Abstract

Internal gravity waves are fully recognised for the relevant role they play in the atmospheric and oceanic dynamics of our planet. These waves, characterised by small-scale wavelengths, permeate the atmosphere and can lead to energy and momentum flux. When gravity waves propagate upwards, the momentum flux can become divergent due to wave breaking processes and consequently be a source for the large scale flow. Over the past decades, several studies have successfully investigated generation, propagation, and dissipation of gravity waves. Although several phenomena are nowadays reasonably well explained, others still remain unclear and, therefore, an active research topic. One of the least understood aspects is the emission of gravity waves from jet and front systems in the atmosphere, which are regions where significant wave activity has been frequently observed. Although many studies have established the importance of these non-orographic sources, the mechanisms responsible for wave emissions are still not fully understood. The complexity of the three-dimensional flow pattern, where a large number of interacting processes occur, and distribution of the sources over large areas point towards the need for laboratory experiments and idealised numerical simulations. Indeed, experiments and simulations can help with the correct interpretation of the fundamental dynamical processes in a simplified, but yet realistic flow.

In this thesis, we propose an experimental laboratory investigation of gravity waves generated from baroclinic jets and fronts using a differentially heated rotating annulus. This experiment consists of a rotating annular tank made of three concentric compartments filled with water, which is held to a constant warm/cold temperature in the outer/inner ring, respectively. Thanks to the radial temperature difference and the rotation about its axis, resembling each one of the fundamental forcing of the planetary atmospheric circulation, this experiment is a well established model of the atmosphere and it has been used for many years to investigate different aspects of its dynamics. Our study, however, reveals that the classical set-up of this experiment, usually showing an aspect ratio of about one, is not a particularly favourable configuration to investigate atmosphere-like emission of gravity waves from baroclinic jets due to an unrealistic ratio between stratification, measured by the buoyancy frequency N, and rotation, measured by the Coriolis parameter f. This ratio is much greater than one for the atmosphere but less than one for the classical annulus, and this difference is crucial when studying gravity waves. Indeed, no proof of gravity waves emission from jets has been found in the classical experiment thus far. Based on this, we offer two modifications of the original experiment to obtain configurations suitable for our purposes.

The first uses the same geometrical configuration, i.e. a tall and narrow annulus, but with the introduction of salinity stratification, which increases N up to values that reach $2 < N/f < 6$. The second solution follows the numerical simulations by Borchert et al. (2014) where a new shallower tank, called the atmosphere-like annulus, was proposed. The newly built tank has a much larger horizontal diameter which leads to a more atmosphere-like $N/f > 1$.

With the use of the Particle Image Velocimetry measurement technique and temperature sensors, the flow at different depths is investigated. Gravity waves are observed along the baroclinic jet in both experimental set-ups, their properties, together with the conditions for their emission and propagation, are examined in detail. In particular, the regions of the regime diagram for which the gravity waves with the largest amplitude can develop are identified. Subsequently, four possible generation mechanisms—i.e. shear instability, lateral wall instabilities, convection, and spontaneous emission—are analysed and matched with the properties of the waves. Despite the differences between both experimental configurations the gravity wave signature shows many similarities suggesting that similar generation processes occur in both cases. Finally, the energy partition among large- and small-scale wave phenomena is shown. The resemblance of the spectra obtained for the atmosphere-like annulus with the ones measured in the atmosphere is noteworthy, therefore proving that this experimental configuration is well suited for the investigation of multi-scale dynamics.

