Monkeypox Cases Prediction with Machine Learning

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Abstract. In May 2022, the monkeypox epidemic broke out worldwide. According to the cases collected by the Centers for Disease Control and Prevention (CDC), as of August 17, 2022, 13,517 cases were confirmed in the United States. Based on the 2022 U.S. monkeypox epidemic data collected by the CDC, the Prophet prediction model released by Facebook in 2017 was used to predict the future trend of the monkeypox epidemic in the United States. The range of daily confirmed cases for the 2022 U.S. Monkeypox epidemic applied from May 17, 2022, to August 10, 2022, with reporting date. The results forecast monkeypox trends in American monkeypox over periods as short as seven days and as long as 17 days, with all values of MAPE in this prediction having good forecasting accuracy between 0.018 and 0.117. The prediction model's accuracy can be affected by the k-value biasing due to strange events and the implementation of epidemic prevention policies.

Keywords: Monkeypox; Machine Learning; Prophet; Regression Model.

1. Introduction

Monkeypox is a viral zoonosis which belongs to the same family of viruses as the smallpox virus. Symptoms of monkeypox are similar to those of smallpox. Patients with monkeypox develop a rash that may appear on or near the genitals, i.e., labia, vagina, penis, testicles, and anus, or on other areas of the body, such as the face, mouth, hands, feet, or chest [1]. Monkeypox can be transmitted by close skin-to-skin contact. pregnant women can transmit the virus to their fetuses through the placenta; and people can potentially get the monkeypox virus from scratches or bites by infected animals [2]. Monkeypox was first discovered in 1958, when two outbreaks of a pox-like disease occurred in a group of monkeys used for research. In 1970 the first human monkeypox infection was recorded in the Democratic Republic of the Congo. Since 1970, 11 African countries have reported monkeypox cases, of which 338 confirmed cases and 33 deaths were reported to the World Health Committee in the Republic of Congo between 1981 and 1986. The monkeypox mortality rate is 9.8% [2]. In 2003, a total of 71 cases of monkeypox were reported in the Midwestern United States, all of which could be traced back to 2003 when electron microscopy studies confirmed that Gambian kangaroos were imported from Accra, Ghana, by a Texas animal dealer carried monkeypox [3]. Several successive outbreaks happened in Nigeria from 2017 to 2019, in the United Kingdom from 2018 to 2019, and in Singapore in 2019. An ongoing global outbreak of monkeypox began in May 2022, with cases reported in an increasing number of countries and regions around the world since May. On July 23, the World Health Organization (WHO) declared the monkeypox outbreak 2022 a public health emergency of international concern. As of August 16, according to the Centers for Disease Control and Prevention (CDC) and WHO reports, 39,434 infections have been reported in 94 countries or regions around the world, with 87 locations being the first reports of the monkeypox virus. Among them, the United States has the most infection cases worldwide. On May 17, 2022, the first confirmed case of monkeypox was in Massachusetts, USA. Beginning May 17, 2022, the CDC updates

confirmed cases of Monkeypox every Wednesday after review and verification. Until August 17, 2022, a total of 13,517 cases of Monkeypox were confirmed [4].

The current CDC states that close skin-to-skin contact with people carrying the monkeypox virus is the primary cause of the 2022 Monkeypox outbreak. The data show that homosexuals, bisexuals, and other homosexuals constitute the majority of cases in the current Monkeypox epidemic. Among male patients with information on sexual activity, 99% (n=624) reported male-to-male sexual contact. Many of the initial patients reported international travel in the 21 days before the onset of the disease. In these visiting countries, Monkeypox was not yet known to be endemic, and attending large festivals and other events where close, personal, skin-to-skin contact could occur. However, in late June, an increasing number of Monkeypox cases showed transmission of the infection by the local community. At the same time, the number of Monkeypox cases began to increase dramatically.

Most researches focus on the mechanism behind this disease. Except for using human judgement to forecast the monkeypox case trend [5], few studies have focused on modelling or predicting future case growth. However, the total number of cases continues to increase, and we might need an accurate forecast to manage medical resource displacement and to illustrate a future situation.

In 2017, Facebook released Prophet, an open-source model initially intended for business time series forecasting [6]. This model has shown its prediction strength in the epidemic forecast. Aditya Satrio et al. found that this model yields a more accurate prediction of the coronavirus case trend in Indonesia than the ARIMA model [7]. Xie et al. confirmed this in research studying the forecasting strength of Prophet and ARIMA on the hand, foot and mouth disease trend in Hubei, China [8].

