Inertia–Gravity Waves Emitted from Balanced Flow: Observations, Properties, and Consequences

PAUL D. WILLIAMS
Department of Meteorology, University of Reading, Reading, United Kingdom

THOMAS W. N. Haine
Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland

PETER L. READ
Atmospheric, Oceanic and Planetary Physics, Oxford University, Oxford, United Kingdom

(Manuscript received 26 March 2007, in final form 1 February 2008)

ABSTRACT

This paper describes laboratory observations of inertia–gravity waves emitted from balanced fluid flow. In a rotating two-layer annulus experiment, the wavelength of the inertia–gravity waves is very close to the deformation radius. Their amplitude varies linearly with Rossby number in the range 0.05–0.14, at constant Burger number (or rotational Froude number). This linear scaling challenges the notion, suggested by several dynamical theories, that inertia–gravity waves generated by balanced motion will be exponentially small. It is estimated that the balanced flow leaks roughly 1% of its energy each rotation period into the inertia–gravity waves at the peak of their generation.

The findings of this study imply an inevitable emission of inertia–gravity waves at Rossby numbers similar to those of the large-scale atmospheric and oceanic flow. Extrapolation of the results suggests that inertia–gravity waves might make a significant contribution to the energy budgets of the atmosphere and ocean. In particular, emission of inertia–gravity waves from mesoscale eddies may be an important source of energy for deep interior mixing in the ocean.

1. Introduction

Inertia–gravity waves are observed ubiquitously throughout the stratified parts of the atmosphere (e.g., Eckermann and Vincent 1993; Sato et al. 1997; Dalin et al. 2004) and ocean (e.g., Thorpe 2005). Orthodox mechanisms for inertia–gravity wave generation include dynamical instability (e.g., Kelvin–Helmholtz shear instability; Chandrasekhar 1961), which is a known source of atmospheric gravity waves (Fritts 1982, 1984). Another possible mechanism is the interaction between the flow and a physical obstruction (e.g., generation in the wake of a ship; Lighthill 1978), which is the mechanism by which mountains generate atmospheric gravity waves (Hines 1989). Direct forcing of the ocean by the atmosphere is a known source of oceanic gravity waves (Wunsch and Ferrari 2004). Finally, inertia–gravity waves are also radiated during the geostrophic adjustment of a hypothetical fluid (Rossby 1938), in which geostrophic balance is approached from an unbalanced initial condition.

Despite the above insights, our understanding of the sources of inertia–gravity waves remains incomplete. In particular, Ford (1994) showed that even balanced flows may undergo a generalized adjustment that is accompanied by the emission of inertia–gravity waves. By “balance” we refer here in a generic way to a dynamical relationship that allows the fluid state to be diagnosed through potential vorticity inversion. In contrast to geostrophic adjustment, the Ford (1994) mechanism involves (weak) departures from balance that arise spontaneously as the flow evolves (Ford et al. 2000; Viúdez and Dritschel 2006), and not those that arise from ageostrophic initial conditions. It is proving extraordinarily difficult to determine whether or not this mechanism is a significant source of inertia–gravity waves in real geophysical flows, however (McIntyre 2001). This...
hinders the development of parameterizations of the waves in general circulation models (Kim et al. 2003). The generation of inertia–gravity waves is intimately related to the concept of the slow manifold, which was introduced by Leith (1980) and Lorenz (1980). The slow manifold is a putative, invariant submanifold of phase space, upon which the fluid remains devoid of fast inertia–gravity waves. The strict existence of the slow manifold, and hence the possibility of a flow evolving without emitting inertia–gravity waves, has long been debated (e.g., Lorenz 1986; Lorenz and Krishnamurthy 1987; Jacobs 1991; Lorenz 1992). The slow manifold breaks down in the numerical experiments of Yavneh and McWilliams (1994). Moreover, the formal nonexistence of the slow manifold is apparently implied by the spontaneous emission of Ford et al. (2000), although in that study the Rossby number is assumed to be greater than unity, which is not appropriate for large-scale geophysical flows (Saujani and Shepherd 2002; Ford et al. 2002).

