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Research report

Decomposing the association of completed suicide with air pollution, weather, and unemployment data at different time scales

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ABSTRACT

Background: Research has implicated environmental risk factors, such as meteorological variables, in suicide. However, studies have not investigated air pollution, known to induce acute medical conditions and increase mortality, in suicide. This study comprehensively assesses the temporal relationship between suicide and air pollution, weather, and unemployment variables in Taipei City from January 1 1991 to December 31 2008.
Methods: This research used the empirical mode decomposition (EMD) method to de-trend the suicide data into a set of intrinsic oscillations, called intrinsic mode functions (IMFs). Multiple linear regression analysis with forward stepwise method was used to identify significant predictors of suicide from a pool of air pollution, weather, and unemployment data, and to quantify the temporal association between decomposed suicide IMFs with these predictors at different time scales.
Results: Findings of this study predicted a classic seasonal pattern of increased suicide occurring in early summer by increased air particulates and decreased barometric pressure, in which the latter was in accordance with increased temperature during the corresponding time. Gaseous air pollutants, such as sulfur dioxide and ozone, were found to increase the risk of suicide at longer time scales. Decreased sunshine duration and sunspot activity predicted the increased suicide. After controlling for the unemployment factor, environmental risks predicted 33.7% of variance in the suicide data.
Conclusions: Using EMD analysis, this study found time-scale dependent associations between suicide and air pollution, weather and unemployment data. Contributing environmental risks may vary in different geographic regions and in different populations.

1. Introduction

Suicide is a complex, multidimensional phenomenon that has been a major public health issue in recent years (Maris, 2002). Research has associated a considerable number of risk factors with suicide (Gould et al., 1996; Kessler et al., 1999; Maris, 2002). The most widely cited, yet poorly understood suicide risks are environmental-related variables, such as meteorological factors. Although substantial efforts have been made to link suicide with weather conditions, studies have been mixed in this regard (Deisenhammer, 2003). For example, some studies have found increased temperature to be positively correlated with suicides (Deisenhammer et al., 2003; Lee et al., 2006; Page et al., 2007; Preti et al., 2007; Ruuhela et al., 2009), but negative or absent in others (Ajdacic-Gross et al., 2007; Dixon et al., 2007; Partonen et al., 2004b,c). Most previous studies have focused on a "seasonal" correlation between

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weather and suicide (i.e., annual peak of suicide in spring or early summer), yet there has been no study to delineate the temporal impact of environmental factors on suicide at other time scales, such as those over several years. Moreover, there is increasing evidence that air pollution could increase the all-cause mortality rate (Dockery et al., 1993), and the risk of various medical conditions, such as asthma (Thurston and Bates, 2003), stroke (Wellenius et al., 2005), or myocardial infarction (von Klot et al., 2005). Air pollution has been linked to emergency visits of depression (Szyszkowicz et al., 2009), and therefore its connection with suicide is plausible and warrants comprehensive investigations.

Suicide risk factors may operate at distinct time scales other than seasonal oscillations. For example, not only seasonal solar influx, but solar activity fluctuation over a longer time scale, affects temperature and sunshine duration (Alnaser and Alothman, 1991; Palle and Butler, 2001). Unemployment rate has a long-term effect on suicide rate (Chen et al., 2010; Gunnell et al., 1999). A broad investigation of a suicide association with these factors at different time scales may shed light on the neurobiology of suicide. Since suicidal behavior represents a complex interaction between individual and psychological, sociological, and environmental factors (Maris, 2002), consecutive suicide time series often show complex fluctuations over time and the associations are difficult to analyze with individual risk factors by conventional methods.

In the present study, we therefore apply an adaptive-based method of empirical mode decomposition (EMD) (Huang et al., 1998; Wu et al., 2007) to de-trend the suicide data. The EMD method provides a generic algorithm to decompose a complex time series (Wu et al., 2007) into a set of intrinsic oscillations, called intrinsic mode functions (IMFs), that are orthogonal to each other. Each IMF has its characteristic time scale, making it suitable for the challenge of analyzing the temporal association between suicide and environmental variables. This work examines the completed suicide data from January 1 1991 to December 31 2008 in Taipei City, Taiwan. Using multiple linear regression analysis with a forward stepwise method, this study comprehensively evaluates significant predictors of suicide from a pool of air pollution and weather and unemployment data, to quantify the temporal association between decomposed suicide IMFs with these predictors at different time scales.

