East European Journal of Physics. 4. 378-385 (2024)
DOI:10.26565/2312-4334-2024-4-44 ISSN 2312-4334

PHYSICAL MECHANISMS OF CLEAR AIR TURBULENCE

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Received August 16, 2024; revised October 10, 2024; in final form November 18, 2024; accepted November 21, 2024

Clear air turbulence (CAT) is a significant type of atmospheric turbulence that poses risks to aviation. Unlike other forms of turbulence, it occurs without substantial cloudiness, often under clear skies or with minimal cloud cover at the observation site. CAT can arise under various meteorological conditions, such as high atmospheric pressure, sunny weather, or in the presence of mountain ranges. Forecasting CAT is crucial for aviation safety, although its prediction is challenging due to its variability, sharp localization in the air flow, and variability in size and duration. Indirect signs can help predict CAT zones; however, direct observation is difficult, making it essential to develop forecasting methods and conduct research to ensure flight safety.
Keywords: *Turbulence; Clear air; Aviation; Instability parameter; Bénard cells*
PACS: 629.7.015:551.557.3

INTRODUCTION

Clear air turbulence (CAT) is a relatively recent innovation in the aviation industry with potential applications in free atmosphere and wind tunnels [1]. Identifying the locations of CAT occurrence is crucial because it allows aircraft to fly without the need for reconnaissance planes and provides data on the presence of turbulence and its potential impact on aviation infrastructure [2]. Moreover, the phenomenon of CAT is used for modeling turbulence levels in wind tunnels to understand the complexity of periodic turbulence [3]. This technology is utilized by airlines to obtain information about turbulence and to facilitate the accessibility of innovations and customer choices [4]. Through this technology, airlines can establish shared code-sharing agreements, allowing them to make reciprocal flights on certain routes. This reduces operating costs, increases flight frequency, and even introduces new routes, which may enhance accessibility for passengers. Such an approach can also foster innovation and customer choice by improving service and expanding routes. Passengers gain more flight options and the convenience of moving around, which can increase their satisfaction and loyalty to airlines. Additionally, payload sensors for measuring turbulent flows are being developed for flights on Hybrid Quadrotor (HQ) drones [5]. However, these sensors failed to directly measure turbulence intensity near the nozzle and the corresponding far field [6].

CAT technology opens many potential scenarios for the aviation industry, some of which are being explored under the Horizon 2020 research and innovation program. It is known that various factors influence CAT occurrence, such as thermal stratification, infrared radiative cooling, horizontal gradients, and large-scale vertical movements [7]. Additionally, temperature rise and changes in wind patterns are potential factors that can increase CAT parameters. To assess such changes in CAT frequency and severity, studies were conducted in the pan-Arctic region, introducing the use of four turbulence indices [8].

Thanks to rapid improvements in onboard instruments and atmospheric observation systems, in most cases, aircraft can avoid regions of adverse weather associated with developed CAT. However, they still encounter unexpected turbulent conditions in regions far from storms and clouds. This phenomenon poses a problem for understanding and predicting CAT. While most CAT incidents lead to mild discomfort, some can be critical, resulting in serious injuries to passengers and damage to the aircraft.

Researchers of CAT have attempted to explain the physical mechanisms and instabilities underlying dynamic processes in the atmosphere. The main instabilities [9, 10] proposed include:

- The impact of the ratio of vertical inhomogeneity of temperature and air velocity, measured by the Richardson number (instability parameter) [1];
- Kelvin-Helmholtz (KH) instability in shear layers [2];
- Bénard cells and related Langmuir circulations [11];
- Rayleigh-Taylor instability [12, 13];
- Waves generated by mountain flows [14], which occur when atmospheric flow crosses mountainous terrain. As a result, gravity waves are formed, which can become unstable and turn into turbulence. Such waves are often observed in mountainous regions and can impact flight safety;
- Inertial-gravity waves from clouds and other sources [15] can be generated from cloud structures and other atmospheric irregularities. They propagate through the atmosphere and can cause turbulence under certain conditions. These waves play a crucial role in the transport of energy and momentum in the atmosphere;

Cite as: V.O. Lykhatskyi, V.I. Tkachenko, L.S. Bozbiei, East Eur. J. Phys. 4, 378 (2024), https://doi.org/10.26565/2312-4334-2024-4-44

- Spontaneous imbalance theory [16] explains the occurrence of turbulence due to spontaneous imbalance in strong anticyclones. In such conditions, instabilities may arise, leading to turbulence. This is important for understanding turbulence in areas with strong anticyclones;
- Horizontal vortex tubes [17] are specific turbulence structures that form in clear skies. They result from complex dynamic processes in the atmosphere and can significantly affect aircraft flights. These structures are difficult to predict and can appear suddenly.