Zusammenfassung

Interne Schwerewellen spielen eine wichtige Rolle für die atmosphärische und ozeanische Dynamik unseres Planeten. Diese Wellen zeichnen sich durch kurze Wellenlängen aus, durchdringen die Atmosphäre und sorgen für einen Impuls- und Energiefluss. Im Falle einer Ausbreitung nach oben, kann durch Wellenbrechen Impuls und Energie auf die großräumige Strömung übertragen werden. In den letzten Jahrzehnten haben viele Studien die Erzeugung, Ausbreitung und Dissipation von Schwerewellen untersucht und obwohl einige Phänomene heutzutage gut erklärt sind, bleiben andere nach wie vor unklar und daher ein aktives Forschungsthema. Einer der nur wenig verstandenen Aspekte ist die Abstrahlung von internen Schwerewellen in atmosphärischen Strahlströmen und Wetterfronten, in denen häufig signifikante Schwerewellenaktivität beobachtet werden kann. Obwohl viele Studien die Bedeutung dieser nicht orographischen Quellen belegen, sind die Mechanismen, die für die Wellenemission verantwortlich sind, noch nicht vollständig geklärt. Die Komplexität des dreidimensionalen Strömungsfeldes, in dem wichtige Wechselwirkungsprozesse ablaufen und auch die großräumige Verteilung der Quellen für Schwerewellen legen nahe, Laborversuche und idealisierte numerische Simulationen durchzuführen. Diese helfen bei der korrekten Interpretation der grundlegenden dynamischen Prozesse in einem vereinfachten, aber dennoch realistischen Szenario.ö In dieser Arbeit schlage ich eine experimentelle Laboruntersuchung von Schwerewellen vor, die im Bereich von baroklinen Jetströmungen und Fronten in einem differentiell geheizten und rotierenden Annulus erzeugt werden. Dieses Experiment besteht aus einem rotierenden ringförmigen Tank mit drei koaxialen Zylindern. Diese Bereiche sind mit Wasser gefüllt und der Außen- bzw. Innenring kann auf einer konstanten Temperatur (innen kalt und außen warm) gehalten werden. Dank der radialen Temperaturdifferenz und der Drehung des Tanks um seine Symmetrieachse, ist dieses Experiment ein etabliertes Analogon der Atmosphäre und wird seit vielen Jahren verwendet, um verschiedene Aspekte der atmosphärischen Zirkulation zu untersuchen. Unsere Studie zeigt jedoch, dass der klassische Aufbau dieses Experiments, der normalerweise ein Seitenverhältnis von etwa Eins aufweist, keine besonders günstige Konfiguration für die Untersuchung von Schwerewellen darstellt. Dies liegt im Wesentlichen an einem unrealistischen Verhältnisses zwischen der Auftriebsfrequenz N und dem Coriolis-Parameters f. Dieses Verhältnis ist viel grösser als Eins für die Atmosphäre, aber kleiner als Eins für das klassische Annulus Experiment und dieser Unterschied ist entscheidend, wenn Schwerewellen entstehen sollen. Tatsächlich wurde im klassischen Experiment bisher kein Nachweis der Schwerkraftwellabstrahlung gefunden. In der vorliegenden Arbeit biete ich zwei Modifikationen des ursprünglichen Experiments an, um Konfigurationen zu erhalten, die für Schwerewellenabstrahlung geeignet sind. Die erste verwendet dieselbe geometrische Konfiguration, d.h. einen hohen und schmalen Aufbau, jedoch mit einer zusätzlichen Salz-Schichtung, die N/f auf Werte von 2-6 erhöht. Eine zweite, bereits von Borchert et al. (2014) vorgeschlagene Variante besteht aus einem neu gebauten, flachen Tank, genannt atmosphärenähn-

licher Annulus, dessen Verhältnis N/f auch ohne zusätzliche Salz-Schichtung größer als Eins ist. Dies kann durch theoretische überlegungen gefunden werden und wurde auch durch numerische Simulationen bestätigt (Borchert et al. 2014). Mit der Particle-Image-Velocimetry Messtechnik und Temperatursensoren untersuche ich in meiner Studie die Strömung in verschiedenen Tiefen. In beiden Versuchsaufbauten werden entlang des baroklinen Jets Schwerewellen beobachtet, deren Eigenschaften sowie die Bedingungen für ihre Emission und Ausbreitung detailliert untersucht werden. Insbesondere werden die Parameterbereiche identifiziert, für die sich eine reproduzierbare Schwerewellenausbreitung finden lässt. Anschließend werden vier mögliche Erzeugungsmechanismen, nämlich Scher- und Grenzschichtinstabilität, Konvektion und spontane Emission analysiert und mit den Eigenschaften der beobachteten Wellen abgeglichen. Trotz der Unterschiede zwischen den beiden genannten Experimentkonfigurationen zeigt deren Schwerewellensignatur viele ähnlichkeiten, die darauf hindeuten, dass in beiden Fällen ein ähnlicher Entstehungsmechanismus vorliegt. Schließlich wird die Energieaufteilung zwischen verschiedenen Wellen und Skalen aus Experimentdaten bestimmt. Die ähnlichkeit der für den atmosphärenähnlichen Annulus gefundenen Energiespektren mit denen der realen Atmosphäre ist bemerkenswert. Letzteres zeigt, dass diese experimentelle Konfiguration für die hier durchgeführte Untersuchung der Multiskalendynamik von Schwerewellen ausgezeichnet geeignet ist.