A reasonably defined slow manifold may persist even when inertia–gravity waves are energized (Wann et al. 1995; Vallis 1996; Wirosoetisno et al. 2002). Furthermore, the waves may be sufficiently weak that they merely perturb the slow manifold into a fuzzy manifold (Warn and Menard 1986), which retains many of its useful properties. The amplitude of inertia–gravity waves and its dependence on the bulk flow properties are therefore of great interest. Despite general agreement that the amplitude should decrease with decreasing Rossby number, Ro, there is much debate about the quantitative variation for $Ro < 1$. In an asymptotic expansion of the governing equations, ageostrophic effects appear at first order in Ro (Pedlosky 1987), so we might expect the inertia–gravity wave amplitude to scale as $Ro^\beta$ for $\beta \geq 1$. In contrast, other theories suggest that the amplitude should scale as $Ro^{-1/2} \exp(-\alpha/\ln(Ro))$ (Vanneste and Yavneh 2004), with $\alpha \geq \pi/2$ (Plougonven et al. 2005, 2006), or as $Ro^{-2} \exp(-\alpha/\ln(Ro))$ (Vanneste 2004). Thus, it remains unclear whether the fuzzy manifold is algebraically or exponentially thin in Rossby number. These two possibilities have potentially very different implications for the fundamental dynamical concepts of balance and potential vorticity inversion.

Despite their importance, the above theoretical Rossby number scalings have never been tested experimentally. Laboratory experiments are not subject to the ad hoc approximations of idealized theoretical and numerical analyses, and they therefore provide the ideal arena in which to investigate this problem. Lovegrove et al. (1999, 2000) first reported the systematic generation of inertia–gravity waves at the interface in a rotating two-layer annulus experiment. The fluid in the experiment was rendered baroclinically unstable by an imposed vertical shear. The amplitude of the large-scale baroclinic shear periodically grew and decayed, and the shorter-scale inertia–gravity waves appeared once each life cycle. The short-scale waves were demonstrated to be inertia–gravity waves by showing that their observed intrinsic frequency was consistent with that predicted by the theoretical inertia–gravity wave dispersion relation. The inertia–gravity waves were so short that they did not satisfy the hydrostatic long-wave limit. In further experiments with the same apparatus, Williams et al. (2003) found that the inertia–gravity waves' back-reaction on the large-scale baroclinic wave was generally weak, except near transitions between different large-scale baroclinic modes.

The mechanism by which the laboratory inertia–gravity waves are generated was studied by Williams et al. (2005, hereafter WHR05). Because the waves continue to be generated long after the start of the experiments, generation by initial-condition adjustment could be ruled out. Because the measurement technique used is noninvasive, generation by a physical obstruction could also be ruled out. Using data from a quasigeostrophic numerical model of the large-scale flow (Williams et al. 2004b), five different indicators of inertia–gravity wave generation were examined by WHR05. The shear instability indicators, including the Richardson number, were shown to be inconsistent with the generation observed in the laboratory. Ford (1994) derived an indicator for the spontaneous emission of inertia–gravity waves in rotating shallow water. Spontaneous emission here refers to wave excitation in the sense of Lighthill (1952), in which nonlinear interactions of the basic state energize linear wave modes with only weak back-reaction on the basic state itself. WHR05 showed that Ford's indicator was qualitatively consistent with the observed laboratory inertia–gravity wave generation.

This laboratory experiment thus provides the first opportunity to test, in a real fluid, the above theoretical predictions about inertia–gravity wave generation. WHR05 did not study the inertia–gravity waves' dependence on Rossby number. However, Fig. 1 shows raw laboratory images from the WHR05 experiments at two extremes of Rossby number (0.16 and 0.45). Different colors correspond to different heights of the internal interface in the two-layer fluid. Both images show a wavenumber-2 baroclinic wave with a coexisting train of inertia–gravity waves in each trough. Crude examination by eye gives the first hint that the inertia–gravity waves' amplitude variation with Rossby number is weak, a finding we pursue in this paper, although cau-
tion is required in the interpretation of Fig. 1 because the relationship between color and interface height is nonlinear (Williams et al. 2004a).

This study is a further analysis of the WHR05 experiments and their fluid dynamics. Our aims are to document some of the properties of the observed inertia–gravity waves and to speculate about the consequences for the atmosphere and ocean. Specifically, we wish to quantify the variation of inertia–gravity wave amplitude with Rossby number in the laboratory experiments, over as wide a range of Rossby numbers as possible. To our knowledge, this is the first study in which inertia–gravity waves are quantified in terms of their Rossby number scaling in a real fluid. We also wish to quantify the leak of power from the large-scale balanced flow into the inertia–gravity waves.