The primary objective of this study was to use a Prophetic Forecasting Model to make accurate predictions of future trends in the Monkeypox epidemic based on the existing 2022 U.S. Monkeypox epidemic data collected by the CDC. The range of daily confirmed cases for the 2022 U.S. Monkeypox epidemic applied from May 17, 2022, to August 10, 2022, with reporting date.

2. Methods

Procedures for conducting this research are shown in Figure 1. First, we fetched data on the U.S. monkeypox trend from the CDC's website. Then, to test the model performance, we forecast on a set of past dates as we have known data on them. The accuracy is measured through two error estimation metrics. Finally, we predict future dates.

2.1 Data Collection and Manipulation

The newly reported monkeypox cases from the outbreak in 2022 are obtained from the CDC website [4]. The number of total cases every day is calculated by adding one day's newly reported cases and the total cases one day before this date. Except for the number of cases on the first date of this outbreak (May 17th, 2022), the total number of cases on that date is, of course, equal to the newly confirmed cases. The total case growth by day is shown in Figure 1.

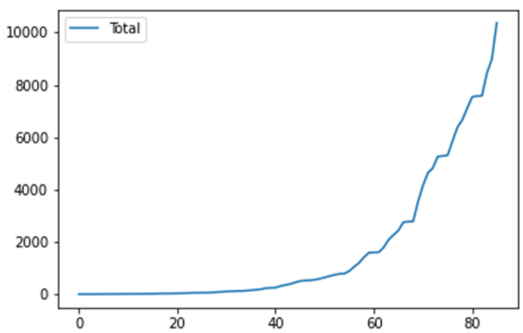


Fig 1. Growth in the number of confirmed total monkeypox cases from May 20th to August 10th (*"U.S. Monkeypox Case Trends reported to CDC"*, 2022)

2.2 The Prophet Model

The number of epidemic cases grows logistically [9]. This model assumes that both carrying capacity and growth rate vary over time. The model growth rate at one timepoint is defined as $k + a(t)\delta$, where δ is a change in rate that occurred at that time point, and $a(t)$ is a function as:

$$a(t) = \begin{cases} 1, & if \geq s_j \\ 0, & otherwise \end{cases} \quad (1)$$

γ_j is the adjustment at one timepoint j. Its formula is given below:

$$\gamma_j = (s_j - m - \sum_{i<j} \gamma_i)(1 - \frac{k+\sum_{i<j} \delta_i}{k+\sum_{i \leq j} \delta_i}) \quad (2)$$

The model is constructed as a variation of logistic growth as:

$$g(t) = \frac{C(t)}{1+e^{-(k+a(t)^T\delta)\left(t-(m+a(t)^T\gamma)\right)}} \quad (3)$$

When initializing the model, the carrying capacity of the growth trend needs to be specified as one parameter (another specifies the growth trend, we set the parameter to be logistic). The carrying capacity, denoted as K, is estimated as:

$$K = \frac{{y_2}^2(y_1+y_3)-2y_1y_2y_3}{{y_2}^2-y_1y_3} \quad (4)$$

where y_1, y_2, and y_3 are the total numbers of cases at times t_1, t_2, and t_3, where t_2-t_1 = t_3-t_2 [10]. Each prediction is yielded with one model specified on its K value.

The prophet model observes past data patterns using the Fourier series. However, the prediction might be more accurate if we specify holidays and events during model initialization. Excluding federal holidays, each state in the U.S. may hold their observances and holidays. All holidays and events considered in this study are given in Table. Forecast results from Prophet are given with an uncertainty interval measured by its algorithm.

2.3 Accuracy Measurement

To measure the model performance, we use two error measurement metrics: mean absolute error (MAE) and mean absolute percentage error (MAPE). Formulae of the two metrics are given below:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - x_i| \quad (5)$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i-x_i}{x_i}\right| \quad (6)$$

In this study, n is the forecast length, y_i is the forecasted value, and x_i is the forecasted value. Values for both metrics are preferably lower as it indicates less error and more accurate prediction.

3. Results

We made forecasts on different periods, trained by a dataset collected one day before the start of that period, and K estimated from that training dataset. To obtain the accuracy of the forecast, we measured the error of each day in the forecasted period and MAE and MAPE scores for the entire

period. In all graphs on future forecasts, the black dashed line marks the carrying capacity, the blue line is the future trend, the blue shadow is the uncertainty intervals, and the black dots are the past total number of cases on each day.

3.1 Forecasting from August 1st to 10th

The model fits on data before August 1st and predicts from August 1st to 10th. K is a constant and is estimated as 10568.0. Figure 2 shows the forecast trend. The model predicts the number of cases will reach 8350.985 on August 10th. Table 2 shows the predicted total cases with the lower and upper bound of the uncertainty interval on each day.

