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Association between ambient temperature and COVID-19 infection in 122 cities from China

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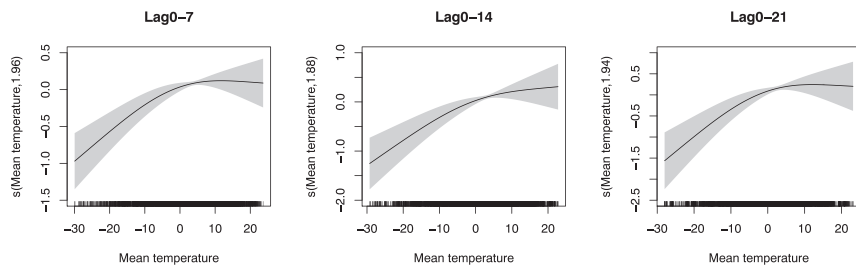
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HIGHLIGHTS

- Mean temperature of last two weeks (when $< 3^{\circ}\text{C}$) was positively associated with newly confirmed COVID-19 cases.
- 1°C rise in the mean temperature of last weeks (when $< 3^{\circ}\text{C}$) was associated with a 4.861% increase in the daily confirmed cases.
- There is no evidence supporting that case counts of COVID-19 could decline when the weather becomes warmer.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Coronavirus disease 2019 (COVID-19) has become a severe public health problem globally. Both epidemiological and laboratory studies have shown that ambient temperature could affect the transmission and survival of coronaviruses. This study aimed to determine whether the temperature is an essential factor in the infection caused by this novel coronavirus.

Methods: Daily confirmed cases and meteorological factors in 122 cities were collected between January 23, 2020, to February 29, 2020. A generalized additive model (GAM) was applied to explore the nonlinear relationship between mean temperature and COVID-19 confirmed cases. We also used a piecewise linear regression to determine the relationship in detail.

Results: The exposure-response curves suggested that the relationship between mean temperature and COVID-19 confirmed cases was approximately linear in the range of $< 3^{\circ}\text{C}$ and became flat above 3°C . When mean temperature (lag0–14) was below 3°C , each 1°C rise was associated with a 4.861% (95% CI: 3.209–6.513) increase in the daily number of COVID-19 confirmed cases. These findings were robust in our sensitivity analyses.

Conclusions: Our results indicate that mean temperature has a positive linear relationship with the number of COVID-19 cases with a threshold of 3°C . There is no evidence supporting that case counts of COVID-19 could decline when the weather becomes warmer, which provides useful implications for policymakers and the public.

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1. Introduction

Coronavirus disease 2019 (COVID-19), caused by the novel coronavirus, was first discovered in Wuhan city, China (Chen et al., 2020; Lu et al., 2020). Subsequently, it spread rapidly to other provinces, although the government has taken timely measures to shut down the

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traffic (Du et al., 2020; Kupferschmidt and Cohen, 2020). As of 29 February 2020, data from the National Health Commission have shown that >79,000 confirmed cases have been identified and over 2800 deaths in the whole of China. Besides China, other countries and regions are also affected by COVID-19, which has become a serious public health problem globally (Sohrabi et al., 2020; Xu et al., 2020).

COVID-19 infection could cause severe respiratory illness, similar to severe acute respiratory syndrome coronavirus (SARS-CoV) (Huang et al., 2020; Xu et al., 2020). Generally, fever, cough, and myalgia or fatigue are common symptoms at the onset of illness (Huang et al., 2020). Early studies have demonstrated person-to-person transmission of COVID-19 through direct contact or droplets (Chan et al., 2020; Lai et al., 2020; Li et al., 2020; Wang et al., 2020). Specifically, a study reported that presumed person-to-person hospital-associated transmission of COVID-19 was suspected in 41% of patients (Wang et al., 2020).

