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A Review of Atmospheric Dynamics on Earth or its Waves

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Abstract: If we want to know how the Earth's atmosphere moves and behaves, we need to research atmospheric dynamics. Solar radiation, pressure gradients, gravitational forces, and frictional interactions are the primary emphasis of this paper's examination of the processes that drive atmospheric circulation. As a result of changes in solar heating, which cause variations in pressure and temperature around the world, the atmosphere is constantly moving. A key component of atmospheric dynamics, waves and oscillations are impacted by convective sources and geographical factors, which in turn impact weather patterns and the behaviour of the climate. When it comes to influencing atmospheric circulation and energy transmission, equatorial waves, gravity waves, and planetary waves are among the most important. The study delves into the mechanisms of wave propagation, hydrostatic balance, conservation of momentum, and application of equations from fluid mechanics and thermodynamics. If we want to make weather prediction models and climate research better, we need to understand these processes better.

Keywords: Waves, Atmospheric Dynamics, Temperature, Solar Radiation, Earth

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INTRODUCTION

Energy from the sun is essential to the functioning of the Earth-atmosphere system. The whole amount of solar energy that is contained within the electromagnetic spectrum is able to pass through the atmosphere of the Earth and reach the surface. Several different kinds of molecules selectively absorb and scatter the radiation as it moves through the atmosphere. This process is known as electromagnetic scattering. Consequently, there is a variance in temperature across the atmosphere. The tilt of the earth and the position of the sun in relation to the earth are two other factors that contribute to differences in the amount of sunlight that reaches different latitudes outside of this phenomenon. The amount of radiation that is received decreases as one gets farther north or south, with the tropics getting the greatest amount of radiation. This generates a temperature difference all around the planet and puts the atmosphere in motion, which in turn causes the atmosphere to move. Consequently, the atmosphere of the planet is constantly shifting in response to this. By creating motion in the atmosphere, waves and oscillations that are caused by topographical features, convective sources, geographical disparities, and other variables further complicate the situation. Specifically, the emphasis of atmospheric dynamics is on the general motions that occur inside the atmosphere. In this particular scenario, the discrete molecule nature of the atmosphere is irrelevant, and one may consider the atmosphere to be a fluid medium that is continuous. [1]

The velocity at which the atmosphere travels is influenced by a variety of different causes. In terms of the forces that have an effect on atmospheric dynamics, the most important ones are the pressure gradient force, the gravitational force, and the frictional force. Both the centrifugal force and the Coriolis force are examples of forces that have a discernible impact on physical motion. When these forces are taken into consideration, the basic atmospheric state may be represented by employing equations that are governed by the laws of thermodynamics and fluid mechanics. These equations include the hydrostatic equation, the continuity equation, and the conservation of momentum and energy.

$$\frac{DU}{Dt} = -2\Omega \times U - \frac{1}{\rho}\nabla p + g + F_r$$

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla \cdot U = 0$$

$$c_v \frac{DT}{Dt} + p\frac{D\alpha}{Dt} = J$$

$$dp = -\rho g dz$$

The conservation of momentum equation is considered to be one of the most fundamental equations in the field of dynamic meteorology. This is basically a statement of the second law of motion, which is applicable to a coordinate frame that is spinning. The Coriolis force is represented by the first term on the right-hand side of equation, the pressure gradient force is represented by the second term, the combined centrifugal and gravitational forces are represented by the third term, and the frictional force is represented by the last term, Fr. Gravity, the Coriolis force, the pressure gradient, and friction are the four forces that contribute to the total zonal acceleration, which is denoted by the equation DU/Dt. [2]

The angular velocity at which the Earth spins is denoted by the symbol Q, which is equal to 7.29 x 10·5 rad every second. A variation of the continuity equation that takes into account the divergence of velocity is denoted by the symbol. According to the law of negative velocity divergence, the fractional rate of increase in density that occurs after the motion of an air parcel is equal to zero. According to the standard form of the thermodynamic energy equation, this fluid is subject to the first law of thermodynamics while it is in motion.

