

Estimating the Prevalence and Mortality of Coronavirus Disease 2019 (COVID-19) in the USA, the UK, Russia, and India

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Objective: The aim of this study is to apply the advanced error-trend-seasonal (ETS) framework to forecast the prevalence and mortality series of COVID-19 in the USA, the UK, Russia, and India, and the predictive performance of the ETS framework was compared with the most frequently used autoregressive integrated moving average (ARIMA) model.

Materials and Methods: The prevalence and mortality data of COVID-19 in the USA, the UK, Russia, and India between 20 February 2020 and 15 May 2020 were extracted from the WHO website. Then, the data subsamples between 20 February 2020 and 3 May 2020 were treated as the training horizon, and the others were used as the testing horizon to construct the ARIMA models and the ETS models.

Results: Based on the model evaluation criteria, the ARIMA (0,2,1) and ETS (M,MD,N), sparse coefficient ARIMA (0,2,(1,6)) and ETS (A,AD,M), ARIMA (1,1,1) and ETS (A,MD,A), together with ARIMA (2,2,1) and ETS (A,M,A) specifications were identified as the preferred ARIMA and ETS models for the prevalence data in the USA, the UK, Russia, and India, respectively; the ARIMA (0,2,1) and ETS (M,A,M), ARIMA (0,2,1) and ETS (M,A,N), ARIMA (0,2,1) and ETS (A,A,N), coupled with ARIMA (0,2,2) and ETS (M,M,N) specifications were selected as the optimal ARIMA and ETS models for the mortality data in these four countries, respectively. Among these best-fitting models, the ETS models produced smaller forecasting error rates than the ARIMA models in all the datasets.

Conclusion: The ETS framework can be used to nowcast and forecast the long-term temporal trends of the COVID-19 prevalence and mortality in the USA, the UK, Russia, and India, and which provides a notable performance improvement over the most frequently used ARIMA model. Our findings can aid governments as a reference to prepare for and respond to the COVID-19 pandemic both in restricting the transmission of the disease and in lowering the disease-related deaths in the upcoming days.

Keywords: coronavirus disease 2019, outbreak, ARIMA model, ETS model, epidemiological indicators, nowcasting

Introduction

Coronavirus disease 2019 (COVID-19) is an acute respiratory contagious disease caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2).^{1,2} This disease was considered to be first detected in the city of Wuhan, China, in December 2019. Since then, COVID-19 has spread rapidly from almost every corner of the world, and, currently, has been presenting a global pandemic that leads to a great tragedy.³ As of May 15, 2020, the number of confirmed COVID-

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19 cases has totaled 4,338,658 notifications and has caused 297,119 deaths in 213 countries, areas or territories worldwide.⁴ Furthermore, it is likely that numerous infected individuals failed to be found because of the limited epidemiological surveillance and detection capabilities on the global scale.³ Unfortunately, there is a present scarcity of the determined clinical treatment for this disease. In this case, accurate forecasting for the upcoming daily prevalence and mortality cases can contribute to plan the health infrastructure and services under dynamic demand and to guide emergency preparedness effectively in responding to the disease outbreak.

Time series analysis based on mathematical models is of great value in constructing hypotheses to show inherent patterns and underlying structures based on the prevalence and mortality data, and to predict the epidemics of diseases.^{3,5-7} Also, stakeholders can apply the time series from the past and present outbreaks to forecast prevalence rates and then identifying how to limit the spread of the virus, and ultimately introducing the most effective vaccination policies.⁵ Numerous modeling techniques (such as machine learning method,⁸ general linear model,⁹ spatio-temporal approach,⁵ artificial neural networks (ANNs),¹⁰ grey GM (1,1) model,¹¹ autoregressive integrated moving average (ARIMA),¹² support vector machine (SVM) regression model,¹³ multivariate time series analysis,¹⁴ and susceptible-exposed-infectious-recovered (SEIR) model)¹⁵ that serve as helpful policy-supportive tools have been utilized to model and estimate the epidemic patterns and even the outbreak of infectious diseases. Among which, the most commonly adopted methods for various predictive objectives are either the linear models (such as general linear model, GM (1,1), and ARIMA) or the nonlinear models (such as SVM and ANNs).^{12,16} Epidemics of infectious diseases are often affected and restricted by varying influencing factors (such as meteorological factors, variations in pathogens, or policy interventions),¹⁷⁻²⁰ which means that the epidemic patterns contain both linear and nonlinear components (that is, including both tendencies and randomness).^{3,19} Under this condition, the basic linear or nonlinear approaches are only sufficient to uncover the epidemic tendencies or randomness, which limits the generalization ability of these basic models.

Over the last decades, though the popular exponential smoothing (ES) approaches under a linear assumption have extensively been adopted for different predictive purposes,²¹ paralleling the methodological developments,

researchers have relaxed the linear assumption of the ES approaches by embedding them in a modern nonlinear model framework, called Error-Trend-Seasonal (ETS) framework (which signifies the three traits including error, trend, and seasonality of a time series).²²⁻²⁶ Such a framework may be more suitable for handling such data with different traits because they take into consideration the possible additive or multiplicative combinations of the secular trend, seasonal pattern, and random disturbances of the data with 30 candidate models.^{19,22,26,27} Recently, researchers have shown an increased interest in the domain of forecasting (such as the forecast for the electricity consumption,²⁸ electricity generation,²⁹ bond yields,²⁹ the number of tourists,²⁹ acute hemorrhagic conjunctivitis incidence,²⁵ and tuberculosis incidence)²² with the ETS framework due to its so many advantages. The ETS models are greatly helpful in capturing the dynamic dependence structure of a target series, considering the rapid fluctuation, changing trends, cyclic variation, and random fluctuation in the given series.

Most recently, a large number of models have been used to nowcast and forecast the epidemic patterns of COVID-19 pandemic around the world, such as ARIMA model,^{3,30-32} machine-learning model,⁸ spatiotemporal approach,⁵ Bats-Hosts-Reservoir-People transmission network model,³³ data mining approach based on a 3rd degree polynomial curve,⁷ SEIR or SIR model,^{18,34} internet search-interest based model,⁹ ad hoc,³⁵ fixed-effects linear model,³⁶ adaptive neuro-fuzzy inference system (ANFIS) model,³⁷ etc. However, most of these models are focused on a short-term estimation for the COVID-19 incidence, mortality, or prevalence, and they can only unearth the linear or nonlinear components in a given series. There is a need to construct a statistical model that can consider both linear and nonlinear components in a target time series simultaneously to assess the epidemic situations and trends of COVID-19. So far, there are no studies that use the ETS framework to estimate the COVID-19 prevalence and mortality. Therefore, in view of the advantages of the ETS framework and the current epidemic status of COVID-19 with the rapidly increased cases per day in the USA, the UK, Russia, and India,⁴ the aim of this work is to use the ETS framework to analyze the epidemic situation of COVID-19 and to nowcast and forecast the temporal trends of COVID-19 prevalence and mortality in the USA, the UK, Russia, and India. Also, we compared the predictive performance of the ETS framework with the most used ARIMA model in the field of time series prediction. The results will provide

a scientific basis for defining strategic choices both in limiting the transmission of COVID-19 and in lowering the disease-related incidence and mortality.