In addition to human-to-human contact, both epidemiological and laboratory studies have shown that ambient temperature is an important factor in the transmission and survival of coronaviruses (Bi et al., 2007; Casanova et al., 2010; Chan et al., 2011; Tan et al., 2005; Van Doremalen et al., 2013). For example, temperature could increase or decrease the transmission risk by affecting the survival time of coronaviruses on surfaces (Casanova et al., 2010; Chan et al., 2011; Van Doremalen et al., 2013). Therefore, it is reasonable to explore the effect of temperature on the spread of this novel coronavirus. To provide useful implications for policymakers and the public, our paper aimed to investigate the relationship between daily mean temperature and newly confirmed COVID-19 cases in 122 cities from China.

2. Materials and methods

2.1. Study area

Our study included 118 prefecture-level cities and 4 municipalities that covered the majority of the Chinese mainland (19.1° to 51.4°

north latitude and 83.4° to 131.6° east longitude). Fig. 1 shows the locations of these 122 cities and the cumulative confirmed cases in each city as of February 29, 2020. We focused on these cities since the meteorological data we have obtained was limited (not including all cities in China).

2.2. Data collection

Daily confirmed cases were collected from the official websites of health commissions in corresponding provinces or cities between January 23, 2020 (i.e., the lockdown of Wuhan) to February 29, 2020. We obtained the data after the closure of Wuhan to minimize the potential inclusion of imported cases in this study.

Meteorological data during the same study period for each city were collected from National Meteorological Information Center (<http://data.cma.cn>). Meteorological factors included daily mean temperature, relative humidity, air pressure, and wind speed.

2.3. Statistical analysis

The generalized additive model (GAM) is a semi-parametric extension of the generalized linear model (GLM), which is useful to explore the nonlinear relationship between weather factors and health outcomes (Lin et al., 2018; Liu et al., 2020; Peng et al., 2006; Talmoudi et al., 2017; Wu et al., 2018). Because the temperature effect could last for several days and the incubation period of COVID-19 ranges from 1 day to 14 days (reported by National Health Commission in China), it is a reasonable choice to use a moving-average approach to account for the cumulative lag effect of temperature (Duan et al., 2019; Li et al., 2018; Lu et al., 2015). Therefore, in this study, a GAM with a Gaussian distribution family (Hastie, 2017; Liu et al., 2020) was applied to examine the moving average lag effect (lag0–7, lag0–14, lag0–21) of mean temperature on daily confirmed cases of COVID-19. The model was

