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Dynamics of Lower–Middle Atmospheric Coupling in Climate and Weather Systems

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Abstract: Daily weather systems and global climate patterns are significantly influenced by the interaction between the lower and middle atmosphere. By facilitating the movement of momentum, energy, and heat across atmospheric layers, dynamic processes including gravity waves, planetary waves, and wave–mean flow interactions connect tropospheric disturbances with stratospheric and mesospheric reactions. Large-scale circulation characteristics like the quasi-biennial oscillation, stratospheric warming episodes, and meridional transport networks are shaped by even small-scale tropospheric disturbances, which have been shown to increase dramatically with altitude in both historical and modern studies. These processes show that the atmosphere functions as a single, interrelated system as opposed to separate levels. The progress of scientific knowledge about lower-middle atmospheric coupling is reviewed in this work, along with the main driving mechanisms governing vertical interactions and their significance for weather dynamics and climate variability. In order to increase forecasting and prediction accuracy, the research highlights the need of integrating these coupling mechanisms into climate models by combining observational data with theoretical advancements.

Keywords: Forecasting, Climate, Atmospheric Layers, Dynamic, Weather, Energy.

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INTRODUCTION

Various atmospheric layers interact in a complicated web that governs Earth's climate and weather systems. The troposphere and lower atmosphere have long been studied independently of the stratosphere and mesosphere, which make up the intermediate atmosphere. The lower and middle atmospheres are intricately linked by dynamic coupling processes, as has been shown by new findings in atmospheric research. These connections enable surface-based disturbances like convection, topographic forcing, or thermal fluctuations to rise into the atmosphere as gravity waves and planetary waves, where they impact the stability, circulation, and temperature patterns in the middle atmosphere.

Theories put out subsequently provide the groundwork for comprehending the behavior of internal gravity waves and quasi-geostrophic planetary waves in an atmosphere that is continually stratified and compressible. Because air density decreases with altitude, even little oscillations in the lower atmosphere may have a large effect on the top layers. This realization was strengthened when observational tools like radar wind measurements and radiosondes offered direct proof of wave propagation. [1]

The creation of the stratospheric polar vortex, the quasi-biennial oscillation, the circulation driven by tides, and abrupt warmings of the stratosphere are all crucial phenomena impacted by these interactions, and their effects on global climate regulation are far-reaching. So, the mid-atmosphere is seen as more than just a place where waves go upwards; it also plays a role in regulating feedbacks related to weather and climate. Seasonal shifts, the distribution of heat between the hemispheres, and large-scale circulation patterns are all influenced by the dynamic energy and momentum exchange that occurs between atmospheric layers. Due to the serious consequences that might result from using an erroneous representation of wave forcing or vertical coupling in climate models, a better understanding of these systems is now crucial for making better predictions. Thus, future climate predictions will be more accurate and scientific understanding will be expanded by a thorough evaluation of lower-middle atmospheric connection. In order to demonstrate how atmospheric connection influences both short- and long-term climatic patterns, this work integrates important theoretical premises, empirical data, and new developments.

ATMOSPHERIC GRAVITY WAVES

Gravity waves on the surface have been studied for ages, but it was Rayleigh who first looked at gravity waves inside a continuously stratified medium. Rayleigh wondered about the origins of the wave-like disruptions seen in stratus cloud formations, which piqued his interest in meteorology. Notably, he took into consideration the exponential drop in air density with altitude and, more critically, he obtained the dispersion relation for linear waves in an incompressible stratified fluid. The anelastic approximation, coined by Ogura and Phillips in 1962, has its origins in this inclusion (1962). [2]

Even though the formulation was more appropriate to oceanic applications, Love's later work was nonetheless conceptually comparable; it dealt with waves in a continuously stratified fluid with a free surface. Following this, Rayleigh rethought the issue in terms of a compressible atmosphere, where the isothermal assumption was made for both the mean state and disturbances, a strategy similar to that of Isaac Newton's first effort to define the speed of sound. Rather than studying small-scale waves, this research focused on the global resonance properties of the atmosphere. An early version of the Lamb wave, a free wave that propagates horizontally, was generated from this formulation. Due of the restricted isothermal assumption, these conclusions have limited quantitative precision, as Rayleigh himself admitted.