The layout of this paper is as follows. Section 2 summarizes the main features of the laboratory apparatus and the method by which we have calibrated it to obtain interface height measurements from the color images. Section 3 describes our methodology for quantifying the inertia–gravity wave activity in any given laboratory image. Section 4 estimates the energy flux from the balanced flow into the inertia–gravity waves. Section 5 quantifies the variation of inertia–gravity wave activity with Rossby number. We speculate about the consequences for geophysical flows in section 6, and we conclude with a summary and discussion in section 7.

2. Laboratory experiment

Figure 2 shows a schematic cross section through the rotating two-layer annulus apparatus used by Lovegrove et al. (1999, 2000), Williams et al. (2003), WHR05, and in the present study. The annulus has an inner sidewall of radius 62.5 mm, an outer sidewall of radius 125.0 mm, and a total depth of 250.0 mm. The annulus gap width is thus $L = 62.5$ mm, and the two immiscible fluid layers have equal resting depths of $H = 125.0$ mm. The base and lid are both horizontal and the annulus is mounted on a turntable. The base
and sidewalls rotate with angular velocity $\Omega$ about the axis of symmetry, and the lid (in contact with the upper layer) rotates relative to the base and sidewalls with angular velocity $\Delta \Omega$, so that the angular velocity of the lid in the laboratory frame is $\Omega + \Delta \Omega$. For all of the experiments described in this paper, we use $\Omega > 0$ and $\Delta \Omega > 0$, implying a superrotation of the lid and working fluids relative to the turntable.

The upper layer is water and the lower layer is a mixture of limonene and CFC-113. The lower-layer constituent liquids are both practically insoluble in water and are mixed in such proportions that the composite density ($\rho_2 = 1003$ kg m$^{-3}$) is slightly greater than that of water ($\rho_1 = 997$ kg m$^{-3}$). Importantly, the lower layer has a large optical activity due to the limonene. Therefore, when the system is illuminated from below with white light and viewed from above through crossed polaroids, there is a relationship between the color perceived and the height of the internal interface. This is the effect responsible for the color gradients in the images of Fig. 1, which were captured by a video camera viewing the annulus from above. This flow visualization technique was proposed by Hart and Kittelman (1986). It is a noninvasive method for visualizing interface perturbations with high resolution in the vertical coordinate (see following paragraph), the horizontal coordinates (in our case, 0.5 mm), and time (in our case, 0.04 s).

Williams et al. (2004a) calibrated the experiment by deriving the quantitative relationship between hue (a measure of the dominant wavelength) and the height of the internal interface. Given an image captured by the camera, the two-dimensional hue field can be calculated from the digitized red, green, and blue pixel information and then projected onto the calibration curve to obtain an interface height map. However, during the present study it was discovered that the pixel jitter noise in the blue channel is much larger than in the red and green channels. This noise limits the vertical resolution of the retrieved interface height measurements, which is a key consideration because we wish to be able to detect small-amplitude inertia–gravity waves. For the purposes of the present study, we therefore disregard the blue channel and modify the Williams et al. (2004a) calibration curve to use only the red and green channels. This strategy reduces the error in retrieved interface height measurements from 1 mm (as reported by Williams et al. 2004a) to 0.3 mm, and it will be used throughout this paper.

For later use, the bulk Rossby number at the lid, the internal rotational Froude number, and the internal Burger number are defined by

$$\text{Ro}_{\text{lid}} = \frac{\Delta \Omega}{2 \Omega},$$  \hspace{1cm} (1)

$$\text{Fr} = \frac{(2\Omega)^2 L^2}{g H},$$  \hspace{1cm} (2)

and

$$\text{Bu} = \frac{1}{\text{Fr}},$$  \hspace{1cm} (3)

respectively, where $g' = 2g(\rho_2 - \rho_1)/(\rho_1 + \rho_2) = 5.9$ cm s$^{-2}$ is the reduced gravity. The internal Rossby radius of deformation for a fluid composed of two layers of equal resting depths is given (e.g., Gill 1982) by

$$R_d = \frac{\sqrt{g' H^2 (H + H)}}{2 \Omega}.$$  \hspace{1cm} (4)

3. Methodology for quantifying inertia–gravity wave activity

In this section, we describe our method for computing the inertia–gravity wave activity in any given raw laboratory image. We must use a severely restricted range of radii to remain within the limits of the calibration curve as the experimental parameters vary, but fortunately the inertia–gravity waves happen to fall within the permitted radii. We illustrate our approach using the image shown in Fig. 3 as a case study. We first digitize the red and green color components at each pixel within the two circles (of radii 78.0 and 82.0 mm) shown in the figure. Then, at each azimuthal angle, we
average over radius between the inner and outer circles to reduce pixel jitter noise. This is an average over around 10 pixels, which reduces the noise by a factor of around $10^{12}$.

