75 + 25 = 99±1, or Some of What we Still Don't Know: Wave Groups and Boundary Processes

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Abstract. The intermittent generation of internal waves at ocean boundaries, the air-sea interface or benthic topography, leads to the formation of packets or *groups* of internal waves which, in the deep ocean, are then prevalent in the vicinity of the generation sites, if not throughout the water column. A consequence is that wave breaking, either of the groups themselves or that induced by their presence as they travel through the background wave field, has structure and periodicity depending on the properties of the wave groups. Wave breaking in downward travelling groups of frequency $2^{½} f/[1+(f/N)^2]^{½}$ may lead to the generation of waves of the same period, but travelling upwards. The reflection and dissipation of internal waves at topography leads to a variety of processes. Amongst these is the generation of alongslope currents which, because of the sporadic temporal and spatial momentum transfer produced by the breaking of the incident waves, results in regions of convergence in the benthic boundary layer, flow ejection from the boundary layer, and possibly the formation of vortical modes communicating into the ocean interior.

1. Prologue

It is probably a mistake to look back at one's past papers or to add up the years. Time is rarely kind. The ideas in the papers are often naive, plain wrong or, to be milder, misguided, and sums are prone to be incorrect too! Whilst the former may not be too great a fault provided that the work eventually had the result of stimulating a quest for further knowledge, the arithmetic may, at least, be a cause of uncertainty and confusion; after all, the paper in question (*Thorpe*, 1975) was actually given at an AGU meeting 1974, not 1975, and the present document is being prepared in 1998, not 1999, the year of the present Aha Huliko'a Winter Workshop.

The work referred to above and written *about* a quarter of a century ago, is a review of what was I thought was then known of the excitation, dissipation, and interaction of internal waves in the deep ocean. Garrett said that it would have been enough if I had just presented the cartoon (*Thorpe*, 1975, fig.5) showing the processes affecting internal waves. As usual, Chris was quite right; this is the only part of my paper which others have found worthy of recall and criticism (e.g., *LeBlond and Mysak*, 1980, use it as figure 53.6 in their text book but they make the fish, my obviously ambiguous symbol of the ocean, generate internal waves! Perhaps it is their proxy for what was once described as a 'cigar-shaped body'? Walter Munk complains that although there is a Sun, there is no Moon and the tides are consequently under-represented.)

One element which seems to be right about the cartoon is that it implicitly suggests that internal waves are intermittent in space and time. Their breaking and association with mixing is explicit, although here still lies the uncertainty of how waves break. What is most obviously missing is the importance of processes at sloping ocean boundaries. (Lee wave generation by flow over topography *is* represented, but nothing more.) This is a serious omission in view of recent observations of high dissipation and mixing near rough topography (*Polzin et al*., 1997; *Toole et al*., 1997). In a belated attempt to correct matters, Figure 1 shows some of the wave-related processes now recognised as occurring on slopes.

Moving from the top left to right these are (i) lee wave generation by flow over topography (e.g., *Bell*, 1975; *Thorpe*, 1996), (ii) wave generation by oscillatory flow, particularly those of tidal period at or near the shelf break or where the slope and stratification lead to critical conditions (e.g., *Baines*, 1974, 1982; *New*, 1988), (iii) resonant interaction between incident and reflected waves (Thorpe, 1987, 1997), (iv) wave breaking when the incident wave is at or near critical (e.g., *Eriksen*, 1982, 1985, 1998; *Ivey and Nokes*, 1989; *Taylo*r, 1993). The second row, left to right shows (v) wave steepening and the formation of fronts on reflection (e.g., *Thorpe*, 1992, 1999a; *Slinn and Riley*, 1998), (vi) the generation of upslope Eulerian flows, V_E , and along-slope Lagrangian flows, U_L , as waves reflect (*Thorpe*, 1987, 1997, 1999b), and (vii) mixing produced by reflecting subcritical waves when the first harmonic is near critical (*Thorpe*, 1999a). The final illustration, bottom left, represents along-slope Eulerian flows, U_E , generated by waves which break and loose

