0.5 indicates that the model reduces uncertainty in predictions by approximately 50% compared to the baseline. Then we find *Mechanistic-4*, with a relative MAE of 0.73, *Statistical-2* (0.77), *Semi-mechanistic-2* (0.84), and *Statistical-1* (0.99). The remaining two models show a relative MAE greater than one, *Semi-mechanistic-1* (1.80) and *Mechanistic-2* (1.86).

We also consider the relative weighted interval score (relative WIS), a metric that evaluates not only the accuracy of the median but also the accuracy of the prediction intervals in bounding actual data (see Section 4.3). The relative WIS is also referenced to the baseline value. In terms of relative WIS, *Mechanistic-1* is the best (0.54), followed by the ensemble (0.57) and *Mechanistic-3* (0.58). In this case, four models have a relative WIS greater than 1.

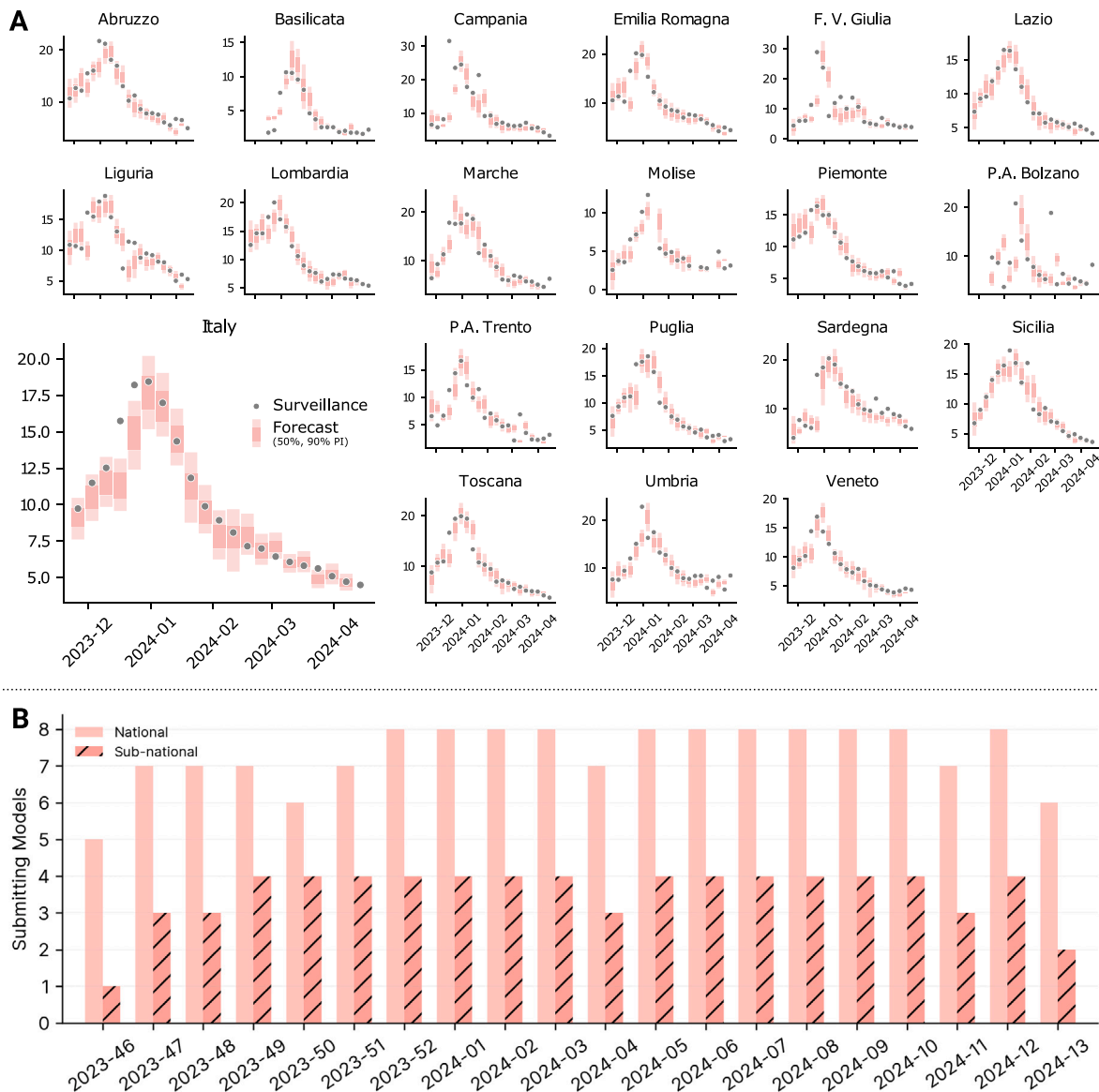


Fig. 1. (A) One-week ahead ensemble forecasts (50% and 90% prediction intervals) at the national and sub-national level in different forecasting rounds. (B) Number of models submitting forecasts at the national and sub-national level.

