LABORATORY STUDIES OF TOPOGRAPHIC EFFECTS ON BAROCLINIC FLUIDS

by

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June 1979

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ABSTRACT

A review is given of laboratory experiments which have been undertaken to examine the effects of non axisymmetric topography on the flows of baroclinic fluids. Experiments using both a two layer mechanically driven system and a continuously stratified, thermally driven system are described. In both systems, in baroclinically stable flows the effects of topography are to deflect the streamlines of the flow and in certain parameter ranges closed circulations are observed. In these stable flows the amplitude of the standing wave forced by the topography is well described by linear theory but the detailed behaviour of the standing wave depends on the potential vorticity gradients in the fluid. In the baroclinically unstable flows non linear interactions occur between the forced waves and the free baroclinic waves which influence both the amplitudes and frequencies of the drifting components. In the continuously stratified system low amplitude topography increases the stability of the flow but larger topography may be destabilising. In this system also the wavelength of the most unstable baroclinic wave appears to be decreased by the presence of topography.

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Introduction

Attempts to predict the behaviour of the atmosphere over periods of several days require an assessment of the effects of interactions between fluid flows and topographical features. It has been demonstrated (see for example James, 1976) that introducing some representation of topography into numerical forecast models can have a substantial effect on the predicted dynamical behaviour of the atmosphere. This effect often exceeds those of other parameterized processes when predictions for a few days ahead are considered. When primitive equation models are used to simulate climate dynamics similar problems arise, although for such uses techniques which are accurate in some statistical sense are required. However for long term climatic studies the use of parameterised models, in which the dynamical transports of heat and momentum are parameterised, becomes necessary. In order to develop such models a detailed understanding of the large scale dynamical interaction between the atmosphere and the topographic features will be required.

When primitive equation models are developed for forecasting purposes, terrain following coordinates, such as the σ -coordinate system, are often used and models using these coordinates exhibit some skill in predicting flows even close to topographic features. In pressure coordinate models parameterisations of topographic effects, such as that developed by Hayes (1975) for use in the Meteorological Office 10 level model, can be used. These methods have their own advantages and limitations but the attempts to verify the techniques have often been limited to assessments of forecasts using atmospheric data. These verifications therefore suffer from the problems of data analysis and from forecast inaccuracies arising from other causes. For the assessment of parameterisation schemes for parameterised climate models it becomes impossible to verify methods using current observational data since the schemes may be required outside the range of variables over which they can be verified; an understanding of the basic dynamical processes is therefore required to estimate the range of applicability of a parameterisation scheme.

In the absence of topographic and other forms of forcing the atmospheric motion at middle latitudes on length scales of $\gtrsim$ 1000km is characterised by the conversion of energy from the available potential energy of the mean flow to the kinetic energy of wavelike disturbances (sloping convection or baroclinic instability). Energy is also transferred between the different scales of motion by non linear interactions. It is clear therefore that while linear theories may be used to assess the effects of large scale topographic forcing they cannot provide other than an approximation to the effects on a system determined by non linear effects. The non linear transfers of energy not only determine heat flow variations but they also determine the ultimate predictability of atmospheric flows (see for example Leith, 1975). The interaction of forced motions with the non-linear dynamics may result in significant changes in the estimation of atmospheric predictability so that it becomes necessary to investigate the non linear effects of topography.

Laboratory experiments currently being undertaken in the Geophysical Fluid Dynamics Laboratory have been designed to improve knowledge of the mechanisms by which topography influences geophysical fluid flows on a large scale, from which the effects on atmospheric flows may be estimated, and they also provide a body of data, obtained under controlled conditions, against which the performance of numerical schemes could possibly be tested. In particular, attention will be confined here to the effects of non axisymmetric topographic forcing in baroclinic flows. The structure of the forced components of the flow and the effects on the structure of the mean flow will be described. The results of experiments to determine the effects of topography on the stability of the flows and on the properties of the baroclinic waves will also be described.

Experimental details

The laboratory experiments have been undertaken in two different systems which exhibit baroclinic instability. In the two layer system a shear is maintained by mechanical methods across the interface between two immiscible liquids of slightly different densities rotating about a vertical axis. For a range of rotation rates and density differences the system may become baroclinically unstable and the waves observed as changes in the height of the interface. In the second system an annulus of liquid, rotating about a vertical axis is subjected to a radial temperature gradient. A stable density stratification arises from the variation of the liquid density with temperature while a vertical shear results from the thermal wind which balances the horizontal temperature gradient. Baroclinic waves in this system are indicated by the presence of a jet stream which meanders between the walls of the convection chamber. The former system is amenable to analytic investigation, and some non-linear analyses have been undertaken for this system (Pedlosky, 1970, 1971,) The thermally driven system is more analogous to the continuously stratified atmosphere but is both less controllable and more difficult to analyse than the two layer system (see Drazin, 1970).

Details of the laboratory systems have been described by Hart (1972) and by Hide and Mason (1975), among others and detailed descriptions will not be given here although schematic diagrams of the two systems are given in figure 1. Extensive experiments on topographic effects in the two layer system have been undertaken by King (1979) who used an infra red absorption technique to detect and measure waves on the interface and a dye release technique to obtain qualitative details of the flow. The experimental investigations on topographic effects in the thermally driven system commenced with those of Kester (1966) and Fultz and Spence(1967) but a more systematic study was undertaken by Leach (1975) whose investigations are being extended by Chamberlain (private communication) and by the author. In these experiments the temperature structure in the fluid was determined using probes and various techniques of flow visualisation were used.

In this review it will be convenient to describe the laboratory observations in two parts. The first part relates to the effects of topographic forcing on flows which are baroclinically stable. In these flows the points of interest concern the structure of the forced disturbances and the drag exerted by the topography as well as the changes in the mean flow profile. The possibility of destabilising the flow by the effects of topography is also important here. The second part of the results describes the effects of topography on the flows which are baroclinically unstable. In these flows there are additional questions to be answered concerning the interactions between baroclinic waves and the topographically forced waves.