We next project the radially averaged red and green pixel information onto the modified calibration curve (see section 2) to obtain interface height as a function of azimuth. The resulting curve is shown in Fig. 4a. The presence of a large-scale baroclinic wave, together with two trains of short-scale inertia–gravity waves, is clear. The baroclinic wave has a dominant wavenumber of 2, but also has a noticeable wavenumber-4 harmonic as suggested by Fig. 3. To isolate the inertia–gravity wave signal, Fig. 4b shows the difference between the original and low-pass filtered interface height curves. Two inertia–gravity wave envelopes, each containing around six

Fig. 4. Analysis of the interface height shown in Fig. 3. In (a)–(c), the zero of azimuth is at 3 o'clock and azimuth increases clockwise. (a) The solid curve is the raw interface height, and the dotted curve is the interface height filtered using a moving boxcar average of azimuthal width 12.5°. (b) The solid curve is the difference between the raw and filtered curves in (a), and the dotted lines are estimates of the noise due to pixel jitter. (c) Morlet-6 wavelet transform of the signal in (b), with contours drawn at 2, 4, 6, 8, 10, 12, and 14 mm. (d) Azimuthal average of the wavelet transform in (c).
complete wavelengths, are clearly seen above the pixel jitter noise. Figures 4c and 4d show, respectively, the wavelet transform of the inertia–gravity wave signal and the azimuthal mean of the wavelet transform. The inertia–gravity waves are seen to have a range of wavelengths centered on 10° of azimuth, implying a typical wavenumber of 36 and a typical wavelength (at radius 80 mm) of 1.4 cm. For comparison, the internal Rossby radius of deformation is given by Eq. (4) to be 1.5 cm.

As a measure of the amplitude of the baroclinic wave, the root-mean-square displacement of the low-pass filtered curve in Fig. 4a is 5.0 mm. We now evaluate four different metrics of the inertia–gravity wave activity:

- the root-mean-square displacement of the inertia–gravity wave signal in Fig. 4b, which is 1.3 mm;
- the maximum displacement of the inertia–gravity wave signal in Fig. 4b, which is 5.3 mm;
- the mean wavelet amplitude in Fig. 4d averaged over the wavelength band 5–20°, which is 2.1 mm; and
- the percentage of the total (baroclinic plus inertia–gravity) wave energy that is stored in the inertia–gravity waves, which is 9.0% (see below and Table 1).

These four metrics each represent a different way of quantifying the inertia–gravity wave activity. A large-amplitude but azimuthally confined inertia–gravity wave packet would result in the maximum displacement metric being large but the other three metrics being small, and vice versa for a small-amplitude but azimuthally extended wave packet. For this reason, the metrics are to be regarded as mutually complementary, and we shall use all four in this study.

We calculate the energy metric as follows. Both wave classes (i.e., baroclinic and inertia–gravity) contain potential energy and kinetic energy. We compute the potential energies (in arbitrary units) by azimuthally inte-

The results of this calculation are summarized in Table 1 and show that, in the case of Fig. 3, 9.0% of the total (baroclinic plus inertia–gravity) wave energy is stored in the inertia–gravity waves.

Some limitations must be borne in mind when interpreting the energy metric defined above. First, the restrictions on radius mean that the metric is not a comparison of the global energies contained in the two wave classes, but rather a local comparison near radius 80 mm. Second, the energy partition formulas apply in the shallow-water limit, and although the baroclinic wave might fulfill this requirement, the inertia–gravity waves do not. However, the fraction of the total wave energy stored in the inertia–gravity waves is fairly insensitive to this choice (see caption of Table 1) and so our qualitative findings are robust. Finally, the sum of the baroclinic wave and inertia–gravity wave potential energies, computed as described above, does not exactly equal the total potential energy computed by azimuthally integrating the squared deviations from the azimuthal means of both the low-pass filtered baroclinic wave signal in Fig. 4a and the inertia–gravity wave signal in Fig. 4b.

We now use the above four metrics to quantitatively compare the inertia–gravity wave activity in the two extreme Rossby number experiments of Fig. 1. The results of this calculation are shown in Table 2 and confirm that the variation with Rossby number is weak.
as suggested in section 1. As the Rossby number increases by a factor of around 3, all four metrics give an increase in inertia–gravity wave activity by a factor of around 2. The quantitative Rossby number dependence is explored more fully in section 5.

