

Flusion: Integrating multiple data sources for accurate influenza predictions

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Abstract

Over the last ten years, the US Centers for Disease Control and Prevention (CDC) has organized an annual influenza forecasting challenge with the motivation that accurate probabilistic forecasts could improve situational awareness and yield more effective public health actions. Starting with the 2021/22 influenza season, the forecasting targets for this challenge have been based on hospital admissions reported in the CDC’s National Healthcare Safety Network (NHSN) surveillance system. Reporting of hospital admissions through NHSN began during the COVID pandemic, and as such NHSN has only a limited amount of historical data about influenza hospitalizations. To produce forecasts in the presence of limited data for the target surveillance system, we augmented these data with two signals that have a longer historical record: 1) ILI+, which estimates the proportion of outpatient doctor visits where the patient has influenza; and 2) rates of laboratory-confirmed influenza hospitalizations at a set of sentinel healthcare facilities. Our model, Flusion, is an ensemble model that combines a Bayesian autoregressive model with two machine learning models using gradient boosting for quantile regression based on different feature sets. All of these component models are trained on all three data signals. In each week of the influenza season, the models produce quantiles of a predictive distribution for influenza hospital admissions in each state in the current week and the following three weeks; the ensemble prediction is computed by averaging these predictions. Flusion emerged as a top-performing model in the CDC’s influenza prediction challenge for the 2023/24 season. In this article, we elucidate the factors contributing to its success.

1 Introduction

There is a long history of forecasting seasonal influenza, often through formal collaborative forecasting exercises organized by the US Centers for Disease Control and Prevention (CDC).

- Long history going back 10 years
- After a pause during the first two years of the COVID-19 pandemic, this forecasting exercise restarted in the 2022/23 flu season.

A challenge in recent forecasting exercises is that new data streams have come online which are being used as the “ground truth” target for these forecasting exercises. These data sources have been great in many ways, but the lack of an extensive history of data for model training introduces difficulty for learning about seasonal patterns in flu. To address this challenge, this season we developed a new model, called ‘flusion’, which pulls in data from external data sources with a long history

of observations. This model was the top-performing model that was contributed to the FluSight Forecast Hub in the 2023/24 influenza season. The purpose of this paper is to describe that model and investigate what aspects of its design were associated with its strong performance.

Relevant literature to review, 1 paragraph each:

- methods for infectious disease forecasting, including methods that integrate multiple data sources.
 - David Farrow cmu thesis on data fusion
 - maybe papers using surveillance signals like Quidel?
 - maybe some covid papers using things like mobility data
- forecasting with gradient boosting.
 - Russ’s paper
 - M5 results paper
- transfer learning/data fusion
 - will need to look into options

2 Data Sources

Our model uses influenza data from four data sources, which are combined to produce three signals measuring the intensity of influenza activity over time and space:

- ‘NHSN’: Influenza hospital admissions as reported at the state level in a data set that is collected as part of the National Healthcare Safety Network (NHSN)
- ‘FluSurv’:
- ‘ILI+’: An approximate measure of the proportion of outpatient doctor visits where the patient has influenza. This is derived by combining measures of influenza-like illness from ILINet (defined symptomatically, may not be influenza) with influenza test positivity rates from WHO/NREVSS

Figure 1:

- original and adjusted data for selected locations
- transformed data, on same scale

3 Model

Our model was constructed as an ensemble of statistical time series and machine learning models. We describe the component models in sections ?? and ?? and the ensemble methods in section ?. The precise formulation of the models included in the ensemble and the ensembling methods varied slightly over the course of the season, and we describe these aspects of our setup for generating real-time predictions in section ?.

3.1 Component Models 1 and 2: GBM

The GBM models learn a mapping from features x_i to prediction target y_i , where i indexes a combination of location $l(i)$, data source $s(i)$, reference date $d(i)$, and forecast horizon $h(i)$. Specifically, we fit 23 quantile regression models, one for each required quantile level $\alpha_k, k = 1, \dots, 23$, using the pinball loss as the learning objective. Models are fit using the LightGBM package in Python with default settings for all hyperparameters. The final prediction at each quantile level is obtained using bagging, by taking the median of predictions from 100 separate fits, where each fit is based on a randomly selected 70% of the seasons in the training set (including partial data for the current season).