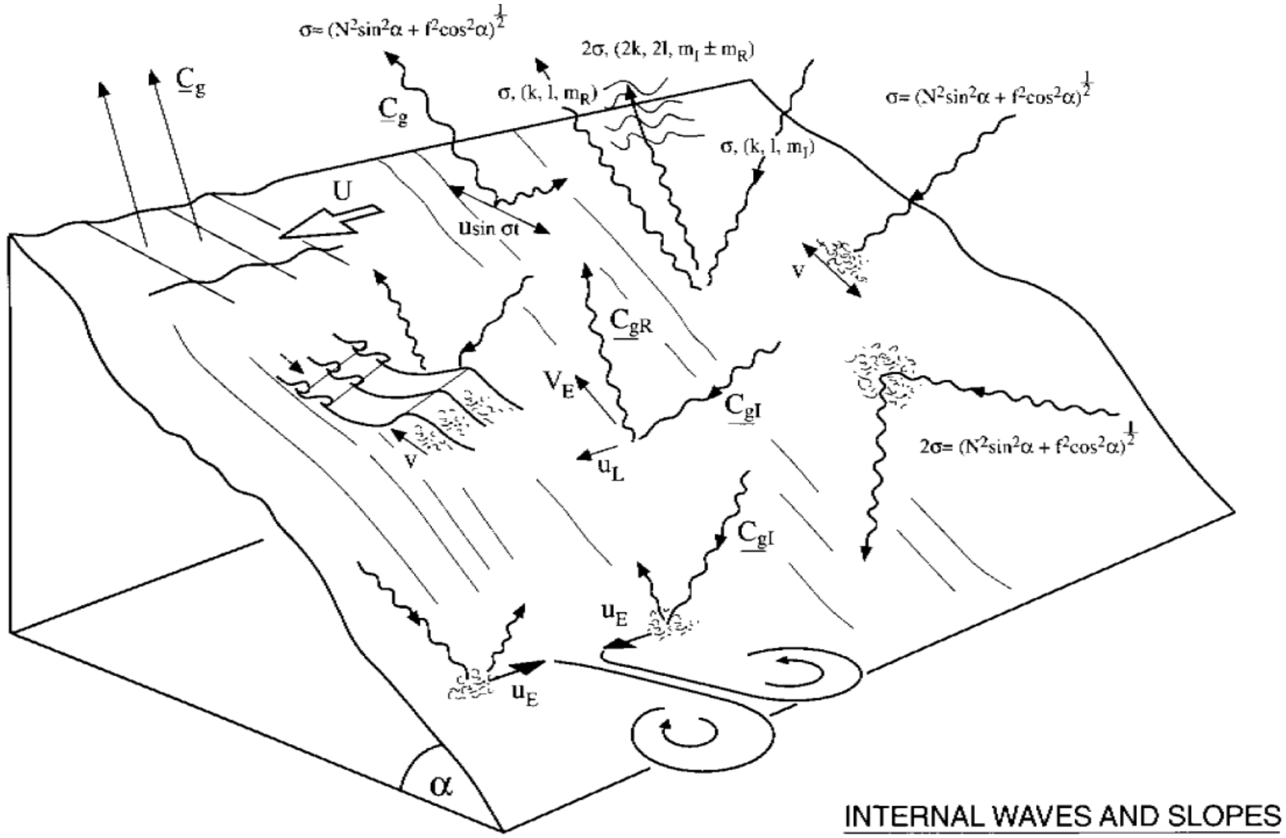

Figure 1 Physical processes involving the interaction of internal waves on sloping topography.

momentum at the boundary (*Dunkerton et al.*, 1998; *Thorpe*, 1999c; *Slinn*, 1999). Since the wave field is irregular and intermittent, waves will approach the boundary from different directions and break sporadically, leading to convergence at the boundary and the ejection of mixed fluid, and possibly the formation of vortical modes (*Müller et al.*, 1986) as illustrated. These processes are poorly known, and as the dates of references imply, are a subject of current research.

