
Turbulence and wave dynamics across gas–liquid interfaces

Julian Hunt¹, Stephen Belcher², Derek Stretch³, Shahrdad Sajjadi⁴
and John Clegg⁵

¹ *Department of Earth Sciences, UCL, Gower Street, London, WC1E 6BT, UK,
E-mail: jcrh@cpom.ucl.ac.uk*

² *Department of Meteorology, University of Reading, PO Box 243, Earley Gate, Reading,
RG6 6B, UK, E-mail: s.e.belcher@reading.ac.uk*

³ *School of Civil Engineering, Surveying and Construction, University of Kwazulu-Natal,
Westville Campus, Kwazulu-Natal, South Africa, E-mail: stretchd@ukzn.ac.za*

⁴ *Dept. Mathematics, Embry-Riddle Aeronautical University, Daytona Beach,
FL32114-3900, USA, E-mail: sajja8b5@erau.edu*

⁵ *Atlas Elektronik UK Ltd., Dorset Green Technology Park, Winfrith Newburgh, Dorchester,
DT2 8XJ, UK, E-mail: john.clegg@uk.atlas-elektronik.com*

Abstract. Mechanisms are reviewed here for the distortion of turbulent flows near thin density interfaces and their effects on transfer processes across them. Firstly the results of rapid distortion calculations show how the inhomogeneous eddy structure depends on whether the turbulence is generated above or below the interface, or in both regions. The flow is unstratified and the buoyancy forces are stable and strong enough relative to the inertial forces that the interface is continuous. It is shown that as the surface blocks the vertical turbulent eddy motions, horizontal straining motions are induced which affect the surface viscous layers and can then induce motions some distance from the interface on the opposite side from where the turbulence is generated. Secondly the paper reviews the physical mechanisms controlling how wind flows over monochromatic and groups of surface waves. The results of triple deck theory for turbulent shear flows, i.e. combining sheltering and unsteady critical layer mechanisms, explain why groups are the most efficient mechanism for waves to extract energy from the wind and therefore enhance transfer properties between atmosphere and water bodies. The third section of the paper reviews the mechanisms for the generation of turbulence coherent roll structures in the ocean surface layer, resulting from surface shear turbulence (normal stress variations), wave-mean shear vortex stretching and rotation, i.e. Langmuir cells, and unstable buoyancy forces (i.e. cooling at the surface) plus mean shear also via vortex rotation. Since these mechanisms are generally additive - exceptional situations exist - they are effective in transporting fluxes downwards into the ocean surface layers.

Key Words: Turbulence, air-sea interface, wind-waves, coherent structures, convection.

1. Introduction

There has been progress in understanding turbulent flows near thin density interfaces and transfer processes across them through detailed studies of the inhomogeneous eddy structure and interactions with local wave motions. These mechanisms are reviewed here along with a physical discussion about how they affect heat/mass transfer across the interface. The main emphasis in this review is on flows where the turbulence and air flow are effectively unstratified above and below the interface. Also it is assumed that the buoyancy forces are stable and strong enough relative to the inertial forces that the interface is continuous. However the surface may be undulating, with surface waves forming on the interface, and over small areas may overturn and break up into small bubbles. One of the key questions is whether there are repeatable patterns of wave groups where these mechanisms occur and have a dynamical effect on the groups.