The models are trained simultaneously for all locations, data sources, and forecast horizons. However, the features x_i contain information only about influenza activity for the particular location $l(i)$ and data source $s(i)$. We emphasize that inclusion of multiple locations and data sources in the training data set allows the model to use past examples from multiple locations and data sources to learn a mapping from x to y , but in our model setup, predictions of NHSN admissions in a particular location are not informed by contemporaneous observations of NHSN admissions in other locations or by contemporaneous observations of other surveillance signals in that same location. The use of contemporaneous observations from other locations or signals to inform predictions remains a topic for future work.

Both the features x_i and the prediction targets y_i are calculated based on a transformed version of the original surveillance signal. Denote the value of a particular surveillance signal s in location l at time t by $z_{l,s,t}$. We apply the following operations to compute the transformed version of the signal, $\tilde{z}_{l,w,t}$:

1. For NHSN admissions, we divide by the population of the location l in units of 100,000 people to convert to a hospital admissions rate per 100,000 population, which is comparable across locations of different sizes. The ILI+ and FluSurv signals are naturally expressed as rates or percents that are comparable across locations.
2. We take a fourth root transformation to stabilize the variance of the signal across times of low and high influenza activity.
3. We scale by dividing by the 95th percentile of all observations for each location and data source, and center by subtracting the mean for each location and data source. These transformations adjust for varying magnitudes of the surveillance signals for different data sources and locations.

The resulting transformed data used as an input to the model are shown in Figure ***.

The prediction target y_i is the difference between the transformed signal value on the target date, $d(i) + h(i)$, and the date of the last available reported data. A prediction of this target is converted to a prediction on the original scale by adding the last observed value and inverting the initial data transformation operations described above.

The primary GBM model is fit to the following 114 features:

1. A one-hot encoding of the data source.
2. A one-hot encoding of the location.
3. A one-hot encoding of the spatial scale of the location ("state", "region", or "national").
4. The population of the location.

5. The difference between the week of the season with the most recent reported data and Christmas week; for instance, a value of 3 means that the most recent data report are for the week three weeks after Christmas.
6. The coefficients of a degree 2 Taylor polynomial fit to the trailing w weeks of data, where $w \in \{4, 6\}$, with the reference point for the polynomial set to the time $d(i)$. These coefficients are estimates of the local level, first derivative, and second derivative of the signal at the time $d(i)$.
7. The coefficients of a degree 1 Taylor polynomial fit to the trailing w weeks of data, where $w \in \{3, 5\}$. These coefficients are estimates of the local level and first derivative of the signal at the time $d(i)$.
8. The rolling mean of the signal over the last w weeks, where $w \in \{2, 4\}$.
9. The values all features from points 6, 7, and 8 at lags 1 and 2, representing estimates of the local level and first and second derivatives of the signal in each of the previous two weeks.
10. The forecast horizon.

Measures of the local level of the surveillance signal (i.e., rolling means and the intercepts of Taylor polynomial fits) had a high feature importance in the primary GBM model; see section *** below for more detail. Starting the week of ***, we fit a second variation on the GBM model that was not allowed to see these “local level” features. This was motivated by two considerations: (1) a model fit without features that had high importance in the primary GBM model might introduce more model diversity to the fusion ensemble; and (2) in seasons with particularly high or low incidence, measures of local level might not be a reliable indicator of the magnitude and direction of changes in future values.

- supplemental figure showing some feature values from roll mean, taylor coeffs

3.2 Component Model 3: ARX

We have implemented a seasonal auto-regressive integrated time series model with external covariates (SARIX). Development of this model is in progress, and we have not carefully evaluated many of the modeling decisions that have been made for this component. Here we describe the state of the model as it was used for real-time forecasting during the 2023/34 influenza season; there are many potential refinements to this model setup, but those extensions are deferred to future work.

The ARX model is trained jointly on data for all locations and all influenza signals (NHSN, ILI+, and FluSurv). However, as with the GBM models, the ILI+ and FluSurv signals are not used as real-time covariates measuring trends in influenza prevalence in the current season to inform NHSN predictions. Rather, those signals are used to provide additional training data to help inform estimation of parameters describing influenza dynamics. Our single covariate is a spike function indicating proximity to the week of Christmas, taking the value

It is worth highlighting a few ways in which our ARX model differs from standard implementations. In our setup, the autoregressive coefficients are shared across locations and datasets, while each location is assigned a separate variance parameter for innovations. Additionally, unlike many ARX model specifications, our model does not take future values of the covariates as known, but rather it predicts

those covariates alongside the primary prediction target. In our current modeling setting, this behavior is not ideal; remedying this to allow for the provision of known future values of covariates is on a short list of model improvements to make.