At last, it was Lamb who gave the first comprehensive account of compressible atmospheres with linear, adiabatic internal gravity waves. The first scenario he thought of had an isothermal mean state, whereas the second one had a consistent temperature drop with height, thereby drawing an upper limit for the atmosphere. The Lamb wave, which represents vertically propagating waves, was first proposed by Lamb, who also demonstrated the potential for a mode that is only horizontally propagating and has its energy concentrated close to the surface. [3]

Surface microbarograph recordings showed quasi-periodic oscillations, which the early studies of atmospheric gravity waves attempted to explain. This is when scientists independently found the equation for the buoyancy frequency in a completely compressible environment, which is the maximum frequency that internal gravity waves can maintain. We now often refer to this value as the Brunt-Väisälä frequency. The buoyancy frequency, under normal tropospheric circumstances, is correlated with oscillation durations of only a few minutes, which is very similar to the timelines of the high-frequency pressure fluctuations seen in the first microbarograph investigations.

One important feature of these preliminary studies is that they didn't pay much attention to what happens to gravity waves as they go up from the ground. Unexplored were the consequences of the square root of the inverse of the mean density, even though Rayleigh, Love, and Lamb's solutions showed that wave amplitudes should expand with height proportionally. Love hypothesized that viscosity would slow the upward amplification, whereas Lamb warned against taking the answers at face value because to the "indefinite increase of amplitude" that was predicated. On the other hand, Rayleigh completely ignored this matter. These pioneering scientists didn't appear to think of the possibility that waves traveling upwards may have noticeable impacts in the upper and intermediate atmosphere.

Gravity waves were almost entirely disregarded in meteorological and aerological investigations before to the 1900s. The atmospheric tidal motion, which occurs every day as a result of both gravitational and thermal forces, was one of them. The model proposed by Pekeris for tidal oscillations in a compressible atmosphere is based on global-scale internal gravity waves that are altered by the Earth's rotation. Tidal disturbances would increase in magnitude at an exponential rate due to the fact that density decreases with height, which he had already seen. According to Pekeris, the daily fluctuations in the geomagnetic field might be caused by a dynamo operating in the higher, electrically conductive layers of the atmosphere, where powerful tidal breezes are often anticipated. More research led scientists to believe that the same process may account for how the moon affects geomagnetic fluctuations.

FIRST RESEARCH ON GRAVITY WAVES IN THE ATMOSPHERE

Prior to the 1900s, the area of the atmosphere above the tropopause was principally teuua inʋo'nita. This changed due to two major events that occurred around the turn of the century. One was the finding of the stratosphere, a worldwide temperature inversion, using in situ balloon measurements. The second came when Marconi discovered long-range radio transmission and then realized that the upper atmosphere needed to be ionized. The ionosphere was the subject of much study due to the practical significance of radio propagation. A close look was given to the daily cycle and changes in solar activity-associated conductivity. A transatlantic shortwave radio transmission fades quasi-periodically every few minutes; the first to propose that these waves are altering the ionization in the F-region. This sparked interest in changes at higher frequencies in the ionosphere. Early accounts of these so-called "travelling ionospheric disturbances" were recorded by several scientists, including.[4]

Using the ionized trails left behind by meteors that collided with Earth's atmosphere allowed for the first measurements of wind speeds at thermospheric and mesospheric heights. In the height range of around 85 to 110 km, also referred to as the'meteor area,' these approaches have shown to be the most helpful. It is possible to create vertical profiles of the wind by measuring the Doppler shifts of radar responses from meteor trails. It is possible to separate the winds from the distorted, long-lived apparent trails by using time-lapse photography. The Liller and Whipple findings had a significant impact, although only covering a small number of meteor encounters. This was because their interpretation as neutral wind indicators was quite clear, and their vertical resolution was very high, at ½200 m. The horizontal wind as a function of height was determined by analyzing the distortions, which seemed to be mostly horizontal. [5]