This is shown by the fact that the equation is standard. The second term on the left hand side (LHS) represents a conversion between thermal and mechanical energy, and it demonstrates the rate of work done by the fluid system per unit mass. This is demonstrated by the number of units of mass that are involved. This process is responsible for the conversion of solar thermal energy, which forms the basis for the movement of the atmosphere. As shown by Equation, the hydrostatic approximation says that, in the absence of atmospheric movements, the vertical component of the pressure gradient force must precisely balance the force of gravity. This is the case even if there are no atmospheric movements. This hydrostatic balancing condition has the potential to provide a good approximation of the vertical dependence of the pressure field in the real atmosphere.

Because of the perturbations that are brought about by the motions that occur within the system, the atmosphere of the Earth often deviates from the ideal state that is anticipated by equations. Waves and oscillations, which are a component of the dynamics of that area, are responsible for the bulk of the motions that occur in the middle atmosphere below the surface of the Earth. Consequently, the sections that are to come will provide more explanation on them. [3]

ATMOSPHERIC WAVES

In the realm of physical systems, a wave is a disturbance that occurs on a periodic and time-repetitive basis. Periodicity, frequency, wavelength, velocity, and other characteristics are some of the distinctive characteristics of this phenomenon. There is a phenomenon known as an atmospheric wave that causes periodic disruptions to the variables that make up the atmospheric field. These variables include pressure, temperature, wind speed, and others. There is a possibility that these waves did not travel across space. It is the waves that go from one location to another that are known as voyager waves. Standing waves, also known as stationary waves, are the waves that remain in place when this does not take place. Waves that propagate through the atmosphere are the most prevalent kind of intermediate atmospheric wave that may have substantial effects on your planet. As can be seen in Figure 1, the field variables are subject to oscillations as a result of how they behave. In addition to the mean component, atmospheric waves usually incorporate a fluctuating component into field variables. Some examples of these variables are temperature and wind speed.

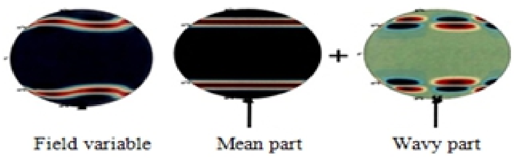

Figure 1: A depiction of how the field variables are affected by atmospheric waves

When it comes to dynamical motions in the middle atmosphere, there is a wide range of geographical (100–10,000 km) and temporal (ten degrees to 108 seconds) regions to choose from. There is a vast variety of sizes that may be found in the atmospheric waves, which are the basic dynamical component of the atmosphere. The bulk of the waves that are seen in the atmosphere of the Earth have magnitudes that vary from a few kilometers to thousands of kilometers, and their durations span from a Brunt VaisaHi (BV) cycle to several days. Both the process of formation and the force that restores it have a significant role in determining the amplitude of the wave.

According to the information shown in Figure, the motion of the atmosphere at any given time is determined by the sum of the motions of a large number of waves at a certain height. When it comes to the transmission of energy and motion, atmospheric waves are an extremely important factor. Wave-wave and wave-mean interactions are the source of the oscillations that they create in the atmosphere. They are responsible for changes in the temperature and composition of the atmosphere. They interconnect several layers of the atmosphere as a consequence of their propagation and the consequences that are related with them. In addition, waves have the potential to allow communication across different hemispheres and across various latitudes. Considering that the middle atmosphere is where atmospheric waves reach considerable amplitudes, it is in this region that they play a major role in the dynamics of the atmosphere. [4]

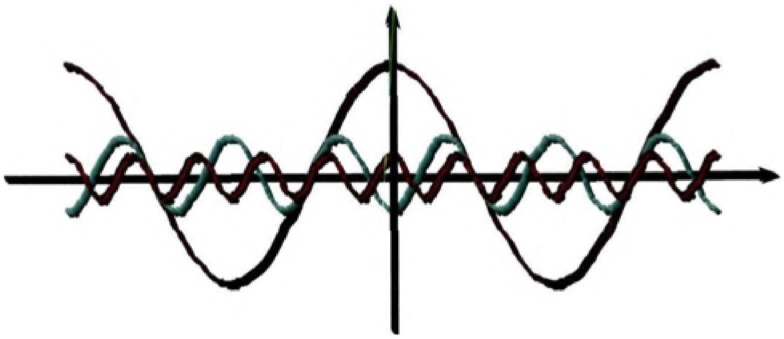

Figure 2: Graph showing the overall induced motion of several waves (represented by different colors) at a certain height, representing the motion of the atmosphere

The classification of waves may be accomplished by the use of a number of factors, such as physical processes, producing mechanisms, and restoring forces. Both dispersive and non-dispersive waves are examples of waves that may be classified into broad categories. When the wave number grows, there is a corresponding shift in the phase speed of diffuse waves. The phase speed is denoted by the equation (eu'k), where ro represents the wave frequency and k represents the wave number. The majority of the time, the value of ro for waves that are moving is determined by the physical features of the medium as well as the value of k of the medium.