1. We take a Bayesian approach

3.3 Ensembling Methods: Quantile averaging and linear pools

3.4 Model adjustments used for real time forecasts

4 Evaluation metrics

In the sections below, we evaluate forecasts using three metrics: the mean absolute error (MAE) of the predictive median, the weighted interval score (WIS), and one-sided quantile coverage rates. MAE measures the average distance between the predictive median and the eventual observation. WIS can be viewed as a generalization of the absolute error to a set of quantile predictions, and is equivalent to an average of quantile scores (sometimes referred to as pinball losses) computed for each quantile prediction. The quantile score for a single quantile prediction assigns an asymmetric penalty to the distance between the prediction and the observation, with the magnitudes of the penalties for underprediction and overprediction set so that in expectation, the quantile score is minimized by the quantile of the predictive distribution at a specified quantile level. The quantile score for the quantile level 0.5 is equivalent to the absolute error.

We also compute relative versions of MAE and WIS.

5 Real-time performance: the 2023/24 season

In this section, we summarize model performance results for real-time submissions to the FluSight Forecast Hub in the 2023/24 season.

5.1 Evaluation setup

To avoid distortion of WIS and AE results, we did not evaluate forecasts that were made at the national level. Although the FluSight forecast hub originally allowed for collection of predictions at a “horizon” of -1 week, these were discontinued; our analysis includes predictions made at horizons of 0 weeks (“nowcasts”), and predictions at horizons of 1, 2, and 3 weeks ahead relative to the reference date.

We included all models that contributed forecasts for at least 75% of the combinations of state-level locations, reference dates, and non-negative horizons for which the Hub collected forecasts over the course of the season. Because a comprehensive evaluation of all Hub contributors is not the aim of this manuscript, we have anonymized the names of other individually-contributed models in these results to focus attention on the comparisons that are of interest for our purposes.

The FluSight hub produced two ensemble forecasts during the season: one using a quantile averaging approach and one using a linear pool. These two ensembles had similar performance, though the linear pool had slightly better calibration. However, the quantile averaging ensemble was used by CDC as the source of official communications throughout the season, and so we include results from only that ensemble here.

We also included results from two baseline methods. **Baseline-flat** is a random walk model produced by the Hub (labeled as **FluSight-baseline** in Hub submissions), which produces forecasts that extend from the most recent observation in a flat line, with expanding uncertainty based on historical differences in weekly hospital admissions. In this method, for each location i the historical differences $\delta_{i,t} = y_{i,t} - y_{i,t-1}$ are collected, along with their negative values $-\delta_{i,t}$ (a process which we refer to as “symmetrizing” the differences). Forecasts at multiple step-ahead horizons are generated by iteratively sampling from this collection of symmetrized weekly differences.

The second baseline method, **Baseline-trend**, follows a similar process with a few modifications that are designed so that the resulting forecasts tend to follow the trend of recent observations. It is a quantile averaging ensemble of 16 variations on the baseline method. Most importantly, it incorporates variations that do not symmetrize the past differences, and rather than using all available history, it collects differences in a rolling window of the past few weeks. The 16 variations are obtained by using different options for the rolling window size, the temporal resolution of data used as an input (daily or weekly), a data transformation that is applied (no transformation or square root), and whether or not symmetrization is used. We emphasize that although this baseline is more methodologically involved than **Baseline-flat**, it produces an epidemiologically naive forecast that pushes forward a local estimate of the trend observed over the few most recent weeks. This model is named **UMass-trends_ensemble** in real-time Hub submissions.

5.2 Evaluation results

Forecasts from the Flusion model often appeared similar to forecasts from the FluSight-ensemble, though in several states (e.g. Florida, California, and New York) Flusion did a better job of capturing the increase in weekly hospital admissions in the early part of the season and a slightly better job of predicting the turnaround after the peak in late December (Figure 1). Qualitatively, it appears that both the FluSight-ensemble and the Flusion model captured trends in hospital admissions better than the baseline models during all phases of the season – during the rise in the early part of the season, near the peak, and on the way down. TODO: add discussion of failure after holidays/before next rise.