The issue of CAT has been widely studied as aircraft flying at altitudes above 5 km have encountered it. Since it is a phenomenon that occurs outside of convective activity, detecting and measuring it has been challenging. Observational studies have shown that CAT is associated with mesoscale phenomena such as jet streams, troughs, ridges, and fronts. Flow conditions such as high vertical speeds, wind shear, and low Richardson numbers have correlated with CAT regions. On the theoretical front, in the 1960s and 70s, KH instability in stably stratified fluid was considered an explanation for CAT formation. Hence, the Richardson number has been used as a CAT index. In subsequent decades, focus shifted to operational forecasting methods, with a range of indices using combinations of the Richardson number, vertical wind shear, horizontal convergence, deformation, etc. Recent years have seen a resurgence of interest in theoretical aspects, with some proposed as sources of intense CAT. Among theories based on inertial-gravity waves, the connection with the actual location where CAT is encountered often remains unclear. Among "local" theories (KH instability, frontogenesis, and spontaneous imbalance), detecting the trigger or critical disturbance remains complex.

While various forecasting methods are employed, key questions remain. The presence of a large number of different indices (about 10) in the GTG procedure indicates the lack of a satisfactory theory. The difficulties in confirming various theories lie in the scarcity of PIREPs, which so far remain the only source of observation. In the future, satellite data may offer global coverage, simplifying the verification of theories. As seen in previous sections, there is a wide range of mechanisms proposed for CAT. Given the different ways of CAT formation, it is likely that a different mechanism operates in each category. In our view, if we look at the two ends of the spectrum, possible mechanisms are: moderate turbulence - inertial and gravity waves; and strong turbulence - horizontal vortex tubes. Rather than trying to find a universal mechanism and prediction method for all forms of CAT, it may be beneficial to focus on the severe form, which is potentially more harmful, although rarer. There is evidence that the formation and existence of horizontal vortex tubes of appropriate scale may be the source of intense clear-air turbulence. Extensive research has been conducted on main shear flows. It would be fruitful to explore the role of secondary structures in shear flows and their connections with atmospheric flows. Studies of the way CAT is sustained/decayed may be a promising area of research. A more holistic approach to the problem, including modeling weather systems, processes on land and sea, air traffic corridors, and urban effects, could be another area of investigation.

Currently, there is no single and universal model that would best define CAT and be easily predicted.

Different theories, such as Kelvin-Helmholtz instability, thermal convection, interaction of air masses, aerodynamic processes and others, choose different explanations for the occurrence of CAT in the atmosphere. Leather with these models has its advantages and limitations.

Therefore, the optimal model of the occurrence of CAT is difficult to complicate, since it is still complex in nature and the phenomenon depends on a large number of factors. Its understanding requires a comprehensive approach, taking into account various theories and factors affecting atmospheric processes. Prediction of CAT requires further research and consideration of various aspects of interaction in complex atmospheric conditions.

The existence of such a large number of mechanisms for the occurrence of CAT does not provide an answer to the question: under what conditions can CAT occur?

The purpose of the work is a critical review of the proposed mechanisms for the occurrence of CAT and the identification of the most likely for CAT prediction.

The article did not mention the specific technologies used to detect CAT. In fact, technologies such as LIDAR (Laser Atmospheric Scanning System), radar systems, satellite surveillance and special sensors on aircraft are used for this purpose. These instruments make it possible to detect turbulence even where it is not accompanied by clouds or other obvious signs.

In practice, mathematical models that take into account the difference in wind speed at different heights (in particular, the analysis of the Richardson number), forecasting based on meteorological data and specialized programs for analyzing weather conditions are used to detect CAT. These techniques help predict where turbulence may occur, which is important for flight safety.