Topographic effects on baroclinically stable flows

King (1979) undertook a series of experiments with the two layer system under conditions giving rise to baroclinically stable flows. Three different types of smooth topography were used, all with a dominant azimuthal wavenumber 3, which were fixed to the lower surface of the apparatus. This dominant azimuthal wavenumber was chosen because this was the most frequently observed azimuthal wavenumber of the waves in unstable flows in this apparatus. The topography had a dominant cross channel wavenumber 1. Two different heights of topography were used, both with a uniform radial slope in addition to the wavenumber 3 topography. The uniform slope gives rise to potential vorticity gradients which have effects similar to those resulting, on a sphere, to the variation of the Coriolis parameter with latitude. In addition the lower topography was also used without the uniform slope.

The amplitudes of the various azimuthal Fourier components of the standing wave forced by the topography on the interface were measured. These were normalised by the amplitude of the same component in the topography, all of the measurements being made at the mid radius of the apparatus. Typical results obtained using topography with no uniform slope are shown in figure 2. For small differential rotation (small Rossby number, ϵ) the amplitudes are insensitive to the differential rotation but for larger differential rotation the amplitudes rapidly increase, the amplitude of the higher wavenumbers increasing most rapidly. The increase in the amplitude was believed to result from a resonance between the topographic forcing and interfacial gravity waves which has the property of occurring at lower differential rotation for higher wave numbers.

In order to understand the observations, King (1979) applied a linear quasi-geostrophic model to the two layer system. The effects of viscosity were neglected and steady state solutions of the equations were sought. It was demonstrated that an important scaling parameter for the amplitude of the disturbances was the parameter $\mathcal{S} \equiv h/2H\epsilon$. This parameter was first introduced by Hide (1961) when considering the conditions under which closed circulation (Taylor columns) would form over topographic features in homogeneous rotating fluids. King suggests that there is a possibility of Taylor column formation with closed streamlines over the topography in the baroclinic flow. The analysis indicated that the wave amplitude would be independent of the Rossby number of the flow (or of the differential rotation) and the predicted amplitudes, which are also shown in figure 2, are in good agreement with the observation. Observations of the displacement of streamlines in the flow as it formed over the topography confirmed the dependence of the flow on $\mathcal{S}$. Similar results were also obtained with the other topographies used in the experiment.

Experiments with very low differential rotation demonstrated the presence of slowly drifting waves of large amplitude which were believed to be barotropic in origin and to arise from the presence of potential vorticity gradients. These waves were not present when the topography was absent from the apparatus and their behaviour depended on the presence or absence of sloping end walls. Sloping end walls provide a contribution to the potential vorticity gradient additional to that resulting from the observed radial profile of the zonal flow. Although the data are not sufficiently detailed to enable tests of theoretical ideas concerning the breakdown of the Taylor columns to be made it is clear that the structure of the wave forced by topography is dependent on potential vorticity gradients.

In the continuously stratified thermally driven system Leach (1975) observed that under conditions which would give rise to an axisymmetric flow in the absence of topography the streamlines were deflected by topography. Under some conditions a closed circulation was observed slightly downstream (with reference to the flow close to the top of the topography) of the topographic peaks but in other examples there was only a deflection of the streamlines. The closed circulations were observed when the Burger number $\mathcal{B}$ $(\equiv N^2d^2/f^2L^2) \lesssim 1$. (Here N is the Brunt Vaisala frequency, f the Coriolis parameter and d and L the depth and gap width of the convection chamber.) Assuming a ratio of obstacle height to fluid depth of 0.1 the condition implies $\delta \gtrsim$ 0.3 which is consistent with the suggestion of Hide (1961) and with the two layer experiments. The nature of the flow did not depend critically on the shape of the topography for a range of smooth and rectangular topographies.

Investigations of the vertical structure of the stationary component of the disturbances forced by topography were undertaken by Leach (1975) and by Chamberlain (private communication). The result of some of these experiments are presented in figure 3 in which the amplitude has been scaled by the mean vertical temperature difference over one bump height. The data shown in figure 3 were obtained with a smooth sinusoidal topography of azimuthal wavenumber 3. The most striking features of the results are the confinement of the perturbation below the mid level in the fluid and the strong dependence on the wave amplitude on the parameter Nf^{-1}. (Experiments with varying aspect ratios suggested that this was more relevent than $\mathcal{B}$ in determining the vertical structure.) Data were also obtained which suggested that the phase of the forced wave varied with the height above the topography and that a phase change of 1 rad between the top and bottom of the fluid was not uncommon but systematic variations of the total phase change were not found. It was demonstrated that when many wavelengths were forced by the topography the vertical penetration of the shorter waves was less than the penetration of the longer waves.

Leach (1975) applied a simple inviscid linear model to the problem of topographic forcing of the continuously stratified system. A uniform vertical shear was assumed with radial and vertical density variation. Topography was not assumed to affect the background flow but steady state perturbations of the flow were sought which were forced by the lower boundary condition which gave rise to a sinusoidal forcing of the vertical velocity. The predicted vertical variation of the amplitude of the perturbation is compared with the observed variation in figure 4 for similar values of the relevent parameters. The amplitude was found to depend on the height above the base according to

$$\Phi = -\frac{\gamma}{2\sinh\gamma}\;\frac{\frac{\gamma}{2}\sinh\gamma(z-\frac{1}{2}) + \cosh\gamma(z-\frac{1}{2})}{\frac{\gamma^2}{4} + 1 - \gamma\coth\gamma}$$

where z is the nondimensional height ($-0.5 \leqslant z \leqslant 0.5$) and $\gamma^2 = B(k^2 + n^2\pi^2)$ where k and n are the azimuthal and cross channel wavenumbers of the perturbation. It should be noted that as $\gamma \rightarrow 2.399$ the denominator tends to zero and the predicted wave amplitude increases. This limit is also the limit at which the flow becomes baroclinically unstable according to the theory developed by Eady (1949) so that, as observed the amplitude of the forced wave increases as the flow becomes less stable. Since Φ can be larger than 1, implying non-dimensional wave amplitudes greater than 0.5, compared with the maximum value of 1 obtained using a similar theory but omitting baroclinic effects the baroclinic flows can amplify the topographic perturbation.