Aggregating across all forecast dates and forecast horizons, the Flusion model had the best performance as measured by RWIS and RAE among all models that contributed to the FluSight Forecast Hub (Table 4). The Flusion model was consistently among the top-ranking models contributing to the forecast hub for individual forecast reference dates and forecast horizons (Figure 2 (b)).

Additionally, while its prediction interval coverage rates tended to be underconfident (i.e., prediction intervals were too wide on average), the 95% PI coverage rates for Flusion came closest to the nominal coverage rate among all models (Table 4). An examination of one-sided quantile coverage rates confirms that Flusion was unique among models contributed to the Hub in that its coverage rates for high quantile levels were too high (indicating that the upper tail of the predictive distributions tended to fall above the eventually observed data more often than expected), while nearly all other models missed in the upper tails more often than expected (Figure 2 (c)). Overall, the probabilistic calibration of the Flusion model was comparable to or better than that of other models contributed to the Hub, and it was superior to the calibration of the baseline and ensemble models.

TODO: Supplemental analysis with similar results, omitting forecasts affected by data revisions?

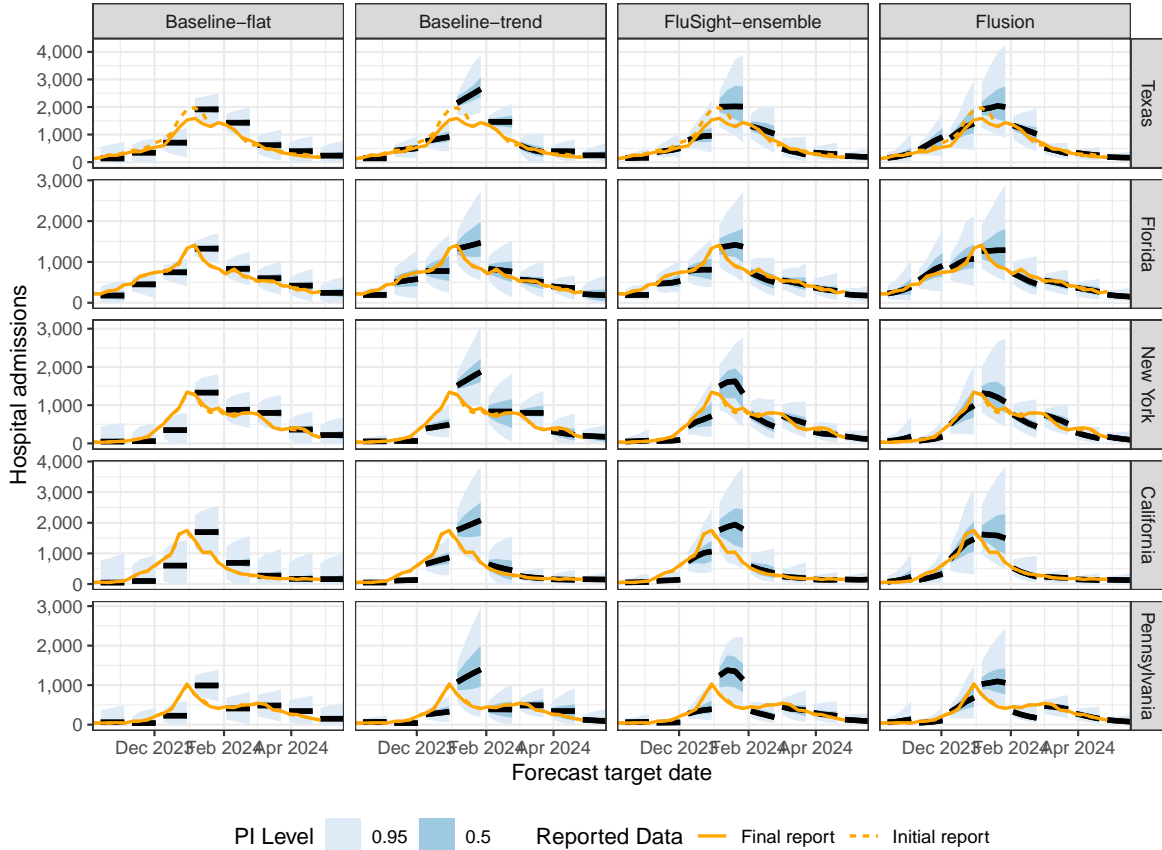


Figure 1: Influenza data and forecasts for the five states with the largest cumulative hospital admissions during the 2023/24 season. To avoid overplotting, in this figure forecasts from every fourth reference date are shown; evaluations include all reference dates. Forecasts are represented by the predictive median (black lines) and 50% and 95% prediction intervals (blue shaded regions). Solid orange lines show the finalized admission counts reported as of TODO, while dotted orange lines show the initial reported values that were available on the date predictions were generated.