Materials and Methods

Data Collection

The number of clinically diagnosed or laboratory-confirmed COVID-19 cases and deaths by countries, territories or areas must be reported to the WHO per day, so we extracted the key epidemiological indicators of COVID-19 (such as prevalence, mortality, incidence, and fatality cases) in the USA, the UK, Russia, and India between 20 February 2020 and 15 May 2020 from the WHO website (<https://www.who.int/emergencies/diseases/en/>). As shown in Figure 1, during the study period, the number of confirmed COVID-19 cases totaled 1,361,522 notifications with a daily average of 15,832 cases in the USA, 233,155 notifications with a daily average of 2712 cases in the UK, 262,843 notifications with a daily average of 3056 cases in Russia, and

81,970 notifications with a daily average of 954 cases in India. The number of deaths owing to COVID-19 totaled 83,543 notifications with a daily average of 972 cases in the USA, 33,614 notifications with a daily average of 391 cases in the UK, 2418 notifications with a daily average of 29 cases in Russia, and 2649 notifications with a daily average of 31 cases in India.

Ethics Statement

The study protocol was approved by the research institutional review board of the Xinxiang Medical University (No: XYLL-2019072), and it is exempt from the institutional review board assessment since all data are publicly available. Besides, this research meets all the guidelines in the Declaration of Helsinki.

ARIMA Model

The ARIMA model, also known as the Box–Jenkins model, has been identified as being the most common forecasting tool as it has the advantages of simple

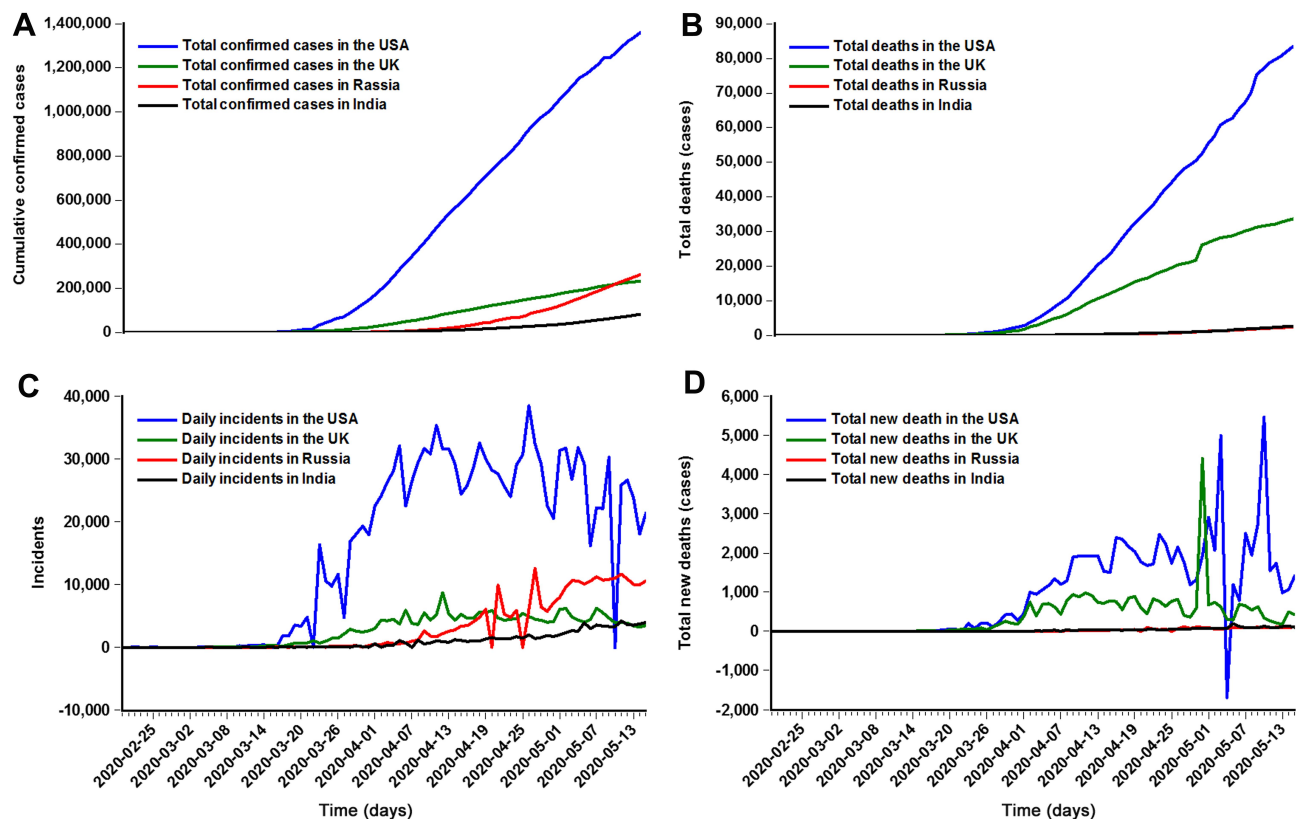


Figure 1 Time series displaying the prevalence and mortality cases of the COVID-19 in the USA, the UK, Russia, and India. **(A)** The total confirmed cases in the USA, the UK, Russia, and India. **(B)** The total deaths in the USA, the UK, Russia, and India. **(C)** The daily incidents in the USA, the UK, Russia, and India. **(D)** The total new deaths in the USA, the UK, Russia, and India. Note, there were some data that were displayed as negative values in the “new cases” or incidents owing to the recent trend of countries performing data reconciliations, some cases or deaths were thus removed from the total notifications. So the total confirmed cases and the total deaths were retrospectively updated based on the additional details available provided by WHO when we constructed the ARIMA and ETS models, in order to obtain accurate and reliable forecasts for the coming days.

structure, predictive stability, and ability to well explain the given series.^{3,38} The traditional ARIMA model can be listed using the standard notation of ARIMA (p, d, q), where p denotes the order of autoregressive parameters, d denotes the degree of differencing, and q denotes the order of moving average parameters.¹² In application, the ARIMA model was often constructed following four key steps (Figure S1): First, checking the stationary of the target series. We determined the stationary of the target series by a visual inspection of the sequence plot and the Augmented Dickey–Fuller (ADF) test, if the series exhibits a clear upward or downward trend and the ADF statistic indicates a *p*-value greater than 0.05, meaning that the series is non-stationary.^{16,30} In this scenario, the series should be square root- or log-transformed, and/or be differenced in order to suit the requirement of stationary for the ARIMA-developing model.²² Second, estimating the model fit. The possible p and q values were identified roughly by plotting the autocorrelation function (ACF) and partial ACF (PACF) graphs on the basis of the stationary series.³⁰ As such, some candidate models were chosen. Of them, the one that has the largest values of R-square (R^2) and stationary R^2 , as well as the lowest normalized Bayesian information criterion (NBIC) value was deemed as the best-fitting model.³⁹ Third, checking the goodness of fit measures for the optimal model. The determined key parameters of the best-mimicking ARIMA model indicated a significantly statistical difference and the produced error series displayed a white noise under the Ljung–Box Q test, intimating that the selected model is adequate for modeling the temporal dependence structure of the prediction object.⁴⁰ Otherwise, the above steps should be repeated until a suitable model was detected. Finally, the best-conducting ARIMA model created can be applied to produce forecasting into the future.⁴¹