To make sure that we are talking about the turbulence of clean air, several indicators are used. The most important of them is the Richardson number, which allows you to determine how likely turbulence is. Sudden changes in wind speed, temperature differences at different altitudes and data from on-board instruments that record pressure changes and other characteristics of air flows are also taken into account.

THE RICHARDSON NUMBER (INSTABILITY PARAMETER)

For analyzing the conditions of turbulence formation in a temperature-inhomogeneous atmosphere, a dimensionless parameter called the Richardson number (R_i) is often used [12]:

$$R_i = \frac{g(\gamma_a - \gamma)}{T\beta^2}, \tag{1}$$

where:

- g is the acceleration due to gravity,
- T is the mean temperature of the layer,
- γ_a is the adiabatic lapse rate,
- γ is the actual vertical temperature gradient,
- β is the vertical gradient of the mean wind speed.

In cases where $R_i < R_{i\,\text{кр}}$ for the layer under consideration, the conditions are favorable for the formation and development of turbulence. The widespread use of the Richardson number is due to its theoretical basis in hydrodynamic stability theory, making it a fundamental dimensionless criterion for clear air turbulence (CAT). To determine Richardson numbers for meteorological support of aviation, layers of thickness 500 m or less should be used. Unfortunately, the lack of such data from network stations makes it difficult to calculate this parameter accurately. According to studies by S.M. Shmeter [19-21], errors in calculating Richardson numbers based on temperature-wind sounding data can reach up to 400 %.

Thus, the Richardson number can only be applied to forecast atmospheric turbulence if sufficient data on vertical profiles of wind and temperature are available. Research by I.G. Bdzhilko [22, 23] has shown that the presence of intense turbulence in the atmosphere should not be noted in layers with small Richardson numbers but rather at those levels where large changes in Ri values with altitude are observed. In addition to the Richardson number, several other empirical functions (indices) are used to assess the potential development of turbulence in the upper troposphere, including the indices of Reshetov [24], Matveev [25], and Buldovsky [26].

The existence of numerous criteria for the turbulent state of the atmosphere using the Richardson number suggests that the problem of predicting atmospheric turbulence that causes aircraft turbulence is being studied by many researchers. This problem has not yet been fully resolved. Both synoptic and physical-statistical methods are practically used for CAT forecasting. Both approaches are characterized by the tendency to comprehensively consider a number of factors associated with CAT development conditions [1].

The method of calculating the Richardson number is used to enhance the accuracy of numerical calculations by interpolating results obtained at different levels of discretization.

Advantages:

1. Increased Accuracy: Allows for more precise results by combining data from various levels of discretization or increasing the calculation step.
2. Efficiency: Can significantly reduce the volume of calculations, as it typically uses existing information from different discretization levels instead of additional calculations.
3. Universality: Applicable to various types of numerical methods, improving their accuracy.

Disadvantages:

1. Sensitivity to Errors: Sensitive to errors in initial data, which can lead to incorrect or insufficiently accurate extrapolation.
2. Increased Computational Complexity: In some cases, achieving additional accuracy may require more computational operations or additional levels of discretization, increasing computational complexity.
3. Limitations in Accuracy: Significant accuracy improvements are not always achievable, especially if the initial data are already of high accuracy or have limited or low precision.

The Richardson number calculation method is a powerful and useful tool for enhancing the accuracy of numerical calculations, but it has its limitations that need to be considered during its application.

Therefore, the Richardson number is a parameter that determines the degree of instability or the conditions for the transition from laminar to turbulent flow in fluid dynamics. This indicator is used to assess the flow regime of a fluid or gas, considering characteristics such as speed and density. The value of the Richardson number indicates which transfer forces (e.g., convection or diffusion) dominate the mass or heat transfer processes in the flow. A condition where the Richardson number is close to a critical value can cause a transition from one flow regime to another, from laminar to turbulent.

Research on the Richardson number is crucial for understanding and predicting turbulent processes in various environments, including the atmosphere, oceans, and technical systems. Determining this parameter helps manage and analyze flows in different media, enhancing technologies and strategies to improve the efficiency and control of these processes.