When viscous effects were incorporated into the theory realistic results were obtained for the variation of the phase of the forced disturbance with height. It was not possible with the simplified theory to explain the detailed shape of the observed curves showing the variations of the amplitude of the forced wave with height. It is probable that these detailed observations require the effects of potential vorticity gradients in the flow to be included in the theory for their explanation. This area requires further study both of an experimental and of a theoretical nature.

Topographic effects on baroclinically unstable flows

When topography is inserted into either two layer or continuously stratified flows in which free baroclinic waves are present, two effects are apparent without detailed measurements. The first is a substantial change in the drift rates of the free baroclinic waves and the second is a change in the location of the transitions between different flows with different azimuthal wavenumbers. The changes in the drift rates can be explained by considering the changes in the mean zonal flow. In the two layer system in which the zonal flow direction is the same at all levels (to a first approximation), the increased drag due to the topography reduces the mean flow and the wave drift rates. However in the continuously stratified system with rigid end walls the zonal flow changes sign at mid level giving a small mean flow which can be increased in magnitude by removing vertical symmetry by increasing the drag exerted by one end wall. The drift rates are observed to be increased substantially by the presence of the topography in this system.

The effects of the topography on the location in parameter space of different transitions are more difficult to explain. King (1979) suggests that in the two layer system there is little change in the location of the transition from axisymmetric (baroclinically stable) to wave flows but that the observed changes in the transitions between flows of different dominant wavenumber are consistent with the changes expected using linear theory allowing for changes in the zonal flow caused by topography. The energetics of the continuously stratified system are rather different from the two layer system and the onset of baroclinic waves can be qualitatively explained as being necessary to ensure efficient heat transport across the convection chamber (see Hide and Mason, 1975). In this system the waves forced by topography may transport heat and it is to be expected that the flows will become stabilised by topography. This is observed and in table 1 the location of the transitions in different systems are presented. Leach's (1975) measurements of the heat flows across the convection chamber tend to confirm this interpretation but the data were not sufficiently accurate to make quantitative estimates of the heat transport due to the forced wave components. An improved apparatus has been developed to enable such changes to be accurately measured but experiments have still to be carried out. The observation that the wavenumber of the dominant free baroclinic wave in the continuously stratified system is higher when topography is present than when it is absent is also apparent from table 1.

In the experiments with baroclinically stable flows it was possible to explain the main features of the observations of the forced waves using linear theories but in the unstable flows the situation is complicated by the possibilities of non linear interactions between the baroclinic waves and topographically forced waves. The observations of the forced waves will be considered first.

In the two layer system, King (1979) demonstrated that non linear interactions between the forced wave and the drifting baroclinic waves could, in certain circumstances, result in an increase in the amplitude of the forced wave. This is demonstrated in figure 5 where normalised standing wave spectra are shown for two experiments; in one of these the dominant baroclinic wave was of the same azimuthal wavenumber as the topographic forcing and in the other experiment the dominant wavenumber was different. The interaction between baroclinic and forced waves is seen to enhance the amplitude of the forced wave. In a non dispersive system with non zero mean flow it is obviously not possible to obtain resonant interactions but in a dispersive system it may be possible to obtain resonant, or nearly resonant, interactions. In the experiments mentioned above a small amount of dispersion was present due to the presence of potential vorticity gradients. When greater dispersion was introduced through the use of sloping end walls to the apparatus even more marked interactions were observed, in particular drifting waves were forced by the topography. These results will be described later. It is perhaps useful to note that a special case of resonant interactions between two forced components and a slowly drifting free wave was considered by Egger (1978) as relevant to the problem of blocking in the atmosphere.

In the continuously stratified system strong interactions were found between topographically forced waves and baroclinic waves (Leach, 1975). It was suggested that in the baroclinically unstable flows the stationary wave penetrated through the entire depth of the fluid instead of being confined to the lower levels, below the level of no motion. The range of Leach's experiments and the vertical resolution of the measuring system were not sufficient to enable quantitative conclusions to be drawn from these results and the implication of a sudden change in the vertical structure of the stationary wave at the transition from stable to unstable flows is not consistent with recent observations by Chamberlain (private communication). Further work needs to be undertaken to clarify this point. The effects of non linear interactions between the forced and free waves were found to result in systematic changes in the amplitudes of the forced and free waves with a frequency equal to the frequency of the drifting wave. The amplitude changes were out of phase suggesting transfers of energy between the two components were an important feature of the dynamics of the system.

Interactions between drifting and stationary waves will not in general only effect the two components but may give rise to additional wave components. In the two layer system it was shown that when considerable dispersion was present the time averaged spectra of the drifting waves showed significant energy in waves whose wavenumbers were combinations of the dominant baroclinic wavenumber and of the topographic wavenumber. Typical results are shown in figure 6. In order for resonant interactions to occur between these waves, the baroclinic wave and the stationary forced wave, it is clear that they should have the same frequencies as the baroclinic wave. In figure 7 the results demonstrate that non linear interactions occur not only between the dominant baroclinic wave and the topographic forcing but also between the harmonic of the dominant wave and the forcing. Data from the continuously stratified system are not so extensive but preliminary results from experiments currently being undertaken are shown in table 2.

The results obtained from these experiments show that the effects of topography on baroclinically unstable flows are, firstly, to change the mean flow profile thereby modifying the drift rates of the drifting waves and, secondly to result in exchanges of energy between drifting and forced waves which result in changes in the amplitudes of these components. The drift of some of the wave components is also influenced by the non linear interactions. In general, as would be exoected, the non linear effects are more important when large amplitude topography is present. Points requiring further investigation concern the changes in the stability of the flows and in particular whether these can be explained using linear theory when changes in the mean flow are taken into account and the way in which non linearity and dispersion interact to determine the condition under which considerable flow changes may result from topographic forcing.