2. Materials and methods

2.1. Suicide data

The Department of Health, Taipei City Government, Taiwan provided suicide data Between January 1 1991 and December 31 2008, there were 4857 deaths by suicide in Taipei city (64.4% male, mean age = 49.6 ± 18.3 years, range = 11–106). The demographic variables in this data included gender, date of birth and death, place of death (geographic district), marital state, and means of suicide by ICD-9-CM. All data were provided in electronic format. The study was approved by the Institutional Review Board of the Taipei Veterans General Hospital (Taipei, Taiwan).

Taipei City is central to the largest metropolitan area in Taiwan and currently has about 2.6 million people. The ecological study design derived the average monthly counts of suicide (22.5 ± 9.6 cases/month, range = 6–59 cases). The suicide time series was normalized by a population factor derived from monthly population data. The population factor of January 1991 was designated as one and this factor increased to 1.30 in December 2008. The population growth rate in Taiwan is relatively low due to low birth and immigration rate.

2.2. Air pollution, weather, and unemployment data

The Environmental Protection Administration, Taiwan provided air pollution data from July 1993 to December 2008. Measurements included sulfur dioxide (SO_2; Model 9850, Ecotech Inc., Australia), nitrogen oxide (NO_x; Model 9841, Ecotech Inc., Australia), ozone (O_3, Model 9810, Ecotech Inc., Australia), carbon monoxide (CO, Model APMA-370, Horiba Inc., Japan), and particulate matter with aerodynamic diameter ≦10 μm (PM_{10}, Mode F701, Verewa, Germany). Measurement of the particulate matter with aerodynamic diameter ≦2.5 μm was implemented only after 2005 and therefore was not included in the analysis.

The Central Weather Bureau, Taiwan provided local weather data in the central Taipei area comprising the full study period. Taipei City is located at the subtropical region characterized by a cool winter and a hot summer. The annual average temperature in Taipei City is about 22 °C, ranging from 15 °C in winter to 27 °C in summer. The primary weather variables employed in this study included ambient temperature, barometric pressure, relative humidity, average wind speed, and total hours of sunshine in a day. All weather variables were monthly average values.

In addition, sunspot activity data was assessed at the Solar Influences Data Analysis Center, Belgium (http://sidc.oma.be). Monthly unemployment data was provided by the Department of Accounting and Statistics, Executive Yuan, Taiwan. The unemployment rate in Taiwan was 3.17 ± 1.27% (range = 1.20–5.35%).

2.3. Empirical mode decomposition (EMD)

The EMD method was developed to de-trend and identify intrinsic oscillations embedded in a complex signal (Huang et al., 1998), and has been widely applied in multiple disciplines (Cummings et al., 2004; Novak et al., 2004; Sweeney-Reed and Nasuto, 2007). Unlike the Fourier-based time series analysis, EMD holds no *a priori* assumption for underlying structures of the time series, and is therefore suitable for analyzing time series consisting of multiple periodic components. The decomposition was based on the simple assumption that any data consists of a finite number of intrinsic components of oscillations. Each oscillation component, termed intrinsic mode function (IMF), was sequentially decomposed from the original time series by a sifting process.

Briefly, the sifting process is comprised of the following steps: 1) connecting local maxima or minima of a targeted signal to form the upper and lower envelopes by natural cubic spline lines; 2) extracting the first prototype IMF by estimating the difference between the targeted signal and the mean of the upper and lower envelopes; and 3) repeating the previous procedures to produce a set of IMFs represented by a certain frequency–amplitude modulation at a characteristic time scale. The decomposition process is complete when no more IMFs can be extracted, and the residual component is treated as the overall trend of the raw data. Although these IMFs are empirically determined, they remain orthogonal to one another, and may therefore contain independent physical meaning that is relevant to other parameters (Lo et al., 2009; Wu et al., 2007).