My 1975 review began by saying that we have very little knowledge about which physical processes are most important in controlling internal gravity waves in the deep ocean. It remarks that "The complexity of three-dimensional propagation in a medium which is itself moving in the mean at speeds" which vary in the vertical by amounts "which are comparable to the speed of the waves, the uncertainty of the processes which dominate generation and dissipation, and the changes which the waves themselves make to the mean density structure of the medium—all these contrive to make this problem far more difficult than that of surface waves." (I was even then seeking to learn about internal waves by thinking of the properties and characteristics of their surface equivalents, and I shall follow this methodology in the section which follows.) Peter Müller's generous invitation to this workshop refers to modeling, "... to what extent we understand and are able to model the observed internal wave field." I don't know about modeling but am interested in "the internal wave field" and its appropriate representation, particularly near generation sites. This is related to the question "How does diapycnal mixing occur in the ocean?" Representing mixing in models in an appropriate way, one which is responsive to physical, temporal and spatial variation (and possibly also to the nature of the quantity being transferred by the mixing) does seem to be important.

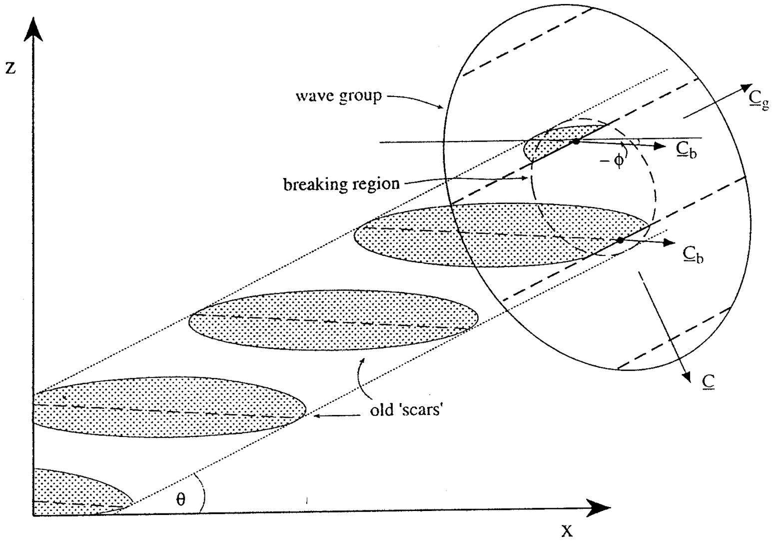

Figure 2 A wave group, the dashed constant phase lines within the solid-line contour, propagating with velocity c_g, at an angle θ to the horizontal *x* axis. The wave phase advances in direction *c*. Waves break (where constant phase lines are solid) within the breaking region moving with the group, producing scars (stippled). Breaking regions advance in direction c_b, inclined to the

2. Internal wave groups and turbulent patches

It is evident to anyone who watches surface gravity waves breaking in deep water that often breaking is repeated after a short interval of time in almost the same location, but slightly ahead (in the direction of wave propagation) of the first breaker. The explanation of this was given by *Donelan et al.* (1973); it is because of the tendency for waves to travel in groups. The group velocity is in the same direction as the phase speed, but is only half its size, and in consequence waves advance through a wave group at a speed which, in relation to the group, is half their phase speed. The time required for a wave to reach the location within its group at which its predecessor, one wavelength ahead, began to break, is therefore twice the wave period. This is the time interval between breaking or, by just the same argument, the time interval between waves reaching a position in a wave group where the wave properties (e.g., wave height or the currents they produce) may reach some particular, or "critical," value; it is the period between "extreme events." The locations at which breaking first occurs as waves break are separated by one wavelength (the first wave breaks one wavelength ahead of the second wave which then travels forward two wavelengths in the two wave periods before it begins to break). It may be that the way in which the wind forces the waves has something to do with the development of wave groups and their breaking, rather than an instability of a periodic wave train in which the wind plays no part, but there is (surprisingly) no theory of wave generation which takes due regards of the presence, shape, and properties of wave groups. Particularly large waves are, however, known to develop when the wind speed happens to be in the same direction and to correspond roughly to the group speed of pre-existing swell (e.g., winds in m/s of about $0.78T$, where T is the swell period in s), conditions in which energy can be fed continuously into the wave field from the wind. Rather little is known of the lifetime of wave groups, but it is possible that groups have properties which make them more robust than are waves in a uniform wave train--which are subject to instability (e.g., the Benjamin-Feir instability, *Benjamin*, 1967).

As we have seen, the presence of wave groups on the sea surface impresses particular properties on the location and periodicity of breakers. If breaking continues for more than one wave period, regions in which the waves have broken, producing patches of turbulence and the clouds of bubbles, will overlap in *space*; the breakers will produce an extended area of turbulent water at the sea surface, although within the area the intensity of turbulence will vary according to the variation of the rate of energy dissipation during the course of wave breaking.