ETS Model

Typically, a time series is composed of three components, including the secular trend (T), seasonality (S), and error (E).^{3,23} Among them, the trend component reflects the secular movement of the given series, the seasonal component characterizes a pattern with known cyclicality, and the random disturbances represent the irregular and unpredictable traits of the series.²⁸ Moreover, these three components may be combined in different additive or multiplicative combinations to generate the original series Y, which may only have an additive model like $Y=T+S+E$ or $Y=S+E$, a pure multiplicative model, say $Y=T \cdot S \cdot E$ or $Y=S \cdot E$, or

models that are comprised of the above mixture, as in $Y=(T \cdot S)+E$ or $Y=(T+S)(1+E)$.^{24,29,42,43} Under these scenarios, the other frequently used models may be incapable of capturing the potential relationships in the time series owing to their linear or nonlinear assumptions.²² In contrast to the basic linear or nonlinear models, the ETS framework provides an expansion for the basic ES approaches and a theoretical foundation for the estimate of the basic ES approaches with state-space based likelihood calculations,^{22,26} and moreover, this framework supports model choice and estimation of predictive standard errors. By doing so, not only will the ETS models be able to reflect the internal rules of the target series but they are also able to explore the dynamic association between the internal rules and the external outputs, and can to describe the internal rules of the target series with the present and past minimum information.^{21,24} These enable the ETS models to have the ability to model any given series even with both heterogeneity and non-linearity and to perform a long-run forecast for the given series. The individual components of an ETS specification are summarized in Table 1. For any ETS models, their parameters and values for the initial states can be expressed as being of the form: $\theta^* = (\alpha, \beta, \gamma, \varphi)$ and $x_0^* = (l_0, b_0, s_0, s_{-1}, \dots, s_{-m+1})$, respectively, where l_0 is the level term of the trend which is invariably present, b_0 is the growth term of the trend which may be present depending on the trend specification, s denotes the seasonal term of the target series, and m represents the periodic length of the target series. Often, for a classical curve of an epidemiological outbreak of infectious diseases (spark-growth-peak-decrease), its growth rate at the end of the past series is unlikely to continue more than a short time into the future. At this time, the ETS model with a damped trend term is greatly suitable when the long-term trend is included in the target time series because it can dampen the trend with the length of the forecast horizon increases, which can frequently favor the improvement of the predictive ability of the ETS models.²⁴ Of the above 30 possible methods, we determined which one more closely simulates the target series by comparing the goodness of fit measures across models, including the Akaike Information Criterion (AIC), the Schwarz Information Criterion (BIC), the Hannan–Quinn Criterion (HQ), the average mean square error (AMSE), and the Log-likelihood (LL).^{22,25} The specification with lower values of the AIC, BIC, HQ, and AMSE, as well as a higher LL value, was recommended as the preferred.

Table 1 The 30 Possible ETS Models in Relation to Different Combinations of Trend, Seasonality and Residual

Trend Component	Seasonal Component		
	N (None)	A (Additive)	M (Multiplicative)
ETS models with additive patterns			
N (None)	N,A,N	N,A,A	N,A,M
A (Additive)	A,A,N	A,A,A	A,A,M
AD (Additive damped)	AD,A,N	AD,A,A	AD,A,M
M (Multiplicative)	M,A,N	M,A,A	M,A,M
MD(Multiplicative damped)	MD,A,N	MD,A,A	MD,A,M
ETS models with multiplicative patterns			
N (None)	N,M,N	N,M,A	N,M,M
A (Additive)	A,M,N	A,M,A	A,M,M
AD (Additive damped)	AD,M,N	AD,M,A	AD,M,M
M (Multiplicative)	M,M,N	M,M,A	M,M,M
MD(Multiplicative damped)	MD,M,N	MD,M,A	MD,M,M

Abbreviation: ETS, error-trend-seasonal method.

Assessing Model Performance

We evaluated the accuracy of forecasts between the ARIMA model and the ETS model by comparing four statistical measures of error, namely the mean absolute deviation (MAD), the mean absolute percentage error (MAPE), the root-mean-squared error (RMSE), and the mean error rate (MER). The model with the lowest values across these four measures can more closely fit the target series.

$$MAD = \frac{1}{N} \sum_{i=1}^N |X_i - \hat{X}_i| \quad (1)$$

$$MAPE = \frac{1}{N} \sum_{i=1}^N \frac{|X_i - \hat{X}_i|}{X_i} \times 100 \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - \hat{X}_i)^2} \quad (3)$$

$$MER = \frac{\frac{1}{N} \sum_{i=1}^N N |X_i - \hat{X}_i|}{X_i} \quad (4)$$

where X_i signifies the observed values, \hat{X}_i denotes the fitted and predicted results, \bar{X} signifies the mean values of the target series, and N denotes the number of data points. To develop an ARIMA model with high accuracy and strong robustness, at least 50 data points are required.⁴⁴ Thus, in this time series analysis, the data subsamples (74 observations) between 20 February 2020 and 3 May 2020 were treated as the training horizon, and the others (12 observations) were used as the testing horizon to compare the

predictive performance between the ARIMA model and the ETS model. Subsequently, we re-created the ETS models based on the whole prevalence and mortality data to undertake forecasting for the upcoming future. Data analyses were performed using SPSS software (version 17.0, IBM Corp, Armonk, NY), R software (version 3.4.3, R Development Core Team, Vienna, Austria), and Eviews10.0 software (IHS, Inc. USA). A p -value of less than 0.05 indicates a statistical difference.

Results

Developing the ARIMA Models

Applying the ADF test to the prevalence and mortality time series of COVID-19 in the USA, the UK, Russia, and India suggesting a unit root present in these series, and given the prevalence and mortality time series plots showing a rising trend (Figure 1), these meant that the variance of the object series varied over time and they were non-stationary. So we performed the log-transformation or square root-transformation and differences for all the series, and the resulting results are presented in Table S1, indicating that the target series became stationary ($p < 0.05$) after taking either the first- or second-order difference. Next, we determined the possible parameters of ARIMA models by comparing the ACF and PACF plots based on these stationary series (Figures S2 and S3), all the candidate ARIMA models created for the prevalence and mortality time series of COVID-19 are listed in Table S2. Of these models, the best-fitting models for the different target series were further detected according to the

goodness of fit tests and the residual ACF and PACF plots (Table 2, Figures 2 and 3), the results suggested that the ARIMA (0,2,1), sparse coefficient ARIMA (0,2,(1,6)), ARIMA (1,1,1), and ARIMA (2,2,1) specifications were identified as being the preferred models for the prevalence data in the USA, the UK, Russia, and India, respectively, and the ARIMA (0,2,1), ARIMA (0,2,1), ARIMA (0,2,1), and ARIMA (0,2,2) specifications were selected as the optimal models for the mortality data in these four countries, respectively, in that the above models had larger R^2 and stationary R^2 values, along with a smaller NBIC value, and all the residual series displayed a white noise owing to the p -values greater than 0.05 under the Ljung–Box Q tests in addition to the residuals for the prevalence data in Russia, where the Ljung–Box Q test showed a p -value

less than 0.05 among all the possible ARIMA models. Moreover, among the optimal ARIMA models for the prevalence and mortality data in these four countries, the determined parameters indicated a statistical significance. All the above-mentioned intimated that the chosen ARIMA methods are adequate for modeling the temporal dependence structures of the COVID-19 prevalence and mortality data in the USA, the UK, Russia, and India. Therefore, these preferred models determined can be utilized to analyze and estimate the epidemics in the upcoming days.

