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Investigating natural ventilation potentials across the globe: Regional and climatic variations

Yujiao Chen [a, b, 1], Zheming Tong [a, b, *, 1], Ali Malkawi [a, b]

[a] *Center for Green Buildings and Cities, Harvard University, Cambridge, MA 02138, USA*
[b] *Graduate School of Design, Harvard University, Cambridge, MA 02138, USA*

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A B S T R A C T

Natural ventilation (NV) that reduces building energy consumption and improves indoor environment has become a key solution to achieving sustainability in the building industry. The potential for utilizing NV strategies depends greatly on the local climate, which varies widely from region to region in the world. In this study, we estimated the NV potentials of 1854 locations around the world by calculating the NV hour. Energy saving potentials of the world's 60 largest cities were calculated with Building Energy Simulation (BES). We demonstrated that NV hour derived from outdoor meteorological data can measure maximum energy saving potential of NV without conducting detailed BES. Our analysis shows the subtropical highland climate, found in South-Central Mexico, Ethiopian Highland, and Southwest China, is most favorable for NV, because spring-like weather occurs all year with little variation in temperature and almost no snowfall. Another climate where NV can be beneficial is the Mediterranean climate, which occurs not only near the Mediterranean Sea, but also in California, Western Australia, Portugal, and Central Chile. In certain regions with desert climate and large diurnal temperature range such as the Middle East and Central Australia, greater-than-expected NV hours are observed due to significant potential of night-purge ventilation. Countries in Southeast Asia, e.g., Singapore and Malaysia, are shown to have little to no NV potential as a result of hot and humid weather all year. These findings provide valuable guidelines for architects and policy makers around the world to effectively utilize NV designs that meet local climatic conditions.

1. Introduction

It is estimated by the United Nations that more than two thirds of the world's population will live in cities by 2050 [1]. Such rapid urbanization has led to significant increase in the energy consumption of buildings due mostly to population growth, climate change, and increased demand for thermal comfort [2–4]. Studies have shown that the building sector accounts for 23–47% of total primary energy consumption in developed and developing countries worldwide [5–11]. Given this enormous energy consumption, many advanced technologies have been developed to achieve high building energy efficiency [6,12–24]. Among them, natural ventilation (NV), which supplies and removes air to and from an indoor space using natural forces of wind and buoyancy, shows great potential to reduce the energy required for cooling and ventilating buildings while still provide acceptable indoor environmental quality [25–34]. To help realize the potential benefits of natural ventilation, a variety of design elements such as solar chimneys, wind towers, and double-skin façades are often used to promote wind or buoyancy driven air movement. In addition to "pure" natural ventilation that is often constrained due to building type and climate suitability, mixed-mode ventilation (i.e., using natural ventilation for periods when the external weather conditions are allowed, but mechanical ventilation takes over when external weather conditions are not suitable) has been proven as a practical and reliable solution for buildings that aim to incorporate NV principles [35].

The design strategy for buildings with natural ventilation systems relies heavily on the characteristics of local climate, which varies considerably from region to region across the globe. Researchers in the past have investigated various aspects with regard to naturally ventilated buildings across different climate zones in the world. Table 1 summarizes existing studies on natural

* Corresponding author. Center for Green Buildings and Cities, Harvard University, Cambridge, MA 02138, USA.
E-mail addresses: ztong@gsd.harvard.edu, zht940@g.harvard.edu (Z. Tong). ychen@gsd.harvard.edu (Y. Chen).
[1] These authors contributed equally to this work.