There will however be gaps in *time* between successive breakers unless the duration of breaking, τ, exceeds 2T, the interval between the onset of breaking in successive waves. The detection by photography of breaking in a wave group or as groups pass fixed measurement points therefore depends on the ratio, τ/T. (In practise, the duration of wave breaking is generally less than T, and bubble clouds from successive breakers are separate in both time and space; e.g., see *Thorpe and Hall*, 1983). Breaking, once initiated in a surface gravity wave, may spread laterally along its crest, but the main direction of advance is in the direction of the phase and group velocity, which of course are the same.

A natural question to ask is whether internal waves may also have group-like structure which dictates the properties of their breaking. There is plentiful evidence that groups of internal waves exist, at least at near-inertial frequencies where the waves are most energetic and, perhaps because the signal is strongest, groups are often evident (e.g., see *Leaman and Sanford*, 1975; *Pinkel*, 1983). Spring-neap modulations in internal tidal waves found at a distance from the wave source may also imply a group-like structure. Recent careful analysis by *Alford and Pinkel* (1999) demonstrates the existence of groups of relatively high frequency internal waves and associated instability or wave breaking. The intermittent nature of wave forcing at the surface or by topography points to the generation of wave packets rather than 'uniform trains'. Indeed the known instability of wave trains (e.g., *Borisenko et al*., 1976; *Thorpe*, 1977) dictates that waves will not be regular. Can more be inferred about the nature or distribution of turbulent regions produced by internal waves breaking in groups from what is known of surface wave breaking?

For internal waves in the deep near-uniformly stratified ocean, the phase, c, and group, c_g, velocities are at right angles. The time interval between 'breaking' in wave groups (or between the reoccurrence of extreme events, which for internal waves may be large amplitude, large amplitude, large current shear, high strain, low Richardson number, high wave steepness, etc.) is the wave period (Thorpe, 1988). The direction in which the "breaking" developes (the direction in which the centre of a patch advances) is given by $c_b = c_g + c$ (Fig. 2). If θ is the inclination of the group velocity vector to the norizontal, then the inclination of the breaking zone is approximately given by

$$\tan\phi = -\left(f/N\right)^2 \cot\theta \; . \qquad (1)$$

As in the case of surface waves, the properties of the patches of water, or "scars," produced by a group of breaking waves depends on the ratio of the time of duration of breaking (or how long a period of time an extreme value is exceeded), τ, and the wave period T (*Thorpe*, 1999d). The ability of different sampling methods to detect mixing is related to the extent of these patches, whether there are gaps left between them in the horizontal (which will affect whether they are sampled by vertical profiles) or in the vertical (for, say towed arrays). Scars will overlap in space if

$$\tau/T > \left(\tau/T\right)_c = \left(c_g/c\right)A/B \qquad (2)$$

where $(\vartheta/T)_c$ is a critical value, and A/B is the aspect ratio of the region (here assumed elliptical) within a wave group in which 'breaking' occurs, the ratio of the length parallel to the group velocity, A, divided by that in the direction of the phase vector, B. Estimates of A/B from oceanic observations are at best approximate. It appears probable however that whilst inertial waves, and internal tides generated at the shelf break, will be quite effective in producing connected scars or 'breaking' patches if the criterion for 'breaking' is exceeded somewhere in the group, since the critical value is small, internal lee waves have high critical values and are less likely to promote connected patches of, say, mixed fluid even if breaking occurs within a wave group (*Thorpe*, 199d).

The scars left by a wave group of one frequency may have the same inclination to the horizontal as the wave group vector of another wave frequency, i.e., using (1), there may exist waves which have group inclination ∃ such that $\tan\beta = -(f/N)^2 \cot\theta$. In this case the scars could be misinterpreted in observations as being group of waves of a different frequency. The relation between the apparent frequency, Φ_A, and the true frequency of the wave group producing the scars is found using the dispersion relation $\sigma^2 = N^2\sin^2\theta + f^2\cos^2\theta$, and is

$$\sigma_A^2 = \left[\sigma^2\left(f/N\right)^2\right] / \left\{\sigma^2\left[1+\left(f/N\right)^2\right] - f^2\right\} \qquad (3)$$