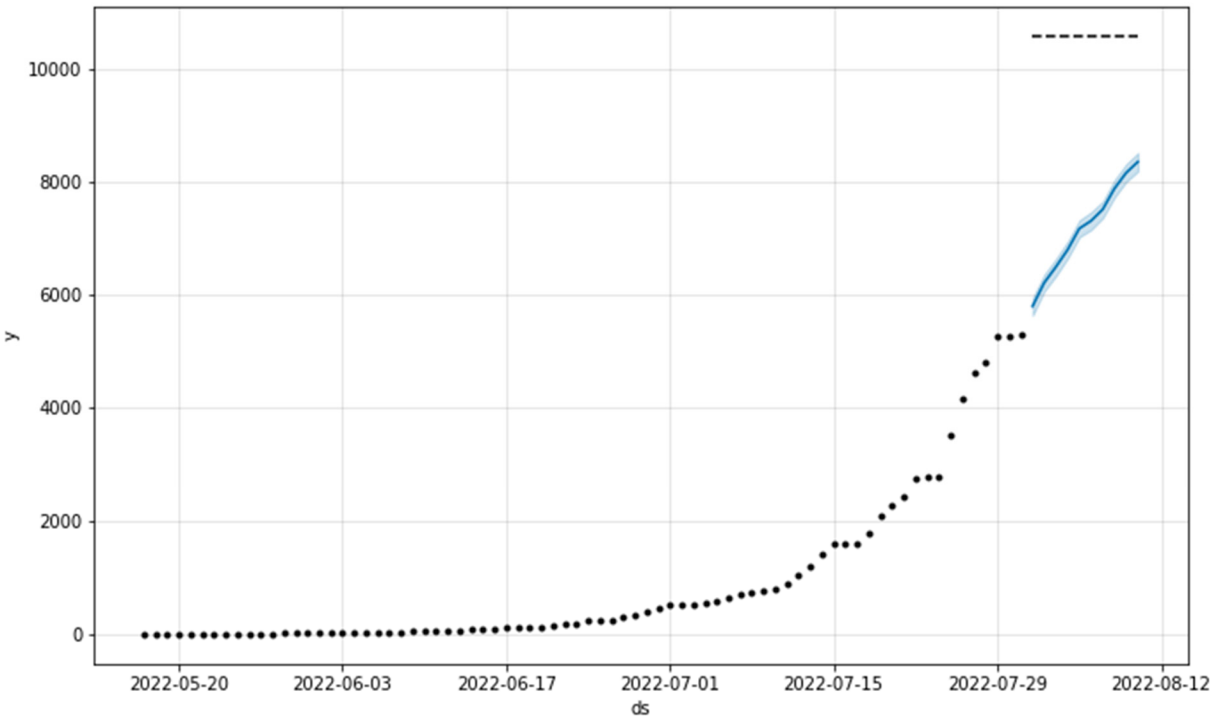


Fig 2. Forecasted monkeypox case growth from August 1st to 10th.

Table 1. List of predicted total cases from August 1st to 10th, with lower and upper bound of uncertainty interval on each day.

Date	Prediction	Lower bound	Upper bound
August 1st	5799.829	5638.615	5956.939
August 2nd	6216.040	6068.114	6365.157
August 3rd	6596.515	6338.629	6644.612
August 4th	6798.184	6650.164	6951.222
August 5th	7173.195	7023.735	7322.416
August 6th	7308.113	7152.167	7464.861
August 7th	7510.237	7360.818	7657.238
August 8th	7877.999	7725.515	8034.017
August 9th	8156.282	8001.136	8312.888
August 10th	8350.985	8184.411	8509.557

The MAE score of this forecast is 478.462, and the MAPE score is 0.055. Figure 3 shows the actual and predicted total cases each day, and Table 3 shows the actual and predictive cases, with the difference each day. The prediction before the sixth day (August 7th) is more accurate, with the highest daily error on August 5th, with a value of 365.805. The error between the actual and predictive

number of total cases increases after August 6th. On August 10th, the actual is greater than predictive cases by about 2012.