Gravity Waves

Gravity waves are produced as a result of the balance that exists between the gravity of the atmosphere and the stratification of the density of the atmosphere. The buoyancy of their bodies allows them to climb, while gravity causes them to descend. These waves are referred to as gravity waves or buoyancy waves, depending on the context. In order for gravity waves to occur, there must be a discontinuity in the density of the environment as well as a presence of stable stratification. The first need is satisfied because, as shown by equation, the density of the atmosphere around the Earth decreases exponentially with increasing height. Stable stratification is characterized by buoyant oscillations, which are experienced by fluid parcels that have been displaced vertically in the atmosphere.[5] In the water that is surrounded on both sides, density decreases as a step function via the environment. Because of this, gravity waves go in a horizontal direction rather than a vertical one. On the other hand, in the air, where there are no fixed restrictions, what we refer to as "internal gravity waves" may flow either vertically or horizontally, depending on the conditions. The stability condition is expressed in terms of the rate at which molecules in the atmosphere lapse. Taking into consideration that ra represents the dry adiabatic lapse rate of the air parcel and re represents the environmental lapse rate, then

(i) ra< re - Unstable atmosphere.

(ii) ra =re - Neutral atmosphere.

(iii) ra > re - Stable atmosphere.

Therefore, gravity waves are amplified and spread further in a stable stratified atmosphere. The amplitude of waves grows exponentially with height because momentum is conserved.

Gravity Waves: A General Overview

The buoyancy frequency N, or BV frequency, defines the restoring buoyancy force acting on a fluid parcel that is vertically moved

$$N^2(z) = \frac{g(z)}{T_0(z)}\left[\frac{\partial T_0(z)}{\partial z} + \frac{g(z)}{C_p}\right]$$

It is possible to rephrase this equation as follows: To(z) is the mean temperature at an altitude z, g(z) is the acceleration due to gravity, and Cp is the specific heat capacity of static air. All of these variables are related to one another. The natural frequency of oscillation of a parcel is denoted by the letter N, and it is depicted when the parcel is pushed vertically from its equilibrium height. This determines the bare minimum amount of time that a wave may be allowed to remain in the atmosphere, which is an extremely important characteristic. In the troposphere, the average value of nitrogen is around 1.2 x 10-2 Hz, and the amount of time when the BV oscillation occurs is approximately 8 minutes. [6]

Gravity Waves and Dispersion Relation

The effect of gravity waves in the intermediate atmosphere causes a departure from the ideal momentum balance condition, as indicated in equation. Since the effect of acceleration due to gravity is negligible, the zonal (x-direction) momentum balance equation may be considered. Because of the extra acceleration induced by the momentum deposition by gravity waves, which is shown in the red box in equation, equation becomes false when these waves are present. The dispersion relation for gravity waves may be obtained by using the procedure outlined by Fritts and Alexander [2003] to equation and the related equations for the Y and z directions from equation and equations. The result is the equation for the intrinsic frequency and the vertical wave number.

Here is the formula:

$$\hat{\omega}^2 = \frac{N^2(k^2 + l^2)}{[m^2 + k^2 + l^2]} = N^2 \cos^2 \alpha$$

$$\frac{(k^2 + l^2)(N^2 - \hat{\omega}^2)}{(\hat{\omega}^2 - f^2)} - 1/4H^2$$

The BV frequency is denoted by N, the scale height is determined by H, the Coriolis parameter is denoted by f, the intrinsic wave frequency is denoted by wi, the zonal wave-number is denoted by k, the meridional wave-number is denoted by l, and the vertical wave-number is denoted by m. For high-frequency waves, we may eliminate the Coriolis force and simplify the dispersion relation by assuming that ro is more than f and m2 is less than 1/4H2. [7]

$$\hat{\omega}^2 = \frac{N^2(k^2 + l^2)}{[m^2 + k^2 + l^2]} = N^2 \cos^2 \alpha$$

Here, a denotes the direction in which waves travel.