Developing the ETS Models

After applying the ETS models to the prevalence and mortality data of COVID-19, we determined the preferred

Table 2 Estimated Parameters of the Best-Fitting ARIMA Methods and Their Goodness of Fit Test Results for the Prevalence and Mortality of COVID-19 in These Four Countries

Country	Variable	Estimate	S.E.	t	p	Stationary R^2	R^2	NBIC	Ljung-Box Q		
									Statistics	p	
USA	ARIMA(0,2,1) model developed with the square root transformed training prevalence data										
	MA1	0.685	0.087	7.848	<0.001	0.418	1.000	16.629	16.098	0.517	
	ARIMA(0,2,1) model developed with the square root transformed training mortality data										
	MA1	0.558	0.112	4.965	<0.001	0.237	1.000	11.706	18.175	0.378	
UK	ARIMA(0,2,(1,6)) model developed with the training prevalence data										
	MA1	0.697	0.076	9.148	<0.001	0.370	1.000	13.190	25.831	0.056	
	MA6	-0.317	0.082	-3.867	<0.001						
	ARIMA(0,2,1) model developed with the training mortality data										
	MA1	0.828	0.082	10.132	<0.001	0.391	0.994	13.215	23.728	0.127	
Russia	ARIMA(1,1,1) model developed with the square root transformed training prevalence data										
	AR1	0.981	0.025	38.646	<0.001	0.039	0.997	15.215	34.875	0.004	
	MA1	0.845	0.082	10.284	<0.001						
	ARIMA(0,2,1) model developed with the log-transformed training mortality data										
	MA1	0.809	0.113	7.152	<0.001	0.410	0.994	6.969	15.243	0.578	
India	ARIMA(2,2,1) model developed with the square root transformed training prevalence data										
	AR1	-0.520	0.150	-3.459	0.001	0.611	1.000	10.861	12.793	0.618	
	AR2	-0.329	0.140	-2.357	0.021						
	MA1	0.810	0.082	9.920	<0.001						
	ARIMA(0,2,2) model developed with the training mortality data										
	MA1	0.938	0.135	6.949	<0.001	0.522	1.000	4.487	10.140	0.859	
	MA2	-0.396	0.135	-2.929	0.005						

Abbreviations: ARIMA, autoregressive integrated moving average; AR1, autoregressive at lag one day; AR2, autoregressive at lag two days; MA1, moving average at lag one day; MA2, moving average at lag two days; S.E., standard error; NBIC, normalized Bayesian information criterion.

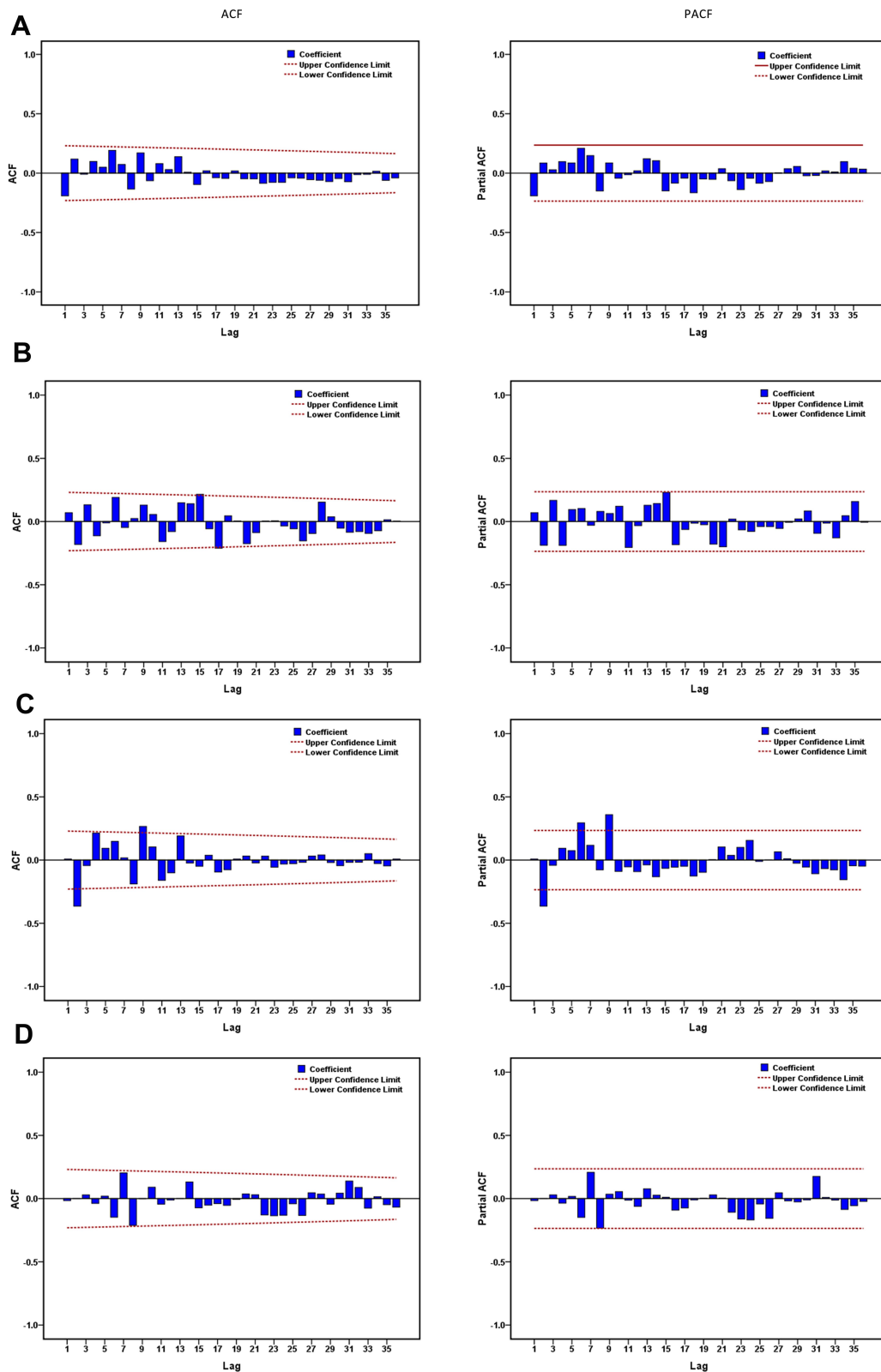


Figure 2 Estimated autocorrelation function (ACF) and partial ACF (PACF) plots to forecast the epidemic trends of the COVID-19 prevalence for (A) USA, (B) UK, (C) Russia, and (D) India. It can be seen that almost all the correlation coefficients fall into the estimated 95% uncertainty interval apart from that in Russia, suggesting that the identified ARIMA methods seem to be suitable for modeling the prevalence data in the study regions.

