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Improved wind prediction based on the Lorenz system

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A B S T R A C T

Atmospheric disturbance is a complex nonlinear process. The Lorenz system was seen as a classical model to reveal essential characteristics of nonlinear systems. It has further improved people's understanding of the evolution of the climate system. Different from traditional studies working on improving the numerical methods for wind prediction, dynamic characteristics of the atmospheric system are fully considered here. This paper proposed the concept of the Lorenz Comprehensive Disturbance Flow (LCDF) and defined the perturbation formula for wind prediction. The Lorenz disturbance has significant influence on wind forecasting, which is proved by using wind data from the Sotavento wind farm. That is to say, the change process of atmospheric motion around the wind farm is more ideally described based on the Lorenz system. This research has important theoretical value in developing nonlinear systems and plays a great role on wind prediction and wind resource exploitation.

1. Introduction

Full use of renewable energy is an effective solution for the energy crisis and push for environmental protection at present. Wind power is one of the most potential and popular renewable resources [1]. By 2050, wind energy will be technically feasible to possess the largest share in energy systems and the installed capacities would range from 18 TW to 24 TW [2]. Wind power generation has greatly promoted the development of the wind energy industry. At present, uncertainty of wind resources is the major challenge of integrating wind power into electric systems. It is highly important to study and develop high-precision wind speed and power forecasting methods. Wind speed prediction is especially primary and critical [3–5]. Currently, wind prediction models, according to different modeling methods, are usually divided into physical models, statistical models, artificial intelligence, and hybrid models [6–8].

Inequality of solar heating drives the atmosphere to move. During the movement, heat and momentum transportations would invite certain nonlinear factors into atmospheric motions. Wind forming is a typical nonlinear process [9]. This paper fully considered the nonlinear dynamics of the atmosphere system and adopted the Lorenz system as an atmospheric disturbance model. Then, a novel short-term wind forecasting model named the Lorenz Disturbance-Wavelet Neural Network (LDWNN) was proposed. In this research, the LDWNN model mixed the traditional physical model and the artificial neural network in the optimal way. This model not only could grasp the seasonal variation rule of wind speed, but also took the atmospheric disturbance effect into account. Different perturbation quantities were adopted according to seasonal characteristics of wind speed.

This paper is organized as follows: Section 2 introduces the basic theory of the Lorenz system and the other two Lorenz-like systems; Section 3 is divided into three parts: definition of the Lorenz comprehensive disturbance flow, modeling process of the LDWNN model, and description of wind speed data; Section 4 presents the main prediction results with relevant analysis; Another example for validation is shown in Section 5; Some unresolved issues and possible explanations are discussed in Section 6; Section 7 concludes this paper.

2. The Lorenz system

Almost all of the atmospheric motions were derived from convections. B. Saltzman's seven-variable fluid convection model perfectly described the evolution of convective motion [10]. The simulation was limited to a parallel-layer with a fixed height, and the two layers were maintained at a constant temperature

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difference. The fluid developed from a small perturbation to finite-amplitude convection. The governing equations can be expressed as follows [10,11]

$$\begin{cases} \frac{\partial}{\partial t}\nabla^2\psi + \frac{\partial(\psi,\nabla^2\psi)}{\partial(x,z)} - g\varsigma\frac{\partial\theta}{\partial x} - \upsilon\nabla^4\psi = 0 \\ \frac{\partial\theta}{\partial t} + \frac{\partial(\psi,\theta)}{\partial(x,z)} - \frac{\Delta T_0}{H}\frac{\partial\psi}{\partial x} - \kappa\nabla^2\theta = 0 \end{cases}. \quad (1)$$

where ψ denotes stream function in the two-dimensional plane, θ denotes the temperature departure from equilibrium state, and constants g, ς, υ, and κ separately denote the acceleration of gravity, the coefficient of volume expansion, the kinematic viscosity, and the coefficient of thermal diffusivity.

The Lorenz system was then extracted from model (1) and regarded as the first mathematical-physical model to exhibit chaotic behaviors [10–13]. Solutions of the Lorenz system not only correctly exhibited the evolutions of Equation (1), but also presented features of deterministic nonperiodic flow in a simplest way. The Lorenz equation is given by Refs. [11,13]

$$\begin{cases} \dot{x} = -\sigma(x-y) \\ \dot{y} = -xz + rx - yx \\ \dot{z} = xy - bz \end{cases}. \quad (2)$$

where x is proportional to convection intensity, y is proportional to the temperature difference between ascending and descending currents, z is proportional to the temperature departure from linearity, σ is the Prandtl number, r is the Rayleigh number, and b is related to the region of microclimate.