Table 1

Models forecasting performance. Performance of different models in terms of relative MAE of the median, relative WIS, 50% and 90% coverage. For each metric, the score of the model achieving the best performance is highlighted in bold and the ranking of top three models is indicated in parentheses.

Model	N. of rounds	Relative MAE	Relative WIS	Coverage (50%)	Coverage (90%)
<i>Mechanistic-1</i>	19	<b>0.56</b> (1st)	<b>0.54</b> (1st)	0.75	<b>0.89</b> (1st)
<i>Mechanistic-2</i>	20	1.86	1.64	0.04	0.49
<i>Mechanistic-3</i>	20	0.58 (2nd)	0.58 (3rd)	0.47 (3rd)	0.70 (3rd)
<i>Mechanistic-4</i>	19	0.73	0.73	0.16	0.37
<i>Semi-mechanistic-1</i>	16	1.80	2.14	0.06	0.27
<i>Semi-mechanistic-2</i>	14	0.84	1.04	0.19	0.30
<i>Statistical-1</i>	20	0.99	1.09	0.17	0.43
<i>Statistical-2</i>	19	0.77	0.85	0.11	0.31
<i>Ensemble</i>	20	0.59 (3rd)	0.57 (2nd)	<b>0.51</b> (1st)	0.80 (2nd)
<i>Baseline</i>	20	1.0	1.0	0.49 (2nd)	0.66

Finally, to assess calibration of models we evaluate the 50% and 90% coverage. Coverage is defined as the proportion of points falling within the specified intervals (more details in Section 4.3). For a perfectly calibrated model, the 50% predictive interval will contain exactly 50% of the observations, resulting in a perfect coverage score

of 0.5. Similarly, for the 90% predictive interval, the perfect coverage score would be 0.9. The ensemble achieves an almost perfect 50% coverage (0.51), while it is slightly under-confident for 90% coverage (0.80). Among the other models, *Mechanistic-3* follows the ensemble for 50% coverage (0.47), while *Mechanistic-1* performs the best for 90%

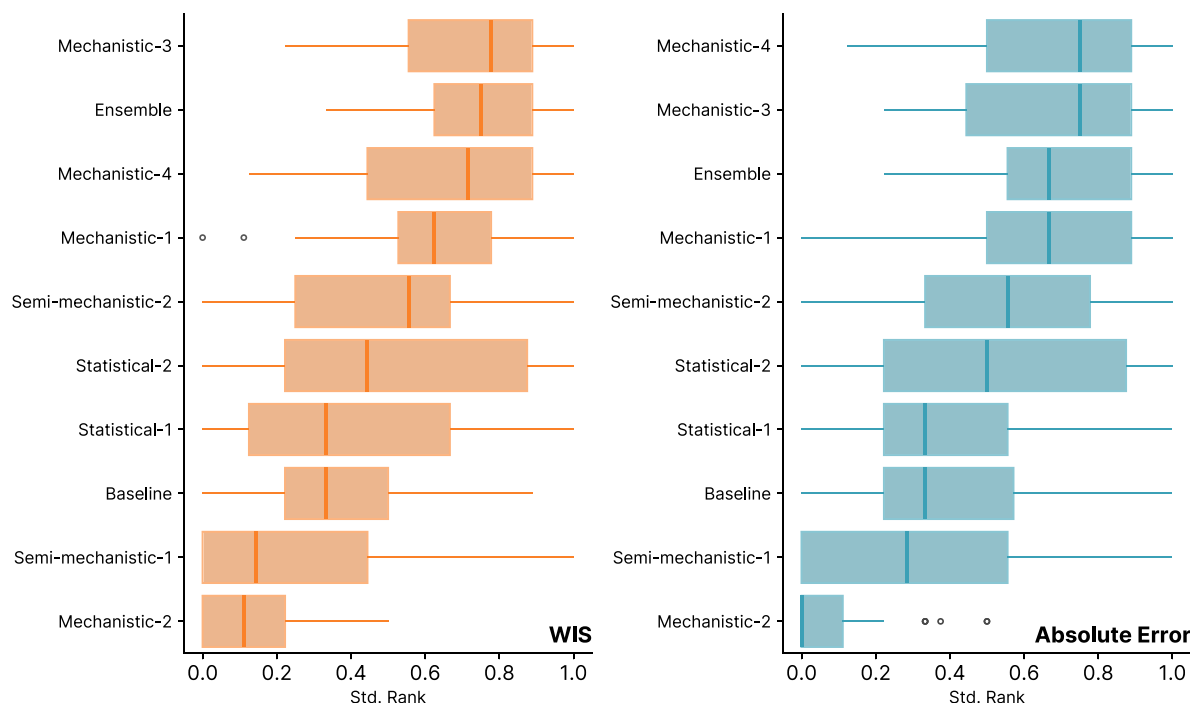


Fig. 2. Standardized rank of different forecasting models. Standardized rank plot (WIS and absolute error of the median) for different models computed combining different horizons and forecasting rounds. Boxplots show the distribution of standardized ranks: the box boundaries represent the interquartile range (IQR), the line inside the box indicates the median and the whiskers extend to 1.5 times the IQR from the quartiles. Outliers are shown as individual points.

coverage (0.89). In the Supplementary Information (Figure S15), we present coverage plots for different models and forecasting horizons, showing that the ensemble model maintains good coverage also across other intervals.