The EMD method served two purposes in this study: (1) to decompose the suicide time series into IMFs; each oscillated at certain time scales, and (2) to de-trend (i.e., to remove residual component from raw data) the time series of air pollution, weather, and unemployment data to produce a zero-mean distribution, thus reducing type I statistical error in subsequent multiple linear regression analysis. This study used a publicly available EMD algorithm based on Matlab software (version 2007; The Mathworks, Natick, Massachusetts) (http://rcada.ncu.edu.tw/research1.htm).

2.4. Statistical analysis

SPSS for Windows Version 15.0 (Chicago, IL; SPSS Inc.) software was used for statistical analyses. Pearson correlations were used to evaluate the relations among the time series of suicide and other environmental variables. Using monthly suicide counts as the dependent variable and air pollution, weather, and unemployment data as predictors, this study used multiple linear regression analysis with a forward stepwise method to identify significant predictors of suicide and to estimate how much of the total variation in the monthly suicide counts could be explained by these predictors. Environmental variables with skewed distributions were log transformed before entering the regression model.

In the first step of analysis, multiple linear regression analysis was used to identify significant predictors in different suicide models, in which suicide data was stratified according to age, gender, and means of suicide. Partial correlations between suicide and predictors, and a summary for each regression model were reported. To investigate the temporal time scale association between suicide and its predictors, this study decomposed the suicide time series into IMFs using the EMD method. Each IMF had characteristic frequency/amplitude modulation at different time scales and used to correlate with predictors previously identified in the first step of regression models. A two-tailed p value of less than .05 was required for statistical significance in all analyses.

3. Results

3.1. Characteristics of suicide and environmental data

Among 4857 suicide cases, 3619 (74.5%) were adult (age≧20 and age≦65), 1126 (23.2%) were elderly (age>65), and 112 (2.3%) were adolescent (age<20). 3553 (73.2%) deaths were by violent means, such as hanging or jumping from heights (ICD-9-CM codes: E953-E958), whereas 1304 (26.8%) were by non-violent means, such as poisoning (ICD-9-CM codes: E950-E952). 1880 (38.7%) were married and the remaining 2977 cases were either single (N=1616, 33.3%), divorced (N=741, 15.3%), a widow/widower (N=436, 9.0%), or unknown (N=184, 3.7%). Notably, 3075 (63.3%) committed suicide at districts of the registered address. Higher rates of violent suicide were associated with males, compared to females (odds ratio: 1.19, 95% CI: 1.04–1.37, p=0.009); and were associated with the elderly, compared to the adult population (odds ratio: 4.07, 95% CI: 3.33–4.99, p<0.001). Marital state was not associated with the type of suicide.

Table 1
Summary of monthly averages of ambient meteorological and air pollutants in Taipei City, Taiwan, January 1991–December 2008.

Predictors	Median	25th Percentile	75th Percentile
Temperature, °C	23.4	18.7	27.5
Barometric pressure, mm Hg	1013.1	1007.0	1018.0
Relative humidity, %	76.1	72.7	78.7
Wind speed, m/s	2.7	2.4	3.0
Sunshine duration, hour	3.7	2.7	5.0
Sunspot activity, #	45.9	14.5	92.7
Sulfur dioxide, ppm	4.7	3.7	5.8
Ozone, ppm	19.4	16.3	24.1
Carbon oxide, ppm	0.85	0.70	1.07
Nitrogen oxide compounds, ppm	46.0	38.7	54.1
PM_{10}, μg/m^3	49.5	43.0	58.0

PM_{10}: Air particulate matter with aerodynamic diameter≦10 μm.
Air pollution data was available from July 1993–December 2008.

Table 1 summarizes the ambient levels of meteorological and air pollution variables. Pearson correlations between the time series of monthly suicide counts and air pollution, weather, and unemployment variables are given in Table S1.

3.2. Prediction of suicide by multivariate environmental variables and unemployment rate

Table 2 summarizes the partial correlation between monthly suicide counts and significant predictors derived from multiple linear regression analysis with a forward stepwise method. In data comprised of all suicide counts, temperature (r=0.183, p=0.014), sunshine duration (r=−0.277, p<0.001), SO_2 (r=0.302, p<0.001), ozone (r=0.244, p=0.001), sunspot activity (r=−0.271, p<0.001), and unemployment rate (r=0.433, p<0.001) predicted 52.5% of variance in suicide data (p<0.001). After controlling for the unemployment factor, environmental risks predicted 33.7% of variance in suicide data.