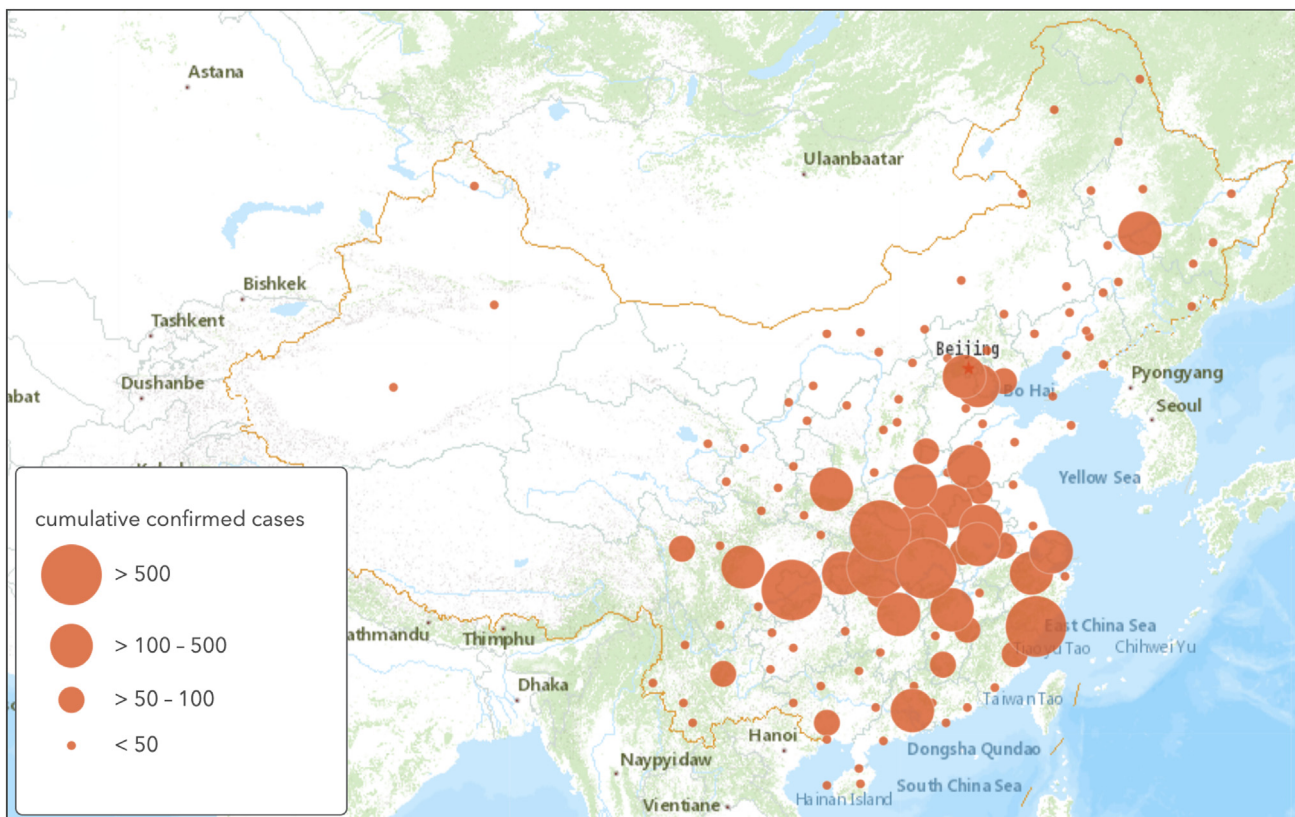


Fig. 1. Locations of 122 cities and cumulative confirmed cases in each city as of February 29, 2020.

Table 1

Descriptive statistics of newly confirmed cases and meteorological variables across all cities and days.

	Mean (SD)	Min	Max
Daily confirmed cases	12.726 (227.082)	0	13,436
Mean temperature (°C)	3.118 (10.286)	-33.8	26.9
Relative humidity (%)	67.480 (17.386)	17	100
Air pressure (hPa)	964.931 (75.816)	668.1	1039
Wind speed (m/s)	2.116 (1.199)	0	15.4

defined as follows:

$$\log y_{it} = a + smeantem_{il} + srhu_{il} + sprs_{il} + swin_{il} + \log y_{i,t-1} + city_i + day_t + \varepsilon_{it}$$

In the model, $\log(y_{it})$ is the log-transformed newly COVID-19 counts in city i on day t (added one to avoid taking the logarithm of zeros) (Liu et al., 2020). a is the intercept and $s(\cdot)$ denotes a thin plate spline function with the maximum 2 degrees of freedom to avoid overfitting (Liu et al., 2020; Wang et al., 2018). $smeantem_{il}$ is the $(l + 1)$ -day moving average term (lag0- l) of daily mean temperature in city i . We also controlled the relative humidity ($srhu_{il}$), air pressure ($sprs_{il}$), and wind speed ($swin_{il}$) during the same period for the possible confounding effect. $\log(y_{i,t-1})$ is the log-transformed COVID-19 counts lagged one day in city i to account for potential serial correlation in the data (Hunter et al., 2019; Liu et al., 2020). $city_i$ is the city fixed effect variable and day_t captures day fixed effect (Amuakwa-Mensah et al., 2017).

According to the results from the GAMs, then we used a piecewise linear regression to determine the relationship between mean temperature and COVID-19 confirmed cases in detail (Cheng et al., 2019; Dukić et al., 2012; Kim et al., 2016; Qian et al., 2008). In the sensitivity analysis, we first excluded Wuhan city from our data because it was the worst-hit region in China and the number of confirmed cases was much larger than that of other cities. Second, we changed the maximum degree of freedom for the spline function to 3 to examine whether our main results were robust.

GAMs in our analysis were implemented via the “mgcv” package (version 1.8–28) of R software (version 3.5.2). The statistical tests were two-sided, and $p < 0.05$ was considered statistically significant.