This is sketched in Figure 3. Generally the wave periods of the apparent and 'true' wave groups will not be the same. Only when $\sigma_A = \sigma = 2^{1/2} f/[1+(f/N)^2]^{1/2}$ will the *periods* match, and the scars are forced, as in resonance, at a frequency which corresponds to a wave with inclination β. In these circumstances it appears possible that if, for example, the wave group is promoting regions of, say, shear in which smaller waves become critical and break, transferring their momentum to the mean flow, then conditions are favourable for energy transfer into a packet with the same frequency as the initial group, but travelling in the opposite vertical sense.

To first order, a wave group reflecting from an inclined plane will retain its frequency and hence the inclination of its group velocity inclination to the horizontal, θ. The ratio, (c_g/c), is a function only of θ, and is therefore conserved. During interaction with the wall, waves will be produced in the reflected group for the same length of time as the incident waves arrive; it follows that the reflected length corresponding to the region of exceedence, A, is A times the ratio of the reflected to the incident group velocities. If the number of waves is conserved in the group, the corresponding length in the direction of the reflected phase vector will be B times the ratio of the reflected to incident wavelengths, or since the period is conserved, the ratio of the reflected to incident phase speeds. The reflected aspect ratio of the group can therefore be found in terms of the incident. Since c_g/c is a function only of θ, it follows that the aspect ratio of the region within the wave in which a particular value is exceeded (i.e., A/B) is unchanged on reflection and so is $(\tau/T)_c$ (see 2). Because wavelength and shear change on reflection (*Eriksen*, 1985), the area of the reflected wave group in which 'breaking' may occur may be increased, as too may be its duration, and the likelihood of the reflected wave group producing overlapping scars will be enhanced.

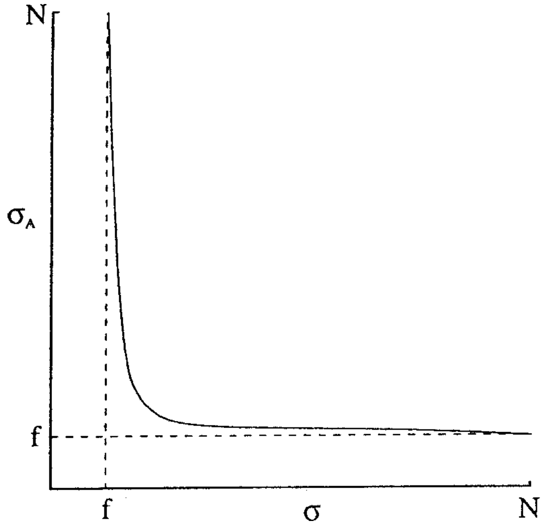

Figure 3 Sketch of the graph Φ vs. Φ_A. N is the buoyancy frequency and f the Coriolis frequency.

3. Discussion

a. The persistence and survival of wave groups

Internal wave groups or packets are generated by intermittent generation. It is not known whether there are circumstances in which internal wave groups are robust against disintegration through wave interactions. We know little about groups because the usual methods of data analysis or measurement are not tuned to reveal their existence. (Would the relations of wave breaking to surface wave groups be known yet if only wave data were available, and not visual images?) The process of continual forcing of waves, or possibly wave groups, which can occur in surface waves driven by wind, may have no equivalent for internal waves. These are usually physically separated from the sources of energy which lead to their generation. Internal wave groups may therefore have a relatively more transient existence and be more susceptible to decay or disintegration by non-linear wave interactions (and at second rather than third order!) than are surface wave groups. Their presence and consequent effect may be most pronounced near generation sites, e.g., close to topography, where groups of lee waves may be formed. It may not however be necessary for wave groups to loose energy in producing a breaking region; they may simply promote conditions of shear or stratification in which other, perhaps smaller, waves may break (e.g., *Thorpe*, 1989). There is also the possibility that such interactions may *reinforce* wave groups, either by resonance or through the injection of momentum at appropriate phase in the waves forming the group by the breaking of smaller waves, and so sustain the groups as they propagate through the ocean.