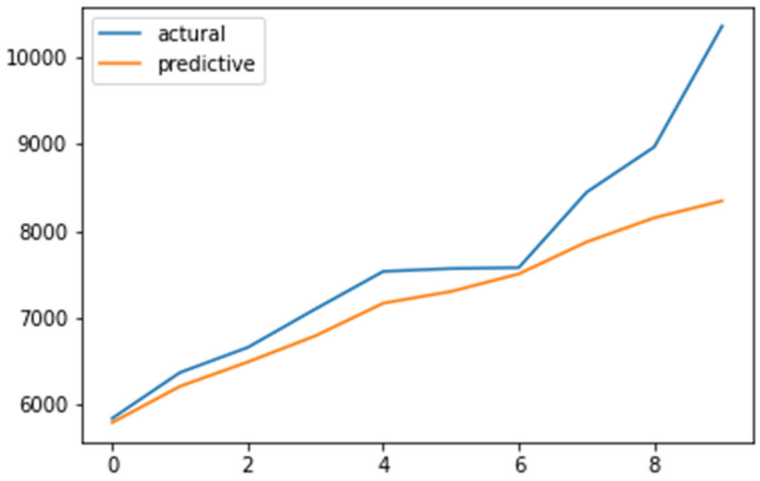


Fig 3. The actual and predicted case trend from August 1st to August 10th.

Table 2. Actual and predicted number of cases on each day with their difference from August 1st to August 10th.

Date	Actual	Prediction	Error
August 1st	5848	5799.829	48.171
August 2nd	6357	6216.040	158.960
August 3rd	6664	6596.515	167.485
August 4th	7107	6798.184	308.816
August 5th	7539	7173.195	365.805
August 6th	7572	7308.113	263.887
August 7th	7582	7510.237	71.763
August 8th	8450	7877.999	572.001
August 9th	8972	8156.282	815.718
August 10th	10363	8350.985	2012.015

3.2 Forecasting from August 1st to 17th

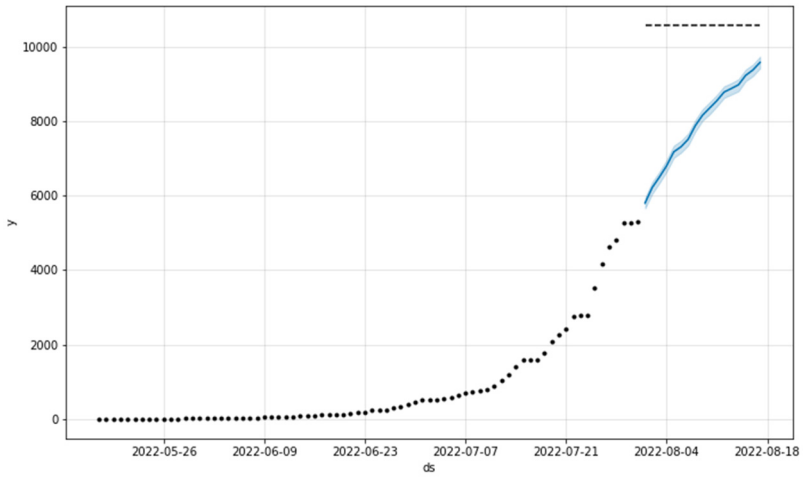


Fig 4. The predicted trend from August 1st to August 17th.

This forecast uses the same K value from the previous section (10568.0). The forecasted trend is shown in Figure 4. Values predicted with lower and upper bounds of prediction uncertainty intervals are given in Table 4. The Prophet Model forecasts the case trend would reach 9573.008 cases on August 17th.

The actual and predictive case trends are given in Figure 5. Errors of prediction are given in Table 5. Compared to the forecast from August 1st to 10th, this forecast is less accurate, with an MAE score of 1246.196 and a MAPE score of 0.117. The forecast error remains over 2000 since August 10th, and the highest error is on August 17th value of 2810.992.

Table 3. Values of the predicted trend and uncertainty intervals on each day.

Date	Prediction	Lower bound	Upper bound
August 1st	5799.829	5654.299	5949.992
August 2nd	6216.040	6052.585	6367.541
August 3rd	6496.515	6336.351	6642.036
August 4th	6798.184	6643.392	6962.431
August 5th	7173.195	7013.722	7342.236
August 6th	7308.113	7152.472	7471.358
August 7th	7510.237	7346.043	7670.467
August 8th	7877.999	7719.966	8033.335
August 9th	8156.282	8011.028	8320.151
August 10th	8350.985	8183.487	8507.624
August 11th	8546.753	8394.889	8704.190
August 12th	8776.678	8622.373	8933.720
August 13th	8871.806	8709.458	9019.426
August 14th	8971.854	8799.906	9124.677
August 15th	9224.337	9070.102	9383.056
August 16th	9367.847	9205.719	9516.341
August 17th	9573.008	9414.022	9730.250

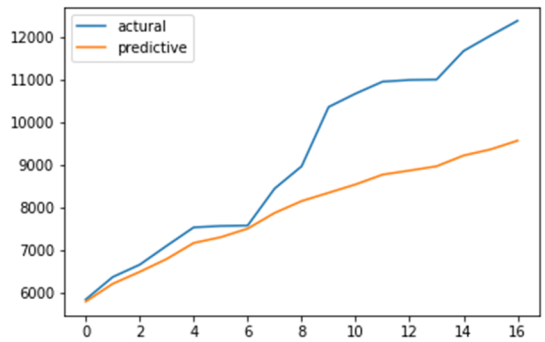


Fig 5. The predicted and actual trend forecast from August 1st to August 17th.