When suicide data were stratified according to gender, this study found that environmental and unemployment factors explained higher in male (R^2=0.418, p<0.001) than in female suicide cases (R^2=0.286, p<0.001). Unemployment rate was significantly correlated higher to male suicide (r=0.463, p<0.001) than female cases (r=0.195, p=0.008). In terms of environmental factors, gender were associated with ozone (male: r=0.213, p=0.004; female: r=0.202, p=0.006) and sunspot activity (male: r=−0.263, p<0.001; female: r=−0.227, p=0.002), whereas the male gender was associated with temperature (r=0.178, p=0.016), sunshine duration (r=−0.241, p=0.001), and SO_2 (r=0.265, p<0.001).

For data classified by means of suicide, environmental and unemployment factors explained higher in non-violent (R^2=0.586, p<0.001) than in violent suicide cases (R^2=0.224, p<0.001). Unemployment rate was significantly associated higher with non-violent suicide (r=0.474, p<0.001) than in violent cases (r=0.242, p=0.001). Violent suicide was associated with ozone (r=0.231, p=0.002), pressure (r=−0.162, p=0.003), and sunshine duration, (r=−0.158, p=0.033). Non-violent suicide was associated with CO (r=−0.373, p<0.001), sunspot

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Table 2
Forward multiple linear regression analyses of suicide with air pollution, weather, and unemployment factors.

Predictors	Normalized monthly counts of completed suicide in the Taipei City, Taiwan, January 1991 to December 2008						
	Total	Violent	Non-violent	Male	Female	Adult	Elderly
						Age 20–65	Age>65
Temperature	0.183			0.178			
Pressure		−0.220					
Sunshine	−0.277	−0.158	−0.250	−0.241		−0.242	
SO_2	0.302		0.334	0.265		0.309	
PM_{10}			0.195				
O_3	0.244	0.231		0.213	0.202	0.194	0.312
CO	−0.163		−0.373		−0.082	−0.168	
Sunspots	−0.271		−0.346	−0.263	−0.227	−0.277	
Unemployment	0.433	0.242	0.474	0.463	0.195	0.458	
R^2 (Std. error)	0.525 (4.82)	0.224 (3.65)	0.587 (2.69)	0.418 (3.97)	0.286 (2.45)	0.522 (4.13)	0.093 (2.01)
F	30.17	14.32	44.85	23.15	19.53	34.63	19.90
Significance	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Data presented are partial correlations for each paired association.
Humidity, wind, and nitrogen oxide were not significant predictors in all models.

activity ($r=-0.346$, $p<0.001$), SO_2 ($r=0.334$, $p<0.001$), sunshine duration ($r=-0.250$, $p=0.001$), and PM_{10} ($r=0.195$, $p=0.009$).

For age groups, elderly suicide was associated only with ozone ($r=0.312$, $p<0.001$), whereas the regression model of adult suicide was similar to that comprising all data. This study did not find an association of suicide with humidity, wind speed, and NO_x in all models.

3.3. Analysis of predictors of suicide at different time scales

Fig. 1a shows the time series of monthly suicide counts normalized by the population growth data. To elucidate the temporal relationship between suicide and those identified predictors at different time scales, this study decomposed the suicide time series using the EMD method. The decomposition of suicide data yielded six IMFs (Fig. 1b–g) and a residual (overall trend; Fig. 1h). The frequencies of these IMFs ranged from 2.7 to 191.1 months per cycle. The overall trend showed a steadily increased rate of suicide at 0.06 subjects per month.