Chapter 1

Introduction

"Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream."

– Lewis Fry Richardson (1922) –

1.1 Motivation and Problem Statement

The study of atmospheric general circulation dates back to the 18th century with the pioneering work of Hadley (1735), who first realised that differential heating is the driving mechanism to the circulation. Since then, much effort has been made for explaining the atmospheric motions and developing a theoretical model of the general circulation. A fundamental point for developing such a model is to understand the dominating factors and mechanisms of the general circulation so that the essential physics of the atmospheric circulation is captured. To this purpose, experiments (both simulations and laboratory) analogues of the atmosphere are the perfect way to test and develop simplifying theoretical hypothesis and separate the fundamental mechanisms driving the atmospheric dynamics to other phenomena that can influence and modify the general circulation. Thanks to all the work done in the past decades, nowadays we have a good understanding of the essential physical model of the atmospheric circulation, which can be summarised as a rotating fluid under the forcing of Solar heating and gravity.

The combination of the development of equations describing the motions of the atmosphere and computers powerful enough to numerically solve them, led in the '50s to the first weather forecasts. Nowadays, weather forecasts, climate models and global circulation models are able to reproduce and predict not only the essential atmospheric features, but also other aspects of secondary importance that are, nevertheless, relevant for the dynamics. Indeed, in addition to the driving mechanisms, several other phenomena can come into play and affect the atmospheric dynamics. Among these phenomena, internal gravity waves—which are the focus of this thesis—are known to have a significant impact on the atmospheric circulation, structure, and variability (Fritts and Alexander 2003).

These small-scale waves, with horizontal dimensions in the order of 100 km to 1000 km, own their name to a combination of the location where they occur in the fluid (the interior) and their restoring force (gravity). When these waves have low frequencies and the rotation of the Earth has a stronger influence on them, they are called ‘inertia-gravity waves’ (IGWs in short). In this thesis, the term internal gravity waves shall be used also for indicating IGWs, regardless of the influence of rotation. Gravity waves develop in any stratified fluid and, therefore, are omnipresent in the oceans and atmosphere. In the latter, waves can be generated mostly in tropospheric regions by several sources among which the most relevant are flow over orography, convective clouds, and jets and fronts. After being emitted, they propagate vertically from the troposphere into the middle atmosphere. As the density decreases with the altitude, the amplitude of gravity waves grows until they break and eventually dissipate. Breaking process can cause turbulence and divergence of the momentum flux, and these can act as sources for other phenomena, for example clear air turbulence, quasi-biennal and semiannual oscillations, or for the generation of other gravity waves, called secondary waves. In addition, gravity waves are known to have a substantial impact also in the oceans, were they transport energy, and upon breaking contribute to the mixing (Sutherland et al. 2019). However, because the focus of this thesis is on atmospheric gravity waves, the following part of this introduction concentrates on the effects they have on atmospheric phenomena.

Since 1960, when Hines (1960) first attributed moving irregularities in the upper atmosphere to internal gravity waves, the dynamical interaction of these waves with other phenomena has been extensively proven. At lower altitudes, for example, gravity waves are involved in clear-air turbulence (CAT), which is of great relevance for air transport since it can cause serious aircraft incidents. One of the causes for such incidents is that CAT usually occurs in areas devoid of clouds (hence the name) and, therefore, cannot be seen and avoided by pilots. Several studies (Sharman et al. (2012) and references therein) have established that breaking gravity waves can trigger clear-air turbulence.