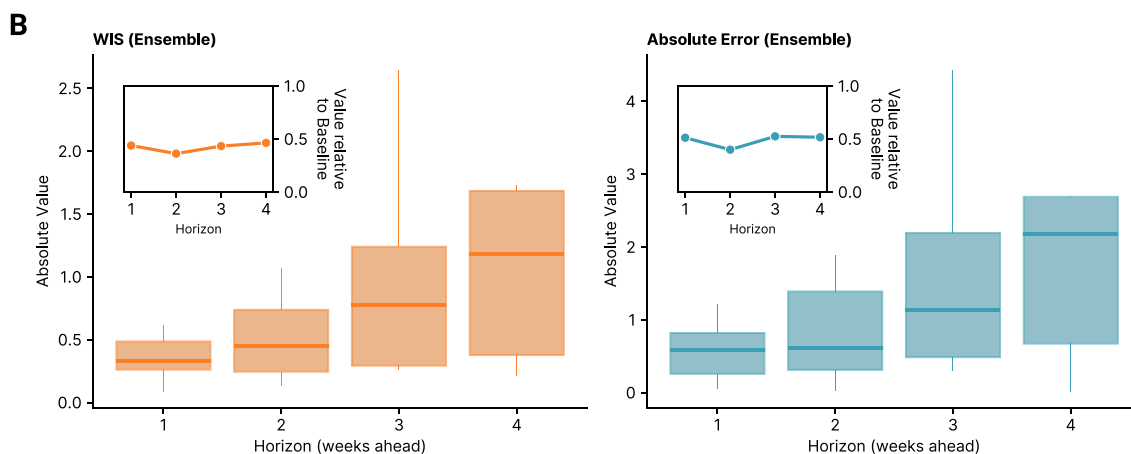
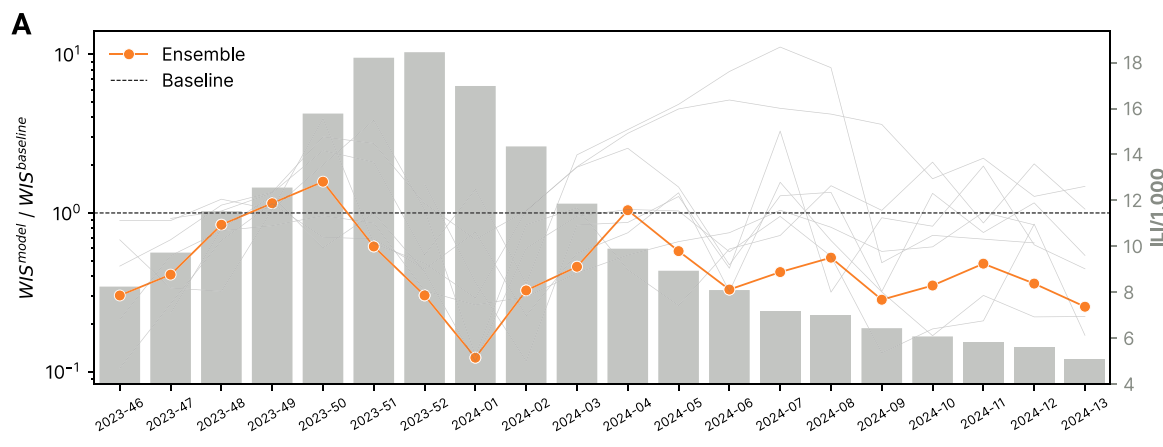
We observe that, on average, mechanistic models perform better. For instance, in terms of relative MAE, the top two models are mechanistic. Similarly, when considering WIS and 90% coverage, the top and third-ranked models are mechanistic, with the ensemble model ranking second in both cases. For 50% coverage, the third and fourth models are mechanistic, while the first and second models are the ensemble and the baseline, respectively.

Fig. 2 shows the standardized rank for the WIS and the absolute error of the median of different models across all horizons and forecasting rounds. We stress how in this case we consider absolute errors rather than MAE (i.e., absolute errors average over different time horizons) as reported in Table 1. More details on standardized rank calculation are provided in Section 4.3. In general, the model that performs the best for a given horizon in a forecasting round will have a standardized score of 1.0, while the worst-performing model will have a score of 0.0. When considering the WIS score, the models' median standardized ranks are as follows: *Mechanistic-3* (median rank of 0.78), the ensemble (0.75), and *Mechanistic-4* (0.71) are the top three models. Following these, *Mechanistic-1* (0.62), *Semi-mechanistic-2* (0.56), *Statistical-2* (0.44), *Statistical-1* (0.33), and the baseline (0.33) feature ranks between 0.30 and 0.70. Lastly, *Semi-mechanistic-1* (0.28) and *Mechanistic-2* (0.22) have the lowest median ranks. When considering the absolute error, we observe a similar pattern: *Mechanistic-3* and *Mechanistic-4* share the top rank, both with a median standardized rank of 0.75. The ensemble model ranks third, tied with *Mechanistic-1*, both with a median standardized rank of 0.67. Following these, we find *Semi-mechanistic-2* and *Statistical-2* with median standardized ranks of 0.55 and 0.50, respectively. The last four models are ranked as follows: *Statistical-1* (0.33), the baseline model (0.33), *Semi-mechanistic-1* (0.28), and *Mechanistic-2* (0.0).