Conclusions

The laboratory experiments described in this review have demonstrated the importance of non linear processes in determining the detailed effects of topography on baroclinic flows. It has been shown that while some of the processes, such as the structure of the forced stationary component of the flow in baroclinically stable flows may be explained using linear models, in the presence of baroclinic waves non linear effects are important. The effects of topography in the thermally driven flows are generally stabilising but there is some evidence that large amplitude topography may be destabilising. It is also clear from the experiments that forcing by stationary topography may give rise to drifting wave components whose major energy sources are non linear interactions.

Present studies are concerned with improving knowledge of the non linear processes in the continuously stratified system and accurate determination of the effects of topography on the radial heat transport by baroclinic waves. The predictability of the flows in the presence of topography will also be compared with that in the absence of topography.

It would be of interest to compare some of these findings with the predictions of numerical models used for weather prediction. In particular the simulations of non linear processes are sensitive to errors in phase speeds of the interacting waves and it would be of interest to test these aspects of integrations against atmospheric observations. The effects of topography in stabilising flows for small amplitude topography and destabilising then when the topographic amplitude is large are also factors which should be reproduced by the numerical models.

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Rotation rate Ω ($\mathrm{rad\ s^{-1}}$)	with no topography	Dominant azimuthal wavenumber with rectangular topography (a)	(b)	(c)	(d)
0.25	0	0	0	0	0
0.50	0	0	0	0	0
0.75	0	0	0	0	0
0.80	1	0	0	2	0
0.90	2	0	0	2	0
1.0	2	1	0	3	0
1.1		2	3		0
1.2		3			3
1.5	3	3	4	3	3
2.0	3	3	4	4	4
2.5	3	4	4	4	4
3.0	3	4	4	3	4
4.0	3	4	4	4	4
5.0	4	4	4	4	4

Table 1 (a)

Variation with rotation rate of the azimuthal wavenumber of the dominant baroclinic wave showing the effects of topography in the thermally driven system (after Leach, 1975). The experimental parameters were; working fluid, water-glycerol mixture; inner and outer cylinder radii, 38 and 84 mm; fluid depth, 120mm; ΔT, 12 K. The topography consisted of rectangular ridges with the ratios of height/ fluid depth and length/ mean circumference of chamber of; (a) 0.08, 0.03; (b) 0.17, 0.03; (c) 0.33, 0.03; (d) 0.08, 0.08.

Rotation rate Ω (rad s^{-1})		Dominant azimuthal wavenumber
	with no topography	with topography
0.2	0	0
0.3	4	0
0.4	4 (5)	0
0.5	5	7 (6)
0.6	5 (6,7)	
0.7	6 (5,7)	8 (7)
0.8	6 (5,7)	8 (9)
0.9	6 (5,7)	
1.0	6 (5,7)	9
1.2	6 (7)	
1.4	6 (7)	9 (8)
1.6	7 (6,8)	
1.8	7 (6,8)	
2.0	7 (8)	

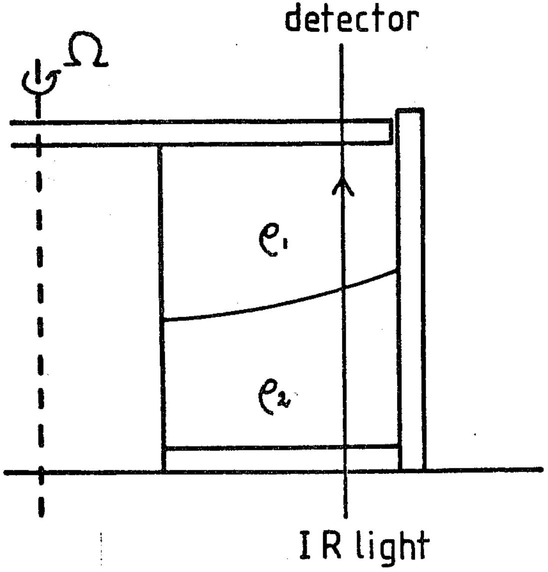
Table 1 (b)

Variation with rotation rate of the azimuthal wavenumber of the dominant baroclinic wave showing the effects of topography in the thermally driven system. Figures in brackets indicate waves which have been observed to dominate but with lower amplitude. The experimental parameters were; working fluid, paraffin; inner and outer cylinder radii, 251 and 384 mm; fluid depth 250 mm; Δ T was constant for each experiment and in the range 3.0 ± 0.3 K. The topography was dominated by azimuthal wavenumber 5 and was of amplitude 0.1 of the fluid depth.

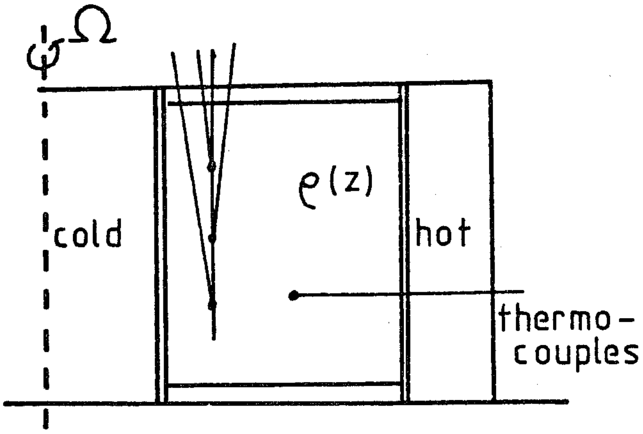
Azimuthal Wavenumber	Mean Amplitude (k)	Frequency x 1000 (s^{-1})
1	0.008	
2	0.011	1.6
3	0.014	5.8
4	0.007	3.0 ±0.3
5	0.007	3.0 ±0.3
6	0.015	4.2
7	0.032	5.0
8	0.086	5.8
9	0.024	6.7
10	0.016	7.5
11	0.008	10.6 ±0.3
12	0.006	7.8 ±0.3
13	0.012	5.8
14	0.005	8.3 ±0.6
15	0.003	9.4 ±0.6
16	0.005	11.0 ±0.6
17	0.003	

Table 2

Time averaged amplitudes and frequencies of the drifting wave components in a thermally driven flow. The dominant baroclinic wave has wave number 8 and the topographic forcing is at wavenumber 5. The non linear forcing of wavenumbers 3 and 13 is apparent. (Experimental parameters; working fluid, paraffin; radii of inner and outer walls, 231 and 384 mm; mean depth of fluid 250 mm; ΔT =3.0°C; Ω =0.74 rad s^{-1}; topographic height, 25 mm)



Two layer system (mechanically driven)



Continuously stratified system (thermally driven)

Figure 1. Schematic vertical cross section through the two laboratory systems used for studies of topographic effects on baroclinic fluids. In both cases topography was attached to the bottom surface. Above: the two layer system in which a shear is maintained by mechanical forcing across the interface between the two liquids of densities ρ_1 and ρ_2 $(\rho_1 < \rho_2)$. Below: the continuously stratified system in which a vertical shear and temperature gradient arise from the horizontal temperature gradient. In the two layer system, waves on the interface are measured by an infra-red absorbtion technique; in the continuous system waves are detected using thermocouple probes.