Table 3 summarizes the association of suicide IMFs with environmental and unemployment predictors at different time scales. Only predictors identified in Table 1 were entered into the regression model. No significant models were derived from the first and second suicide IMFs. For weather variables, pressure was associated with the third suicide IMF ($r=-0.417$, $p<0.001$), and sunshine duration was associated with the fifth suicide IMF ($r=-0.192$, $p=0.009$). For air pollution variables, PM_{10} was associated with the third suicide IMF ($r=0.162$, $p=0.028$), SO2 was associated with the fourth to sixth suicide IMFs ($r=0.156$, $p=0.034$; $r=0.365$, $p<0.001$; $r=0.451$, $p<0.001$), and ozone and CO were associated with the sixth suicide IMF ($r=0.338$, $p<0.001$; $r=-0.236$, $p=0.001$). Unemployment rate was associated with the fourth to sixth suicide IMF ($r=0.210$, $p=0.004$; $r=0.382$, $p<0.001$; $r=0.194$, $p=0.009$).

Fig. 2 illustrates the temporal association of pressure and PM_{10} with the third suicide IMF. For comparison, temperature time series was included in the figure because of its high correlation with pressure ($r=-0.922$, $p<0.001$). The cross correlation coefficient indicated that the peak of suicide was in June for most years and preceded the trough of pressure as well as the peak temperature for a month ($r=-0.427$, $p<0.001$; $r=0.445$, $p<0.001$), and lagged the peak of PM_{10} for three months ($r=0.252$, $p<0.001$).

4. Discussion

In this analysis of the eighteen-year completed suicide data using the EMD method, this study identified significant associations of suicide with a set of factors related to air pollution, weather, and unemployment data varying at different time scales, and by different suicide samples. A classic seasonal pattern of increased suicide counts occurred in early summer as predicted by increased PM_{10} and decreased barometric pressure, in which the latter was in accordance with increased temperature during the corresponding time. Gaseous air pollutants, such as SO_2 and ozone, appeared to increase the risk of suicide at longer time scales. Decreased sunshine duration and sunspot activity correlated with increased suicide counts at a period of over five years. After controlling for the unemployment factor, these environmental risks predicted 33.7% of the variance in suicide data.

Interest is growing in air pollution as a trigger of a variety of acute medical conditions. Air pollution represents a complex mix of pollutants, including coarse and fine particulate and gaseous constituents. The study results indicate that increased PM_{10} in spring correlate to increased suicide later in early summer. Particulate is known to cause acute respiratory symptoms, and a recent report has shown that poor respiratory function was a risk of suicide (Giltay et al., 2010). The study finding may provide further evidence to support the suicide/pollutant association at seasonal time scales.

Exposure to other gaseous pollutants has been related mostly to respiratory diseases (Koenig et al., 1987; McConnell et al., 2002), yet these air pollutants could alter neurotransmitter balance and may result in aggression and suicidal behaviors (Biermann et al., 2009). Animal studies have shown exposure to ozone to affect serotonin metabolism and its metabolites (Gonzalez-Pina and Paz, 1997), and has been