Interestingly, while the ensemble model does not achieve the highest median standardized rank, it is the model that most frequently

ranks in the top half. This occurs in more than 75% of rounds across both metrics, meaning that over 75% of the rank distribution for the ensemble lies in the range of ranks greater than 0.5. This suggests that the ensemble's performance is more stable than other models across rounds, a desirable feature especially in the context of short-term epidemiological forecasts. This finding is further supported by the results presented in Section S2 of the Supplementary Information, where we analyze model rankings across different forecasting rounds. While model rankings show variability over time, the ensemble model achieves rankings comparable to the top-performing models while showing a much lower variance in its performance.

In Fig. 3A, we present the ratio between average WIS of different models and of the baseline (both computed averaging WIS values of 1, 2, 3 and 4-week ahead horizons) in different forecast rounds. Values below 1 indicate better performance relative to the baseline, while values above 1 indicate worse performance. The performance of the ensemble model is highlighted in orange. The background of the plot also displays the evolution of reported ILI incidence. Overall, the ensemble model provides more accurate forecasts compared to the baseline, with only a few exceptions. Indeed, we observe a reduction in performance during the forecasting rounds for weeks 2023-49 and 2023-50, just before the epidemic peak. This pattern is observed for the majority of models. In the Supplementary Information, we repeat this analysis for the absolute error of the median, finding analogous results (Figure S16). Additionally, in section S1 of the Supplementary Information we compare the ensemble to each individual model in terms of WIS and absolute error of the median for each forecasting horizon separately. When considering the WIS, we find that only models *Mechanistic-3* and *Mechanistic-4* outperform the ensemble in more than half the rounds for horizon 1, while in all other cases, the ensemble always achieves a lower WIS than any individual model in at least half of the forecasting rounds. In the case of the absolute error of the median, only model *Mechanistic-3* outperforms the ensemble for horizons 1, 2, and 3, achieving lower absolute error in 70%, 60%, and 53% of forecasting rounds, respectively. Similarly, *Mechanistic-1* achieves lower absolute error than the ensemble in 63% of rounds



**Fig. 3.** Models performance in time and by horizon. (A) Ratio between average WIS of different models and of the baseline (both computed averaging WIS values of 1, 2, 3 and 4-week ahead horizons) in different forecast rounds. It follows that values smaller than 1 indicate better performance with respect to the baseline, while values greater than 1 indicate worse performance. The ensemble model is highlighted in orange, the baseline model as a black dashed line. The background displays the reported ILI incidence for the corresponding weeks. (B) On the left, we show the absolute WIS values of the Ensemble for different forecasting horizons (from 1 to 4 weeks ahead). In the inset, the figure also shows the median WIS relative to the baseline model by horizons. On the right, we repeat the analysis considering the absolute error of the median as a performance metric. The box boundaries represent the interquartile range (IQR), the line inside the box indicates the median and the whiskers extend to 1.5 times the IQR from the quartiles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

