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Temporal and spatial trends of residential energy consumption and air pollutant emissions in China

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HIGHLIGHTS

- Two new concepts of *HD* and HDD_p were introduced to predict residential fuel use.
- Temporal variation of energy use was characterized by space-for-time substitution.
- Residential energy use and pollutant emissions in China were mapped at 1° × 1°.
- Seasonality of energy use and pollutant emissions in China were characterized.
- Effects of climate warming on energy use and pollutant emission were quantified.

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ABSTRACT

Residential energy consumptions of both electricity and fuels are associated with emissions of many air pollutants. Temporally and spatially resolved energy consumption data are scarce in China, which are critical for a better understanding of their environmental impacts. In this study, a space-for-time substitution method was proposed and two models for predicting fuel and electricity consumptions in residential sector of China were developed using provincial data. It was found that fuel consumption was not directly proportional to heating degree day and was also affected by heating day, defined as the number of days when heating is required in a year. The models were validated against a set of historical annual data and two sets of survey data on seasonal variations. The models were applied to predict spatial and temporal variations of residential energy consumptions and emissions of various pollutants and to predict net effects of climate warming on energy consumptions and pollutant emissions. The emissions of black carbon (BC), carbon monoxide (CO), and polycyclic aromatic carbons (PAHs) in winter were significantly higher than those in other seasons. For the emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x), there were two peaks in winter and summer, with the latter increasing gradually over years. It was predicted that per-capita residential energy consumptions would reach 0.43, 0.33, and 0.26 toe/cap in 2050 for IPCC scenarios of A1B, B1, and A2, respectively. Climate warming in the future would lead to less residential fuel but more electricity consumptions. Consequently, emissions of BC, CO, and PAHs would decrease mainly in cold climate zones, while emissions of CO_2, SO_2, and NO_x would increase largely in southeast China.

1. Introduction

Energy is of fundamental importance to our society. However, the acquisition, production, and utilization of energy have great adverse impacts on environment by emitting pollutants, greenhouse gases, and heat [1]. A portion of energy, mainly electricity and fuels, is used in residential sector for heating, cooling, cooking, lighting, and appliances. According to the National Bureau of Statistics of China, electricity and various fuels account for 11% and 89% of the total residential energy consumption in China, respectively [2]. Although the quantities of fuels, mainly coal and biomass fuel, used in residential sector contribute to a relatively small fraction of total energy consumption, the environmental impacts of residential fuel consumption cannot be ignored due to relatively low combustion efficiencies and high emission factors [3–6]. For example, it was estimated that over 50% of black carbon and approximately 70% of polycyclic aromatic hydrocarbons (PAHs) emitted in China were from residential fuel combustions [7,8].

Residential energy consumption is affected by temperature and socioeconomic conditions [9,10], both of which vary in space (hot or cold, rich or poor) and over time (month–month, year–year),

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resulting in spatial and temporal variations in residential energy consumptions. The concept of degree-day, defined as the accumulated degree deviations from predefined base temperatures, is widely applied to characterize the relationship between energy use and temperature [11–14]. Both heating degree day (*hdd*) and cooling degree day (*cdd*) are used by assuming that the heating (or cooling) energy requirement is proportional to *hdd* (or *cdd*) [10,15,16]. However, this assumption is questionable for *hdd* because an 'initial fuel (a minimum quantity of fuel to be used to start a fire for heating no matter how far the temperature below the base temperature)' has to be consumed once the ambient temperature drops below a given base temperature. Moreover, heating demand may not increase linearly as the difference between the base and daily temperature increases.

In long term, rise in temperature due to climate warming may also lead to a change in residential energy consumption. The effects of climate warming on energy consumptions have been demonstrated previously [17–19]. In general, reduction in heating requirement would outweigh the increase in cooling requirement in regions with cold climate, and vice versa in cooling-dominated hot climates [12,20]. For example, Pilli-Sihvola et al. found that in north and central Europe, electricity consumption would decrease since heating demand decreases as temperature rises, while in the south, increment in summer cooling electricity would exceed the reduction in winter heating [18]. Similar results were also found in Australia [19].

Effects of climate change on energy consumption in China have been investigated by several researchers [21–23]. Lam et al. developed a regression model to predict electricity consumed by air conditioners in Hong Kong based on meteorological variables, and concluded that average annual consumptions during the periods from 2039 to 2068 and from 2069 to 2100 would be 12.8% and 18.4% higher than that from 1979 to 2008 for B1 scenario [21]. However, the method can hardly be applied to other parts of China due to lack of monthly data. Lam et al. and Wan et al. used principal component analysis to study heating and cooling loads in office buildings in Hong Kong and other four cities in China, and found a decreasing trend in heating load and an increasing trend in cooling load, with overall variations from 4.2% reduction in Harbin in north China to 4.3% increase in Hong Kong in south China [22,23]. To the best of our knowledge, no study has been conducted on energy consumptions in rural China thus far.