6 Post hoc model exploration

In this section, we investigate the degree to which the following aspects of the Flusion model contributed to its strong performance: 1. the formulation of Flusion as an ensemble of three individual models; 2. joint training on multiple data sets and multiple locations; 3. data preprocessing, including corrections for reporting inconsistencies in the ILINet and FluSurvNET data, the use of a fourth root data transform, and the importance of the features we used

6.1 Component models and ensembling

To investigate the skill of our individual component models and the added value of ensembling, we computed scores for each of the three component models that were members of the Flusion ensemble and for ensembles formed using two of the three components. As documented in section 3 the component models and ensembling method that we used in real time changed over the course of the season. To enable a clearer understanding of the contributions of these models, the results we present here are based on the specifications of the individual GBQ, GBQ-no-level, and ARX models and the quantile averaging ensemble method that were used for the Flusion model starting the week of December 2,

Model	% Submitted	MWIS	RWIS	MAE	RAE	50% Cov.	95% Cov.
Flusion	99.9	29.6	0.610	45.6	0.670	0.583	0.967
FluSight-ensemble	100.0	35.5	0.731	55.4	0.814	0.516	0.926
Other Model #1	100.0	35.6	0.731	54.0	0.792	0.558	0.940
Other Model #2	89.1	40.4	0.773	61.5	0.840	0.479	0.908
Other Model #3	97.8	39.9	0.806	59.3	0.857	0.363	0.793
Other Model #4	100.0	40.0	0.823	60.5	0.890	0.497	0.884
Other Model #5	67.3	45.0	0.827	68.7	0.899	0.487	0.866
Other Model #6	100.0	41.5	0.851	64.4	0.945	0.466	0.903
Other Model #7	85.5	45.7	0.852	66.1	0.878	0.418	0.824
Other Model #8	100.0	41.6	0.856	60.7	0.893	0.460	0.855
Other Model #9	100.0	42.1	0.865	60.9	0.894	0.442	0.827
Other Model #10	98.8	44.3	0.901	67.7	0.986	0.456	0.939
Baseline-trend	99.9	43.9	0.906	67.0	0.990	0.618	0.922
Other Model #11	95.7	45.0	0.908	66.2	0.956	0.554	0.870
Other Model #12	87.0	45.0	0.936	70.7	1.050	0.449	0.929
Other Model #13	96.4	42.4	0.948	64.2	1.030	0.429	0.896
Other Model #14	93.6	48.7	0.980	70.8	1.020	0.473	0.838
Other Model #15	99.2	47.3	0.993	58.1	0.870	0.596	0.793
Baseline-flat	100.0	48.5	1.000	67.9	1.000	0.282	0.888
Other Model #16	72.2	59.1	1.010	87.1	1.060	0.416	0.823
Other Model #17	96.3	51.8	1.040	65.3	0.934	0.242	0.751
Other Model #18	98.2	51.3	1.040	73.0	1.060	0.395	0.773
Other Model #19	76.7	61.9	1.090	87.8	1.100	0.288	0.717
Other Model #20	84.2	52.6	1.150	72.0	1.130	0.368	0.768
Other Model #21	85.1	57.8	1.180	73.2	1.070	0.316	0.615
Other Model #22	88.3	61.3	1.180	89.1	1.230	0.377	0.802
Other Model #23	69.0	42.6	1.280	59.0	1.270	0.386	0.772
Other Model #24	85.5	65.2	1.300	83.5	1.200	0.219	0.494
Other Model #25	92.5	80.2	1.550	110.0	1.520	0.389	0.821
Other Model #26	92.6	126.0	2.540	154.0	2.220	0.174	0.429

Table 1: Overall evaluation results for forecasts submitted to the FluSight Forecast Hub. Model names other than **Flusion**, **FluSight-ensemble**, **Baseline-flat**, and **Baseline-trend** are anonymized. The percent of all combinations of location, reference date, and horizon for which the given model submitted forecasts is shown in the “% Submitted” column; only models submitting at least 2/3 of forecasts were included. Results for the model with the best MWIS, RWIS, MAE, and RAE are highlighted. Results for the models where empirical PI coverage rates are closest to the nominal levels are highlighted.