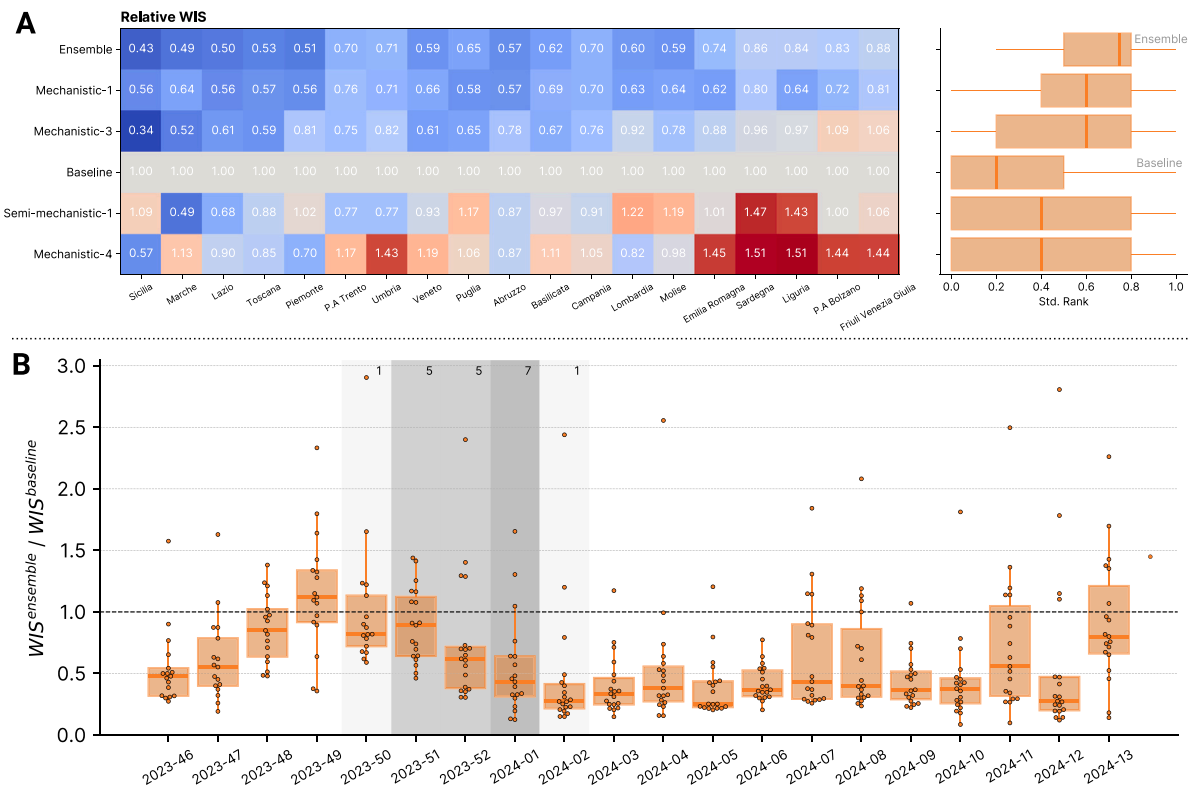
for horizon 1, 53% for horizon 2. Finally, *Mechanistic-4* outperforms the ensemble in 53% of rounds for horizon. In Fig. 3B, we focus on the ensemble and show its performance in terms of absolute WIS and absolute error of the median for different horizons, from one to four weeks ahead, aggregating results from different rounds. As expected, forecasting performance deteriorates for longer horizons. For WIS, the median value increases from 0.33 for one-week-ahead forecasts to 1.18 for four-week-ahead forecasts, a 3.5-fold increase. For absolute error, the median rises from 0.58 to 2.18, a 3.7-fold increase. In the inset, the figures also show the WIS and absolute error of the ensemble divided by the WIS and the absolute error of the baseline (median values) for different horizons. In this case, we observe a fairly stable trend, with the ensemble’s WIS and absolute error being 0.3 to 0.5 times that of the baseline model, indicating improved performance across all forecast horizons.

**Sub-national forecasts.** In Fig. 4A, we present the forecasting performance at the sub-national level. Two regions (Valle d’Aosta and Calabria) did not activate epidemiological surveillance for the 2023/2024 winter season and therefore were excluded from the analysis. On the left, we show the relative WIS for different regions for models providing forecasts at the sub-national level. Relative WIS is computed following the same procedure used for quantities reported in Table 1 and as detailed in Section 4.3. The models are ordered from best to worst in terms of performance. The ensemble is the best model, with a relative WIS of less than one in all regions. Regions are

ordered from best to worst performance. We notice heterogeneity in forecasting performance across regions, with Sicilia, Marche, and Lazio showing the best performance, while Liguria, Provincia Autonoma di Bolzano, and Friuli Venezia Giulia showing the worst performance. On the right, we show the standardized rank of the relative WIS for different models across all regions. The ensemble is the top performer with a median rank of 0.8, while the baseline is the worst in terms of median standardized rank. In the Supplementary Information, we repeat the analyses considering the relative absolute error, finding analogous results.

Finally, in Fig. 4B we show the performance of the ensemble model over time also in the case of sub-national forecasts. Specifically, box-plots and swarmplots are used to display the average ratio of the WIS of the ensemble model to the baseline model for each forecasting round across different regions. The gray shaded areas in the background represent the weeks during which regions reached their epidemic peak, and the number of regions peaking in each week is reported above the shaded areas. We see that 17 out of 19 regions peaked in three consecutive weeks: 2023-51, 2023-52, and 2024-01. The remaining two regions peaked in weeks 2023-50 and 2024-02. This evidence indicates a strong correlation between the epidemic curves of different regions. A similar pattern to the national forecasts is observed, with performance decreasing right before most of the regions reached the epidemic peaks. Nonetheless, the WIS of the ensemble model is worse than that of the baseline model, in median terms across all regions, only in week





**Fig. 4.** Models subnational forecasting performance. (A) On the left is shown the relative WIS of different models providing sub-national forecasts in different regions. Relative WIS calculation is detailed in Section 4.3. On the right is shown the standardized WIS rank of different models over all regions. The box boundaries represent the interquartile range (IQR), the line inside the box indicates the median and the whiskers extend to 1.5 times the IQR from the quartiles. (B) Comparison of the average WIS of the ensemble to the baseline across different forecast rounds and regions. The box boundaries represent the interquartile range (IQR), the line inside the box indicates the median and the whiskers extend to 1.5 times the IQR from the quartiles. Individual points, each representing a region, are also shown above boxplots. The gray shaded areas represent the weeks during which regions reached their epidemic peak, with darker shades indicating a higher number of regions peaking in that week. Additionally, the actual number of regions peaking in each week is reported above the shaded areas.