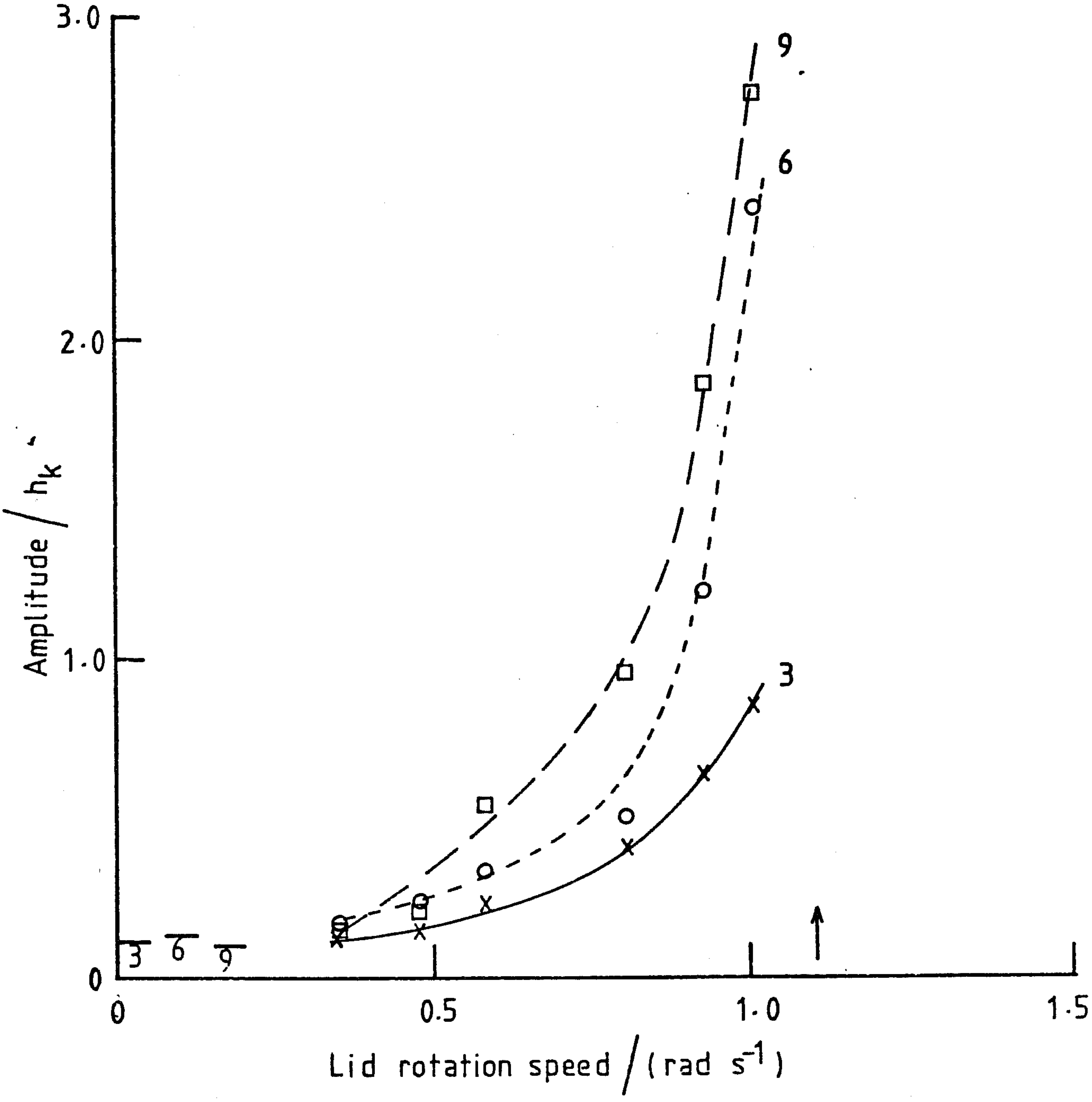


Figure 2. Variation of the amplitude of three azimuthal components of the standing wave observed in the two layer system with lid rotation speed. The amplitudes are normalised with the amplitude of the same Fourier component of the topographic height. Amplitudes calculated using linear theory are shown at the left of the diagram while the arrow indicates the resonance of the wavenumber 9 interfacial gravity wave. The topographic forcing was of dominant wavenumber 3 and the flow was baroclinically stable. Experimental parameters; $\Omega = 3.26$ rad s^{-1}, $\Delta\rho/\bar{\rho} = 0.013$, annular gap width, L=57 mm, mean layer depth, H=125 mm. (after King, 1979).