4. Energy flux from balanced flow into inertia–gravity waves

As noted in section 1, the amplitude of the large-scale baroclinic wave in these experiments periodically grows and decays. This periodic variation is known as amplitude vacillation (Lorenz 1963; Pedlosky 1977). The inertia–gravity waves appear once each life cycle, and in this respect their generation resembles that seen in the atmospheric baroclinic life cycle simulations of O’Sullivan and Dunkerton (1995).

We now examine the variation of inertia–gravity wave activity during one complete baroclinic life cycle. Figure 5 shows raw laboratory images at various phases, where a phase of 0° refers to the peak of the life cycle and a phase difference of 360° refers to a single complete life cycle (in this case, 132 s). At the peak of the baroclinic life cycle (Fig. 5a), inertia–gravity wave activity appears to be absent. As the baroclinic wave decays (Figs. 5b–d), inertia–gravity waves are clearly visible, first azimuthally confined with large amplitudes and then azimuthally extended with smaller amplitudes. Finally, as the baroclinic wave grows (Figs. 5e,f), inertia–gravity waves are once again barely visible.

We now quantify the variation of inertia–gravity wave activity during the course of the life cycle shown in Fig. 5, using the methodology of section 3. Figure 6 shows the evolution of the baroclinic wave amplitude and the four metrics of inertia–gravity wave activity. The covariation between baroclinic wave and inertia–gravity wave activity, suggested in the previous paragraph, is confirmed. According to all four metrics, the inertia–gravity waves grow as the baroclinic wave decays, and vice versa. Note that differences in each of the four inertia–gravity wave metrics in Fig. 6 between the phases of 0° and 360° give some indication of the interlife cycle variability of inertia–gravity wave activity.

Although knowledge of the energy stored in the inertia–gravity waves is valuable, the energy flux into them from the balanced baroclinic wave is arguably of greater consequence. The growth rate of the inertia–gravity waves in Figs. 5 and 6 gives some indication of this energy transfer, which we now quantify. Figure 6e shows that the peak energy transfer into the inertia–gravity waves occurs between the phases of 120° and 220°. During this time interval, the percentage of the total wave energy that is stored in the inertia–gravity waves increases from around 0% to around 20%. Because a phase difference of 100° corresponds to 36.7 s, and because the turntable rotation rate is 2.0 rad s^{-1}, this time interval corresponds to 11.7 turntable rotation periods. We therefore estimate that, at this Rossby number, the balanced flow leaks around 1.7% of its energy per “day” (i.e., rotation period) into the inertia–gravity waves at the peak of their generation. We discuss the consequences of this energy flux for the atmosphere and ocean in section 6. For comparison, Afanasyev (2003) estimates that approximately 4% of the energy is radiated as inertia–gravity waves in a nonrotating, linearly stratified laboratory fluid during the adjustment after the collision of two translating vortex dipoles.

5. Variation of inertia–gravity wave activity with Rossby number

We now extend the life cycle analysis of section 4, which was done for one particular Rossby number, to study variations with Rossby number. Using the experiments of WHR05, we analyze flows with different values of $\Delta \Omega$ but with $\Omega$ fixed at 2.0 rad s^{-1} to give a varying Rossby number but a fixed Burger number and rotational Froude number. The baroclinic wave in each case is an amplitude-vacillating wavenumber-2 flow.

Before proceeding, we must address an important technical point. The bulk Rossby number calculated using the lid rotation speed, that is, $R_{\text{O hid}}$ defined by Eq. (1), does not reflect the true flow speed. An analysis of the variation of inertia–gravity waves with $R_{\text{O hid}}$ might therefore be misleading. We must instead use the bulk Rossby number within the fluid, and specifically at the interface $R_{\text{O int}}$, because that is where the inertia–gravity waves appear. Unfortunately, we cannot measure the internal flow speed directly with the current apparatus. We instead use the equilibrium torque balance theory of Williams et al. (2004a), who derived, for the axisymmetric rotating two-layer annulus, two coupled nonlinear torque balance equations that may be solved iteratively for the rotation rates of the interface and the two layers, for any given $\Omega$ and $\Delta \Omega$. This axisymmetric calculation does not include baroclinic waves, and therefore neglects the (small) mean-flow correction that they induce.