2. Turbulent momentum transfer across a flat gas-liquid interface

The interactions between turbulence with no mean shear (*i.e.* $U = \text{constant}$) in two regions (denoted as $+$, $-$) on either side of a nearly flat horizontal interface are controlled by several mechanisms, which depend on the magnitudes of the ratios (α , β , γ) of the densities (ρ_+ , ρ_-) and kinematic viscosities (ν_+ , ν_-) of the fluids and the r.m.s. velocities of the turbulence u_{0+} , u_{0-} above and below the interface (Brutsaert and Jirka 1984). We focus on gas-liquid interfaces so that $\alpha \ll 1$, and also where turbulence is generated either above or below the interface, *i.e.* cases where γ is very large or very small. It is assumed that vertical buoyancy forces across the interface are much larger than internal forces so that where the interface is nearly flat, so that coupling between turbulence on either side of the interface is determined by viscous stresses. A formal linearized rapid-distortion analysis with viscous effects extends the previous study by Hunt and Graham (1978) (HG) of shear-free turbulence near rigid plane boundaries (Hunt, Stretch and Belcher 2010). The physical processes accounted for in our model include both the blocking effect of the interface on the normal components of the turbulence and the viscous coupling of the horizontal field across thin interfacial viscous boundary layers, whose thickness is order $L\text{Re}^{-1/2}$ where $\text{Re} (= u_{0-L}/\nu_-)$. The horizontal divergence in the perturbation velocity field in the viscous layer drives a weak inviscid irrotational velocity fluctuations outside the viscous boundary layers in a mechanism analogous to Ekman pumping. These are the essential components of Danckwert's (1951) 'surface renewal mechanism'.

As with other RDT analyses, the results are formally valid only for times that

are small compared with the Lagrangian time scales T_L and if all eddies have similar time scales they have a low Reynolds number. (a) The results show that the blocking effects are similar to those near rigid boundaries on each side of the interface, but through the action of the thin viscous layers above and below the interface, the horizontal and vertical velocity components differ from those near a rigid surface and are correlated or anti correlated respectively, (b) because of the rapid growth of the viscous layers on either side of the interface, the ratio of the r. m. s. values of the interfacial velocity fluctuations, u_i , to that of the homogeneous turbulence far from the interface, u/u_0 , does not vary with time. At the interface the horizontal straining is increased by the blocking, but as a result of viscosity decreases with time. Also the horizontal component of vorticity decreases with time with the growing viscous layer. If the turbulence is driven in the lower layer with $\alpha \ll 1$ and $\gamma \ll 1$, then $u_i/u_{0-} \sim 1$ and $R \gg 1$ (as shown previously by Calmet and Magnaudet (2003)) where $R = (1/\alpha)\sqrt{1/\beta}$. But if $Re \gg 1$, microscale eddies form with length scale $LRe^{-3/4}$ within the thicker surface layer, and are advected towards it (fig 1a).

As Bannerjee and Turney (2010) and Da Silva (2010) have shown the microscale eddies can significantly increase the scalar transport at the surface. For shear-free gas–liquid interfaces where homogenous turbulence is generated in the gas ($\gamma \ll 1$) $u_i/u_{0+} \sim 1/(1+R)$. (c) Other non-linear effects become significant over periods greater than T_L . When turbulence is generated in the liquid layer, at high enough Reynolds number gas motions in the upper viscous layer are turbulent. Because of low stress in the surface, the horizontal vorticity tends to decrease and the vertical vorticity of the eddies dominates their asymptotic structure (Tsai 1998). When shear-free turbulence is generated in the upper layer and if the Reynolds number is less than about $10^6 - 10^7$ the fluctuations in the viscous layer do not become turbulent. Non-linear processes of the interface increase the ratio of u_i/u_{0+} for sheared or shear free turbulence in the gas above its linear value (see (b)) to $\sqrt{\alpha} \sim 1/30$ for air–water interfaces. This estimate agrees with the DNS results from Lombardi *et al.* (1996). Because the linear viscous-inertial coupling mechanism is still significant; the eddy motions on either side of the interface have a similar horizontal structure, although their vertical structure differs. In this case if additional fluctuations are stimulated in the lower layer by other mechanisms, such as mean shear, convection, waves, raindrops, etc.

3. The effects of grouping on wave growth and transfer processes

When there is a significant mean flow above the interface, inertial forces become comparable with the buoyancy forces and the Froude number $F_r \sim 1$,