Vertical wavelengths of these objects' wind profiles range from ½1 to 20 km, displaying a complicated mix of oscillations. From several millimeters per second to tens of millimeters per second, the amplitudes of the whe fluctuations varied. In the 1950s, meteor radar sightings caused quite a stir. One possible explanation for the radar data is the relatively large-scale distortions of the meteor trails seen in the optical Liller and Whipple investigations. Even while they acknowledged the existence of large-scale fluctuations in the data, they contended that they were really elements of a three-dimensional isotropic turbulent cascade. As time goes on, people start to point up problems with Booker's concept. [6]

It was a huge step forward when radar data were initially used to determine the horizontal and temporal scales of wind changes at meteor level. Greenhow and Neufeld discovered decorrelation scales of ½2 h, ½6 km in the vertical direction, and ½150 km in the horizontal direction for the wind fluctuations they saw above their radar at Jodrell Bank in England. [7] A simple turbulent cascade could not explain the lengthy timelines and substantial spatial anisotropy. At sufficiently wide separations, Greenhow and Neufeld found that the wind's spatial and temporal autocorrelations tend to become highly negative, indicating the existence of coherent wavelike oscillations. [8]

PROGRESS IN THE THEORY OF GRAVITY WAVES AS THEY RELATE TO THE MIDDLE AND UPPER ATMOSPHERE'S HIGH-FREQUENCY FLUCTUATIONS

While there was increasing evidence of high-frequency fluctuations in the circulation over 80 km in the 1950s, many fundamental questions remained fairly ambiguous by the decade's conclusion. There was much discussion over the relationship between wind fluctuations in the meteor zone and ionospheric disturbances higher up, the extent to which wind fluctuations in the meteor zone might be explained by tides, and the potential involvement of turbulence in generating these fluctuations. His initial hypothesis that traveling ionosphere disturbances may be explained by non-tidal gravity waves was later withdrawn.

Referring to the then-newly-available Greenhow and Neufeld findings, the idea that internal gravity waves may explain the high-frequency changes seen in the upper atmosphere was brought back to life and explained in detail. The plane-wave solutions for linear perturbations around a stationary, iso-thermal basic state atmosphere were determined by Hines in his 1900 work. He neglected spinning and the Earth's sphericity, but accounted for all compressibility effects. He discovered that the answers belonged to one of two groups: either low-frequency internal gravity waves or high-frequency acoustic waves that were somewhat altered by the influence of gravity. The dispersion relation that Hines established was found to be compatible with the Green-Meteor level wind changes, as shown by him. In keeping with the most straightforward explanation, he pointed out that waves with periods of ½100 min, which is far longer than the Brunt−Vaisala period, would mainly be caused by oscillations I. [9]

Along the axis of horizontal wind flow. According to his interpretation of the results, a lower mean density should cause the wind amplitude of the waves to grow. Despite the limited range of mean densities covered by the available optical and radar meteor wind observations, he did uncover some evidence for the projected amplitude growth with height. Above all else, Hines got the gravity wave field's projected amplitude growth with height, which is a general knowledge of great importance. Considerations such as the atmospheric density reduction between 90 km and the ground and the effects of wind and weather at lower altitudes make it clear that, within the same height range, the amplitudes of plane internal gravity waves may increase by a factor of 700. This was something that Hines noticed while talking about meteor levels winds. The greater atmospheric winds that have been observed may be due to a wave generation mechanism in that area, as the accompanying oscillatory motions in the lower atmosphere would only be a few millimeters per second. Such wave amplitudes might theoretically be generated in the troposphere. It seems that Hines was the first researcher to completely understand the effects of the wave amplitude increasing with height in relation to the high atmospheric circulation.