Table 4. Actual and predicted number of cases with their difference on each day from August 1st to August 17th.

Date	Actual	Prediction	Error
August 1st	5848	5799.829	48.171
August 2nd	6357	6216.040	158.960
August 3rd	6664	6596.515	167.485
August 4th	7107	6798.184	308.816
August 5th	7539	7173.195	365.805
August 6th	7572	7308.113	263.887
August 7th	7582	7510.237	71.763
August 8th	8450	7877.999	572.001

August 9th	8972	8156.282	815.718
August 10th	10363	8350.985	2012.015
August 11th	10677	8546.753	2130.247
August 12th	10957	8776.678	2180.322
August 13th	10996	8871.806	2124.194
August 14th	11006	8971.854	2034.146
August 15th	11676	9224.337	2451.663
August 16th	12037	9367.847	2669.153
August 17th	12384	9573.008	2810.992

3.3 Forecasting from August 11th to 17th

For this prediction, the model is fit on data before August 11th. Since we changed the training set, we re-estimated the value of K as 17943.999. The predicted monkeypox trend is shown in Figure 6, and the exact values, lower and upper bound of the uncertainty interval on each day are given in Table 6. We predict there would be 12630.081 cases on August 17th in total, with the uncertainty interval ranging from 12424.257 to 12835.754.

This prediction's MAE and MAPE scores are 225.641 and 0.020, suggesting a good prediction. A comparison of the actual and predictive case trends is shown in Figure 7, and the details of actual, predictive and error values on each day are given in Table 7. It is worth noting that the forecast predicts more cases after the third day (August 13th), though the error is insignificant as both the actual and predictive values reach over 11000, while no error is over 250 each day.

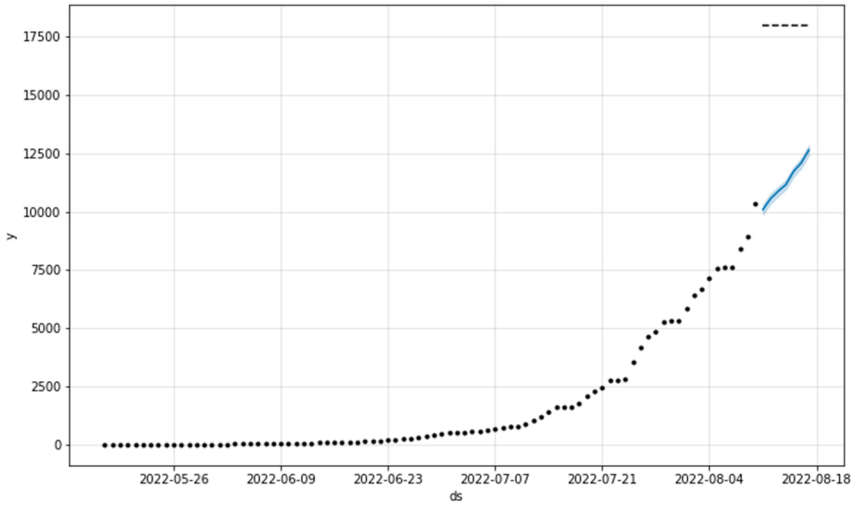


Fig 6. The predicted trend from August 11th to 17th.

Table 5. Prediction from August 11th to 17th with lower and upper bounds of the uncertainty interval on each day.

Date	Prediction	Lower Bound	Upper bound
August 11th	10095.297	9890.887	10299.792
August 12th	10557.456	10362.808	10785.414
August 13th	10876.186	10671.065	11067.239
August 14th	11154.770	10969.901	11369.200
August 15th	11716.733	11508.892	11912.205
August 16th	12079.845	11866.517	12284.569
August 17th	12630.081	12424.257	12835.754