3. Results

3.1. Descriptive analysis

Table 1 summarizes the descriptive statistics for COVID-19 confirmed cases and meteorological variables. This study included >58,000 cases during the observation period (January 23, 2020 to February 29, 2020) and the average number was 12.726. Average daily mean temperature, relative humidity, air pressure, and wind speed were 3.118 °C, 67.48%, 964.931 hPa, and 2.116 m/s, respectively.

Table 2 shows the correlation coefficients among the meteorological variables. Mean temperature had significantly positive correlations with relative humidity ($r = 0.354, p < 0.05$) and air pressure ($r = 0.163, p < 0.05$). However, mean temperature was negatively correlated with wind speed ($r = -0.053, p < 0.05$).

Table 2

Spearman correlation coefficients between meteorological variables across all cities and days.

	Mean temperature	Relative humidity	Air pressure	Wind speed
Mean temperature	1.000			
Relative humidity	0.354*	1.000		
Air pressure	0.163*	0.274*	1.000	
Wind speed	-0.053*	-0.117*	0.127*	1.000

* $p < 0.05$.

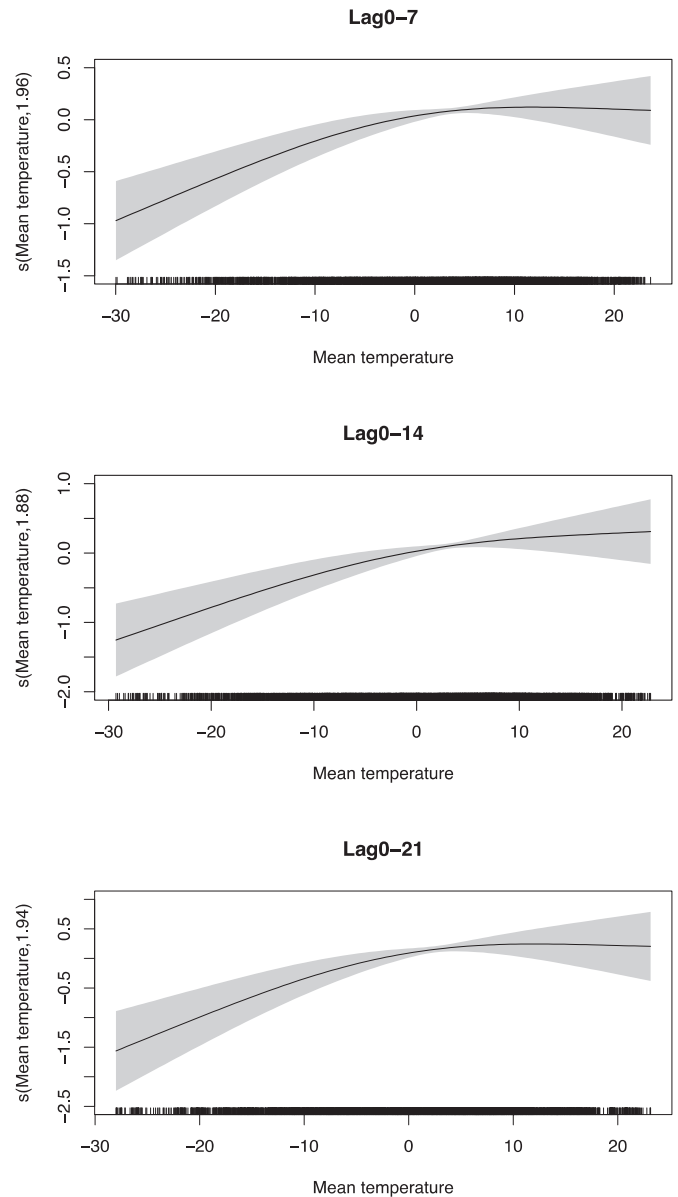


Fig. 2. Exposure-response curves for the effects of temperature on COVID-19 confirmed cases. The x axis is the mean temperature (7-day, 14-day and 21-day moving average). The y axis indicates the contribution of the smoother to the fitted values.

3.2. Relationship between temperature and COVID-19 confirmed cases

The exposure-response curves in Fig. 2 suggested that the relationship between temperature and COVID-19 confirmed cases was significantly nonlinear (lag0-7: $p < 0.001$, lag0-14: $p < 0.001$, lag0-21: $p < 0.001$). Specifically, the relationship was approximately linear in the range of <3 °C and became flat above 3 °C, indicating that the single threshold of the temperature effect on COVID-19 was 3 °C.