The dispersion relation simplifies dramatically for medium-frequency waves, N>>ro>>f, which aids in comprehending the wave dynamics. This is called the mid-frequency approximation, and it is provided by

$$\hat{\omega}^2 = \frac{N^2(k^2+l^2)}{m^2} = \frac{N^2(k^2{}_h)}{m^2}$$

The Earth's rotation significantly affects low-frequency waves, often known as inertia-gravity waves (co-f) for short. Hence, we can't ignore the Coriolis force. Accordingly, the dispersion relation is expressed as

$$\hat{\omega}^2 = \frac{N^2(k^2+l^2)}{m^2} + f^2$$

For several applications involving gravity waves, the equations provide approximations of the dispersion relation.

- **The Most Important Gravity Wave Origins**

Topography, orographical features, convective systems, wind shears, and instability are the main causes of gravity waves. Their genesis is either on the surface or in the lower atmosphere. Jet streams, geostrophic adjustment, and other atmospheric processes also contribute to the generation of gravity waves. Secondary wave generators may be located higher in the sky, but they won't be as efficient. The most common ways waves are created are covered here. A review explains much of the topic on main gravity sources in depth.

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Convection: Despite the fact that it has been known for a long time that convection has the potential to create gravity waves, convection is the wave source that is the least understood of all the wave sources. Characterizing the source is made more difficult by the fact that it is inherently and inherently intermittent. When it comes to waves that are formed by convection, there is no one dominating phase speed or frequency that characterizes them. Convection, on the other hand, is that which is able to generate waves over the whole range of phase velocities, wave frequencies, and horizontal and vertical scales. There is a possibility that some of these waves may be recorded in the middle atmosphere at substantial horizontal distances from the source, which will make it more difficult to establish a relationship with the source of creation. There have been a number of studies that have been conducted on the topic of convectively generated gravity waves. The three primary ways that convectively created gravity waves have been characterized up to this point are a "mechanical oscillator" effect, a "obstacle" or "transient mountain" effect, and a "purposefully thermal forcing" effect.

There is just a connection between heat and the mechanism that lies behind thermal forcing. What causes gravity waves to be pushed outward is the discharge of huge amounts of latent heat that is contained inside a convective system (such as a cloud system or a convective storm). In this particular instance, the vertical wavelength of the created gravity waves and the heated depth are very similar to one another. The heating is projected onto a wave with a vertical wavelength that is twice as long as the depth of the heating. This is the most intense projection. However, after passing the tropopause, which undergoes a twofold increase in buoyancy frequency, the wave is subsequently refracted to half of its vertical wavelength. This occurs because the velocity of the wave is increased by a factor of two. Several numerical studies and observations have shown that the vertical wavelength of gravity waves is dependent on the depth of the heating zone. This was discovered by examining the relationship between the two variables. [8]

- **The Propagation, Saturation, and Breaking of Gravity Waves**

The propagation of gravity waves and the inference of their effects in the intermediate atmosphere are both made more complicated by a number of different components. It is useful to have an understanding of how gravity waves flow upwards and downwards from their place of origin. The wave packet travels in a direction that is perpendicular to the axes that represent phase separation. It is possible to differentiate between the two by using Two-Dimensional frequency-vertical wave-number spectra or by directly measuring the phase development of individual waves. Increasing densities in the real atmosphere cause the wave's downward transmission to be dampened, which in turn causes the wave's amplitude to decrease significantly. On the other hand, the amplitude of the wave that is propagating upwards grows until the movement of the wave is restricted by dissipative elements. For waves to propagate vertically, ducting is another essential component that must be present. Wave propagation constraints result in the ducting or trapping of waves with reflection (or turning) levels above and below as they move vertically. This occurs because waves are unable to flow horizontally. However, in general, the gravity wave structure inside a duct is evanescent on both sides and displays no vertical phase variation across the duct. This is despite the fact that more sophisticated wave patterns are feasible. [9]

- **Planetary Waves**

After atmospheric microwaves, there is the planetary scale wave category. Their horizontal scales cover the whole Earth, which is where their name comes from. That is, the wavelengths of the planetary scale waves are on the order of the Earth's diameter or somewhat smaller. Whereas small-scale disruptions tend to be disorganized and transient, they are spatially and temporally ordered and persistent. These large-scale waves, which may reach heights up to the MLT, are a prevalent component of the spatial and temporal variability in the Earth's middle atmosphere, much like gravity waves. Their impact on wind and temperature speeds, as well as the dispersion of ozone and other atmospheric components, is substantial. [10]

As they rise and fall, transferring energy and momentum from lower to higher regimes, waves on the size of planets have a significant impact on the dynamics of the upper and intermediate atmosphere. As they travel vertically through the atmosphere, planetary waves with easterly or westerly phase speeds may affect the meanflow accelerations and drive oscillations by depositing their easterly or westerly momentum at different altitudes. That is why they are so important; they may change the patterns of circulation and link different parts of the environment.