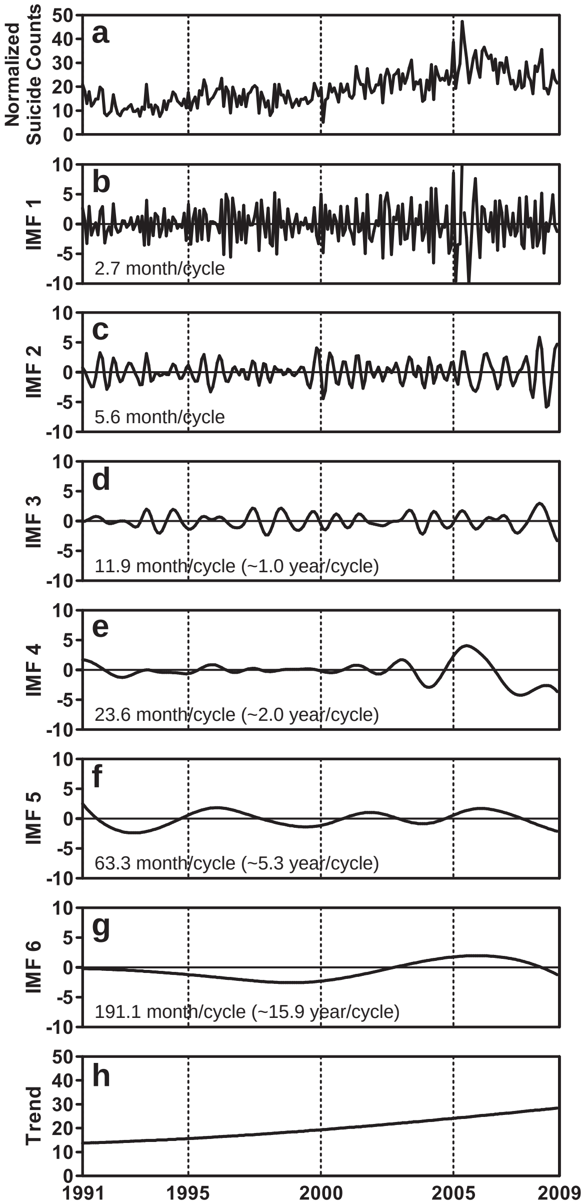

Fig. 1. Decomposition of normalized monthly counts of completed suicide time series: (a) raw suicide time series from January 1991 to December 2008. (b–g) Decomposed intrinsic mode functions (IMFs). Frequency of each IMF is shown in each panel. The raw suicide data can be recovered by summing all IMFs (panels b–g) and (h) the overall trend.

linked to sleep disturbance (Gonzalez-Pina and Alfaro-Rodriguez, 2003; Huitron-Resendiz et al., 1994; Paz and Huitron-Resendiz, 1996). Despite the small percentage of explanation power by ozone in the study (under 10%), ozone was particularly associated with violent and elderly suicides, implying a possible role of ozone in aggression. In contrast, SO_2 was associated with non-violent and adult cases. CO had strong negative correlation with ozone, therefore explaining its association with suicide by ozone alone. The biological effect of gaseous pollutants on suicide remains unclear but is likely long-term.

Studies have proposed solar activity to be associated with mental illness (Borelli et al., 2010; Richardson-Andrews, 2009; Vaquero, 2009) and suicide (Partonen et al., 2004a). The negative correlation finding between suicide and sunspot activity in this study is interesting but could have simple explanations. The suicide/sunspot correlation was mainly at 5.3 years per cycle (5th IMF), which coincided with half of the 11-year solar cycle. Decreased sunshine duration notably predicted increased suicide at the same time scale (5th IMF). Sunspot activity is highly correlated to solar radiation, and has been implicated in climate patterns, such as increased sunshine duration (Palle and Butler, 2001). This study speculates that the association of sunspot activity with suicide is because of its impact on sunshine duration, which primarily implicates affective disorder.

The study complements previous reports in several aspects. First, in agreement with the majority of literatures (Deisenhammer, 2003; Deisenhammer et al., 2003; Lee et al., 2006; Page et al., 2007; Preti et al., 2007; Ruuhela et al., 2009), the study results show that pressure change in accordance with increased temperature was associated with seasonal suicide IMF and violent cases. The seasonal effect of weather on suicide was significant in high-latitude countries (Deisenhammer, 2003). However, this effect is likely small in the Taipei area, representing a subtropical weather pattern, and therefore could not be of clinical importance in this region. Second, as anticipated, unemployment rate had significant impact on suicide, particularly the male gender and non-violent suicides in the study data. These findings are contrasted to another study based on US data that unemployment was associated more with females than males (Kposowa, 2001), and the discrepancy might be due to cultural difference.

The strength of this study includes the length of the study period and the use of the EMD method to decompose complex suicide data into orthogonal, identifiable oscillations. Traditional methods of time series decomposition include cosinor analysis, seasonal decomposition of time series by local regression, or autoregressive algorithms. These methods require either predefined frequency of oscillations or the assumption of stationarity, which the later is often invalid in epidemiologic time series. EMD is empirical and adaptive, without requiring any predetermined assumption of data (Wu et al., 2007), thus allowing us to investigate the temporal relationship between suicide and environmental variables at different time scales. Prior studies have found that the empirically decomposed IMFs reflected certain physical meanings related to underlying mechanisms. For example, EMD has been successful to isolate traveling waves in dengue hemorrhagic fever incidences across Thailand (Cummings et al., 2004), or to evaluate the risk of stroke by identifying oscillations in cerebral blood flow related to cerebral auto-regulations (Novak et al., 2004).