In this study, equivalency of spatial and temporal variations in residential energy consumptions was proposed as a hypothesis to be tested. Space-for-time method is occasionally used in plant succession studies to infer the series of communities forming the succession, based on the assumption that temporal dynamics in the community are autogenic and thus all sites had the same trajectory and endpoint. As such, a number of parameters, such as species composition, dominance, and richness, were used as independent variables in space-for-time studies of succession, to extrapolate temporal trend based on the observations on different sites [24]. For residential energy consumption, it is assumed that spatial and temporal variations in energy use are primarily affected by a same set of factors including ambient temperature and household income. If this assumption is hold, the difference in residential energy consumptions among various areas is comparable to the change over time. Consequently, it is possible to develop regression models based on spatial data and apply these models to predict the temporal change over time (intra- and inter-annual) in the case when only spatial data, rather than temporal data, are available.

2. Methods

2.1. General approach

To test the hypothesis in this study, provincial data of annual residential energy consumptions, ambient temperatures, and a number of socioeconomic parameters from 2001 to 2007 were collected and used to identify the main factors affecting residential fuel and electricity consumptions. Accordingly, multivariate regression models were developed for predicting energy consumptions based on the key factors identified. After validation, the models were applied to predict time trends (seasonal and inter-annual) and high resolution ($1^\circ \times 1^\circ$) spatial variations of residential energy consumptions and pollutant emissions in China. The models were also used to characterize potential net effects of future climate warming on residential energy consumptions and emissions of CO_2 and air pollutants in China.

2.2. Energy data

Residential energy was classified into fuels (crop residues, firewood, coal, liquefied petroleum gas (LPG), coal gas, natural gas, central heating) and electricity. Annual fuel and electricity consumptions for all provinces from 2001 to 2007 were collected [25]. Outliers (13%), defined as those with at least 35% relative difference from the mean values of the previous and following years, were not included in the study, assuming that these data were recorded with significant error. Fuels were all converted into heat values (Table S1) and added up as the total fuel consumptions. Per-capita consumptions of fuel (F_{cap}) and electricity (E_{cap}) are presented as ton of oil equivalent (toe) per capita.

2.3. Modeling

A number of climate and socioeconomic parameters were tested for their influences on F_{cap} and E_{cap} using stepwise multiple regression. The climate parameters tested included two from the literature (*hdd* and *cdd*) and two defined in this study (heating day, *HD*, and power function based *hdd*, HDD_p). *hdd* (*cdd*) is heating (cooling) degree day defined as $\Sigma\lambda(T_b - T_i)$, where T_b and T_i are base and daily mean temperatures. For *hdd*, λ is 0 when $T_b < T_i$, or 1 when $T_b \geqslant T_i$. For *cdd*, λ is -1 when $T_b < T_i$, or 0 when $T_b \geqslant T_i$. *HD* is defined as the number of days when daily temperature is below the base temperature and heating is required. To take into consideration of possible non-linear response of fuel consumption to temperature, HDD_p was introduced and defined as $\Sigma\lambda(T_b - T_i)^n$. The deviation of the exponent (n), which was derived from least-square fitting, from 1 indicates non-linear relationship. The tested socioeconomic variables included per-capita gross domestic production (GDP_{cap}, RMB), per-capita income (I_{cap}, RMB), urbanization rate (R_u, ratio of urban population over total population), and energy intensity. Theoretically, energy consumptions should be affected by energy price [14,17]. However, electricity price in residential sector is not market-driven in China, which is controlled by government at a below-cost price and twisted by subsidies [26–28], and the result of a preliminary modeling demonstrated that there is no significant effect of price on residential electricity consumption in China. Moreover, biomass fuels, which dominate residential energy in rural China, are generally not commercially available and are freely collected by users. Therefore, energy price was not taken into consideration in this study. As a result, the model can only be used for such a specific case in China for the modeled period. The effect of price on electricity consumption was taken into consideration in future predictions.

The models were validated against a set of annual consumption data not used in the model development (provincial data in 1995, 1996, and 2000, and national data from 1991 to 2007) [29] and two sets of monthly consumption data of fuel and electricity from the literature [30,31].

2.4. Climate and socioeconomic data

For *hdd*, 5 °C was adopted as the base temperature according to "Code for Design of Heating, Ventilation and Air Conditioning"