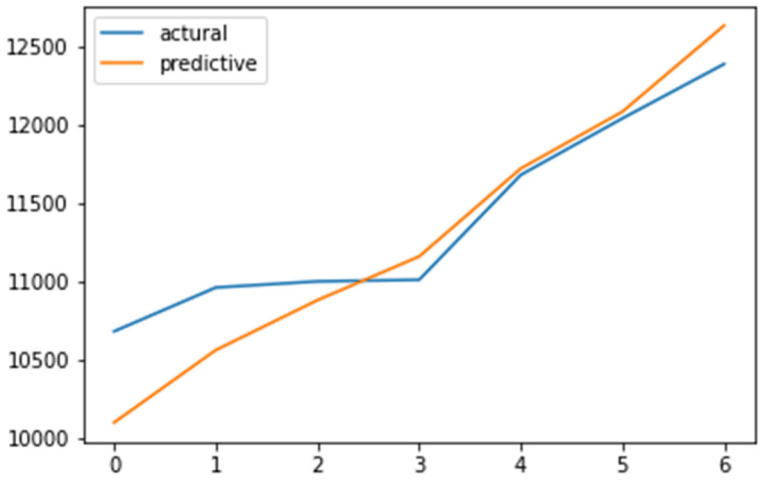


Fig 7. Prediction and actual trends from August 11th to August 17th.

Table 6. Actual and predicted number of cases on each day from August 11th to 17th, and their differences.

Date	Actual	Prediction	Error
August 11th	10667	10095.297	581.703
August 12th	10957	10557.456	399.544
August 13th	10996	10876.186	119.814
August 14th	11006	11154.770	-148.770
August 15th	11676	11716.733	-40.733
August 16th	12037	12079.845	-42.845
August 17th	12384	12630.081	-246.081

3.4 Forecasting from August 11th to 24th

The same training set (number of cases till August 10th) and the same K value (17943.999) from the previous section are used to fit the model for generating this forecast. Values of the prediction and the uncertainty intervals are given in Table 8. Figure 8 shows the predicted trend.

Figure 9 compares the actual and predicted trends. The MAE and MAPE of this forecast are 219.606 and 0.018, respectively. Details of the actual and predictive values are given in Table 9. Though the error is still not significant, the model generally predicts less since August 14th.

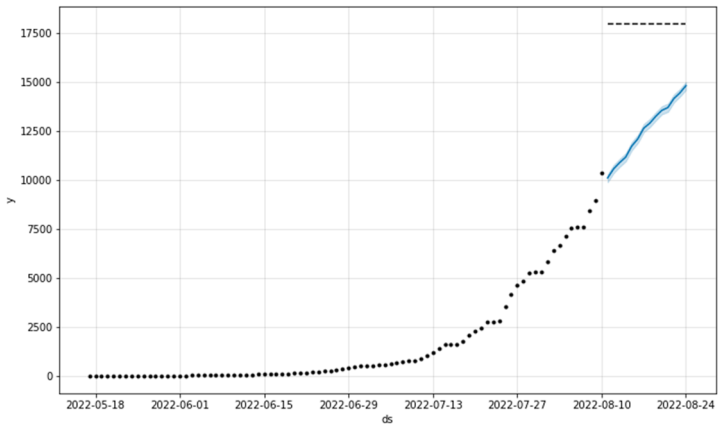


Fig 8. The predicted trend from August 11th to 24th.

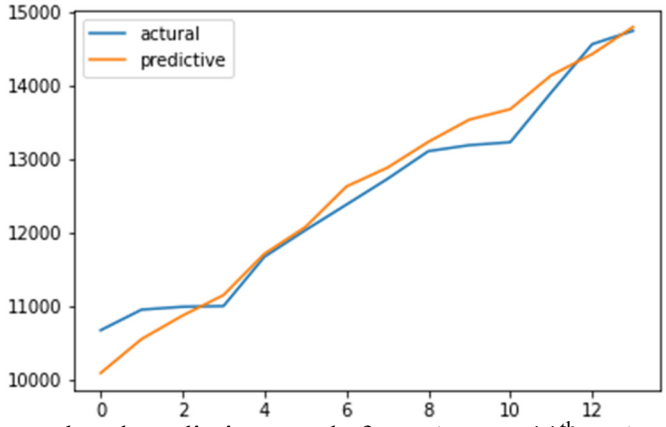


Fig 9. Actual and predictive trends from August 11th to August 24th.

Table 7. The predicted number of cases with the upper and lower bounds.

Date	Prediction	Lower Bound	Upper Bound
August 11th	10095.297	9899.274	10295.737
August 12th	10557.456	10359.746	10762.199
August 13th	10876.186	10670.904	11072.379
August 14th	11154.770	10947.317	11348.114
August 15th	11716.733	11515.506	11930.510
August 16th	12079.845	11873.054	12287.788
August 17th	12630.081	12409.893	12829.819
August 18th	12885.670	12682.580	13111.343
August 19th	13236.665	13041.329	13420.269
August 20th	13538.828	13337.522	13750.702
August 21st	13680.918	13462.974	13889.091
August 22nd	14141.163	13934.366	14339.022
August 23rd	14429.245	14224.163	14643.238
August 24th	14797.999	14585.794	14997.245

Table 8. Actual and predictive daily cases with their difference from August 11th to 24th.