2023-49 throughout the entire period considered. Additionally, also for sub-national forecasts we observe lower performance in the epidemic tail. However, the median performance of the ensemble model across all regions remains below the baseline threshold.

### 3. Discussion

In this paper, we presented Influcast, the first Italian forecasting hub focused on real-time short-term predictions of influenza-like illness incidence. Our performance analysis indicates that: (i) most submitted models demonstrated superior performance compared to the baseline across various metrics, and (ii) the ensemble model outperforms the baseline and most individual models. Indeed, when considering aggregated performance metrics such as relative WIS, relative MAE, and coverage, the ensemble model is always among the top three performers. Additionally, in terms of standardized rank for both WIS and absolute error, the ensemble ranks in the top three and most frequently appears in the top half for both metrics, indicating a more stable and uniform accuracy over time.

We observed that the forecasting performance of the ensemble deteriorates as the forecast horizon increases, with four-week-ahead predictions being generally more than three times worse than one-week-ahead predictions. Nonetheless, the ensemble performs better than the baseline across all forecasting horizons. Additionally, the ensemble outperforms the baseline and most individual models in the majority of forecasting rounds, with few exceptions. Specifically, we observe a reduction in performance, at both national and sub-national level, right before the epidemic peak. This pattern is observed for the majority of models. This period is typically the most uncertain phase of the epidemic. The reduction in performance can also be attributed to

the flattening of the curve around the peak, where the baseline model performs relatively better. Additionally, around the peak, prediction intervals may widen due to increased uncertainty. Interestingly, while the performance of some models declines toward the tail end of the epidemic, the ensemble model continues to outperform the baseline even during this phase.

When evaluating model performance at the regional level, the ensemble is again the top performer, outperforming the baseline in all regions and each individual model in the majority of cases. Overall, we observed heterogeneous performance across different regions. Although a single round of forecasting limits our ability to explore these differences in depth, we expect that with data from future seasons, we will gain a clearer understanding of the factors driving regional performance, such as data quality or inherent regional characteristics.

We observed that mechanistic models tended to perform better compared to other model classes. Interestingly, past research on influenza forecasts in the US found that statistical models performed similarly or slightly better than mechanistic ones (Reich et al., 2019), while in the context of COVID-19, top-performing models included both mechanistic and statistical components (Cramer et al., 2022). However, due to the limited number of models submitted over a single season, this comparison cannot be considered definitive and may be specific to the particular problem being analyzed. Additionally, the observed differences in performance may be influenced by factors beyond the model's characterization, such as the integration of external data and signals, the techniques used for parameter estimation, and the model's robustness to data quality issues. Future work will be needed to systematically disentangle these factors to better understand their contribution to model performance and to guide the development of more effective forecasting approaches.

The present work comes with limitations. First, while ILI incidence is a good proxy for the burden of respiratory diseases, it is not a disease-specific signal. Since it is based purely on symptoms, multiple pathogens contribute to this signal, including influenza viruses, coronaviruses (including SARS-CoV-2), and respiratory syncytial viruses. This limits the ability to break down the impact by disease and provides limited information on what is driving ILI dynamics. In future seasons, we aim to address these limitations by incorporating new data to refine the definition of forecasting targets, specifically incorporating data from virological surveillance. In Italy, the National Institute of Health conducts virological surveillance alongside epidemiological surveillance every winter. By combining data from these two surveillance systems, we aim to define targets that are more specific to individual pathogens, thereby providing more interpretable information. It is plausible that making targets more disease-specific could enhance the accuracy of forecasts (Viboud and Vespignani, 2019). Additionally, this objective aligns with broader trends observed in similar forecasting challenges, such as the CDC's FluSight forecasting initiative, which recently shifted from ILI incidence to laboratory-confirmed influenza hospitalizations as forecasting target (Mathis et al., 2024). Second, the limited number of submitted models challenges the comparison of different model classes and the exploration of methodologies to further enhance the ensemble (e.g., weighted or trained ensembles) (Ray et al., 2023). However, the number of submitted models meets the minimum requirement to create an effective ensemble, as demonstrated also by a recent study on optimizing the number of ensemble members (Fox et al., 2024).

Overall, we confirmed the relevance of multi-model efforts in real-time short-term forecasting of infectious diseases, applying for the first time these approaches in Italy for influenza-like illness. More broadly, Influcast is one of the first epidemic forecasting hubs built post-COVID-19 for other respiratory diseases in Europe. We hope it will serve as a model for implementing similar approaches in other countries. Besides providing short-term forecasts during the winter season to support response to respiratory disease epidemics, Influcast overarching goal is to improve outbreak preparedness by building a network of epidemic modelers and public health officials who share best practices and data. These efforts contribute to the establishment of robust collaboration pipelines that can be rapidly deployed in emergency situations.

## 4. Materials and methods

### 4.1. Forecast submission and visualization platform

The infrastructure supporting Influcast consists of two primary components: the GitHub collaborative platform, which is utilized for the submission of forecasts, and a dedicated website for visualizing the output results (InfluCast, 2024).