According to Hines, traveling ionospheric disturbances occur when internal gravity waves distort the ionization of the F-layer. Observations that had become accessible. It was hypothesized that alterations to the ionization in the F-layer often made their way downward. Gravity waves produced in the lower atmosphere are compatible with upward energy transmission, as Hines understood when he saw this downward phase trend. The fact that the traveling ionospheric disturbances seemed to have bigger horizontal phase speeds and distinctive horizontal wavelengths than the meteor wind data was another element that required explaining. [10]

When it was initially proposed that gravity waves, in addition to topography waves, might significantly affect atmospheric movements, several meteorologists were skeptical. Some people couldn't make sense of the group's apparent contradiction with the gravity wave phase velocities. The use of artificially manufactured tides as an explanation for meteor level wind readings has been considered by several scientists. Within a few years, it was recognized that the high-frequency wind fluctuations in the upper atmosphere were caused by vertically-propagating gravity waves, which were primarily stimulated in the troposphere. There are still noticeable turbulence patterns even in the upper and intermediate atmospheres. At large scales, energy is supposedly fed into the atmosphere by gravity waves. At smaller scales, this energy is transferred non-linearly. Isotropic turbulence at mesospheric or lower thermospheric levels mimics the flow at small enough scales. A spectral cascade is believed to be sustained at these levels. We still don't know how small-scale turbulence contributes to kinetic energy dissipation, how much spatial and temporal intermittency there is, how exactly non-linear energy transfer works, or how much of a role linear theory plays in explaining motions of different sizes.

Gravity wave impacts on average flow

It seems that thinking about how gravity waves could affect the mean flow was first motivated by the issue of topographical drag on the atmosphere. Both the "mountain torque" and the combined effects of viscous drag, caused by changes in pressure downstream and upstream across topographical features, contribute to the momentum transfer from the atmosphere to the surface. Even at large distances from the surface, the mountain torque may impact the mean flow in the presence of stable stratification. The force that propels the mean flow is determined by the upward radiation of gravity waves induced by flow across terrain and is unrelated to the divergence of the Reynolds stress associated with the waves. A notable impetus for Lawyer's research was an attempt to enhance the technique used to parameterize the impacts of topographic gravity waves in previous versions of air-scale numerical simulation models. The attorney proposed a quick fix for numerical models based on the assumption that tropospheric stress would decrease linearly with altitude, while still admitting that mean flow and dissipation would play a significant role in the Reynolds stress profile. [11]

First, Eliassen and Palm considered linear, two-dimensional, gravity waves propagating vertically in a time-invariant but vertically-varying stratification. Whey shown that the Reynolds stress remains constant for continuously moving waves outside forcing and dissipation zones, as long as critical values are not present (i.e., when the wave's intrinsic horizontal phase speed is zero). In order to generate mean flow driving, waves must be either transient, dissipate, or forced. In the case of topographic waves, waves act as catalysts, transporting mean momentum from the surface of the Earth to the level at which the waves dissipate. In the case of more generalized waves, waves generally originate in a wave driving zone. Using airplane data at many troposphere levels, the authors directly confirmed this image by deducing the eddy momentum flow linked to a topographic gravity wave. [12]

A Doppler-shifted phase speed of zero is achieved when the critical values of the adiabatic linear equations controlling gravity waves are approached. A discrete layer model was used to study and address the behavior of gravity waves at critical layers more thoroughly. The critical level would absorb gravity waves with even a little degree of dissipation, assuming it actually exists, and weak dissipation would allow the mean flow force from a single monochromatic wave to concentrate in a narrow band around it.

A theory for the quasi-biennial oscillation (QBO) of the tropical stratosphere was put out using the results of these studies of the critical level behavior of gravity waves. They stumbled into QBO while poring over mountains of data on zonal winds close to the equator, which they were using to analyze early tropical stratospheric wind observations. It was first quite puzzling that the QBO existed, given that the oscillation seemed to be very periodic, yet was evidently not directly driven by astronomical shifts. An additional factor that was challenging to understand was the continuous descent of wind reversals into the middle and lower stratosphere. Earlier attempts to attribute it to extraterrestrial interference were obviously unsuccessful. The significance of eddies has been highlighted due to the fact that the observed QBO features cannot be accounted for by models that are strictly zonally-symmetric. Highlighted the QBO's key properties by conjuring the average flow effects of a continuous spectrum of gravity waves injected into the troposphere & subsequently traveling into the stratosphere