2023. In instances where predictions from one or more component models were not created in real time, we created post hoc model fits and predictions using the data that would have been available in real time.

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Model	% Submitted	MWIS	RWIS	MAE	RAE	50% Cov.	95% Cov.
GBQ, ARX	100.0	29.9	0.618	45.3	0.668	0.570	0.958
Flusion	100.0	30.2	0.622	46.6	0.686	0.558	0.963
GBQ	100.0	30.3	0.625	46.3	0.682	0.529	0.947
GBQ, GBQ-no-level	100.0	30.4	0.628	47.1	0.694	0.546	0.958
GBQ-no-level, ARX	100.0	33.2	0.685	52.2	0.769	0.528	0.958
GBQ-no-level	100.0	33.9	0.698	52.6	0.775	0.523	0.944
ARX	100.0	39.5	0.815	60.0	0.884	0.485	0.917
Baseline-flat	100.0	48.5	1.000	67.9	1.000	0.282	0.888

Table 2: Evaluation results for individual component models in the Flusion ensemble, ensembles of pairs of components, and the full Flusion ensemble, with the flat baseline as a reference. The percent of all combinations of location, reference date, and horizon for which the given model submitted forecasts is shown in the “% Submitted” column; only models submitting at least 2/3 of forecasts were included. Results for the model with the best MWIS, RWIS, MAE, and RAE are highlighted. Results for the models where empirical PI coverage rates are closest to the nominal levels are highlighted.

Model	% Submitted	MWIS	RWIS	MAE	RAE	50% Cov.	95% Cov.
GBQ	100.0	30.3	0.625	46.3	0.682	0.529	0.947
GBQ-by-location	100.0	37.8	0.780	57.9	0.854	0.327	0.891
GBQ-only-NHSN	100.0	41.5	0.857	63.7	0.939	0.361	0.838
Baseline-flat	100.0	48.5	1.000	67.9	1.000	0.282	0.888

Table 3: Evaluation results for the GBQ model, which is trained jointly on data for all locations and data sources, and variations trained separately for each location (GBQ-by-location) and trained only on hospital admissions from NHSN (GBQ-only-NHSN). The percent of all combinations of location, reference date, and horizon for which the given model submitted forecasts is shown in the “% Submitted” column; only models submitting at least 2/3 of forecasts were included. Results for the model with the best MWIS, RWIS, MAE, and RAE are highlighted. Results for the models where empirical PI coverage rates are closest to the nominal levels are highlighted.

Model	% Submitted	MWIS	RWIS	MAE	RAE	50% Cov.	95% Cov.
GBQ-no-reporting-adj	100.0	29.1	0.600	44.4	0.654	0.510	0.940
GBQ	100.0	30.3	0.625	46.3	0.682	0.529	0.947
GBQ-no-transform	100.0	31.1	0.642	48.0	0.708	0.497	0.948
Baseline-flat	100.0	48.5	1.000	67.9	1.000	0.282	0.888

Table 4: Evaluation results for the GBQ model, which makes use of reporting adjustments designed to improve the degree to which ILINet and FluSurvNET data reflect influenza activity as well as a fourth-root power transform, and variations that do not incorporate reporting adjustments (GBQ-no-reporting-adj) or a fourth-root transform (GBQ-no-transform), along with the flat baseline as a reference. The percent of all combinations of location, reference date, and horizon for which the given model submitted forecasts is shown in the “% Submitted” column; only models submitting at least 2/3 of forecasts were included. Results for the model with the best MWIS, RWIS, MAE, and RAE are highlighted. Results for the models where empirical PI coverage rates are closest to the nominal levels are highlighted.