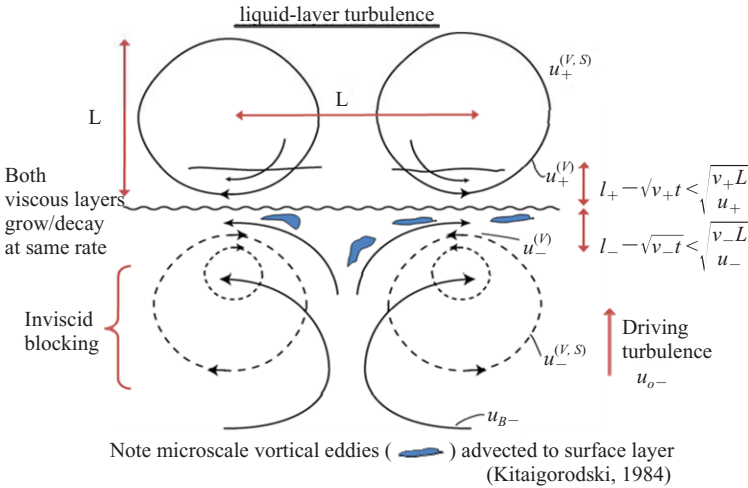


Figure 1a Blocking/coupling RDT model of turbulence across gas-liquid interface

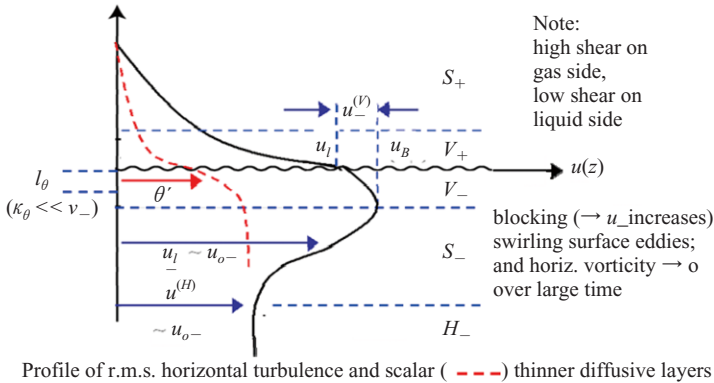
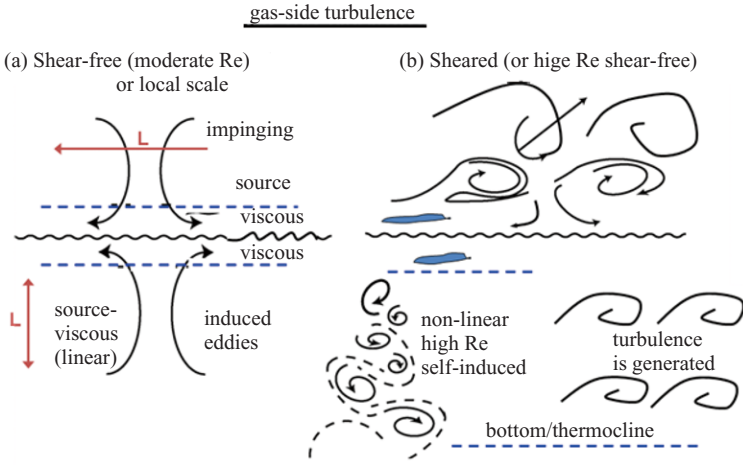


Figure 1b Typical profile of horizontal velocity as liquid-side turbulence generates turbulence in the gas side

Figure 1 Schematic diagrams of the streamlines (a) and velocity profile (b) for regime (i) where the velocity fluctuations in the lower layer drive velocity fluctuations in upper layer eddies having opposite circulation. The dashed stream-lines in (a) denote the contribution of the viscous perturbation in the lower layer.

where $F_i = u_o^2 / [g'L]$, and $g' = 2(\rho_- - \rho_+) / (\rho_+ + \rho_-)$. A number of mechanisms have been proposed for how such an air-flow over a horizontal body of liquid produces waves on its surface (Sajjadi *et al.* 1999). Most of those proposed have been linear and therefore can be applied to any spectrum of waves. But the mechanisms and models based on them are regularly applied when the surface disturbances significantly affect the gas and liquid flows, so that the mechanisms



Note that with very high Re shear-free, impinging turbulence → surface shear → influence on gas-side and liquid-side eddies

Figure 2a,b Shear-free gas-side turbulence induces large ‘slave’ eddies in liquid