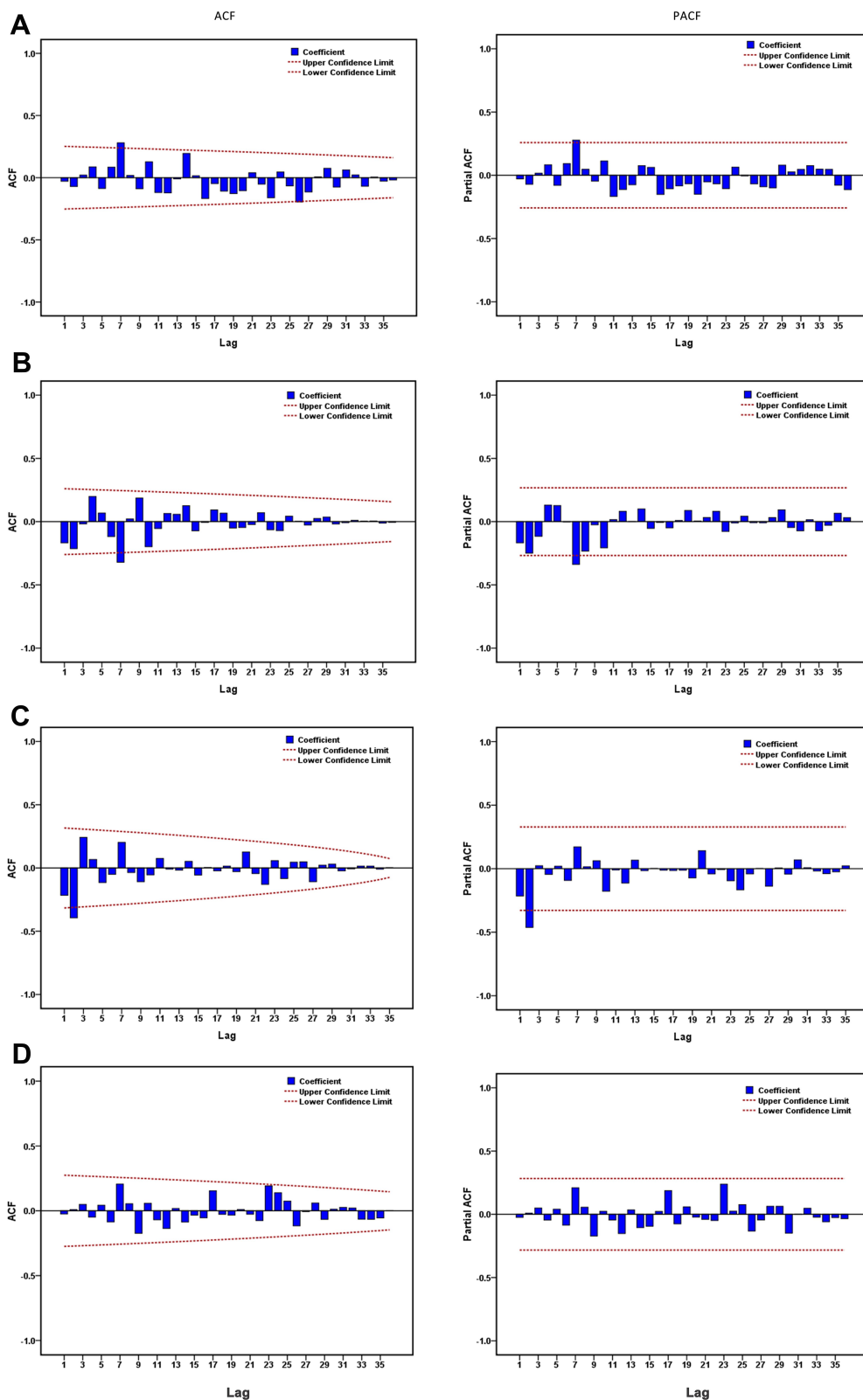


Figure 3 Estimated autocorrelation function (ACF) and partial ACF (PACF) plots to forecast the epidemic trends of the COVID-19 mortality cases for **(A)** USA, **(B)** UK, **(C)** Russia, and **(D)** India. It can be seen that almost all the correlation coefficients fall into the estimated 95% uncertainty interval apart from that in Russia, suggesting that the identified ARIMA methods seem to be suitable for modeling the mortality data in the study regions.

ETS specifications for the target series by comparing different statistical indices, and the estimated parameters and their goodness of fit test results are given in [Tables S3-S11](#). Among all the possible models, the ETS (M,MD,N), ETS (A,AD,M), ETS (A,MD,A), and ETS (A,M,A) specifications were considered as the optimal models for the prevalence data, and the ETS (M,A,M), ETS (M,A,N), ETS (A,A,N), and ETS (M,M,N) specifications were recommended as the preferred models for the mortality data in the USA, the UK, Russia, and India, respectively, as these chosen models gave lower values of the AIC, BIC, HQ, and AMSE, together with greater values of the LL and compact LL ([Table 3](#)). These best-fitting ETS specifications can then be employed to conduct forecasting for the prevalence and mortality data in the USA, the UK, Russia, and India in the near future.

Assessing the Predictive Ability Between Models

[Table 4](#) provides the summary statistics for the forecasting ability between the best-fitting ARIMA models and the best-fitting ETS models, it can be seen from the data in this table that the ETS models reported the errors significantly lower than the ARIMA models for the prevalence and mortality testing data in the USA, the UK, Russia, and India, which showed that the ETS models are well suitable for tracking the dynamic dependence structure of the prevalence and mortality data of COVID-19. As such, we remodeled the ETS models based on the entire data from 20 February 2020 to 15 May 2020 to nowcast and forecast the prevalence and mortality of COVID-19 between 16 May 2020 and 31 May 2020 (future 16 days) (the estimated parameters are presented in [Table S12](#)). As illustrated in [Tables 5](#) and [6](#), [Figure 4](#), the next 16-day forecasts of the prevalence and mortality cases may be 1,640,383 (95% uncertainty interval [UI] 1,454,307 to 1,826,458) and 102,785 (95% UI 84,903 to 120,666) in the USA, respectively, 278,912 (95% UI 245,286 to 312,539) and 39,696 (95% UI 30,948 to 48,444) in the UK, respectively, 425,838 (95% UI 54,126 to 2,693,247) and 3785 (95% UI 3227 to 4343) in Russia, respectively, and 133,806 (95% UI 120,383 to 147,229) and 4127 (95% UI 3527 to 4728) in India, respectively.

Discussion

Early nowcasting for the epidemic patterns of the COVID-19 key epidemiological indicators (eg, prevalence,

mortality, incidence, and fatality cases) is essential to define strategic preparedness and response plan (eg, implementation of the adequate health interventions, rational allocation of the limited health resources, regulation of the production activities, etc.) both in restricting the transmission of the disease and in lowering the disease-related deaths.^{3,5,6,18,35,45} Therefore, it is imperative to develop adequate warning models that can aid governments in acting as a reference to prepare for and respond to this crisis consistent with the strategic preparedness and response plan. In this work, we described the current epidemics of the COVID-19 in the USA, the UK, Russia, and India, and nowcasted the extent and duration of the prevalence and mortality time series using the advanced ETS models, and the predictive ability of the ETS models for various datasets was compared with the ARIMA model that was recommended as being the most commonly used time series forecasting tool.⁴⁶ Our results indicated that the ETS models can better track the dynamic dependence structures of various datasets in the forecasting aspect than that in the ARIMA models. Furthermore, the ETS models provided a highly accurate estimation as the predictive performance provided MAPE values of less than 10% in the different testing data.⁴⁷ Thus, the ETS framework can be recommended as a flexible and instrumental tool to nowcast and forecast the prevalence and mortality trends of COVID-19.