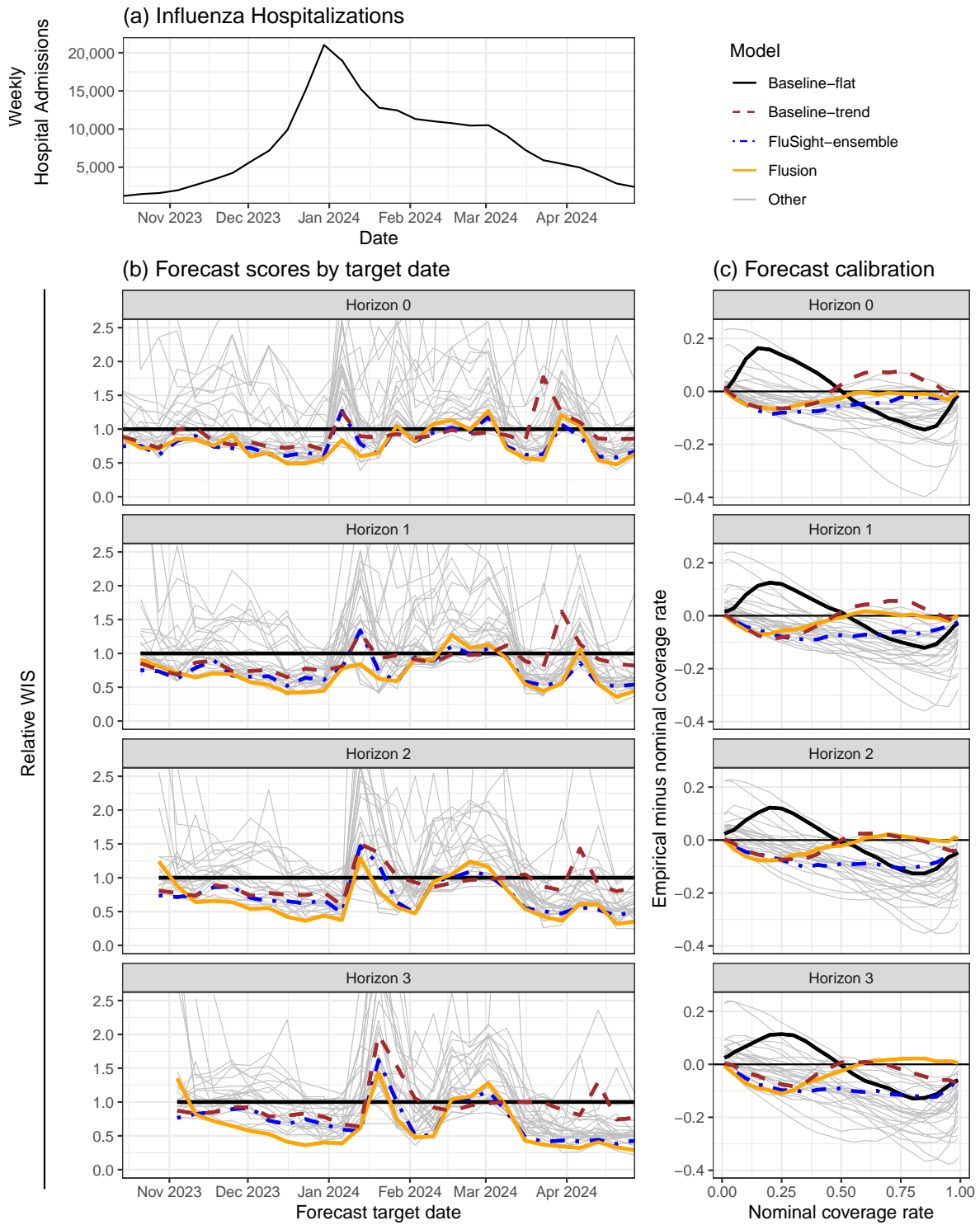


Figure 2: Influenza data and evaluation results. Panel (a): Target influenza hospital admissions data for the 2023/24 season, aggregated across all forecasted state-level geographic units. Panel (b): RWIS for models contributing to the FluSight Forecast Hub, stratified by forecast horizon (panels) and target date (horizontal axis). Lower relative WIS indicates better forecast performance. To focus on areas of interest, RWIS values greater than 2.5 are not displayed. Panel (c): One-sided quantile coverage differential, computed as empirical coverage rate minus nominal coverage rate. A well-calibrated model has a differential of 0, while a conservative method (with wide prediction intervals) has a negative differential at nominal coverage rates that are less than 0.5 and a positive differential at nominal coverage rates greater than 0.5. In panels (b) and (c), we highlight performance for the Flusion model, two baselines, and the FluSight ensemble; results for other models contributed to the hub are shown in light grey.