Furthermore, upward propagating gravity waves play a dominant role in the tropical stratosphere by driving the quasi-biennial oscillation (QBO) and the semiannual oscillation (SAO) of the zonal wind at equatorial latitudes. The QBO is the reverse of zonal winds from easterlies to westerlies (and vice-versa), which occurs at latitudes between 15°N and 15°S with a periodicity of approximately two years. The SAO has a periodicity of about six months and influences the upper stratosphere and lower mesosphere. It was already proposed in the ’70s that these oscillations arise from a combined effect of the interaction between internal-gravity waves and the mean flow and equatorial waves (Lindzen and Holton 1968). There is a fairly good agreement of the proposed driving of QBO by gravity waves with observations (Ern et al. 2014), whereas the contribution and more details about the gravity wave drag is still not completely understood (Ern et al. 2015).

In the mesosphere, gravity waves become even more significant: by breaking wave processes the momentum flux can become divergent and, therefore, decelerate the zonal mean winds causing the reversal of the vertical shear and induce a summer-to-winter pole residual circulation. A sketch of such residual circulation is depicted in figure 1.1, where the mesospheric branch driven by gravity wave breaking is visible at the top. Because of this circulation, with rising motions in the summer hemisphere which lead to adiabatic cooling, and sinking ones in the winter hemisphere which lead to adiabatic heating, the resulting meridional temperature gradient is inverted compared to the one induced by solar radiation and observed at lower altitudes (Fritts and Alexander 2003). Indeed, the mesosphere at the summer pole is characterised by the temperature minimum, whereas the mesosphere at the winter pole is relatively warm.

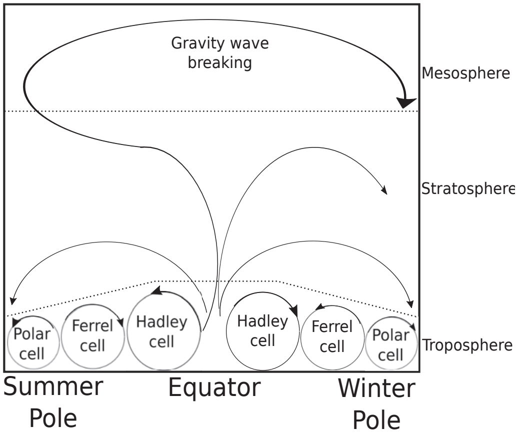

Figure 1.1: Schematic of the residual mean meridional circulation in the atmosphere. The circles denotes the Hadley, Ferrel, and Polar cells in the troposphere. The other lines indicated branches of the stratospheric and mesospheric circulation. The drawing is inspired by Plumb (2002).

It is clear that gravity waves have a substantial impact on several phenomena that are of relevance for the physics of the atmosphere; therefore, they cannot be neglected in realistic general circulation models and consequently in climate and weather models, which aim to predict the atmospheric dynamical features. Despite this, gravity waves have had a controversial position in the weather forecasts models. Even before such forecasts were run on computers, gravity waves had a fundamental role in the first ever prediction, done by hand by the father of the numerical weather forecasting Lewis Fry Richardson. As described in the book by Lynch (2006), Richardson's prediction of the change in the atmospheric pressure resulted in an unrealistic overestimation of two orders of magnitude because he used, as initial condition, the rate of pressure due to gravity waves to calculate a long term trend. To solve this problem and provide realistic forecasts several approaches have been followed, most of which are based on the same concept: the fast oscillation gravity waves need to be separated from the slowly evolving flow. One of the proposed and adopted solutions consists in the development of equations of motion that exclude gravity waves from the solutions. The development of models that completely filter out gravity waves—like the quasi-geostrophic model which eliminates the 'meteorological noises', as its founder Charney called gravity waves—is more than a simple matter of practicality. Indeed, this is at the core of the concepts of balanced and unbalanced dynamics and whether the evolution of the first one is possible in the complete absence of the second one.

Nowadays, it is clear that gravity waves cannot be filtered out of the numerical weather forecast and climate models, and that quasi-geostrophic equations are not sufficient enough to adequately describe the dynamics of the atmosphere, although they are useful for a basic understanding of the large-scale flow. However, the remaining problem is that part of the range of scales spanned by gravity waves is smaller than the current resolution of climate models and, therefore, need to be parametrised. Despite recent efforts to investigate IGW properties and their generation mechanisms, some aspects remain poorly understood, among which the gravity wave radiation process from jets and fronts which is an active research topic (Plougonven and Zhang 2014b).