During the 2023/24 influenza season, participating teams submitted probabilistic forecasts on ILI incidence for the upcoming four weeks on a weekly basis. Specifically, Influcast considers the number of cases per 1000 patients reported by the network of sentinel physicians across Italy as the target variable for the forecasts. This data is communicated every Friday by the Italian National Institute of Health through the RespiVirNet bulletin (Istituto Superiore di Sanità, 2020). The incidence data published pertains to the previous week, while Influcast is updated the following Wednesday, allowing teams time to process the new data and produce new forecasts. Consequently, the forecasts published on Influcast on Wednesday refer to the previous week (for which there is no consolidated public data yet), the current week, and the next two weeks. Teams were required to submit forecasts in a standardized file format, and an automated validation process was implemented to verify the filename, contents, and compliance with the allowed submission window. Forecasts had to be provided in quantile format, with teams required to submit 23 quantiles for each forecasting horizon. Teams could choose to submit forecasts at the national level only or include subnational-level forecasts as well. Beyond the shared targets

and standardized file format, we allowed teams flexibility in other aspects, such as incorporating additional data or signals, making assumptions about data quality and revisions, and considering exogenous factors (e.g., behavior changes or seasonality) that could influence the short-term progression of the epidemic. Detailed information about the forecast format and the submission pipeline is provided on the Influcast GitHub Wiki page (Github, 2024). The Influcast GitHub repository also collects weekly surveillance data, including historical records from past seasons, for both Italy and its regions. In each round, forecasts from each model are automatically combined to produce ensemble predictions, which are stored in the repository as an additional model, alongside the baseline model (more details in Section 4.2).

The Influcast web platform features an interface allowing one to examine both individual model forecasts and the ensemble output. An example of the interface is presented in Fig. 5. Forecasts for the next four weeks from each model are represented using prediction intervals. The default values include the 90% and 50% intervals, but users can select a specific prediction interval via the menu located in the bottom right corner of the visualization. By default, the most recent forecasts are displayed. However, users can also explore forecasts from previous weeks by dragging the vertical bar on the graph. White points represent historical data that were unavailable at the time of model calibration. This approach allows for a visual assessment of each model's predictive ability, enabling verification of whether the actual data fell within the estimated prediction intervals. Through the menu on the left, users can select the geographical unit of interest, either Italy or one of its regions, as well as a specific season. Additionally, it is possible to display the predictions of multiple models by selecting them from the menu located in the bottom left corner.

### 4.2. Baseline and ensemble models

**Baseline model.** The baseline forecasting model consistently predicts a median value matching the last observed data point during the calibration period. To generate quantiles, we use the previous 1-step increments. Specifically, we compute 1-step differences up to time  $t$ :  $\delta = (d_2, d_3, \dots, d_t)$ . To ensure the median forecast matches the last calibration point, we create a symmetrized set of increments  $\delta' = (\delta, -\delta)$ . For a forecast with a maximum horizon of  $H$ , we sample  $H$  increments from  $\delta'$ . The prediction at horizon  $h$  is calculated as:  $f_h = v_t + \sum_{i=1}^h \hat{d}_i$ , where  $v_t$  is the last observed data point. Using this approach, we generate 10,000 baseline stochastic trajectories to compute quantiles and prediction intervals. We note that this baseline model is the same one used in other epidemiological forecasting challenges, such as FluSight and the US and European COVID-19 Forecasting Hubs (Mathis et al., 2024; Cramer et al., 2022; Sherratt et al., 2023).

**Ensemble model.** Individual forecasts are combined into an ensemble forecast by taking a simple average across quantiles. This method is also known as quantile averaging or Vincent method (Howerton et al., 2023). In practice, quantile of level  $q$  of the ensemble forecast at time  $t$  will be:

$$f_q^{ens}(t) = \frac{1}{M_t} \sum_{m=1}^{M_t} f_q^m(t),$$

where  $M_t$  is the number of models that submitted a forecast at time  $t$ . All models except for the baseline are included in the ensemble calculation.

### 4.3. Evaluation metrics

**Weighted Interval Score.** The Weighted Interval Score (WIS) is an approximation of the continuous ranked probability score (CRPS) (Bracher et al., 2021). For a given prediction interval  $(1 - \alpha) \times 100\%$  (e.g., 90% for  $\alpha = 0.1$ ) of a model's forecast  $F$ , the interval score is defined as:





Fig. 5. The Influcast web interface. The visualization dashboard allows displaying the four weeks ahead prediction for the ensemble and for specific models, choosing the season, the location and the prediction intervals to show.

$$IS_{\alpha}(F, y) = \begin{cases} u - l + \frac{2}{\alpha}(l - y) & \text{if } y < l, \\ u - l & \text{if } l \leq y \leq u, \\ u - l + \frac{2}{\alpha}(y - u) & \text{if } y > u, \end{cases}$$

where  $u$  ( $l$ ) represents the upper (lower) limit of the prediction interval and  $y$  is the actual observed value. The WIS generalizes the interval score to multiple prediction intervals and is defined as:

$$WIS_{\alpha_0:\alpha_K}(F, y) = \frac{1}{K + 1/2} \times \left( w_0 \times |y - m| + \sum_{k=1}^K [w_k \times IS_{\alpha_k}(F, y)] \right).$$

Here,  $K$  denotes the total number of intervals considered,  $m$  is the forecast median, and  $w_k$  are the non-negative weights assigned to the different intervals. Following a standard approach, we set  $w_0 = 1/2$ ,  $w_k = \alpha_k/2$ , and consider 11 prediction intervals ( $\alpha_k = 0.02, 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90$ ).