KELVIN-HELMHOLTZ INSTABILITY IN SHEAR LAYERS

Most theoretical analyses conducted in the 1960s and 1970s suggested that clear air turbulence (CAT) results from Kelvin-Helmholtz (KH) instability due to shear layers in the atmosphere. Kelvin-Helmholtz instability arises when there is a velocity shear across the interface between two fluid layers. The formation of a two-dimensional vortex ring caused by KH-type instability can be explained as shown in Figure 1. Low-speed (bottom) and high-speed (top) regions create a shear layer, as shown in Figure 1A–B. Then, the instability of the shear layer (KH instability) forms a ring-shaped vortex through the transfer of shear into a pair of rotations, as seen in Figure 1C–D. In other words, this process involves converting non-rotational vorticity or shear into rotational vorticity, or converting shear into Liutex. Afterward, the pair of rotations merges into a single vortex but still contains a pair of cores within the rotation, as shown in Figure 1E–H. Therefore, vortex pairing is a prominent feature of KH instability. Note that although KH instability relates to inviscid flow, it can still be used to describe "shear layer instability" for viscous flow as an approximation [3]. The formation, growth, and decay of KH waves similar to those observed in laboratory shear flows near regions associated with turbulence have been observed [2].

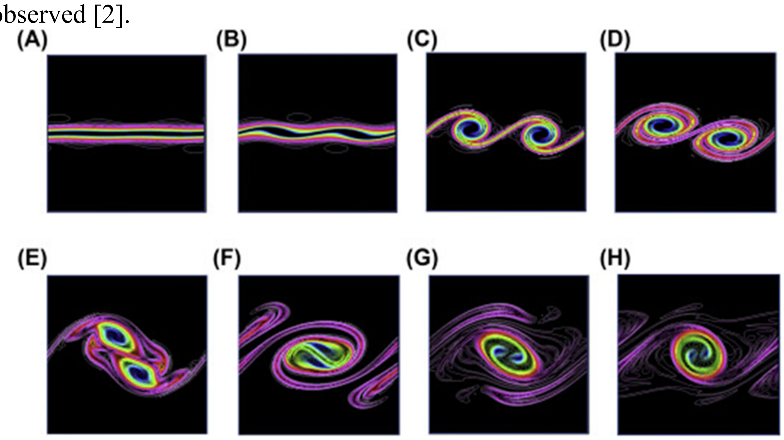

Figure 1. Numerical simulation in 2-D of KH instability (starting from (A) to (H) respectively) [3]

KH instability is a linear instability of the interface between two flows. For two fluid flows with different densities (ρ_1, ρ_2) and velocities (U_1, U_2) separated by a horizontal interface under the assumptions of inviscid conditions and no surface tension at the interface, the speed of wave-like disturbances is given by:

$$c = \frac{\rho_1 U_1 + \rho_2 U_2}{(\rho_1 + \rho_2)} \pm \sqrt{-\frac{\rho_1 \rho_2 (U_1 - U_2)^2}{(\rho_1 + \rho_2)^2} - \frac{\rho_2 - \rho_1}{(\rho_1 + \rho_2)} \frac{g}{k}}, \tag{2}$$

where:

- g is the acceleration due to gravity,
- k is the wave number [4].

If there is no velocity difference, the configuration is unstable for $\rho_2 > \rho_1$, meaning that the heavier fluid is on top [4]. This situation corresponds to Rayleigh-Taylor instability [9]. If there is a velocity difference, the flow becomes unstable for large wave numbers:

$$k > \frac{\rho_1^2 - \rho_2^2}{\rho_1 \rho_2 (U_1 - U_2)^2} g. \tag{3}$$

Other effects, such as surface tension, viscosity, and rotation, have been studied [5-8]. Viscosity and rotation have a stabilizing effect and impose a limiting wave number, but higher wave numbers remain unstable. Surface tension suppresses instability if:

$$(U_1 - U_2)^2 < \frac{2(\rho_1 + \rho_2)}{\rho_1 \rho_2} \sqrt{Tg(\rho_1 - \rho_2)}. \tag{4}$$

Surface tension is significant for high curvature or high wave numbers and is relevant for the air-sea interface but not for atmospheric fronts [8]. The latest data on the effect of surface tension on KH instability can be found in [12]. If there is continuous stratification and velocity changes as a function, the Howard-Miles criterion for instability is given as:

$$R_i < \frac{1}{4}. \tag{5}$$

based on the Richardson number ($R_i = N^2/(U')^2$, where $N^2 = -(g/\bar{\rho}) d\bar{\rho}/dz$, $N -$ Brent $-$ Weissal frequency and $U' = dU/dz$) [13]. This criterion was initially used as a CAT predictor. However, large regions with low RiRiRi values can exist without triggering CAT, and it is now considered only a necessary condition for CAT [13].