Table 3
The effects of a 1 °C increase in mean temperature on COVID-19 confirmed cases.

	Mean temperature ≤ 3 °C		Mean temperature >3 °C	
	Percentage change (%)	95% CI	Percentage change (%)	95% CI
Lag0–7	3.432*	(2.277–4.586)	–0.895	(–2.493–0.703)
Lag0–14	4.861*	(3.209–6.513)	–0.750	(–3.022–1.522)
Lag0–21	6.953*	(4.681–9.225)	–1.858	(–4.502–0.786)

* $p < 0.05$.

Based on results from GAMs, a piecewise linear regression was adapted with a threshold at a 3 °C to quantify the effect of temperature above and below the threshold. As showed in Table 3, each 1 °C rise in mean temperature (lag0–7) led to a 3.432% (95% CI: 2.277–4.586) increase in the daily number of COVID-19 confirmed cases when mean temperature was below 3 °C. This positive effect is largest at lag0–21 (percentage change = 6.953%, 95% CI: 4.681–9.225). When mean

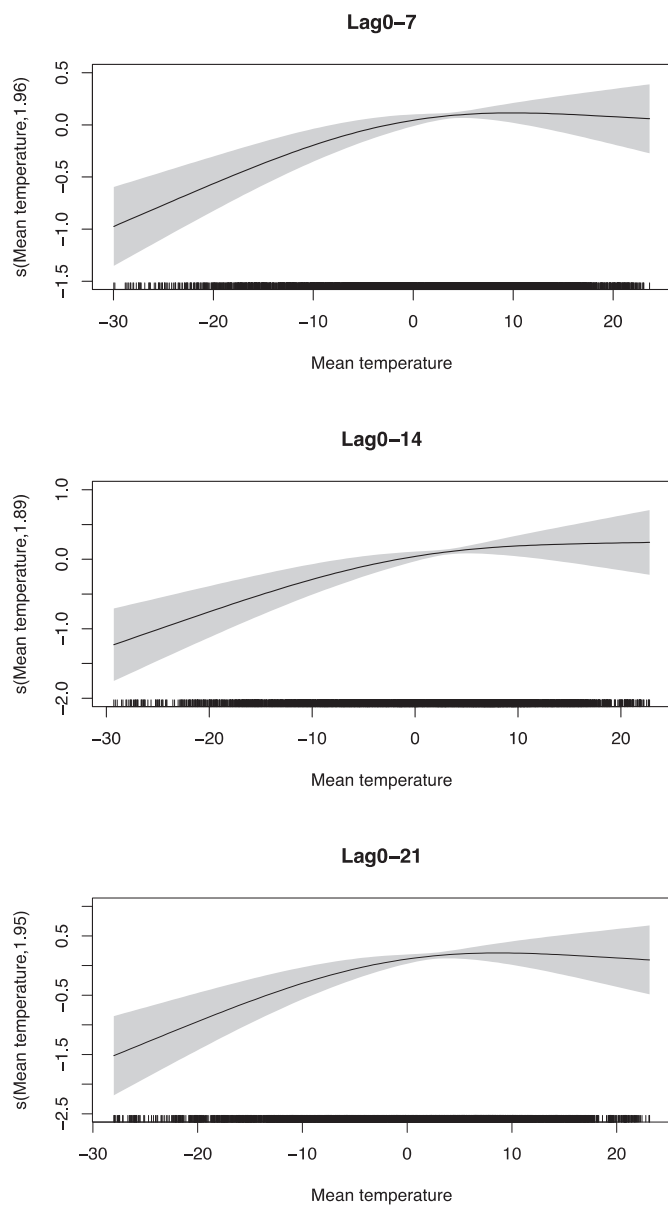


Fig. 3. Exposure-response curves for the effects of temperature on COVID-19 confirmed cases after excluding Wuhan. The x axis is the mean temperature (7-day, 14-day and 21-day moving average). The y axis indicates the contribution of the smoother to the fitted values.

temperature was above 3 °C, the negative effect of temperature was not statistically significant.