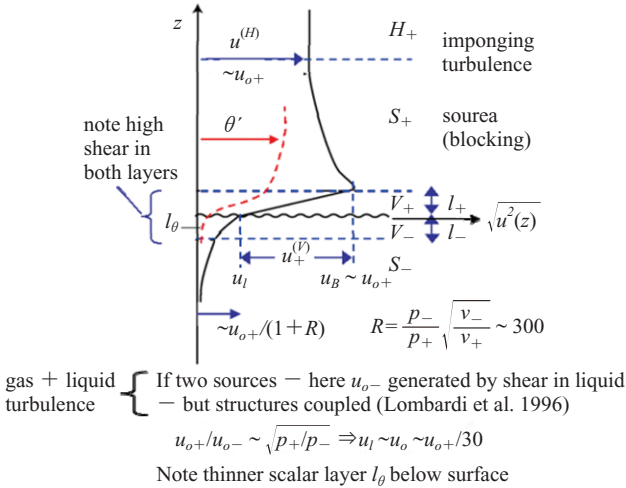


Figure 2c Vertical profile of horizontal rms fluctuation-gas side shear turbulence-moderate Re

Figure 2 Schematic diagram of the flow zones of the turbulence profiles at a gas-liquid interface showing turbulence driven by shear-free gas-side turbulence in the upper layer, regime (iii). (a) the r. m. s. horizontal component u'_i , (b) eddy structure distorted by linear processes (e.g. when a large eddy impacts), (c) eddy structure when non-linear effects become significant (e.g. shear in upper layer, and eddy diffusion in the lower layer).

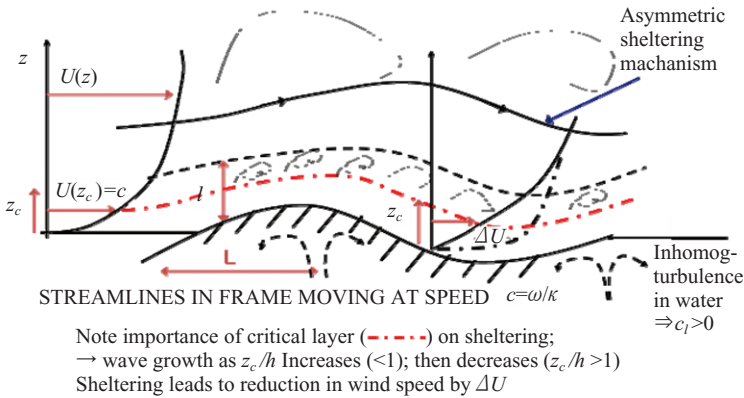


Figure 3 Schematic of wind over wave mechanisms for simple waves. Sheltering dynamical critical layers?

are non-linear, and the waves are not monochromatic. Typically the waves move in groups, which affect how the wind flows over the waves, how the waves break and thence how droplets form. This weakly non-linear interaction of mechanisms significantly influence the average momentum, heat and mass transfer associated with waves.

Very small unsteady waves are initiated by turbulence and/or growing Tollmien-Schlichting instabilities in the sheared air flow over the surface and Kelvin-Helmholtz coupled instability of the airflow over the liquid (Tsai *et al.* 2005). When steady waves are generated artificially in an airflow, *e.g.* in a wind-wave tank, the linear mechanisms for the growth of the waves are the pressure drag caused by asymmetric slowing of airflow over the downwind slopes of the waves and turbulence stresses caused by the disturbed flow, and wind-induced variations of surface roughness disturbed surface (Belcher and Hunt 1993, 1998). Both mechanisms are affected by the relative speed of the wave, c_r , to the friction velocity, u_* , of the airflow, and the disturbed flow changes at the critical height, z_c , where the wave speed, c_r , is equal to the wind speed, $U(z_c)$ (fig3).

Consider when the waves, with wavenumber k , begin to grow at a rate kc . If this is comparable with the frequency of wave passing, *i.e.* $u_* k$, then the critical layer is above the inner shear layer near the surface. Also the dynamics across the critical layer are determined by inertial forces as the flow accelerates and decelerates over the wave. But only if the wave is growing (or decaying), *i.e.* $c_t \neq 0$, is there a net force on the wave caused by critical layer dynamics (Belcher, Hunt and Cohen 1999). Their triple deck analysis agrees with that of Miles' (1957) different method of analysis for a growing wave. Hence they do not agree with his, and many subsequent authors' (*e.g.* Lighthill 1962), conclusion is that

there is a net inviscid force on monochromatic non growing waves, (*i.e.* $c_i=0$).