It is essential to note that the Howard-Miles criterion (5) coincides with the criterion for the onset of KH instability in equal-density environments, which can be represented by the stability parameter $w^2 > 2$ [12]:

$$w^{-2} = R_i < \frac{1}{4}. \tag{5a}$$

Hence, the KH instability criterion serves as a supplementary criterion to the Richardson number and addresses all shortcomings mentioned in Section 2 of this study.

The KH instability calculation method for shear layers is used to analyze instability phenomena in hydrodynamics, particularly during the interaction of two media with different densities and velocities.

Advantages:

1. Explanation of Turbulence Formation: It allows a better understanding of the conditions and mechanisms for the emergence of turbulent flows during the interaction of different media.

2. Risk Prediction: Helps predict instability and the risks of vortex formation or inhomogeneities in moving media.

3. Practical Applications: Has significant importance in studying hydrodynamic phenomena in nature and engineering systems, such as oceanography, aerodynamics, and hydroelectric power.

Disadvantages:

1. Complexity of Calculations: Calculations can be complex and require significant computational power, especially when analyzing complex systems or large scales.

2. Model Limitations: Only considers certain aspects of instability, which may limit accuracy in predicting turbulent phenomena under specific conditions.

3. Non-homogeneous Conditions: In real-world conditions, KH instability can be influenced by various factors altering its characteristics, complicating precise prediction.

The KH instability calculation method is valuable for understanding turbulent processes, but it requires cautious application and consideration of its limitations when analyzing complex hydrodynamic systems.

Thus, KH instability is a significant phenomenon in hydrodynamics and aerodynamics because it influences turbulence development and flow pattern formation in fluid or gaseous environments. This process occurs when two media with different densities or velocities meet, leading to the formation of shear layers. Research into KH instability is crucial for understanding mixing processes, mass, and energy transfer, and for developing turbulence management strategies in natural and technical systems. This opens up opportunities for improving prediction and control of such processes in various fields where KH instability significantly impacts.

The alignment of KH instability and Howard-Miles criteria based on the Richardson number makes KH instability in shear layers the most likely candidate for describing the emergence of CAT.

BENARD CELLS

A separate series of experimental studies was dedicated to the formation of ordered convective cells in a two-layer medium, with both layers initially at rest. The lower layer consisted of Bénard cells made from an oil-aluminum suspension. The upper layer was composed of air above the surface of the suspension, confined by a thin transparent glass plate. The results of experimental and theoretical investigations are provided in [12].

Experimental studies have shown that in a two-layer medium at rest in the horizontal plane (with the lower layer being oil and the upper layer being air) heated from below, convective cells form in each layer. The cells in the liquid and air layers, which are in contact with each other, are arranged in pairs, one above the other, and have approximately the same geometric dimensions. Convective motion occurs in opposite directions inside and on the periphery of the cells: in the air layer, the air moves upward inside the cell, and in the oil, it moves downward. The coincidence of the sizes of Bénard cells in oil and air indicates their similarity, so it can be assumed, as noted in [27], that the Rayleigh and Prandtl numbers for these media are the same.

The theoretical study was conducted using cylindrical geometry, unlike the classical Rayleigh theory, which uses a Cartesian coordinate system. Cylindrical geometry is more natural because the thermal columns arising at the lower boundary of the layer have a cylindrical geometry. This approach made it possible to describe internal convective flows, formulate the energetic principle of forming cells of a specific diameter, and confirm these findings experimentally.

In concluding this section, it should be noted that observational data on solar granulation evidently suggest that the system of equations used in cylindrical geometry correctly describes the convective mass transfer of solar material when neglecting the Sun's rotation and magnetic field generation.