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ventilation by location. For example, Yang et al. [36] developed a simple prediction model for natural ventilation potential in Chinese residential buildings, and introduced pressure difference Pascal hours (PDPH) as a metric to predict NV potential. Yao et al. [37] investigated the natural ventilation cooling potential of office buildings in five climate zones of China using the Thermal Resistance Ventilation model, and demonstrated that the NV cooling potential depends on climate, building thermal characteristics and internal gains. Tong et al. [6] quantified the energy saving potential of natural ventilation at 35 major Chinese cities, considering the impact of ambient air pollution, in which they introduced the methodology for estimating NV hours defined as the number of suitable hours for using natural ventilation per year. Tantasavasdi et al. [38] conducted a study in Bangkok, Thailand, suggesting that natural ventilation can provide a thermally comfortable indoor environment for 20% of the year. The natural ventilation threshold for indoor air velocity was derived from the climate and thermal comfort analysis. Calautit et al. [39], Bahadori [40], and Bouchahm et al. [41] discussed the physics behind the design of wind towers, and how they are utilized to improve natural ventilation in the Middle East and North Africa, both of which have an arid and hot desert climate. Artmann et al. [42] evaluated the passive cooling of buildings by night-time ventilation by analyzing climatic data at 259 stations in Europe. Their results showed a high potential for night-time natural ventilation cooling potential over Northern Europe and significant potential in Central and Eastern Europe, and certain areas in Southern Europe. Oropeza-Perez and Ostergaard [43] estimated the natural ventilation potential in Denmark, showing that 90% of the hours for which mechanical ventilation was used can be potentially reduced through the use of natural ventilation during summer. Van Hooff and Blocken [44,45] introduced a coupled CFD (Computational Fluid Dynamics) modeling approach for urban wind flow and indoor natural ventilation, and applied it to study a large semi-enclosed stadium in Netherlands. They demonstrated the importance of meteorological conditions and surrounding urban environment for natural ventilation analysis at building-scale. Hiyama and Glicksman [46] presented target air change rate as a desired criterion for designing buildings with natural ventilation, and provided maps of target air change rate of 60 cities in the United States. Tong et al. [47] estimated NV potential for high-rise buildings in major cities from six climate zones in the United States. An in-house boundary-layer meteorology model was developed to quantify the effect of atmospheric stability on the vertical structure of NV potential for high rises. Cândido et al. [48] proposed guidelines for naturally ventilated buildings in Brazil that consider occupants' adaptive potential as well as thermal and air movement acceptability. The guidelines were based on results from field experiments in different climatic zones and existing studies. Deuble and de Dear [49] investigated the effect of mixed-mode ventilation on occupant comfort in an academic office building using 1359 subjective comfort questionnaires in Sydney, Australia. Their findings suggested that the building's mode of operation such as air-conditioned and naturally-ventilated modes has a greater impact on thermal perceptions than the objective indoor climate conditions.

Existing studies focus largely on natural ventilation systems at a specific region in the world. The regional variations in natural ventilation potentials have never been investigated from a global perspective. Building ventilation strategies are highly dependent on climatic conditions at the location of interest. As climate varies from region to region in the world, it is critical to understand the variation between regions in order to utilize natural ventilation more effectively. Our objective is to assist policy makers and architects in recognizing quantitatively the natural ventilation potentials at various regions and climates around the world, and in properly developing sustainable strategies considering local climatic characteristics.

In this study, we have provided an early effort to estimate, visualize, and understand regional natural ventilation potentials by analyzing available climate data at 1854 locations from six continents (Africa, Asia, Europe, North America, Oceania, and South America). Energy savings potentials of the world's 60 largest cities

Table 1
Summary of past studies on natural ventilation sorted by method and location.

Author and Year	Location	Method	Ref.
Yang et al. (2005)	China	Simulation	[36]
Luo et al. (2007)	China	Simulation	[50]
Yao et al. (2009)	China	Simulation	[37]
Yin et al. (2010)	China	Simulation	[51]
Tong et al. (2016)	China	Simulation	[6]
Indraganti (2010)	India	Survey & experiment	[52]
Tantasavasdi et al. (2001)	Thailand	Simulation	[38]
Liping et al. (2007)	Singapore	Data analysis	[53]
Kubota (2009)	Malaysia	Survey & Experiment	[54]
Bahadori et al. (1994)	Middle East	N/A Review	[40]
Ayata et al. (2006, 2007)	Middle East	Simulation	[55,63]
Calautit et al. (2013)	Middle East	Simulation	[39]
Mathews (1986)	South Africa	Simulation & Experiment	[56]
Bouchahm (2011)	Algeria	Simulation & Experiment	[41]
Artmann et al. (2007)	Europe	Data analysis	[42]
Kolokotroni and Aronis (1999)	U·K.	Simulation	[57]
Pasquay (2004)	Germany	Experiment	[58]
van Hooff and Blocken (2010)	Netherlands	Simulation & Experiment	[44,45]
Oropeza-Pereza and Østergaardb (2014)	Denmark	Simulation	[43]
Germano (2007)	Switzerland	Data analysis	[59]
Ballestinia et al. (2005)	Italy	Simulation	[60]
Santamouris et al. (2008, 2010)	Greece	Experiment & Simulation	[61,62]
Hiyama and Glicksman (2015)	U.S..	Simulation	[46]
Dutton et al. (2013)	U.S.	Experiment	[64]
Malkawi et al. (2016)	U.S..	Simulation	[13]
Tong et al. (2017)	U.S..	Simulation	[47]
Oropeza-Pereza and Østergaardb (2014)	Mexico	Simulation	[65]
Cândido et al. (2011)	Brazil	Experiment & Survey	[48]
Deuble and de Dear (2012)	Australia	Experiment & Survey	[49]