1.1.1 General circulation

The Earth's atmospheric circulation is primarily driven by the incoming radiation from the Sun. Since the Earth's orbit around the Sun is elliptical and its axis has a current tilt of 23.4°, the energy received varies seasonally. To capture the main features of the observed atmospheric circulation in a simple model, we will neglect seasonal variations and assume that the tilt is 0°. In this configuration, the maximum incoming radiation is at the equator, and this leads to atmospheric motions acting to transport the heat excess from the equatorial towards the polar region. The resulting circulation would then be—similarly to what Hadley had imagined—two convective hemispheric cells extending from the equator to each of the poles, from where the warm air rises to where the cold air sinks. However, this single giant cell is not what is observed in the atmosphere for latitudes larger than 30° in both hemispheres, as it can be seen in the sketch in figure 1.2. Instead, three cells can be seen: two having the same overturning direction (polewards in the upper branch) and one in the opposite direction, sandwiched between them. Since there is a symmetry between the two hemispheres, we will focus our analysis on the North one. The winds at the surfaces, corresponding to the lower branch of each cell, are easterlies in the low latitudes. They then reverse to westerlies at mid-latitudes, and again easterlies (although weaker) near the poles.

To successfully model this observed global circulation of the Earth's atmosphere, a second forcing process has to be taken into account: the rotation around its axis. If friction is neglected, a parcel of air conserves the absolute angular momentum, $I = \Omega a^2 \cos^2\phi + ua\cos\phi$ where Ω is the rotation, a, the radius, ϕ the latitude of the Earth, and u the eastward component of the wind. In the upper branch of the circulation cell, the air moving towards increasing latitudes will have an increasingly strong eastward wind whilst the opposite occurs in the lower branch, i.e. close to the surface where the so-called trade winds arise. The extension of the Hadley cell and the strength of the circulation can be obtained with a nearly inviscid theory by assuming an energetically closed circulation (Held and Hou 1980).

At mid-latitudes, the air is observed to circulate in the opposite direction, i.e. towards the equator, and the zonal symmetry of the flow breaks and waves appear. In this second cell, the 'Ferrel cell', the zonal winds become unstable—because of the 'baroclinic instability'—and show meanders of typical synoptical scales (Callies et al. 2014). The term synoptic derives from the Greek συνοπτικός, which literally means 'general view as a whole', but in meteorology it is used for large-space scales (Markowski and Richardson 2011), which have typical lengths of a few thousand kilometres. These winds and temperature fluctuations are associated with the formation of high- and low-pressure systems, which are mainly responsible for the weather variations at mid-latitudes. The effect of these eddies on the global circulation is to reduce the poleward temperature contrast by carrying cold air to the tropics and warm air towards the poles.

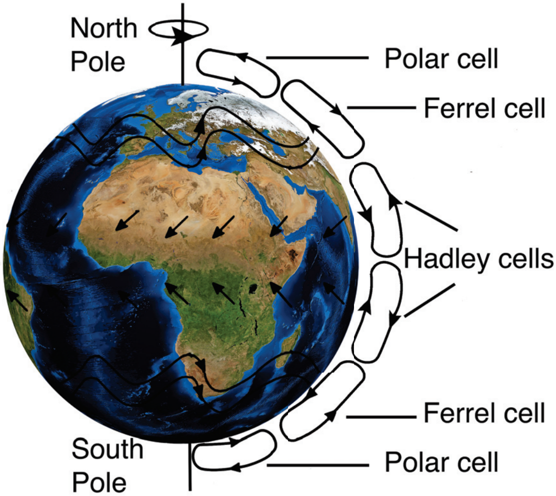

Figure 1.2: Schematic sketch showing some of the essential features of the atmospheric general circulation planet under equinox conditions. The three cells (Hadley, Ferrel, and polar) are drawn on the right hand side. The direction of the winds close to the surface are indicated on the globe by the black arrows and lines. At low latitudes, where the Hadley cells are developing, the winds are easterlies. For higher latitudes, under the Ferrel cells, westerlies with wavy patters can be observed. Near the poles, the winds turn again into easterlies (not indicated in the sketch). Drawing inspired by Wallace and Hobbs (2006).