As a meteorologist, Saltzman had simulated the convective motion in liquid rather than in air. Thus the Prandtl number σ in liquid was selected to be 10.0. Following Saltzman and Lorenz [11], b was chosen as 8/3, and the Rayleigh number r was variable. The critical Rayleigh number was obtained through analyzing the stability of the equilibrium state of the Lorenz system, and was used to distinguish different forms of air motions, shown in Table 1 [13].

The famous Reynolds experiment provided an intuitive description of turbulent motion by adopting a staining method [14]. Lorenz assumed Equation (2) to be an atmospheric convection model and observed its evolution through numerical simulations. He discovered that a deterministic system could perform a nonperiodic status in the simplest manner. But the Lorenz system was not able to perfectly simulate solutions of Equation (1), especially when considering the impact of extreme truncation caused by the strong convection [11]. The two models were slightly different. In fact, model (1) described fluid convection heated and driven from below. Lorenz studied atmosphere motion driven by horizontal temperature difference.

Large amounts of scholars were devoted to studying the basic theories of the Lorenz system, such as the nonperiodic nature, bifurcation behavior, and the way to chaos. Chaos was no longer a topic avoided by people. On the contrary, it was sometimes necessary to strengthen or even generate chaos on purpose in some fields [15]. Hence, some other classical Lorenz-like systems were proposed. The Chen system (1999) [16] and Lü system (2002) [17] were the top two famous Lorenz-like systems at the time. They were proposed under the guidelines of Vanecek and Celikovsky [18]. The Lorenz system, Chen system and Lü system had similar basic properties: (1) Third-order quadratic autonomous equations and three equilibrium points. (2) Symmetric solutions about z axis. (3) Dissipation systems and existence of attractors. (4) Similar topological properties and bifurcation diagrams. To facilitate the study and application, these three systems were integrated into a unified system as the following two forms: the generalized Lorenz system introduced in the literature [19,20] and the single-variable Lorenz system families in the literature [15].

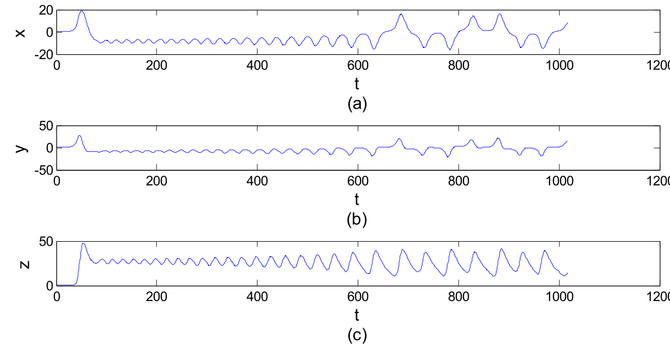

Fig. 1. Subgraphs (a), (b), and (c) represent time series of variables x,y,z, respectively, in the Lorenz convection model. Each sequence extends 1017 time units.

3. LDWNN short-term wind speed prediction model

3.1. Lorenz comprehensive disturbance flow

Seen from Table 1, the Lorenz system is able to present different motion states by taking appropriate values of r. Random turbulent perturbation in the atmospheric system usually happens in the following two situations: (1) The air and the surface may undergo different levels of friction due to terrain differences, which were very likely to yield turbulence. (2) Fluctuations in temperature or atmospheric density may result in vertical movement of air masses, i.e. air convection or turbulence.

The solutions of Equation (2) provided a series of disturbance data, which are essential to establish the LDWNN model. Let (0,1,1), a small deviation from the equilibrium state, be the initial condition. The parameters are taken as $\sigma = 10$, $b = 8/3$, $r = 28$. Fig. 1 intuitively depicts nonperiodic features of the evolution of the Lorenz system. The randomness of Lorenz equations' solutions is the theoretical support to extract and use Lorenz disturbance. According to the classification in Table 1, the Lorenz system exhibited nonperiodic states when $r = 28$. Fig. 1 also provides the ranges and changing rules of the three perturbation variables x,y,z.

Irregular turbulence belonged to a stochastic process [14]. All the turbulent motion states were regarded as sample space Ω. Then the three-dimensional perturbation variable was defined by the mapping $p(x,y,z)$, which denotes fluid motion state, given by

$$p(x,y,z) : \Omega \rightarrow R^3. \quad (3)$$

Wind is a two-dimensional vector, wind speed is a real number, and the perturbation variable is a three-dimensional vector. In this paper, a linear perturbation model was adopted. The first step was

Table 1
The actual fluid motions presented by Lorenz system under conditions of $\sigma = 10$, $b = 8/3$ and variable r.

r	$0 < r < 1$	$1 < r < 24.74$	$r > 24.74$
Actual fluid motion	Heat conduction	Regular convection	Irregular turbulent motion