The interpretations made from this study have limitations. The ecological design of the study did not allow us to assess individual exposure to environmental risks. The study was based on completed suicide data; attempted suicide may have distinct risk profiles with completed suicide in this study (Haukka et al., 2008; Valtonen et al., 2006). Finally, as the suicide data was from a metropolitan area, this study could not evaluate the difference in exposure to air pollutants in

Table 3
Forward multiple linear regression analyses of decomposed suicide IMFs with air pollution, weather, and unemployment factors.

Predictors	IMF 3	IMF 4	IMF 5	IMF 6
	11.9 month/cycle	23.6 month/cycle	63.3 month/cycle	191.1 month/cycle
Pressure	−0.417			
Sunshine			−0.192	
SO_2		0.156	0.365	0.451
PM_{10}	0.162			
O_3				0.338
CO				−0.236
Sunspots			−0.396	−0.213
Unemployment		0.210	0.382	0.194
Adjusted R^2 (Std. error)	0.177 (1.09)	0.046 (1.69)	0.217 (0.96)	0.316 (1.28)
F	19.65	5.50	13.78	18.05
Significance	<0.001	0.005	<0.001	<0.001

Data presented are partial correlations for each paired association.
IMF1 and 2 did not yield significant models.
Temperature, humidity, wind, and nitrogen oxide were not significant predictors in all models.

urban and rural areas and its impact on suicidal behaviors. Replication of these findings is required in other populations and geographical regions. In conclusion, this report presents the first evidence of suicide associated with air pollution data at different time scales and may stimulate a new line of research associated with suicide and environmental risks.

Supplementary data associated with this article can be found, in the online version, at doi: 10.1016/j.jad.2010.08.010.

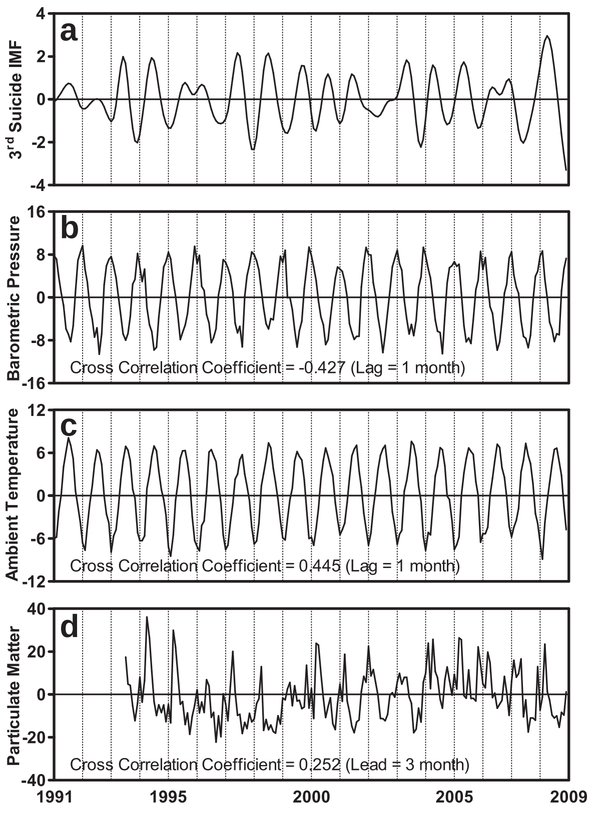

Fig. 2. Comparison of (a) the third intrinsic mode function decomposed from monthly suicide counts using the empirical mode decomposition (EMD) method, and (b) barometric pressure time series, (c) ambient temperature time series, and (d) particulate matter with aerodynamic diameter ≦10 μm. Vertical dashed line indicates the beginning of each year. Time series in panels (b–d) was detrended by the EMD method to produce a zero-mean data to reduce type I statistical error. The cross correlation coefficient was given in panels (b–d) to indicate the maximal correlation between suicide and the corresponding variable at certain lead or lag time scales.

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Conflict of interest

All authors declare that they have no conflicts of interest.

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