From the obtained results regarding the emergence of Bénard cells, it follows that vertical air movement occurs in the studied air layer: upwards in the center of the cells and downwards at their periphery. For an external observer moving horizontally through an ordered structure of such cells, there is a periodic action of lifting and lowering forces. Such almost periodic action of forces depends on the direction of movement in the horizontal plane and can be observed as a consequence of the emergence of CAT.

Thus, this section presents data on the experimental and theoretical foundations of studying Bénard cells in air that contacts Bénard cells made from oil below. It has been shown that Bénard cells in the air can create mutually opposing air movements that may be perceived by a horizontally moving object as manifestations of CAT.

The method of Bénard cells calculation [12] can be used to analyze and predict the characteristics of fluid or gas flows, particularly their instabilities and the formation of periodic structures.

Advantages:

1. Understanding Flows: Allows better understanding of the structure and movement within a fluid or gas, which is useful in hydrodynamics and aerodynamics.

2. Nature Studies: Helps analyze and understand natural phenomena, such as currents in rivers, oceans, atmospheric processes, and the movement of solar material on the Sun.

3. Practical Applications: Used to improve technologies and engineering solutions, particularly in transportation, energy, and aerospace industries.

Disadvantages:

1. Complexity of Calculations: Calculations involving Bénard cells can be quite complex due to the need to consider many factors and parameters.

2. Model Limitations: The method is linear and may be limited in predicting the behavior of fluid or gas under complex conditions or in systems with numerous influencing factors.

3. Need for Accurate Data: Calculation results may be sensitive to initial conditions and input data, requiring high measurement accuracy.

The Bénard cell method is a valuable tool for flow analysis, but its application requires caution and consideration of its limitations when studying complex hydrodynamic and aerodynamic systems.

Thus, Bénard cells represent a unique and complex pattern of movement arising in fluid or gas flows under the influence of instability factors, such as gravity, incompressibility, viscosity, and surface tension. These cells form regular geometric structures similar to hexagonal or honeycomb patterns, which are observed in various natural conditions, such as in atmospheric phenomena or convective mass transfer on the Sun.

Research on Bénard cells helps understand and study complex physical processes occurring in fluid or gaseous environments. This is important for developing new forecasting technologies for natural phenomena and creating effective engineering solutions, especially in areas related to fluid motion, transport, aerodynamics, and geophysics.

RAYLEIGH-TAYLOR INSTABILITY

Rayleigh-Taylor instability occurs at the interface between two fluids of different densities when the denser fluid is positioned above the less dense one in a gravitational field. This leads to the development of disturbances at the interface, which gradually increase and result in the mixing of the fluids. A monograph [12] is dedicated to a comprehensive study of instability in stratified viscous media. One of the key aspects of this work is the analysis of Rayleigh-Taylor instability, which plays a significant role in various fields of science and engineering.

The main characteristics of this phenomenon include:

1. Primary disturbances at the fluid interface gradually grow if the denser fluid is on top, leading to the development of complex structures and mixing of the fluids.

2. The influence of viscosity and surface tension significantly impacts the development of instability. High surface tension can suppress the growth of disturbances, while high viscosity slows down the instability process [12].

Advantages:

1. Simplicity of the Model: The Rayleigh-Taylor instability model is based on relatively simple mathematical equations, making it easy to analyze and predict the primary aspects of the process.

2. Widespread Application: The method is used in many fields, including astrophysics, geophysics, and industrial processes, making it a versatile tool for research and practical applications.

Disadvantages:

1. Idealized Theoretical Model: The theoretical model of Rayleigh-Taylor instability is idealized and does not consider many real-world factors, such as turbulence, medium heterogeneity, and external influences, which can significantly affect the results.

2. Dependence on Initial Conditions: The method's outcomes are highly dependent on initial conditions and disturbances, which can complicate its application in real-world scenarios and require additional adjustments.

Thus, the studies presented in the monograph highlight the importance of the Rayleigh-Taylor method for understanding hydrodynamic instability. The authors emphasize that although the method is an effective tool for theoretical research, its application requires caution and consideration of all limitations and specific conditions. Further research is aimed at improving models and expanding their applications, particularly by including additional factors for a more accurate assessment of instability processes in real-world conditions.

