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Planetary-scale wind formation mechanisms: fundamentals of global atmospheric circulation

Mecanismos de formação dos ventos em escala planetária: fundamentos da circulação atmosférica global

Mecanismos de formación de los vientos a escala planetaria: fundamentos de la circulación atmosférica global

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Abstract:
Wind, as an energy resource, is the final product of complex thermodynamic and dynamic processes occurring in Earth's atmosphere. This article presents a qualitative literature review aimed at analyzing planetary-scale wind formation mechanisms and detailing the phenomena that govern global atmospheric circulation. The methodology is based on an integrative literature review grounded in seminal works on dynamic meteorology and climatology. The results indicate that the origin of macroscale winds is governed by differential solar heating of Earth's surface together with the apparent forces generated by Earth's rotation, particularly the Coriolis force. It is concluded that a structural understanding of the three-cell climate system (Hadley, Ferrel, and Polar cells) is essential not only for meteorology but also for strategic wind-energy planning, since this system determines the planet's macroregions with the greatest energy potential.

Keywords:
Atmospheric circulation. Planetary scale. Coriolis force. Pressure gradient. Meteorology.

Resumo:
O vento, enquanto recurso energético, é o produto final de complexos processos termodinâmicos e dinâmicos que ocorrem na atmosfera terrestre. O presente artigo apresenta uma revisão bibliográfica qualitativa com o objetivo de analisar os mecanismos de formação dos ventos em escala planetária, detalhando os fenômenos que regem a circulação atmosférica global. A metodologia fundamenta-se em uma revisão integrativa da literatura, baseada em obras seminais de meteorologia dinâmica e climatologia. Os resultados indicam que a gênese dos ventos em macroescala é governada pelo aquecimento diferencial da superfície terrestre pela radiação solar, em conjunto com as forças aparentes geradas pela rotação da Terra, notadamente a Força de Coriolis. Conclui-se que a compreensão estrutural do sistema climático tricelular (células de Hadley, Ferrel e Polar) é imprescindível não apenas para a meteorologia, mas para o planejamento estratégico da matriz eólica, visto que determina as macrorregiões de maior potencial energético do planeta.

Palavras-chave:
Circulação atmosférica. Escala planetária. Força de Coriolis. Gradiente de pressão. Meteorologia.

Resumen:
El viento, como recurso energético, es el producto final de complejos procesos termodinámicos y dinámicos que ocurren en la atmósfera terrestre. Este artículo presenta una revisión bibliográfica cualitativa cuyo objetivo es analizar los mecanismos de formación de los vientos a escala planetaria, detallando los fenómenos que rigen la circulación atmosférica global. La metodología se fundamenta en una revisión integradora de la literatura basada en obras seminales de meteorología dinámica y climatología. Los resultados indican que el origen de los

vientos a macroescala está gobernado por el calentamiento diferencial de la superficie terrestre debido a la radiación solar, junto con las fuerzas aparentes generadas por la rotación de la Tierra, en particular la fuerza de Coriolis. Se concluye que la comprensión estructural del sistema climático tricelular (células de Hadley, Ferrel y Polar) es imprescindible tanto para la meteorología como para la planificación estratégica de la matriz eólica, pues determina las macrorregiones de mayor potencial energético del planeta.

Palabras clave:
Circulación atmosférica. Escala planetaria. Fuerza de Coriolis. Gradiente de presión. Meteorología.

1. Introduction

In wind-resource prospecting, although local topography plays a crucial role, the primary availability of wind is intrinsically dictated by macroscale meteorology. Earth's atmosphere acts as a gigantic heat engine whose main function is to redistribute heat accumulated in equatorial regions toward the poles, thereby mitigating global thermal imbalance (WALLACE; HOBBS, 2006). In this sense, wind is not a random phenomenon but a vector that transports mass and energy within a global dynamic system. Understanding the forces that drive and deflect these air masses is fundamental to comprehending climate seasonality and predictability (VAREJÃO-SILVA, 2006). This study aims to analyze the physical principles and thermodynamic mechanisms that generate planetary-scale winds and to describe the structure of the general atmospheric circulation.

2. Theoretical framework

2.1. Radiation balance and the pressure-gradient force

Solar radiation is the primary driver of wind formation. Because of Earth's spherical shape and axial tilt, low-latitude regions (the equator and tropics) receive a much greater solar-radiation load than high-latitude regions (the poles). This differential heating causes warm, less dense equatorial air to rise, creating low-pressure zones at the surface, while cold, dense air descends at the poles and forms high-pressure zones (AHRENS, 2012). This spatial difference in atmospheric pressure gives rise to the pressure-gradient force (PGF). Fluid dynamics establishes that air is compelled to move from high-pressure areas toward low-pressure areas, characterizing the primary mechanism that initiates wind motion (HOLTON, 2004).

2.2. The Coriolis force and the three-cell system

If Earth were stationary, winds would blow in straight lines from the poles to the equator. Planetary rotation, however, introduces an inertial force known as the Coriolis force, which deflects wind trajectories to the right in the Northern Hemisphere and to the left in the Southern Hemisphere (HOLTON, 2004). The interaction between the pressure gradient and the Coriolis force prevents direct pole-to-equator circulation and divides atmospheric flow into a three-cell model, as described by Wallace and Hobbs (2006):

- Hadley cell: located between the equator and approximately 30° latitude, it is responsible for forming the trade winds, which are extremely important, for example, to the high wind-energy productivity of Brazil's northeastern coast.
- Ferrel cell: operates at midlatitudes (30° to 60°), generating the prevailing westerly winds.
- Polar cell: extends from 60° latitude to the poles and is characterized by cold easterly winds.

3. Materials and method

This qualitative research was structured through an integrative review of specialized atmospheric-science literature. Data collection was based on classic books on dynamic and physical meteorology that are essential to training specialists in the field. The analysis period was not restricted to recent publications because the physical principles of atmospheric circulation have been well-established postulates of climate science for decades. The data were analyzed to synthesize the causal chain of wind, from its thermodynamic origin to its vector manifestation at different latitudes.

4. Results and discussion

The theoretical analysis reveals that planetary wind systems are highly predictable on the macroscale, providing a solid basis for long-term climate models. The stability of Hadley cells and trade winds explains why coastal intertropical regions offer the world's best capacity factors (productivity) for wind farms (AHRENS, 2012). Current literature, however, points out that planetary circulation is not static. Changes in the global energy balance, influenced by sea-surface temperature anomalies such as El Niño and La Niña, cause shifts and changes in the intensity of circulation cells (VAREJÃO-SILVA, 2006). These events introduce temporary

anomalies into wind regimes, requiring wind-forecasting models to go beyond historical averages and account for risks associated with climate anomalies.

5. Final considerations

The study shows that wind, which is fundamental to renewable-energy generation, results from Earth's atmosphere continuously seeking thermodynamic equilibrium under the modulation of planetary rotational forces. Mastering these planetary-scale mechanisms is crucial to understanding the wind climatology of any region. This study contributes by recovering the purely meteorological foundation and connecting it to an understanding of the spatial feasibility of wind resources. Future work should investigate in detail how global climate change, by reconfiguring the thermal gradient between the poles and the equator, may alter the strength and position of jet streams and trade winds over the coming decades.

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