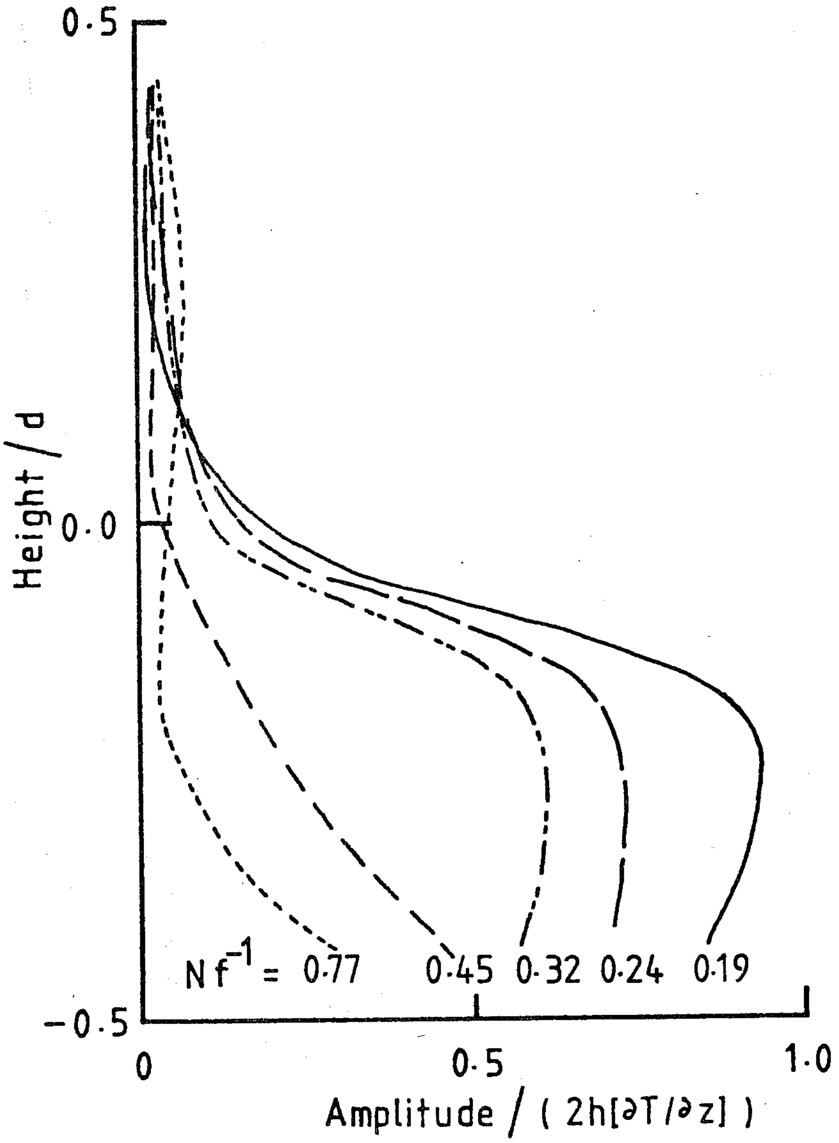


Figure 3. Variation with height of the amplitude of the standing wave component with azimuthal wavenumber 3 in the continuously stratified system for different values of the parameter Nf^{-1}. The amplitudes are normalised with the vertical temperature difference over the topographic height. The topographic forcing was of of dominant azimuthal wavenumber 3 and radial wavenumber 1 and the flow was baroclinically stable.
Experimemtal parameters; annular gap width, L=46 mm, fluid depth, d=3.44 L, topographic amplitude= 0.034 d. (after Leach, 1975).

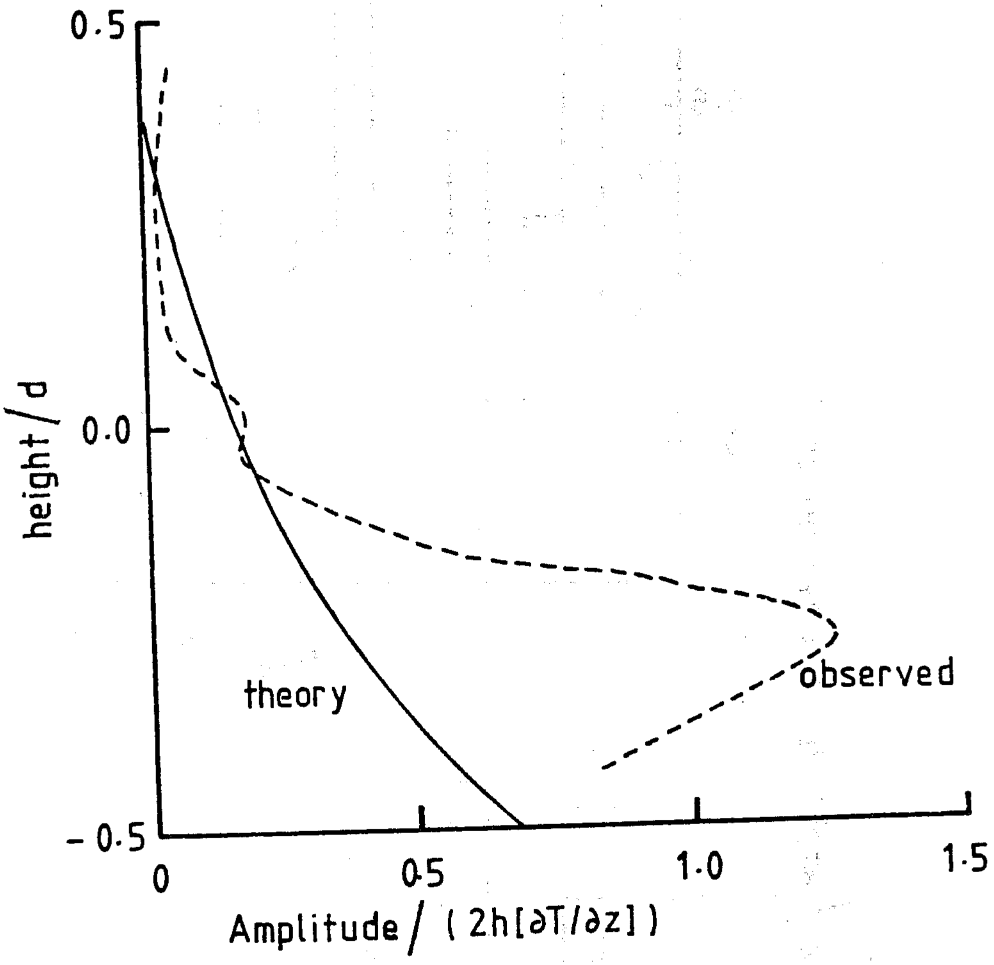


Figure 4. Variation with height of the amplitude of the standing wave calculated using linear theory compared with the observed variation. Results were obtained for Nf^{-1}=0.19. Other experimental parameters were similar to those of figure 3. (after Leach, 1975).