Specifically, they built a basic model that incorporates the Reynolds stress divergence linked to each wave spectral component into a height-and time-dependent mean flow (representing the equatorial zonally-averaged zonal wind). When waves go east (west), they accelerate mean flows east (west) at the levels where they are absorbed. The waves' impacts are limited in scope because, for example, higher areas will be protected from waves with eastward phase velocities less than ϋ if a mean shear region is created with winds between zero and ϋ. [13]

In remarkable concordance with observations, numerical studies demonstrated that oscillating mean winds, driven by self-limiting eastward and westward mean flow processes, might cause wind reversals to decrease with time. An updated version of their model where the mean flow accelerations were thought to be caused by the interaction with discrete monochromatic equatorial planetary-scale waves flowing westward and eastward became available. Modeled these waves using parameters that were in close agreement with significant equatorial waves seen in radiosonde data, and the resulting mean flow oscillation was strikingly comparable to the genuine QBO in respect to amplitude, period, and vertical phase structure.

Using case studies of waves at the mesopause, the potential impact of gravity waves on the extratropical zonal mean circulation was evaluated, and it was shown that the resulting

Reynolds stress divergence may, on rare occasions, reach several hundred m s−1 day−1. Hines' recommendation went unnoticed for a while since many meteorologists at the time thought the numbers were too big to be true. Still, the mesosphere required a substantial dynami-cal drag, as was shown before.

A substantial flow from the summer mesophere into the winter mesosphere was needed for continuity, according to early research on the radiative balance in the middle atmosphere, which posited that the summer hemisphere must experience strong rising and the winter hemisphere must experience significant sinking. In the winter upper mesosphere, there is evidence of a strong (Ï10m s−1) poleward flow, according to the available rock-etsonde data. In order to counteract the Coriolis torque caused by the mean meridional circulation, some kind of dynamical drag would be required. To be more specific, the winter hemisphere mesosphere needs high westward drag to slow down the eastward polar night jet, while the summer hemisphere jet needs strong eastward drag to slow down the westward jet. To clarify the observed zonal-mean wind and temperature structure in the stratosphere and mesosphere, a massive eddy transporting the average flow is required. [14]

INTERPLANETARY PLANETARY WAVES

While the fundamentals of internal gravity waves' physics are obvious, it wasn't until the theoretical work of that linear waves in a purely barotropic (two-dimensional horizontal) fluid were considered that the large-scale horizontal gradient of potential vorticity could restore wavelike flow perturbations. Considering the planetary vorticity varies with latitude, the barotropic system may be able to sustain transversely-polarized wave movements. An other significant contribution by Rossby was the demonstration, under the 'b-plane' approximation, that a planar geometry could be a good approximation of the whole spherical system at the mid-latitudes, provided that the planetary vorticity varied with the meridional coordinate. [15]

A clear differentiation between the lower-frequency, large-scale planetary-wave fluctuations and the higher-frequency, gravity waves was made possible by Charney's creation of the quasi-geostrophic theory (1947, 1948). Another framework for dealing with planetary waves in three dimensions was given by wha-quasi-geostrophic theory. The mid-tropospheric planetary wave pattern, as pushed by the surface wind blowing across topography, was computed using a basic formula. Incorporating the consequences of zonal asymmetries in stationary heating was an expansion of this study.

Although the original work with the quasi-geostrophic system did not primarily concentrate on applications in the intermediate atmosphere, Charney did discover that his equations could be used to describe planetary waves that propagated vertically. If linearly-propagating-planetary waves are in a resting mean condition, their group velocity is estimated to be ½5 km/day. Based on this, he estimated that stratospheric input data that is poor or nonexistent for 48 hours would have no effect on a mid-latitude surface weather forecast. Interestingly, the outcome of Charney's straightforward calculation is in line with more recent predictions of the influence of predictability. Using the same analysis, he sought to determine if transient solar forcing might produce planetary wave pulses in the upper atmosphere and how they would propagate downward. [16]

Planetary waves in the middle atmosphere were first understood during the late 1950s, a period marked by important theoretical and observational advances. Truly, there were many parallels to the situation with gravity waves; however, the significant advancements in planar wave observation did not result from new technological developments, but rather from the extension and research application of the global balloon sounding network that had been set up for weather forecasting.