Date	Actual	Prediction	Error
August 11th	10677	10095.297	581.703
August 12th	10957	10557.456	399.544
August 13th	10996	10876.186	119.814
August 14th	11006	11154.770	-148.770
August 15th	11676	11716.733	-40.733
August 16th	12037	12079.845	-42.845
August 17th	12384	12630.081	-246.081
August 18th	12733	12885.670	-152.670
August 19th	13110	13236.665	-126.665
August 20th	13192	13538.828	-346.828
August 21st	13232	13680.918	-448.918
August 22nd	13908	14141.163	-233.163
August 23rd	14564	14429.245	134.755
August 24th	14746	14797.999	-51.999

3.5 Forecast from August 18th to 24th

Prophet fits on data collected before August 18th to make this forecast. We re-estimate the value of K as 24074.0. This forecast predicts the cumulative cases would reach 16440.882 cases on August 24th.

Figure 10 shows the forecasted monkeypox trend. The exact values, including the lower and upper bounds of the uncertainty intervals, are given in Table 10. This forecast predicts more cases every day over this period. The MAE and MAPE scores are lower than the previous forecast, as of values 1340.484 and 0.098, respectively. Figure 11 depicts both the actual and predictive case trends. The actual and predicted total cases and their difference by day are in Figure 11.

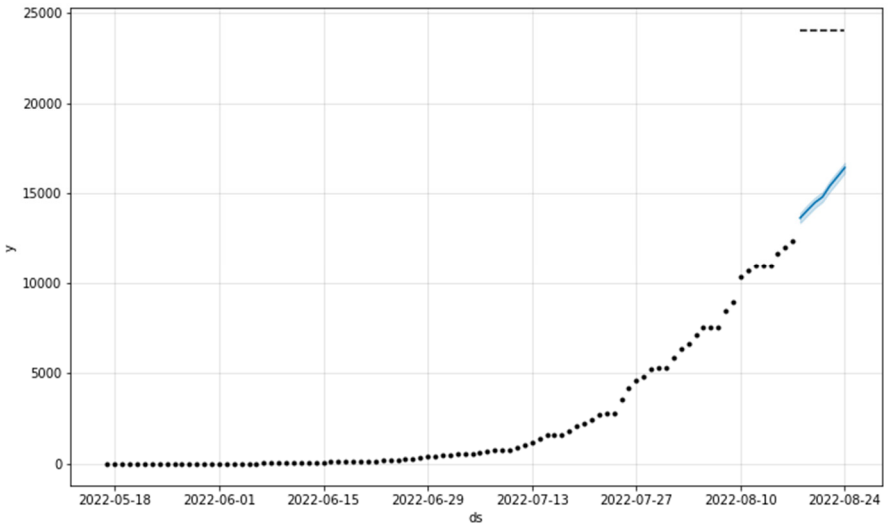


Fig 10. Forecasted monkeypox case trend from August 18th to 24th.

Table 9. Forecasted daily cumulative cases and the uncertainty intervals from August 18th to 24th.

Date	Prediction	Lower Bound	Upper bound
August 18th	13648.220	13385.786	13962.688
August 19th	14089.448	13811.168	14368.038
August 20th	14508.501	14244.295	14810.841
August 21st	14813.358	14520.225	15121.813
August 22nd	15435.645	15159.834	15720.217
August 23th	15932.331	15617.263	16225.155
August 24th	16440.882	16137.679	16718.880

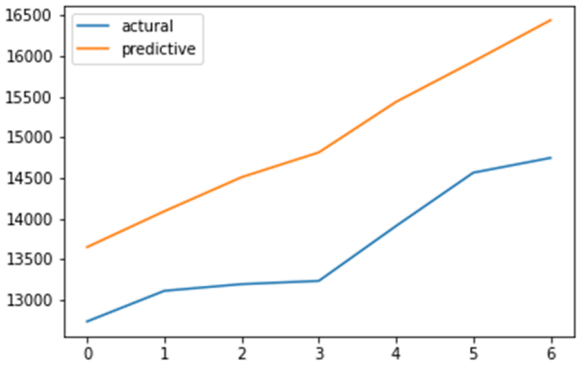


Fig 11. Predicted and actual monkeypox trend from August 18th to August 24th.