Results of calculations using the torque balance theory are shown in Fig. 7. As anticipated, Fig. 7a shows that the Rossby number at the lid is a poor estimate of the Rossby numbers in the two layers and at the interface. Figure 7b shows that the interface Rossby number is given in terms of the lid Rossby number by

$$R_{\text{O int}} = \gamma R_{\text{O hid}},$$

(5)
The factor $\gamma$ is a function of the turntable rotation rate $\Omega$, but all the flows analyzed in this study have $\Omega = 2.0 \text{ rad s}^{-1}$, for which $\gamma = 0.31$. In contrast, quasigeostrophic theory gives $\gamma = 1/2$ (e.g., Hart 1972) for all values of $\Omega$, which is an overestimate due to the neglect of Stewartson layer drag at the sidewalls. In the following analysis, we use $R_{\text{oint}}$ (with $\gamma = 0.31$) as the Rossby number, rather than $R_{\text{lid}}$. The range of accessible lid Rossby numbers, $0.16 < R_{\text{lid}} < 0.45$, becomes a range of accessible interface Rossby numbers of $0.05 < R_{\text{oint}} < 0.14$.

Continuing with the main analysis, at 11 different

![Fig. 5. Raw laboratory images at the phases indicated, showing one complete baroclinic life cycle. Successive images are separated by phases of 60°, which in this case is 22 s. The experimental parameters are identical to those in Fig. 3. The images are taken from experiment 8 of WHR05.](image-url)
Rossby numbers we compute the baroclinic wave amplitude and the four inertia–gravity wave metrics at six phases of the baroclinic life cycle. In each case, we perform the analysis for two successive life cycles, to give an indication of the inter–life cycle variability as well as the intra–life cycle variability. The results are shown in Fig. 8. While the baroclinic wave amplitude shows little systematic variation with Rossby number, all four inertia–gravity wave metrics show an increase with increasing Rossby number. Inter–life cycle variability in inertia–gravity wave activity—which may be thought of as defining error bars for the curves—is present but is clearly smaller than both the intra–life cycle variability and the mean variation with Rossby number.

To obtain a single curve describing the inertia–gravity waves’ amplitude variation with Rossby number in the laboratory, we take an average over the 12 curves in Fig. 8b. The resulting life cycle–averaged curve is plotted in logarithmic coordinates in Fig. 9. The data lie on a straight line of slope 1.2 ± 0.1 in these coordinates and therefore indicate variation as $Ro^{1.2}$. If the average is taken instead over the 12 curves in Figs. 8c–e, then the

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Fig. 6. Quantitative analysis of the baroclinic life cycle shown in Fig. 5, but using 37 images each separated by phases of 10° (3.7 s) to give a higher temporal resolution. The RMS displacement of the baroclinic wave is plotted together with the four metrics of inertia–gravity wave (IGW) activity defined in section 3.
slopes obtained are $1.3/110060.2$, $1.3/110060.1$, and $2.1/110060.2$, respectively. The laboratory data are therefore consistent with a linear variation of inertia–gravity wave amplitude over a threefold range of Rossby number and a corresponding quadratic variation of inertia–gravity wave energy. Furthermore, when extrapolated to lower Rossby numbers, the line of best fit to the laboratory data in Fig. 9 passes close to the origin, indicating not only linearity, but proportionality.

The exponential and polynomial predictions from theory, discussed in section 1, are also plotted in Fig. 9 for comparison. There is a sharp mismatch between the laboratory curve and the exponential curves. There is also a sharp mismatch between the laboratory curve and the quadratic and cubic polynomial curves. Only the linear polynomial curve is consistent with the laboratory data. Our observations therefore challenge the notion that inertia–gravity waves generated by balanced motion will be “exponentially small” (e.g., Vanneste and Yavneh 2004).

6. Consequences for the atmosphere and ocean

The findings of this study may have important consequences for geophysical fluid flows. Our laboratory observations imply an inevitable emission of inertia–gravity waves at Rossby numbers similar to those of the large-scale atmospheric and oceanic flow. The appreciable energy leak from the balanced laboratory motions, reported in section 4, suggests that the geophysical analog of our laboratory emission might be a significant source of inertia–gravity waves in the atmosphere and ocean. Furthermore, the linear Rossby number scaling, reported in section 5, suggests that the inertia–gravity waves might be far more energized than predicted by at least some theories.