b. Models and wave breaking

Perhaps for modeling ocean circulation it doesn't matter very much whether or not internal waves break in groups, but it may if, for example, the goal of prediction is to forecast the mean distribution of active mixing regions, the recurrence of extreme events which are caused by internal waves, or even the probability of their detection by different sampling strategies. It seems quite possible that existing models of non-linear interactions do not account properly for waves with a group-like structure. Calculations of resonant interaction are sensitive to dissipation, the strength of interactions becoming uncertain when dissipation occurs; breaking and dissipation are still poorly understood and weakly constrained by observations. The conditions in which internal waves break is an area of great uncertainty. Even in the case of a simple uniform wavetrain travelling though a uniformly stratified ocean, let alone the case of time-dependent waves in a wave group, knowledge is imperfect. The pendulum of understanding about instability has swung from favouring convective overturn (*Orlanski and Bryan*, 1969), to shear (Kelvin-Helmholtz) instability (*Garrett and Munk*, 1972), to parametric instability (*McEwan and Robinson*, 1975), and now towards possibly all three depending on the relative wave, buoyancy and inertial frequencies (*Lombard and Riley*, 1996; *Thorpe*, 1999e). The development of instability and its transition to turbulence are even more poorly known although advances via numerical methods, directed primarily towards understanding of wave breaking in the atmosphere, have provided considerable insight into the processes following the onset of convective instability (e.g., see *Fritts et al*., 1996). Questions of how turbulent *regions* are produced by breaking waves cannot be separated from that of how instability occurs in individual internal waves, or, for example, whether *collective* instability spanning several waves is possible. If however the dynamics of the ocean interior at the scale of internal waves is dominated by wave groups, then it follows that turbulence at smaller scales, those at which breaking and diapycnal diffusion occur, is controlled by the wave groups, occurs in association with them and has an intensity which is related to wave groups parameters.

c. Boundary generation

There is certainly a need to discover more about the processes near boundaries. What is most needed are observations capable of resolving the temporal and spatial structure of currents and density variations (i.e., the internal wave field, including its directional and dissipative properties) near a sloping boundary. A pre-requisite is that the bathymetry is known, at least to a scale at which internal waves may be generated. Polzin and colleagues at WHOI and elsewhere have undertaken an observational study in a region off the U.S. eastern seaboard to begin addressing these requirements. The cartoon in Fig.1 illustrates some of the internal wave-related phenomena at sloping boundaries (but not groups!), including the possible ejection of fluid in regions where convergence occurs on isopycnal surfaces, akin to rip currents in the surf zone. This provides a presently unquantified means of connection between the boundary layer and the interior, a mechanism whereby the boundary processes can influence the interior, perhaps via the generation of vortical modes.

4. Epilogue

Discussion at the workshop included the suggestion that the internal wave field in the ocean is similar to that of the light field in a cloud where multiple scattering results in an almost isotropic directional field of light, even though the primary external source is highly directional, coming from the Sun. This received some opposition, since the internal wave generation sources are intermittent whilst the Sun shines continuously. Briscoe remembered that the IWEX data showed evidence that packets of waves could sometimes be observed propagating from one sensor to another through the array over distances of about 1 km. Where wave packets (or groups) are best observed is near the source of the two prominent narrow band frequency oscillations, diurnal tides and inertial waves. The propagation distance of wave packets of different frequency and mode number appears to be still uncertain. Whether 'groups' can retain form within an ambient wave field and against its interaction appears still uncertain, but sufficiently close to generation sites (i.e., for waves of low frequency, at least within about 1 km of the ocean surface and regions of rough benthic topography) it is known that wave packets can survive. It is in this zone that mixing (large ε and *Kv*) is greatest. Here the internal wave field appears akin to a light field in which flashes (possibly of different colour) come intermittently from nearby generation zones. It is likely that, in the deep ocean, there is often a blue pulsation due to tidal generation, although this may be tinged with lighter and redder hues which correspond to topographic structure, the short, high frequency, lee waves generated by tidal flow over the small-scale topography. We need to know more about mode structure in these near-generation regions, for which there is no obvious light analogue, as well as frequency. A central question for observations and models is "Is the ocean full of internal waves or internal wave groups?"

The only certain conclusion is that those of you still here in 25 years time will then be able to recall how wrong people were 25 years ago, and how little they knew which was of use to help solve the then-important problems. You will however probably understand better what should really be known, but isn't yet.

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