3.3. Sensitivity analysis

The nonlinear relationship was robust after excluding Wuhan city from our data (Fig. 3). We also used a piecewise linear model to quantify the effect in this sensitivity analysis (Table 4). Below the threshold 3 °C, the confirmed cases increased by 6.949% (95% CI: 4.692–9.205) for every 1 °C rise in mean temperature (lag0–21). Our main finding was robust when we changed the maximum degree of freedom for the spline function to 3 (Figs. S1–S2)

4. Discussion

In this paper, we explored the nonlinear relationship between ambient temperature and COVID-19 confirmed cases by using a generalized additive model. The exposure-response relationship was positive linear when the mean temperature below 3 °C and became flat above 3 °C, indicating that higher temperature may not limit the transmission of this novel coronavirus.

Previous studies have showed that temperature is also an important factor in the survival and transmission of other coronaviruses, like SARS-CoV and MERS-CoV (Bi et al., 2007; Casanova et al., 2010; Chan et al., 2011; Tan et al., 2005; Van Doremalen et al., 2013), so we compared our main findings with results in these studies. Tan et al. (2005) found that the optimum environmental temperature related to SARS cases was from 16 °C to 28 °C based on data from Hong Kong, Guangzhou, Beijing, and Taiyuan. Moreover, Bi et al. (2007) reported that temperature had a negative relationship with SARS transmission in Hong Kong and Beijing in 2003. A laboratory study using surrogate viruses to investigate the effect of temperature on coronavirus survival on surfaces showed that viruses were inactivated more rapidly at 20 °C than at 4 °C (Casanova et al., 2010). Another laboratory study found that coronavirus on smooth surfaces was stable for over 5 days when temperature at 22 °C–25 °C, and virus viability was rapidly lost at higher temperatures (e.g., 38 °C) (Chan et al., 2011). Van Doremalen et al. (2013) also observed that MERS-CoV was less stable at high temperature. In brief, most studies showed that there was an optimum temperature for coronavirus and high temperature was harmful to its viability. However, this paper could not observe a negative effect of high temperature on COVID-19 infection. A possible reason may be that the study period was limited in winter, with maximal mean temperature 26.9 °C. Further laboratory studies also need to be conducted to determine the underlying mechanism.

Our study has some implications. First, the nonlinear relationship between ambient temperature and COVID-19 confirmed cases showed COVID-19 may not perish of itself without any public health interventions when the weather becomes warmer. So, the public and governments could not expect the high temperature to eradicate this novel virus. Additionally, increasing temperature in regions or periods below 3 °C is related to the high risk of transmission, which provides useful information for policymakers if the novel coronavirus coexists with human for a long time.

Table 4

The effects of a 1 °C increase in mean temperature on COVID-19 confirmed cases after excluding Wuhan.

	Mean temperature ≤ 3 °C		Mean temperature >3 °C	
	Percentage change (%)	95% CI	Percentage change (%)	95% CI
Lag0–7	3.471*	(2.322–4.619)	–1.151	(–2.747–0.446)
Lag0–14	4.845*	(3.204–4.486)	–1.305	(–2.572–0.961)
Lag0–21	6.949*	(4.692–9.205)	–2.606	(–5.245–0.032)

* $p < 0.05$.

However, several limitations should be acknowledged. First, we could not conduct subgroup analysis by gender and age group to explore the sensitive population because there was a lack of patient information. Second, although the government has established a good disease surveillance system, under-reporting may still occur and could affect our main findings, especially at the beginning of COVID-19 outbreak. Third, our data only covered cities in China. Further studies on the effects of temperature on COVID-19 transmission in other countries are needed.

5. Conclusion

To the best of our knowledge, this is the first study to investigate the nonlinear relationship between ambient temperature and daily COVID-19 confirmed cases. Our results indicate that mean temperature has a positive linear relationship with the number of COVID-19 cases when the temperature is below 3 °C. There is no evidence supporting that case counts of COVID-19 could decline when the weather becomes warmer, which provides useful implications for policymakers and the public.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2020.138201>.

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