The relevance of these large-scale waves to our study is that they have been observed to be a significant source of small-scale gravity waves (Ghil et al. 2010). The emission of gravity waves from jets and fronts is only one of the possible generation mechanisms. Other relevant sources in the atmosphere are the blowing of wind over topography and convective cumulus clouds. However, whilst these last two processes are reasonably well understood and flow-dependent parameterizations for the radiation of internal gravity waves from orographic and convective sources do exist, the situation is less developed for the gravity waves generated at the jets and fronts.

1.1.2 Gravity waves emitted from jets and fronts

Several atmospheric observations have highlighted consistent gravity wave activity at the jet front in the absence of orography. Uccellini and Koch (1987) firstly identified a common state of the background flow within which gravity waves are most likely to be emitted. In the studies considered, an enhancement of low-frequency gravity waves is recursively found in the exit region of the jet, where the flow decelerates. Successive observations (Fritts and Nastrom 1992, Sato 1994, Thomas et al. 1998, Hertzog et al. 2001, Wu and Zhang 2004) and numerical simulations (O'Sullivan and Dunkerton 1995, Zhang 2004) have confirmed these early studies and it is now accepted that gravity waves can be generated at the exit region of the jets. However, how these waves are generated is

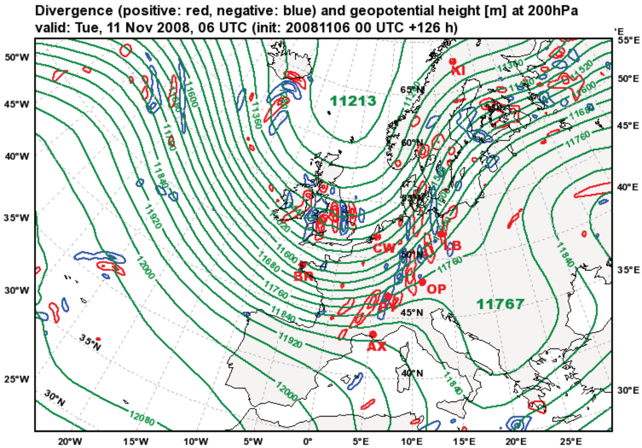

Figure 1.3: European Centre for Medium-Range Weather Forecasts (ECMWF) maps of horizontal divergence (negative values in blue, and positive values in red) at an altitude of 200 hP. The plot of the geopotential heights (green lines) show the ridges and troughs of the synoptic-scale waves.

still not completely understood. Furthermore, the exit region is also important for wave propagation e.g. via mechanisms like wave capture, which can modify the characteristics of the gravity waves moving through these areas (Bühler and McIntyre 2005, Plougonven and Snyder 2005). A horizontal map at 200 hPa showing the jet and the gravity wave packets along it is shown in figure 1.3 (the data and the plot are taken from the ECMWF model).

One of the main difficulties of studying gravity wave emission from jets and fronts is that the precise generation mechanism is still not fully evident since several potential sources coexist in the jet region, among which are the spontaneous imbalance of the mean flow, moist convection, and surface fronts (Wang et al. 2009). Moreover, contrarily to the case of orographic sources, there is no external forcing acting on the flow and, therefore, triggering the emission of gravity waves. In jets and fronts, the internal dynamic itself is responsible for such emission (Plougonven and Zhang 2014a). For this reason, one particularly challenging question is how the large scale flow, which is mostly balanced and only slowly evolving, can produce flow imbalance that forces the small-scales and high-frequency gravity waves. In fact, for many years scientists have debated whether this emission is even possible based on the existence or non-existence of the associated mathematical concept of the 'slow-mainfold'. According to Leith (1980) and Lorenz (1980) who postulated the existence of such a mainfold, balanced flows evolving along the slow mainfold will never emit fast waves since it would continue to remain balanced. The recent proof that such a slow mainfold cannot exist directly implies that balanced motions will inevitably emit internal-gravity waves and led to the introduction of the concept of spontaneous emission (Vanneste 2013). This represented a turning point in our understanding