- **Rossby Waves**

A significant subgroup of planetary scale waves, the Rossby waves were discovered in 1949 and were given their name in honor of its discoverer, C. G. Rossby. As far as meteorologists are concerned, these waves are far more significant than any other waves that are present in the atmosphere. This article sheds light on the mechanism that is responsible for the generation and maintenance of these waves. There is a motion known as the Rossby wave, which is an absolute vorticity conserving motion. This motion is caused by the so-called P-effect, which causes the Coriolis parameter to change with latitude. As a result of the isentropic gradient of potential vorticity, the Rossby wave, which is a motion that conserves potential vorticity, is present in baroclinic atmospheres.

- **Equatorial Waves**

Waves that occur on a planetary scale may be further subdivided into a number of key categories, including equatic waves. As the name suggests, these waves are seen in the regions that are located at the equator. In spite of the fact that Rossby waves were generated by the absence of the Coriolis force, the primary reason for the Equatorial waves is the absence of the force. As one moves closer to the equator, the Coriolis force begins to weaken and finally vanishes, causing the atmosphere to display an unexpected response to the forces that are applied to it. To be more specific, the atmosphere near the equator will behave differently from the atmosphere at the mid-latitudes when it is exposed to the same categories of forces. Because of this particular characteristic of the equatorial zone, a collection of waves that are referred to as Equatorial waves may be produced. [11]

- **Kelvin Waves**

Due to the fact that they are symmetrical at the equator, Kelvin waves only have an effect on the zonal wind and pressure of the atmosphere; they do not contain any meridional component. The changes in temperature that are brought about by Kelvin waves are estimated to be between two and three kin in the middle atmosphere, as stated. At a latitude of around 15 degrees, the wave's strength decreases by a factor of two as it advances away from the equator. In the same way as buoyancy waves with an eastward direction are organized vertically, Kelvin waves likewise propagate in an eastward direction. Kelvin waves are responsible for a significant portion of the equatorial stratosphere's eastward velocity, as a consequence of this. Typical periods for them range from four to twenty days. The wave periods that are most evident in the lower atmosphere occur between the ages of 0 and 20 days ago. On the other hand, when one moves upward in height, the Kelvin wave spectrum is characterized by shorter periods, which correspond to higher frequencies. Wave number one is the most apparent of the two zonal wave numbers, and there are two wave numbers with this designation.

- **Mixed Rossby Gravity (MRG) Waves**

The MRG waves are equatorial air waves that travel in a westward direction. They include features of both Rossby waves and gravity waves. MRG waves were found by Matsuno in 1966, which is an amazing discovery. Through the use of linear equations, he was able to explain two distinct types of wave motions: a Rossby wave that went in a westward direction and an inertia gravity wave that moved in both an eastward and one westward direction. With low frequencies, he made the discovery that amplitudes are restricted to places that are quite near to the equator. When the number of zonal waves rises, the frequency of this wave continues to decrease until it reaches a level that is close to Rossby waves. As the number of waves diminishes, the frequency approaches that of gravity waves on a more consistent basis. [12]

CONCLUSION

The interplay between solar radiation, pressure gradients, and gravitational forces is a key component of atmospheric dynamics that ultimately decide Earth's weather and climate. This research shows that equatorial waves, gravity waves, and planetary waves are the most important atmospheric waves for controlling the flow of momentum and energy across atmospheric strata. These waves affect weather systems on a local and regional level and also contribute to climatic fluctuations on a larger scale. Meteorological forecasts are more reliable when the underlying concepts of atmospheric motion, such as momentum conservation and the application of hydrostatic equations, are known. Improving models to foretell wave interactions and their long-term effects on air circulation should be the goal of future studies. This will help with disaster management and adaptation to climate change.

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