This conclusion of Miles' has been used to correlate data on the growth of wind-generated waves, and became the standard model for ocean forecasts, etc. (Janssen 2004). Subsequently this was contested by several authors, both on mathematical and physical grounds, (*e.g.* Mastenbrook *et al.* 1996). They showed that similar predictions for the magnitude of average wave growth correlations could be derived by the viscous/turbulence sheltering mechanism (Belcher and Hunt 1993). But this perturbation sheltering theory which assumes c_r is small, is found experimentally to be an under estimate for the force on waves when c_r is comparable with the mean wind speed. One reason is that it does not represent the dynamics of waves which grow and decrease in groups.

A conceptual model has been developed for the laminar/turbulent shear flow over steadily moving wave groups, whose significance was first pointed out by M. E. McIntyre. Weakly non-linear theory is used to analyse the disturbed air flow over the waves in groups, which shows how the air flow over the downwind part of the group is lower than over the upwind part. This asymmetry causes the critical layer height z_c to be higher and the wind shear at z_c to be weaker over the downwind part. Therefore the positive growth of the individual waves on the upwind part of the wave group exceeds the negative growth on the downwind part (which would not be true if z_c was the same over the whole group). This leads to the critical layer group (CLaG) effect producing a net horizontal force on the waves, in addition to the sheltering effect. This analysis is supported by numerical simulations (*e.g.* Touboul *et al.* 2008).

Wave shapes also affect the wave growth (*e.g.* Sajjadi *et al.* 1999). Whether (as in the photographs in Jeffreys 1925) the wave groups are capillary waves on a Cambridge duck pond or breaking rollers in the Atlantic ocean, the wave shapes as well as their height vary in a group. Since their slopes tend to increase downwind, this is likely to amplify the CLaG mechanism. By considering the dynamics of typical wave groups, it becomes possible to estimate rationally how air flow affects the non-linear interactions between waves, and compare how this relates to the wave-wave hydrodynamic interactions, that are assumed to dominate the distribution of ocean waves. Thus variations of wave shapes within a group could also affect the net wave growth, while violent erratic winds can prevent the formation of wave groups, so that wave growth may be reduced (but spray from waves is increased) as is observed near the centre of hurricanes.

At higher wave speeds, another mechanism is also significant, namely the displacement of the critical layer outside the surface shear layer (*i.e.* $c_r > u_*$) (see fig4). This acts to reduce the sheltering mechanism, by contrast with Belcher and Hunt's (1992) analysis (when $c_r < u_*$) which showed how the critical layer within the shear layer increases the sheltering mechanism (see Cohen and Belcher 1999).

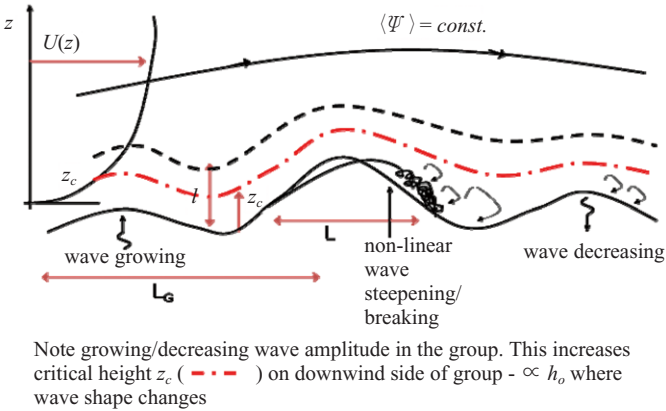


Figure 4 Wind over groups of waves \rightarrow unsteady critical layer dynamics (BHC 1999-Sajjadi)-can add to sheltering

Thus the decrease of the growth rate as c/u^* increases is compensated by the increase in growth rate as waves form into groups at higher wind speeds (which also needs to be modelled). The decrease in the local sheltering mechanism as z_c increases over the downwind part of a wave group further affects the dynamical effect of the critical layer. (We note that the existence of a critical layer over a monochromatic with a significant role on the boundary layer dynamics still does not mean that the Miles inviscid mechanism is operative (*cf.* Sullivan *et al.* 2000).)