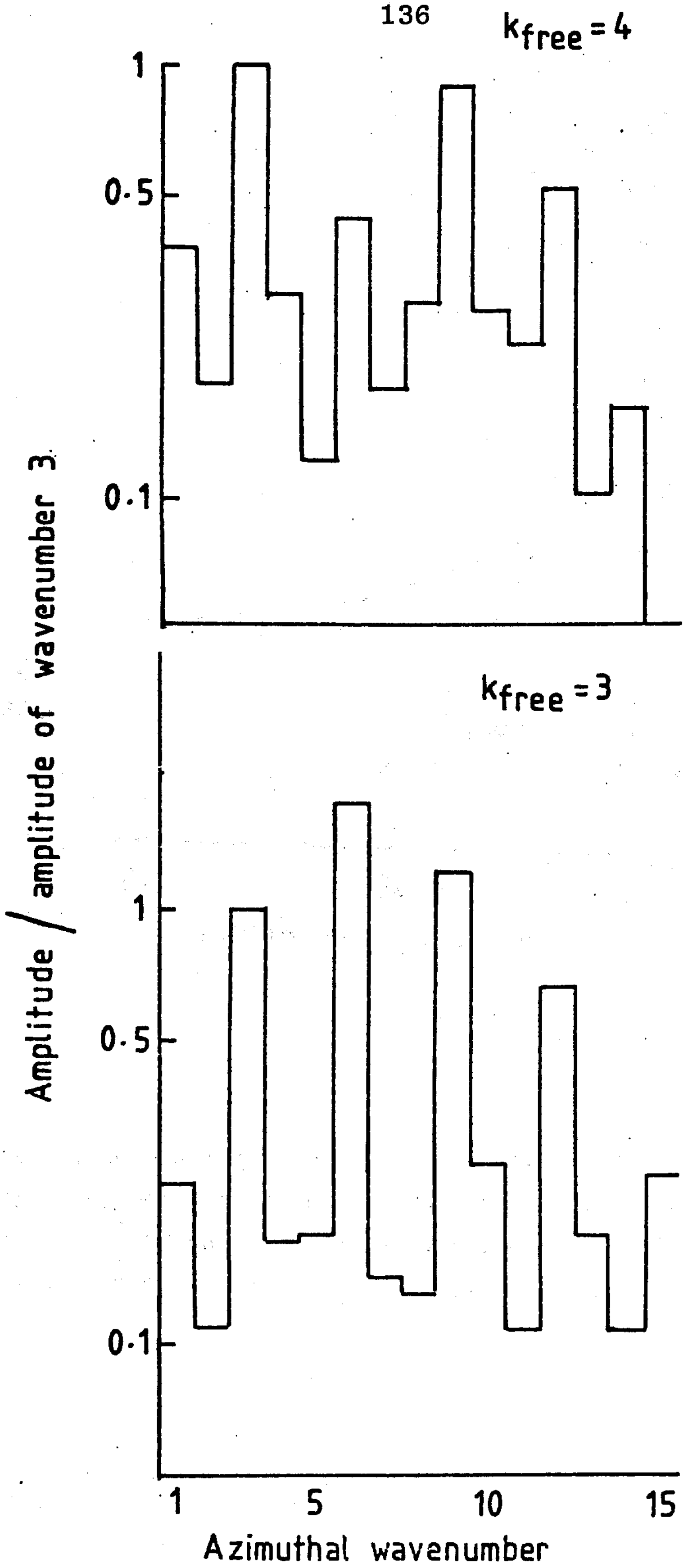


Figure 5. Spectra of the standing waves measured in baroclinically unstable flows in the two layer system. The amplitudes are normalised with the amplitude of wavenumber 3. Azimuthal wavenumbers of the free waves are: above, 4; below, 3. In both cases the topographic forcing has dominant azimuthal wavenumber 3. Geometrical parameters are similar to those of figure 2. (after King, 1979).