DISCUSSION AND COMPARISON

Clear air turbulence (CAT) is a complex physical phenomenon that occurs in the atmosphere under clear skies or with minimal cloudiness. To understand this phenomenon, we will consider the main mechanisms that cause turbulence formation under such conditions:

1. Solar Radiation: Solar radiation heats the Earth's surface, which, in turn, heats the air. Hot air rises, while cooler air descends. This process creates vertical air currents, which can be a source of turbulence.

2. Mountain Ridges: When air passes over mountain ridges, changes in altitude occur. This can lead to the formation of wave-like structures that cause turbulence.

3. Thermal Instability: Differences in air temperature and humidity can create instability and promote turbulence development.

4. Horizontal Wind Speed Gradients: Variations in wind speed at different altitudes can lead to the development of horizontal turbulence.

Compared to other types of atmospheric turbulence, clear air turbulence has a less pronounced nature and can be challenging to predict. Research into this phenomenon is essential for the safety of air transportation and the development of effective forecasting methods.

Several primary instability mechanisms have been identified as playing a crucial role in CAT development:

- Richardson Number (Instability Parameter): A dimensionless parameter that determines the conditions for transition from laminar to turbulent flow in fluid dynamics. A critical value of the Richardson number indicates potential turbulence.
- Kelvin-Helmholtz Instability: Occurs in shear layers when there is a velocity difference between two fluid layers, leading to the formation of vortices and turbulence.
- Bénard Cells: Convective cells that form due to temperature differences and can create periodic structures affecting airflow stability.
- Rayleigh-Taylor Instability: Develops at the interface of two fluids with different densities, resulting in the denser fluid descending into the less dense one, which can lead to mixing and turbulence.

By comparing these mechanisms, it becomes clear that each plays a role under specific conditions, contributing to the overall complexity of CAT. Understanding and modeling these mechanisms can help improve CAT prediction and enhance aviation safety.

CONCLUSIONS AND SUMMARY

The results of the study confirmed the importance of understanding and accounting for various instability mechanisms for predicting clear air turbulence (CAT). From our perspective, the most likely mechanisms for CAT formation include:

- The Richardson Number: Used as a primary instability parameter to determine conditions under which turbulence is likely to occur.
- The Stability Parameter for Kelvin-Helmholtz Instability: This parameter helps predict turbulence resulting from velocity differences in shear layers.
- Conditions for the Stability of Bénard Cells: These cells create ordered convective patterns that can influence turbulence.
- Conditions for Rayleigh-Taylor Instability: This occurs when a denser fluid lies atop a less dense one, leading to instability and potential turbulence.

Recent studies show a correlation between the Richardson number and the inverse value of the stability parameter for Kelvin-Helmholtz instability. Therefore, the combined use of these criteria is both reasonable and promising. Utilizing the aforementioned mechanisms for CAT formation helps reduce risks for passengers and aircraft while enhancing overall comfort and efficiency of air travel.

To improve CAT forecasting, further research is needed, especially in the integration of different approaches and the development of more accurate predictive models. Comprehensive data collection from satellite observations, in-flight sensors, and other technological advancements can aid in verifying existing theories and refining CAT prediction methods. Addressing the complex interactions between various instability mechanisms and their impact on atmospheric turbulence is essential for ensuring the safety of aviation and advancing our understanding of atmospheric dynamics.

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ФІЗИЧНІ МЕХАНІЗМИ ТУРБУЛЕНТНОСТІ ЧИСТОГО ПОВІТРЯ

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Турбулентність чистого повітря (CAT) – це значний тип атмосферної турбулентності, який становить ризик для авіації. На відміну від інших форм турбулентності, вона виникає без значної хмарності, часто при ясному небі або з мінімальною хмарністю в місці спостереження. CAT може виникати за різних метеорологічних умов, таких як високий атмосферний тиск, сонячна погода або при наявності гірських хребтів. Прогнозування CAT має вирішальне значення для авіаційної безпеки, хоча його прогнозування є складним через його мінливість, різку локалізацію в потоці повітря та мінливість розміру та тривалості. Непрямі ознаки можуть допомогти передбачити зони CAT; однак безпосереднє спостереження є складним, тому необхідно розробляти методи прогнозування та проводити дослідження для забезпечення безпеки польотів.

Ключові слова: *турбулентність; чисте повітря; авіація; параметр нестабільності; комірки Бенара*