Table 10. Actual and predicted cumulative monkeypox cases each day from August 18th to 24th, as well as the difference between the actual and predicted total cases by day.

Date	Actual Total	Predicted Total	Error
August 18th	12733	13648.220	-915.220
August 19th	13110	14089.448	-979.448
August 20th	13192	14508.501	-1316.501
August 21st	13232	14813.358	-1581.358
August 22nd	13908	15435.645	-1527.645
August 23th	14564	15932.331	-1368.331
August 24th	14746	16440.882	-1694.882

4. Discussion

Until we started writing the paper, few researchers focused on monkeypox epidemic growth—even fewer research investigated the performance of the Prophet model on epidemic growth prediction. We are not sure whether this model's performance in predicting monkeypox case growth is more accurate compared with other models, and this will leave for further research.

We predict the monkeypox trend in the U.S. over different time periods, from as short as seven days to as long as seventeen days. The highest MAPE score (0.117) was obtained from the forecast from August 1st to 17th, with a K value of 10568.0. The second highest MAPE score of value 0.098 is from the forecast on August 18th to 24th, where we estimate the value of K as 24074.0. The other three forecasts, predicting either a 7-day or 14-day period, are accurate, with MAPE scores ranging from 0.018 to 0.055. The difference in forecasting time length does not lead to significant prediction inaccuracies.

We suspect that the more significant inaccuracies result from over or underestimation of the K value, based on the difference between the MAPE score on the forecast from August 18th to 24th and the one on August 11th to 24th, where the latter yields a more accurate prediction result. Despite the difference in time scale in the two forecasts, the two forecasts also use different values of K. Probably, the K's value (17943.999) used in the forecast from 11th to 24th is closer to the actual carrying capacity until August 24th.

Unforeseen incidences that may accelerate the case growth could also affect the prediction accuracy. Based on later predictions, we could conclude that the inaccuracy in the forecast from August 1st to 17th is not due to a fault of the model but may be an unknown incidence that happened on one day in that period (or prior to, considering the incubation period of monkeypox) that makes the monkeypox case trend grow faster. Because of this incidence, we underestimate the K value and yield a more inaccurate result. A suitable K value must be estimated for an accurate forecast using the prophet model.

Generally, a less than 20 percent of MAPE score indicates a good prediction. Therefore, we could conclude that the Prophet model gives accurate predictions of the monkeypox growth trend in the outbreak in the U.S. in the year 2022 on a 7 to 17-day time scale.

5. Conclusion

Due to limitations in detailed data on Monkeypox case reporting and contact tracing, there are many uncertainties in the trajectory of the U.S. Monkeypox outbreak at this study stage. In addition, the CDC still has knowledge and data gaps associated with Monkeypox transmission dynamics, case ascertainment, clinical characteristics, and other critical features of this outbreak. Therefore, the Prophetic Forecasting Model of Monkeypox outbreaks can help understand trends in outbreaks and improve the ability to respond to them.

The prognostic prediction model for monkeypox predicted trends in monkeypox in the United States over periods as short as 7 days and as long as 17 days. The K value from August 1 to 10 is a constant, estimated at 10568.0, with a MAPE score of 0.055. The error increases after August 6, with approximately 2012 more actual cases than predicted on August 10. From August 1 to 17, the K value is the same as in the previous section (10568.0), and the MAPE value is 0.117. It has the highest MAPE value, with a larger error, the highest error being the value of 2810.992 on August 17. From August 11 to 17, K is estimated to be 17,943.999, and the MAPE value is 0.020. The error is not significant and does not exceed 250 each day. From August 11 to 24, setting K at 17943.999 yields a MAPE score of 0.018. the error is still modest, but the model's forecast volume generally decreases from August 14 onward. From August 18 to 24, the K value is 24074.0, and the MAPE score is 0.098. In general, MAPE scores below 20% indicate good forecasting results. The results showed all MAPE values between 0.018 and 0.117, the difference in forecast length did not result in large forecast inaccuracies, and the Prophet model accurately predicted the increasing trend of the 2022 outbreak of monkeypox in the United States over a time range of 7 to 17 days.

Nevertheless, the prediction model will have some shortcomings. For example, unknown events can increase the number of monkeypox cases, such as holiday party transmission and imported cases due to vacations. Meanwhile, the response of epidemic prevention agencies can reduce monkeypox cases appropriately, such as vaccine promotion and the effectiveness of epidemic prevention measures. The incidence of such variation will eventually affect the k-value biasing the predictions of the Prophetic Forecasting Model. Considering these factors, obtaining an accurate k-value in future predictions is crucial.

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