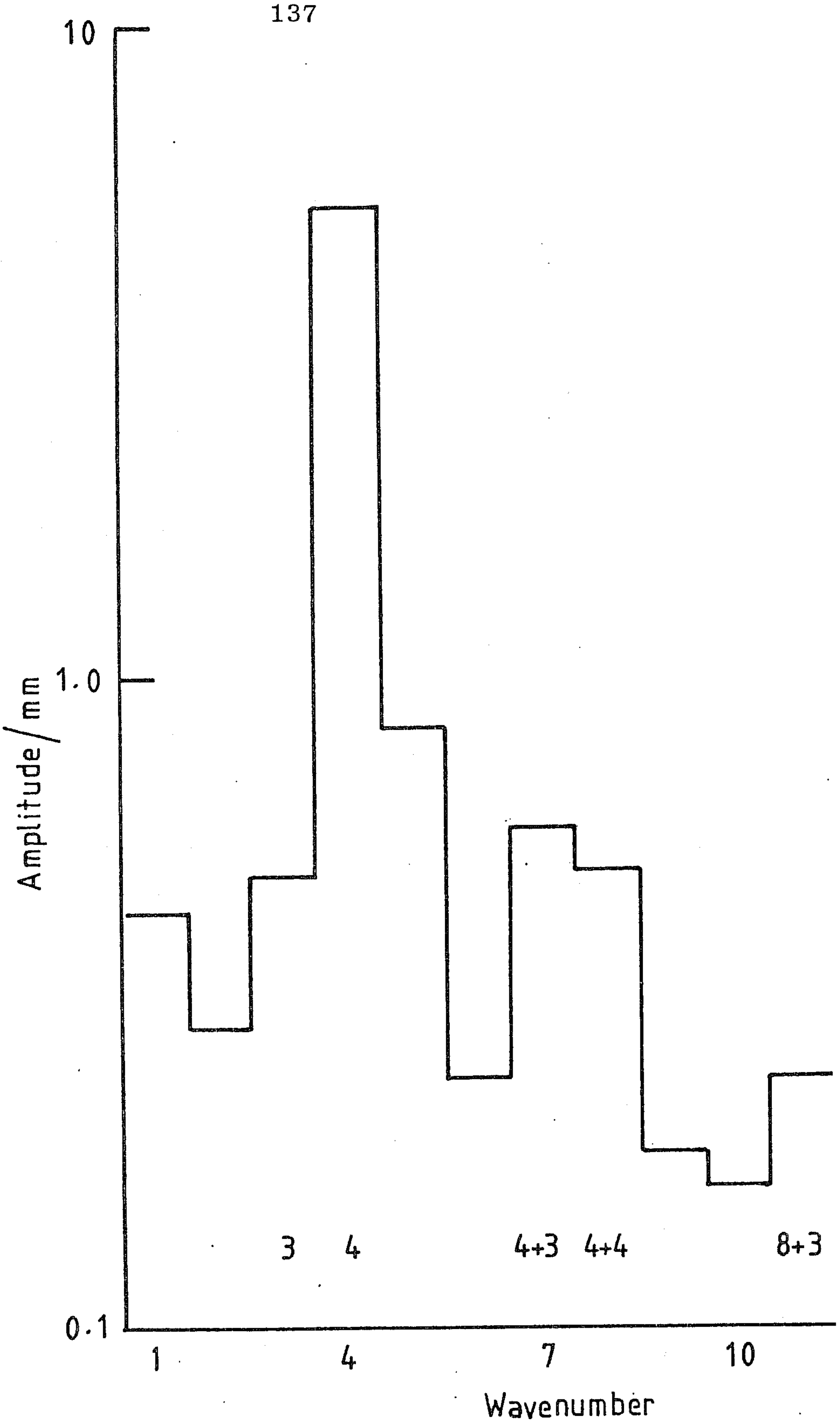


Figure 6. Spectra of the drifting waves measured in a baroclinically unstable flow in the two layer system. The dominant baroclinic wave has azimuthal wavenumber 4 and the topographic forcing is at wavenumber 3. The large amplitudes in the non linearly forced components are evident. For geometrical parameters see figure 2. (after King, 1979).

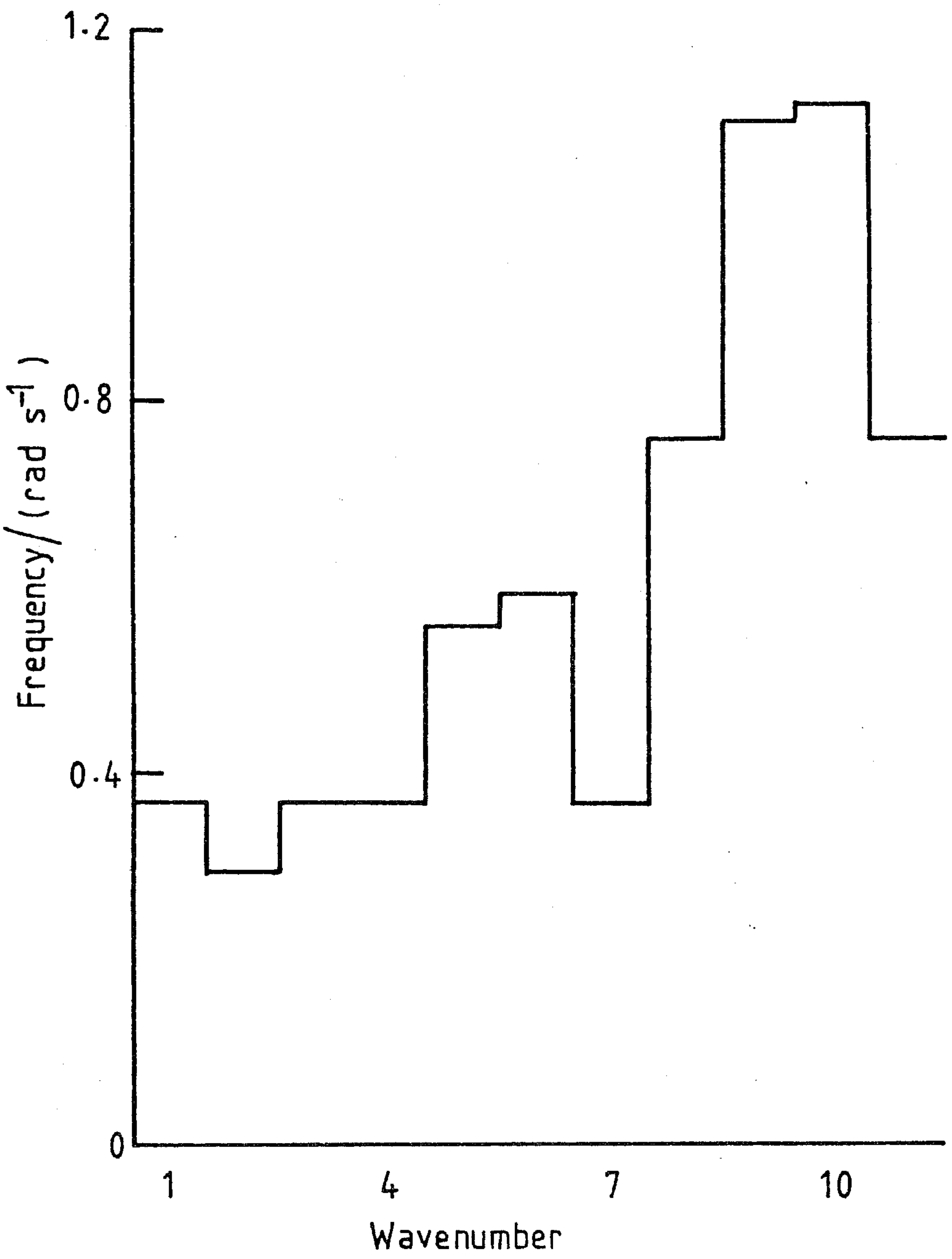


Figure 7. Frequencies of the drifting waves measured in the same experiment as that from which figure 6 was obtained showing the equal frequencies of wavenumbers 1,4 and 7 and also of wavenumbers 8 and 11. (after King, 1979).