The ETS models can also play a pivotal role in estimating the effects of current and future prevention and control measures taken for the COVID-19 pandemic (eg, lockdown, an optimization of the present tools, an introduction of the available vaccine, increasing intensive care unit availability, an increase in the number of mobile cabin hospitals, and/or other intervention strategies).^{1,7,20,48,49} If our ETS models eventually gave an overestimation for the epidemiological trends of the prevalence and mortality of the COVID-19 pandemic, meaning that the current countermeasures play a role; otherwise, additional prevention and control measures are required to prepare for and response to the COVID-19 outbreak. To our best knowledge, this is the only study to perform the prevalence and mortality time series forecasting of the COVID-19 pandemic using the advanced ETS models in the USA, the UK, Russia, and India, and our findings from different prevalence and mortality datasets confirmed the flexibility and usefulness of the ETS models in forecasting the outbreak of COVID-19. Besides, recent studies have demonstrated that some hybrid models can also provide a close

Table 3 Estimated Parameters of the Best-Fitting ETS Methods and Their Goodness of Fit Test Results for the Prevalence and Mortality of COVID-19 in These Four Countries

Country	Parameter	Compact LL	LL	AIC	BIC	HQ	AMSE
USA	ETS(M,MD,N) model developed with the training prevalence data						
	$\alpha=0.500$ $\beta=0.267$ $\gamma=0.000$ $\delta=0.950$	-760.290	-706.040	1530.580	1542.100	1535.180	9.90E+07
	ETS(M,A,M) model developed with the training mortality data						
	$\alpha=0.313$ $\beta=0.313$ $\gamma=0.443$ $\delta=0.000$	-473.070	-433.100	956.139	966.775	960.315	499,399
UK	ETS(A,AD,M) model developed with the training prevalence data						
	$\alpha=0.332$ $\beta=0.332$ $\gamma=0.899$ $\delta=1.000$	-650.860	-596.610	1313.720	1327.540	1319.230	2,219,036
	ETS(M,A,N) model developed with the training mortality data						
	$\alpha=0.986$ $\beta=0.456$ $\gamma=0.000$ $\delta=0.000$	-443.900	-408.440	895.796	904.038	899.006	855,802
Russia	ETS(A,MD,A) model developed with the training prevalence data						
	$\alpha=0.071$ $\beta=0.009$ $\gamma=0.359$ $\delta=0.967$	-687.150	-632.900	1386.300	1400.120	1391.810	1,936,007
	ETS(A,A,N) model developed with the training mortality data						
	$\alpha=0.972$ $\beta=0.342$ $\gamma=0.000$ $\delta=0.000$	-192.820	-176.720	393.646	400.301	396.034	1445.800
India	ETS(A,M,A) model developed with the training prevalence data						
	$\alpha=0.402$ $\beta=0.402$ $\gamma=0.374$ $\delta=0.000$	-560.730	-506.480	1131.460	1142.980	1136.050	180,865
	ETS(M,M,N) model developed with the training mortality data						
	$\alpha=0.184$ $\beta=0.152$ $\gamma=0.000$ $\delta=0.000$	-239.520	-210.570	487.041	494.846	490.034	1766.340

Abbreviations: ETS, error-trend-seasonal method; LL, log-likelihood; AIC, Akaike information criterion; BIC, Bayesian information criterion; HQ, Hannan-Quinn criterion; AMSE, average mean square error.

Table 4 Comparisons of Predictive Performances for the Prevalence and Mortality of COVID-19 Between the Best-Fitting ETS and ARIMA Models in These Four Countries

Country	Model	Predictive Power of Prevalence				Predictive Power of Mortality			
		MAD	MAPE	RMSE	MER	MAD	MAPE	RMSE	MER
USA	ETS	9479.520	0.753	11,334.000	0.008	3499.770	4.641	4079.010	0.048
	ARIMA	52,331.000	4.038	65,195.000	0.042	6814.330	8.896	7923.090	0.093
	Percentage reductions (%)								
	A vs B	81.885	81.352	82.615	80.952	48.641	47.830	48.517	48.387
UK	ETS	3316.240	0.015	4365.290	0.016	3022.130	9.474	3413.960	0.097
	ARIMA	9293.330	4.190	11,801.700	0.044	19,571.000	60.471	25,675.600	0.266
	Percentage reductions (%)								
	A vs B	64.316	99.642	63.011	63.636	84.558	84.333	86.703	63.534
Russia	ETS	4563.780	2.300	4781.900	0.022	131.450	6.394	157.411	0.07
	ARIMA	92,280.100	39.244	129,008.000	0.452	1169.920	54.392	1642.080	0.624
	Percentage reductions (%)								
	A vs B	95.054	94.139	96.293	95.133	88.764	88.245	90.414	88.782
India	ETS	1215.220	1.967	1374.670	0.020	68.282	3.350	77.429	0.033
	ARIMA	3747.080	5.751	4084.620	0.061	187.417	8.774	201.966	0.092
	Percentage reductions (%)								
	A vs B	67.569	65.797	66.345	67.213	63.567	61.819	61.662	64.130

Abbreviations: ARIMA, autoregressive integrated moving average method; ETS, error-trend-seasonal method; MAD, mean absolute deviation; MAPE, mean absolute percentage error; RMSE, root-mean-squared error; MER, mean error rate; A denotes the ETS, model; B, represents the ARIMA model.

Table 5 Projection of the COVID-19 Prevalence into the Next 16 Days Using the ETS Models Based on the Entire Data