One application of our findings is to the role of inertia–gravity waves in deep ocean mixing. Figure 10 shows the energy budget for the global ocean circulation as estimated by Wunsch and Ferrari (2004). The thermohaline circulation is partly composed of the sinking of dense surface waters at high northern latitudes. But to close the circulation and maintain the abyssal stratification, the dense waters must rise up again through vertical mixing. This process requires a source of energy roughly estimated to be 2 TW ($1 TW = 10^{12}$ W). Previous work has concluded that tides and winds may adequately supply the required power, but the conceivable role of loss of balance from mesoscale eddies, resulting in the generation of internal inertia–gravity waves and associated vertical mixing, has hitherto been considered to be “of unknown importance” (Wunsch and Ferrari 2004).

We may crudely extrapolate our laboratory results to estimate the energy leak from mesoscale ocean eddies to internal inertia–gravity waves. The energy stored in the eddies is given as 13 EJ (1 EJ = $10^{18}$ J) in Fig. 10. If roughly 1% of this energy is lost to inertia–gravity waves each day, as suggested in section 4, then the power leak in the global ocean is 1.5 TW. We claim no accuracy for this figure, which is only indicative. Nevertheless, we are persuaded that generation of inertia–gravity waves from the balanced mesoscale flow may be an important source of energy for deep interior mixing in the ocean. Our finding supports the view that the “loss of balance” energy pathway in Fig. 10 is potentially important and deserves further study. The known fluxes of Fig. 10 are possibly in error by factors as large as 10 (Wunsch and Ferrari 2004), so by comparison our extrapolation is perhaps not as crude as it first seems.
Finally, we note that a power leak of 1% per day implies a 100-day decay time scale, which is broadly consistent with the observed decay time scales of mesoscale ocean eddies (e.g., Swart et al. 2008).

7. Summary and discussion

We have observed the emission of internal inertia–gravity waves from balanced flow in a rotating two-layer annulus laboratory experiment. The wavelength of the waves is very close to the internal Rossby radius of deformation. We have investigated some of the waves’ properties and speculated on the consequences for the atmosphere and ocean.

Our starting point was laboratory images of internal interface height at two extremes of Rossby number. Casual observation of the images suggested that the inertia–gravity wave amplitude does not depend as strongly on Rossby number as at least some theories

Fig. 8. Variation of IGW activity with Rossby number, as observed in the laboratory experiment. The rotational Froude number is fixed at Fr = 8.5. The RMS displacement of the baroclinic wave is plotted, together with the four metrics of IGW activity defined in section 3. The red curves correspond to phases of 30°, green to 60°, blue to 90°, yellow to 120°, magenta to 150°, and cyan to 180°. Two consecutive life cycles are analyzed, represented respectively by dashed–dotted and dotted curves. The analysis uses experiments 1–11 of WHR05.
predict. We quantified this observation by defining various metrics of inertia–gravity wave activity, which could be computed for any given color laboratory image by projecting onto a calibration curve. For the internal rotational Froude number fixed at 8.5 (i.e., internal Burger number fixed at 0.12), we evaluated the inertia–gravity wave metrics at interface Rossby numbers (calculated from the lid Rossby number using a torque balance theory) in the range 0.05–0.14. Although we have only been able to access variations in Rossby number by a factor of 3, the Ford (1994) source term varies as Rossby number squared, and so we have almost a decade of variation in this source term. The results show a linear variation of inertia–gravity wave amplitude with Rossby number in this range. This observed linear scaling challenges the notion, suggested by several dynamical theories, that inertia–gravity waves generated by balanced motion will be exponentially small. A full theoretical explanation for the mismatch is eagerly awaited.

Finally, we have estimated that the balanced laboratory flow leaks roughly 1% of its energy each “day” (i.e., rotation period) into inertia–gravity waves at the peak of their generation. This suggests that inertia–

FIG. 9. Variation of relative IGW amplitude with Rossby number, as observed in the laboratory experiment (at Fr = 8.5) and according to theory. The life cycle–averaged laboratory data are obtained from Fig. 8b as described in the text. Error bars indicate the phase-averaged inter–life cycle variability, also determined from Fig. 8b. The exponential curves are curves of $R^2_0 \exp(-\alpha/R_0)$ (Vanneste and Yavneh 2004). The polynomial curves are curves of $R_0^6$. The exponential and polynomial curves are arbitrarily normalized to pass through (1, 1). The laboratory data are also arbitrarily normalized.