**Absolute Error.** Given a median forecast  $f_i$  and an actual corresponding value  $a_i$ , the absolute error is simply computed as:

$$AE = |f_i - a_i|$$

When averaged over different time steps  $i$  we obtain the mean absolute error (MAE).

**Coverage.** Prediction interval coverage is the fraction of times a prediction interval of a given level covers the observed data. Intuitively, 90% coverage is the fraction of times actual data are included in the 90% prediction interval. For a perfectly calibrated model, prediction interval coverage will be equal to the nominal coverage. Following the example, this means that exactly 90% of times points will be included in the 90% prediction interval. Mathematically, for a prediction interval of level  $\alpha$  and a set of  $N$  data points  $y_i$  it is computed as:

$$Cov_{\alpha} = \frac{1}{N} |\{i \in \{1, \dots, N\} : l_{\alpha,i} \leq y_i \leq u_{\alpha,i}\}|,$$

where  $l_{\alpha,i}$  and  $u_{\alpha,i}$  are the lower and upper limits of the prediction interval.

**Relative performance.** We apply the procedure presented in Ref. Cramer et al. (2022) to compute relative performance. For simplicity, we will present the steps to compute the relative MAE, but an analogous procedure can be performed to obtain the relative WIS. First, for each pair of model  $m$  and  $m'$ , we compute the pairwise relative MAE skill as:

$$\theta_{m,m'} = \frac{MAE_m^{avg}}{MAE_{m'}^{avg}},$$

where  $MAE_m^{avg}$  is the average MAE of model  $m$  computed using all available forecasts where both  $m$  and  $m'$  participated. Then, for each model  $m$  we compute the geometric mean of different  $\theta_{m,m'}$ :

$$\theta_m = \left( \prod_{m'=1}^M \theta_{m,m'} \right)^{1/M}.$$

Finally, for easier interpretation, we divide each  $\theta_m$  by the result of the baseline model:

$$\theta_m^* = \frac{\theta_m}{\theta_B}.$$

Then, the obtained quantity  $\theta_m^*$  represents the relative MAE of model  $m$ , adjusted for the difficulty of the forecasts it produced and rescaled such that the baseline model has a relative performance of 1. It follows that,  $\theta_m^* < 1$  indicates that model  $m$  is better than the baseline, while  $\theta_m^* > 1$  indicates that model  $m$  is worse than the baseline.

**Standardized rank.** For model  $m$ , and observation  $i$  we compute its standardized rank as:

$$rank_{m,i}^{std} = 1 - \frac{rank_{m,i} - 1}{N_i - 1},$$

where  $N_i$  is the number of models submitting forecasts for observation  $i$  and  $rank_{m,i}$  is the rank of model  $m$  and observation  $i$  according to the metric considered (WIS or absolute error). The model with lowest WIS (or absolute error) for observation  $i$  will rank first (i.e.,  $rank_{m,i} = 1$ ), therefore it will have a standardized score of 1. On the contrary, the model with the highest WIS will rank last ( $rank_{m,i} = N_i$ ) and therefore will have a standardized score of 0.

Evaluation metrics were computed using the *scoringutils* package (Bosse et al., 2022).

#### 4.4. Epidemiological data

We use data provided by the Italian National Institute of Health through their weekly bulletins (Istituto Superiore di Sanità, 2020). During the 2023/24 season in Italy, the epidemiological surveillance of respiratory diseases ran from week 42 of 2023 (ending on October 22, 2023) to week 17 of 2024 (ending on April 28, 2024). Sentinel physicians

diagnosed potential cases of influenza-like illness based on specific symptoms and reported these cases to the National Institute of Health. This data was then aggregated by the institute, which released weekly estimates of ILI incidence at both national and regional levels. Two regions, Valle d'Aosta and Calabria, did not activate epidemiological surveillance for the 2023/2024 winter season and therefore were excluded from the analysis. The data reflected the previous week; thus, the report published in week  $t$  contained data from week  $t-1$ . Weeks are defined from Monday to Sunday, and the data was subject to revision due to delays in submissions from some sentinel physicians. Historical incidence data are published on GitHub in a machine-readable format (RespiVirNet, 2020).

### CRedit authorship contribution statement

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### Declaration of competing interest

Authors declare no competing interests

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### Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.epidem.2025.100819>.

### Data availability

All forecasts are available at <https://github.com/Predizioni-Epidemiologiche-Italia/Influcast>.

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