Time	ETS (A,AD,N) in the USA		ETS (A,AD,N) in the UK		ETS (M,MD,N) in Russia		ETS (A,AD,N) in India	
	ForeCast	95% UI	Forecast	95% UI	Forecast	95% UI	Forecast	95% UI
16/05/20	1,381,655	(1,371,294, 1,392,015)	236,468	(234,869, 238,068)	274,926	(173,774, 381,403)	85,588	(85,005, 86,170)
17/05/20	1,401,448	(1,383,658, 1,419,238)	239,715	(236,764, 242,666)	284,284	(177,923, 394,705)	89,276	(88,313, 90,240)
18/05/20	1,420,845	(1,394,713, 1,446,978)	242,898	(238,438, 247,357)	293,765	(178,529, 426,898)	92,891	(91,399, 94,384)
19/05/20	1,439,855	(1,404,556, 1,475,153)	246,016	(239,898, 252,134)	303,362	(176,222, 467,229)	96,434	(94,315, 98,553)
20/05/20	1,458,484	(1,413,289, 1,503,679)	249,072	(241,159, 256,985)	313,072	(171,109, 516,747)	99,906	(97,085, 102,727)
21/05/20	1,476,741	(1,420,997, 1,532,484)	252,067	(242,238, 261,896)	322,889	(162,167, 570,818)	103,308	(99,723, 106,893)
22/05/20	1,494,632	(1,427,756, 1,561,509)	255,002	(243,148, 266,856)	332,808	(150,013, 666,743)	106,643	(102,240, 111,046)
23/05/20	1,512,166	(1,433,628, 1,590,703)	257,879	(243,901, 271,856)	342,825	(142,996, 764,882)	109,911	(104,643, 115,178)
24/05/20	1,529,349	(1,438,671, 1,620,027)	260,697	(244,507, 276,888)	352,933	(127,369, 870,997)	113,113	(106,938, 119,288)
25/05/20	1,546,188	(1,442,933, 1,649,444)	263,460	(244,974, 281,946)	363,129	(115,791, 1,026,851)	116,251	(109,131, 123,371)
26/05/20	1,562,691	(1,446,458, 1,678,924)	266,167	(245,312, 287,022)	373,406	(105,390, 1,135,801)	119,327	(111,227, 127,427)
27/05/20	1,578,863	(1,449,286, 1,708,441)	268,820	(245,527, 292,113)	383,760	(91,692, 1,362,363)	122,341	(113,229, 131,452)
28/05/20	1,594,712	(1,451,453, 1,737,972)	271,420	(245,626, 297,214)	394,185	(84,743, 1,637,715)	125,295	(115,143, 135,446)
29/05/20	1,610,244	(1,452,992, 1,767,497)	273,968	(245,616, 302,321)	404,677	(74,169, 1,960,151)	128,189	(116,971, 139,407)
30/05/20	1,625,466	(1,453,934, 1,796,997)	276,465	(245,500, 307,430)	415,229	(63,915, 2,303,692)	131,026	(118,717, 143,335)
31/05/20	1,640,383	(1,454,307, 1,826,458)	278,912	(245,286, 312,539)	425,838	(54,126, 2,693,247)	133,806	(120,383, 147,229)

Abbreviations: ETS, error-trend-seasonal method; UI, uncertainty interval.

approximation to the temporal patterns of the COVID-19 outbreak.^{50,51} For example, Singh et al proposed a new hybrid model by combining wavelet decomposition and

ARIMA model to make forecasting for the total death cases of COVID-19 in Italy, Spain, France, the UK, and the USA.⁵¹ Chakraborty et al developed a novel hybrid

Table 6 Projection of the COVID-19 Mortality Cases into the Next 16 Days Using the ETS Models Based on the Entire Data

Time	ETS (A,AD,N) in the USA		ETS (A,AD,N) in the UK		ETS (A,AD,N) in Russia		ETS (A,AD,N) in India	
	Forecast	95% UI	Forecast	95% UI	Forecast	95% UI	Forecast	95% UI
16/05/20	84,936	(83,739, 86,134)	34,054	(33,121, 34,988)	2516	(2483, 2549)	2757	(2722, 2791)
17/05/20	86,302	(84,283, 88,320)	34,486	(33,043, 35,929)	2613	(2557, 2669)	2861	(2802, 2921)
18/05/20	87,640	(84,767, 90,513)	34,909	(32,990, 36,828)	2708	(2627, 2789)	2964	(2878, 3051)
19/05/20	88,951	(85,171, 92,731)	35,323	(32,932, 37,714)	2801	(2693, 2910)	3065	(2949, 3181)
20/05/20	90,236	(85,497, 94,975)	35,730	(32,862, 38,598)	2893	(2754, 3031)	3164	(3015, 3312)
21/05/20	91,496	(85,747, 97,244)	36,128	(32,774, 39,482)	2982	(2812, 3152)	3260	(3078, 3443)
22/05/20	92,730	(85,926, 99,534)	36,518	(32,668, 40,368)	3070	(2867, 3273)	3355	(3137, 3573)
23/05/20	93,940	(86,037, 101,843)	36,900	(32,544, 41,257)	3156	(2918, 3394)	3448	(3193, 3704)
24/05/20	95,125	(86,084, 104,166)	37,275	(32,401, 42,148)	3240	(2966, 3515)	3539	(3245, 3834)
25/05/20	96,287	(86,071, 106,502)	37,642	(32,241, 43,043)	3323	(3011, 3635)	3628	(3293, 3963)
26/05/20	97,425	(86,002, 108,849)	38,002	(32,065, 43,939)	3404	(3054, 3754)	3716	(3339, 4092)
27/05/20	98,541	(85,878, 111,203)	38,355	(31,871, 44,838)	3483	(3093, 3873)	3801	(3382, 4221)
28/05/20	99,634	(85,704, 113,564)	38,700	(31,662, 45,738)	3561	(3130, 3991)	3885	(3422, 4348)
29/05/20	100,706	(85,482, 115,929)	39,039	(31,438, 46,639)	3637	(3165, 4109)	3968	(3460, 4476)
30/05/20	101,756	(85,214, 118,297)	39,371	(31,200, 47,541)	3712	(3197, 4226)	4048	(3495, 4602)
31/05/20	102,785	(84,903, 120,666)	39,696	(30,948, 48,444)	3785	(3227, 4343)	4127	(3527, 4728)

Abbreviations: ETS, error-trend-seasonal method; UI, uncertainty interval.

ARIMA-wavelet-based forecasting (WBF) model to make real-time forecasts and risk assessment for the morbidity cases of COVID-19 in India, Canada, France, South Korea, and the UK.⁵⁰ Therefore, future work is supposed to compare the reliability level in forecasting the epidemiological indicators of the COVID-19 outbreak between the ETS model and the mentioned hybrid techniques. Also, it should be noted that there may be underfitting or overfitting in the process of establishing the ETS framework, which may affect the predictive performance of the ETS model.²² In this study, to prevent the ETS model from underfitting or overfitting, we determined the preferred ETS framework based on multiple goodness of fit measures such as AIC, BIC, HQ, AMSE, and LL, and if these measures displayed the same values between the training horizon and the testing horizon simultaneously, and then this ETS model could be recommended as the optimal specification.

Currently, great concerns are that the health system capacity in the countries of the COVID-19 outbreak can effectively meet the need of the infected persons who are hospitalized or require intensive care and whether there are a sufficient number of doctors and nurses, as well as personal protective gear. Particularly in the USA, the total confirmed cases and deaths showed a rapid rise since 18 March 2020, and the current epidemic trends still remain relatively high levels in the morbidity and mortality of COVID-19. Unfortunately, according to the

projections into the next 16 days (Figure 4A), it appeared that the daily confirmed cases and deaths may continue to increase with a daily average of 17,429 and 1203 cases, respectively, and the estimated total prevalence and mortality cases may reach 1,640,383 (95% UI 1,454,307 to 1,826,458) and 102,785 (95% UI 84,903 to 120,666), respectively (Tables 5 and 6). Therefore, it is essential to continuously implement strict prevention and control strategies in the USA. Meanwhile, Russia, the second-worst-hit country with a total of 262,843 confirmed cases and 2418 deaths around the world, is still experiencing a remarkable rise in the incidence and mortality of COVID-19. Regrettably, similar to the USA, the estimated confirmed cases and deaths may continue to increase with a daily average of 10,188 and 86 cases, respectively (Figure 4C), and the aggregated confirmed cases and deaths may be 425,838 (95% UI 54,126 to 2,693,247) and 3785 (95% UI 3227 to 4343), respectively, in the next 16 days (Tables 5 and 6). Likewise, India is also witnessing a rapid increase in the reported cases and deaths of COVID-19 (Figure 4D), the estimated confirmed cases and deaths may continue to increase with a daily average of 3240 and 93 cases, respectively, and the accumulative reported cases and deaths may reach 133,806 (95% UI 120,383 to 147,229) and 4127 (95% UI 3527 to 4728), respectively, in the next 16 days (Tables 5 and 6). Contrast to the continued increase in the numbers of reported confirmed cases and deaths of COVID-19 in the