FIG. 10. Energy budget for the global ocean circulation, from Wunsch and Ferrari (2004). The boxes in the top row represent energy sources and the shaded boxes represent energy reservoirs. Energy fluxes between the different components are given in units of TW. Note the energy flux from mesoscale eddies to internal waves, labeled “loss of balance” and with its value indicated by a question mark. The value given for the internal wave energy is erroneous and should read 1.4 EJ rather than 14 EJ (C. Wunsch 2007, personal communication).
gravity waves might make a significant contribution to
the energy budgets of the atmosphere and ocean. In
particular, the mechanism represents a potentially large
supply of energy for deep ocean mixing, which we
cruelly estimated to be 1.5 TW in the global ocean. It
is interesting to compare this flux with the recent ob-
servational estimate of Polzin (2008, manuscript sub-
mitted to J. Phys. Oceanogr.) He finds that the transfer
of energy from eddies to internal waves is \(4 \times 10^{-10}\) W
kg\(^{-1}\) in the depth range 600–800 m. Extrapolating this
to the entire ocean (of volume \(1.34 \times 10^9\) km\(^3\) and
mean density \(1026\) kg m\(^{-3}\)) gives a total flux of 0.5 TW,
which compares quite well with our own estimate. Our
quantitative results also have applications to the atmo-
sphere, for which they could be used to guide inertia–
gravity wave parameterizations.

It is worth remarking that the systematic emission of
inertia–gravity waves has not been observed in other
similar laboratory experiments, even though they have
been used for decades to investigate baroclinic waves.
We speculate that this is because our flow visualization
technique allows a much higher spatiotemporal resolu-
tion than has been achieved in previous studies. Also,
on the rare occasions that inertia–gravity waves have
been reported previously [e.g., Read (1992), although
the amplitudes were an order of magnitude smaller
than in our study], they were measured by probes in the
fluid and it was natural to attribute their generation to
an interaction between the flow and the probes. Un-
usually for rotating laboratory experiments, the visual-
ization technique that we use is noninvasive, ruling out
this possibility.

Our observation that the inertia–gravity wave ampli-
tude is only linearly dependent on Rossby number, and
not exponentially dependent, might be due to dissip-
ative processes. In these experiments, the inertia–gravity
waves could be affected, or possibly even controlled, by
viscosity and surface tension. Thus, we are not able to
rule out the possibility that the inertia–gravity waves
are fully saturated over the range of Rossby numbers
we have been able to access, and that their amplitude is
determined more by the dissipation than by the forcing.
If this were the case, then our estimate of the energy
flux into the inertia–gravity waves must be considered a
lower bound. We plan future experiments to investigate
this possibility, if practicable.

Inertia–gravity wave generation may depend upon
the Burger number (or its reciprocal, the rotational
Froude number) as well as the Rossby number. Unfor-
luckily, for two independent reasons, it is virtually
impossible to study the dependence upon the former
using the present laboratory apparatus. First, it is evi-
dent from Fig. 3 of WHR05 that over the part of pa-
rameter space at which inertia–gravity waves coexist
with a regular baroclinic wave, the range of possible
Froude numbers at constant Rossby number is much
smaller than the range of possible Rossby numbers at
constant Froude number. Second, the interface be-
comes steeply sloped at high Froude numbers, and the
fluid begins to access interface heights outside the
range of the calibration curve, so that we can no longer
infer interface heights (and hence inertia–gravity wave
amplitudes) from the color laboratory images.

To interpret the present laboratory results in the con-
text of other analytical and numerical studies, it is help-
ful to compare the dynamical regimes in the (Ro, Bu)
space. The present laboratory experiments are at Ro \(\approx
0.1\) and Bu \(\approx 0.1\). This lies in the frontal geostrophic
regime and is outside the standard quasigeostrophic re-
gime (Ro \(\ll 1\) and Bu \(\gg Ro\)), the Ford et al. (2000)
spontaneous emission regime (Ro \(> 1\) and Bu \(\gg Ro^2\)),
and the Vanneste (2004) and Plougonven et al. (2005,
2006) regimes (Ro \(\ll 1\) and Bu \(\sim 1\)).

We acknowledge that the extrapolation of our results
to geophysical flows is crude and provisional. Although
the laboratory fluid and geophysical fluids share similar
Rossby numbers, they have different Burger numbers,
geometries, stratifications, and aspect ratios. Neverthe-
less, this is the first time the emission of inertia–gravity
waves has been studied in this way in a real fluid rather
than a numerical model or theoretical analysis. Our
study therefore makes a vital contribution to the debate
about the role of inertia–gravity waves in geophysical
flows.

Acknowledgments. PDW is funded through a Fel-
lowship from the U.K. Natural Environment Research
Council (reference: NE/D009138/1). TWNH is sup-
ported by the National Science Foundation (DMS-
0530844).

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