The first meridional cross-sections of zonal wind & temperature that extended into the stratosphere were constructed in the mid-1950s, marking a significant milestone in atmospheric research. The robust winter polar vortex that moves eastward and the westward summer stratospheric jet were both uncovered by these first assessments. As the worldwide radiosonde network expanded in the 1950s and 1960s, meteorologists started to use horizontal maps of geopotential height, wind, & temperature to study zonal asymmetries on a planetary scale. Early research mostly used data from the North American sector, but trustworthy stratospheric analyses for the whole extratropical Northern Hemisphere were developed during the International Geophysical Year (1957–58). A basic comprehension of the extratropical stratosphere's synoptic meteorology had developed by the early 1960s.

These observations revealed that the summer stratosphere is considerably less disturbed than its winter counterpart. In winter, the polar vortex is frequently distorted by large-scale quasi-stationary planetary waves and by transient disturbances that, while smaller in scale, remain far larger than typical tropospheric synoptic systems. Despite substantial phase variation with height, mid-stratospheric analyses consistently showed an Aleutian anticyclone positioned above the surface-level Aleutian low, indicating that these quasi-stationary stratospheric waves were upward extensions of tropospheric planetary waves.

A major theoretical breakthrough followed with the influential work of Charney and Drazin (CD), who examined the propagation of stationary quasi-geostrophic waves. Their research was initially motivated by questions surrounding the energy balance of the upper atmosphere. Scientists at the time explained the Sun's extremely hot corona by invoking mechanical heating from breaking acoustic waves generated deep in the solar interior. This raised the question of why Earth did not exhibit a similar "terrestrial corona," given that meteorological processes in the lower atmosphere could also generate vertically propagating waves. CD cited Hines's earlier work on gravity waves as an important foundation for exploring how large-scale quasi-geostrophic planetary waves propagate vertically. [17]

CD analyzed stationary planetary-wave propagation on a simplified β-plane in the presence of a vertically varying mean flow. They demonstrated that the mean stratospheric wind has a dominant control on whether stationary waves—generated by topographic forcing or zonally asymmetric heating—can propagate upward or become vertically trapped. In particular, strong mean westward winds or excessively strong eastward winds prevent upward propagation, causing waves to be confined to lower levels. For eastward flows, the trapping threshold depends on the horizontal scale of the wave. Their calculations showed that, under realistic wintertime mean-flow conditions, only zonal wavenumbers 1 and 2 should propagate into the stratosphere. Consequently, CD predicted that the time-mean stratospheric flow would be fundamentally different from the troposphere: nearly free of zonal asymmetries in summer and dominated only by large-scale stationary waves in winter.

Although the extent to which contemporary observational studies directly influenced CD remains unclear, their conclusions were broadly consistent with the observational analyses available at the time. CD noted that their theoretical predictions matched the large-scale, low-frequency circulation patterns evident in daily stratospheric analyses from the U.S. Weather Bureau and the Free University of Berlin, although they provided few additional details. [18]

CONCLUSION

To comprehend the climatic variability and weather behavior of Earth, one must grasp the dynamics of coupling between the lower and middle atmosphere. Crucial channels for vertical energy and momentum exchange are highlighted in the study as processes including gravity wave propagation, planetary-wave forcing, tidal oscillations and wave-mean flow interactions. Important atmospheric phenomena such as the quasi-biennial oscillation, stratospheric abrupt warmings, and hemisphere circulation patterns may be better understood with the aid of these processes. According to the data, changes in the troposphere may have a major impact on the structure of the middle atmosphere, which in turn affects the lower atmosphere via feedback mechanisms that affect jet streams, temperature gradients, and storm tracks. Realistic depiction of these vertical interactions is crucial for contemporary climate research in order to make accurate weather predictions and long-term climate models, so understanding that this coupling is bidirectional is necessary. Future weather and climate forecasting systems will be able to capture the whole complexity of atmospheric connection, thanks to ongoing improvements in observational technology, theoretical modeling, and computer simulations.

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