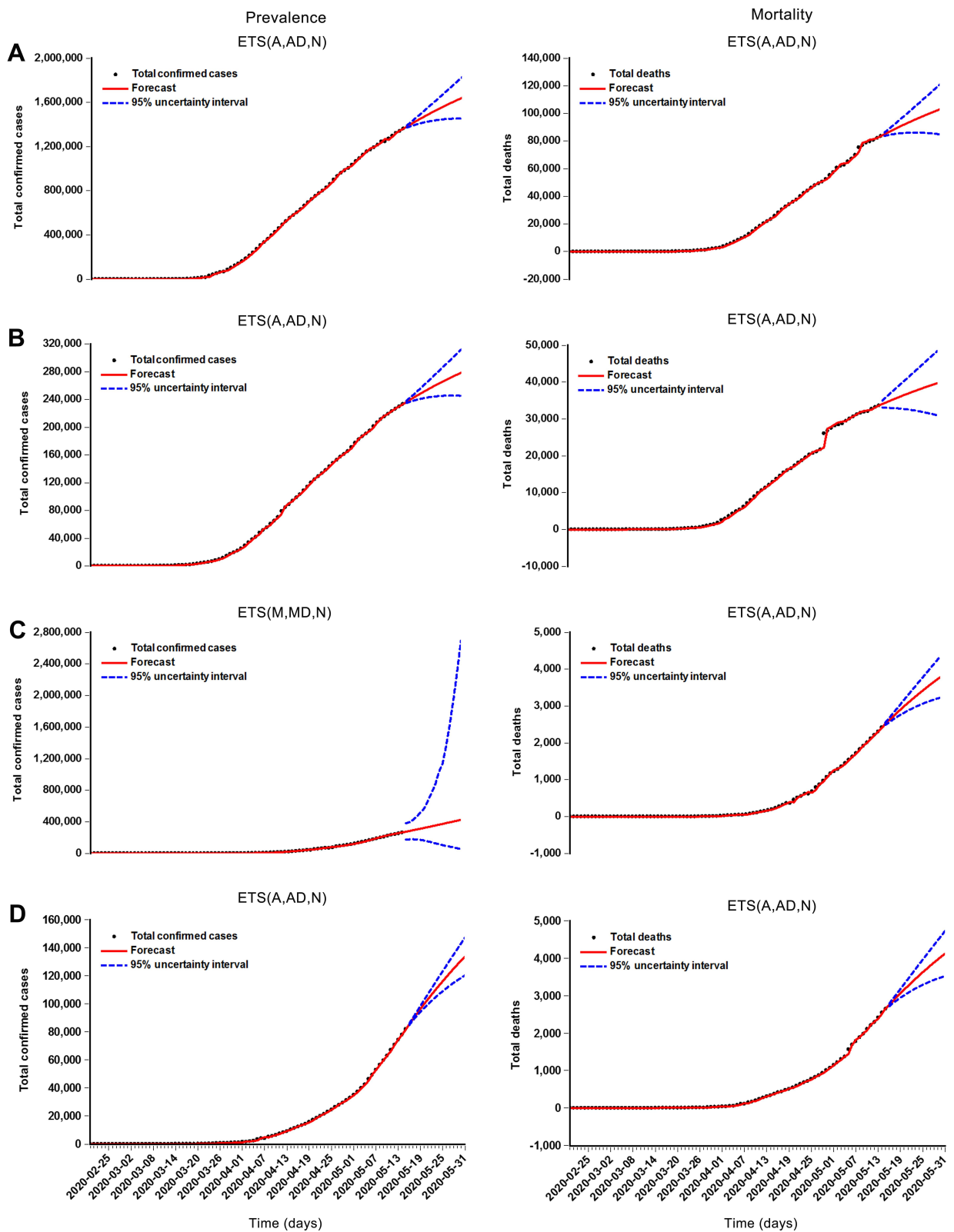


Figure 4 Time series plots showing the projections and their 95% uncertainty intervals of the prevalence and mortality of the COVID-19 for (A) USA, (B) UK, (C) Russia, and (D) India, between 16 May 2020 and 31 May 2020 using the ETS models constructed with the data between 20 February 2020 and 15 May 2020.

USA, Russia, and India, it seems that the daily new notified cases and deaths have reached the plateau in the UK as the total number of estimated reported cases and deaths owing to COVID-19 may be 278,912 (95% UI 245,286 to 312,539) and 39,696 (95% UI 30,948 to 48,444), respectively, with a daily average of 2859 notified cases and 381 deaths in the next 16 days (Tables 5 and 6, Figure 4B), which was well below the daily average numbers of new cases (4690) and deaths (699) due to COVID-19 between 1 April 2020 and 15 May 2020. Overall, strict prevention and control strategies should be conducted in the USA, the UK, Russia, and India to control the COVID-19 outbreak, although a downward trend was seen in the UK in the next 16-day forecasts. If the COVID-19 pandemic failed to be controlled, then these countries will encounter a severe shortage of hospitals, which will make the upcoming situation of COVID-19 pandemic even worse, and thus may lead to an unprecedented disaster.

There are several limitations to this study. First, accurate statistics on the key epidemiological indicators of COVID-19 (such as prevalence, mortality, incidence, and fatality cases) are crucial for the ETS model development, whereas the limited epidemiological surveillance and detection capabilities may cause underestimations for the mentioned epidemiological indicators in the study regions. Second, whether the ETS framework can provide an accurate forecast for the prevalence and mortality time series of COVID-19 in other countries, areas or territories, it is required to perform further validation. Lastly, the forecasting accuracy level of the ETS framework may be deteriorated as the increase in the predicted length of time, and thus the prevalence and morbidity samples are expected to be updated in real-time.

Conclusions

Accurate forecasting for the prevalence and mortality trends of COVID-19 can contribute to plan the health infrastructure and services under dynamic demand and to guide emergency preparedness effectively in responding to this disease outbreak. In this work, the ETS framework can be used to nowcast and forecast the long-term temporal trends of the COVID-19 prevalence and mortality in the USA, the UK, Russia, and India, and which provides a notable performance improvement over the most frequently used ARIMA model. Our findings can aid governments as a reference to prepare for and respond to the COVID-19 pandemic consistent with the strategic preparedness and response plan (eg, implementation of the

adequate health interventions, rational allocation of the limited health resources, regulation of the production activities, etc.) both in restricting the transmission of the disease and in lowering the disease-related deaths in the upcoming days. However, for more accurate estimates and future perspectives, the prevalence and mortality series should be updated in time.

Data Sharing Statement

All data can be extracted from the WHO website.

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Author Contributions

All authors contributed to data analysis, drafting or revising the article, gave final approval of the version to be published, and agree to be accountable for all aspects of the work.

Disclosure

The authors report no conflicts of interest for this work.

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