This wave group analysis can be extended to many environmental and industrial wave-interface problems, and also for estimating mass and heat transfer, by generalizing the results of Raupach *et al.* (1992).

4. Effects of roll eddies in surface layers caused by waves and shear/buoyancy turbulence

Mean shear flows above and below gas-liquid interfaces generate turbulence with length scales of the order of that of the shear layer thicknesses h_+ , h_- . Unstable buoyancy fluxes further increase the turbulent energy (see fig5). Also as two dimensional waves moving parallel to the mean flow develop on the liquid surface, turbulence production is increased in the gas flow above the surface through displacing and stretching of the vortex lines of the turbulent eddies (Texeira and Belcher 2002, Ardhuin and Jenkins 2005). The longitudinal component of the vorticity of these gas-side eddies induced parallel to the mean flow is systematically stretched as the flow moves over and under the waves. Thence quasi-steady roll structures are generated in the down-wind direction (Belcher and Hunt 1998). These structures are observed in the air flow over rigid

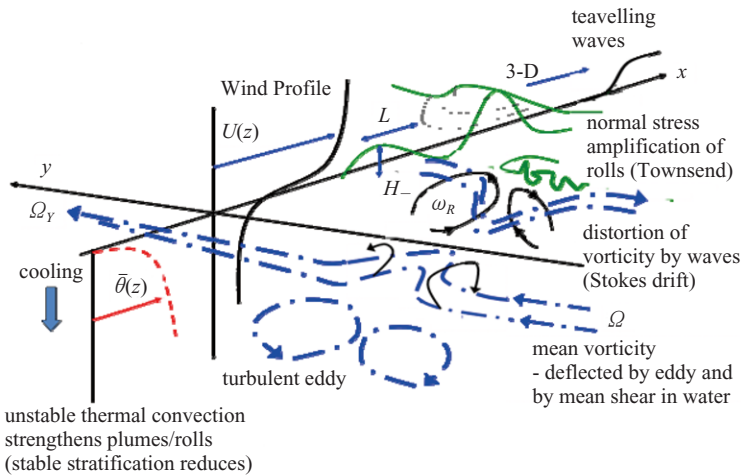


Figure 5 Effects of roll eddies in ocean surface layers-waves plus shear/buoyancy turbulence

wavy surfaces in wind tunnels (Gong *et al.* 1996) and, in the atmosphere over rough surfaces like urban areas. This low frequency, low wave number eddy motion interacts with the shear turbulence and can significantly amplify the heat transfer between the gas flow and the surface, *e.g.* by 20% in the atmosphere (Smedman *et al.* 2004).

Similar structures are also observed below liquid wavy surfaces in organised regular patterns in turbulent flows with r.m.s. velocity u_R driven by a strong gas shear flow (with friction velocity u_*) above the surface (Leibovich 1983). They can increase scalar transfer to the surface by a factor of 50-100%. These organised rolls above or below the surface are also non-linearly amplified by the presence of the turbulence. Applying the analysis of Townsend (1976), extra turbulence is generated where the motions in the rolls impinge on the resistive surface, and less where the motions leave the surface, thus producing stresses parallel to the surface which further drive the roll motions. This explains why extra turbulence ($\sim w^*$) produced by buoyancy forces (*e.g.* heated liquid layer) also amplifies the strength of rolls until $w^* > u_R$ (Li *et al.* 2005). Shorter and less coherent roll structures also form, on the length scale of surface waves, if the gas flow amplifies the surface waves sufficiently that they become three-dimensional (Komori *et al.* 1993, Eames *et al.* 2003).

Based on this overview of the main mechanisms, an ‘engineering’ unsteady simulation is being developed for the structure of roller eddies, in which the smaller scale turbulent motions and wave effects are parameterised.

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