Recent Advances in Our Understanding of Air-Sea Interaction

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SUMMARY According to a recent survey by Barnett and Kenyon (1975), it is very apparent that our present knowledge is still insufficient to construct a satisfactory theory for most phases of air-sea interaction, particularly wind-wave generation as it occurs in the ocean.   In this paper the results of very recent work will be reviewed critically.

1   INTRODUCTION

The dynamics of the air-sea interface have been the subject of much attention in recent years, especially the mechanisms involved in wind-wave generation.   The notion that an asymmetry in the air flow field with respect to the wave profile could lead to growth (or decay) of the wave through work done by the pressure forces can be traced back to Jeffreys' (1924, 1925) 'sheltering' hypothesis. He speculated that the air flow separated from the leeward side of the wave crest and reattached somewhere on the windward face of the wave crest ahead of it.   In the absence of any direct support, this hypothesis fell into disfavour largely because ill-conceived measurements over solid waves in wind tunnel experiments indicated that the pressures developed were too small for Jeffreys' mechanism to be effective.   Around the mid-1950's, the problem became actively pursued once again with several authors advancing theoretical models (see Barnett and Kenyon (1975) pp. 670, 1).   Most attention has been given to Miles' (1957), (1962) shear flow instability theories.   However, these theories have been found to underpredict ocean wave growth rates by about a factor of 10.   More seriously, the predictions of these models depend strongly on the closure form assumed for the turbulence interaction with the wave-induced motions in the air flow (Davis (1969)).

The apparent inadequacy of the earlier models led to Longuet-Higgins (1969) "maser" model in which short gravity waves were an intermediary in transferring energy from the wind to an underlying large-scale wave motion (swell).   He envisaged that the role of the wind was solely to create small-scale waves (perhaps via a Miles-type mechanism).   The mechanical interaction between the two wave systems causes compression and steepening of the short waves at the crests of the swell and a stretching in the troughs of the swell.   The tendency is then for the short waves to break predominantly near the crests of the swell and in so doing, to yield their momentum to the underlying swell.   This asymmetry in the short wave distribution would constitute a virtual shear stress in phase with the orbital velocity field of the swell and so an effective rate of working on the swell.   Soon afterwards, Hasselmann (1971) refuted this model on the grounds that an additional mass transfer term omitted by Longuet-Higgins would cancel the effect.

Very recently, interest in the two-scale notions has been revived; some fundamental matters have been resolved.   This paper will deal critically with these latest findings.

2   AIR FLOW SEPARATION

Barnett and Kenyon ((1975),p.671) comment "Jeffreys' theory may yet emerge as being important since the more recent theories (though not completely evaluated yet) based on perturbation techniques have not yielded the major growth for wind-waves.   It is still not known, though, whether or not air flow separation does in fact occur over wind-waves".

In the past, direct studies on this problem have not appeared because of the observational difficulties associated with defining the air flow structure near the surface of a travelling water wave.   However, the presence of air flow separation has been inferred from time to time in isolated laboratory wind-wave studies (e.g. Chang, Plate and Hidy (1971), Wu (1969)).   Very recently, Banner and Melville (1976) appear to have resolved this long-standing question and have demonstrated the potential dynamical importance of air-flow separation when it occurs.   They examined the viscous sublayer flows in the air and water and applied the vorticity balance equation to predict that the conditions for air flow separation (stagnation point on the boundary and vanishing shear stress in a frame in which the wave profile is steady) require the onset of wave breaking.   In a complementary laboratory wind-water tunnel study in which a train of stationary surface waves was formed by a submerged cylinder in a flowing stream, flow visualization studies were found to strongly support the theory for low windspeeds (1 m/sec) (see figures 1, 2).   At higher windspeeds (~5m/sec), pressure measurements also strongly supported the wave-breaking — air flow separation contention.   In addition they demonstrated that the drag induced by a breaking wave, with its concomitant separated air flow was 40-50 times higher than the drag over an unbroken wave.   The drag coefficient for the air flow over a broken wave was in close agreement with the drag coefficient of the sea surface (at the logarithmically extrapolated windspeed to 10 metres).

This work has the following implications:
(a) equilibrium (necessarily breaking) wind-waves induce most of the drag on the wind blowing over the sea surface; it appears that the air flow separation over breaking waves explains how wind-driven ocean currents are generated.

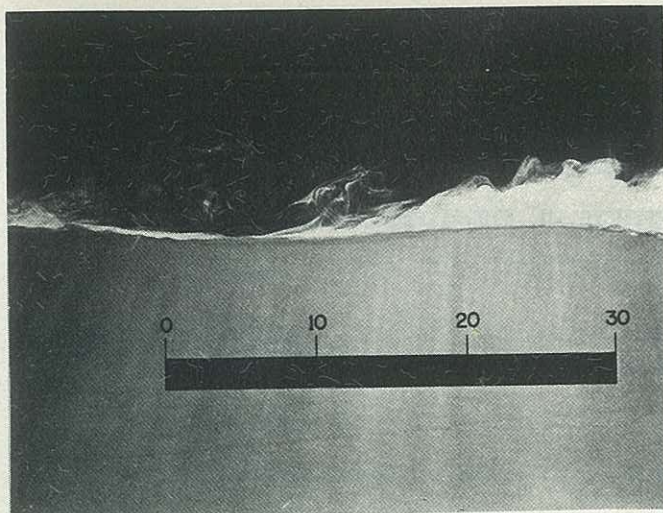(b) wind-wave generation can proceed via a revised

FIGURE 1   Smoke visualization for the air flow over an unbroken finite amplitude wave.   The super imposed scale is in cm.   The air flow is from left to right with a centreline speed of 0.9 m/s.   The water flow is from right to left at 0.75 m/s.   The smoke was introduced continuously at the far right-hand side.
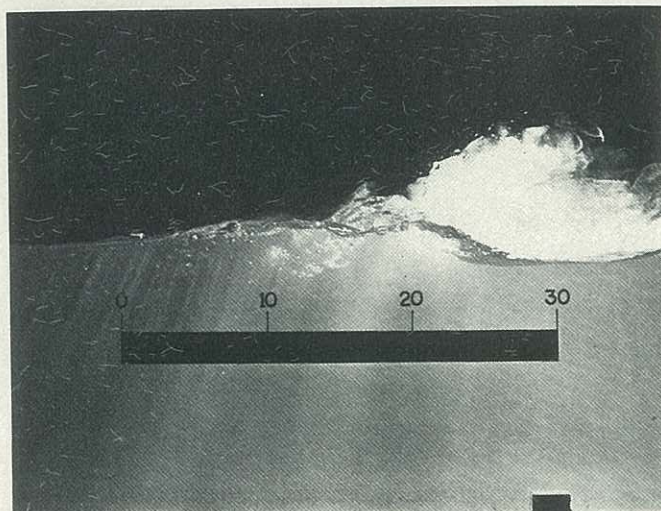
FIGURE 2   Smoke visualization for the air flow over a breaking water wave.   The same conditions prevailed as in figure 1.

They assumed a locally logarithmic mean wind profile over the wave and explored the energy flux to the wave as a function of wave steepness, constant versus variable local roughness length, etc.   A major result of this study was the significant increase in energy flux to the wave when the roughness length varied along the wave profile.   Other details were also reported and their paper should be consulted for details.   It is interesting to note that in another paper, Gent and Taylor (1976b), using the same model, observed regions of locally vanishing surface shear stress, yet found that the streamlines corresponded to attached flow.   They concluded that the onset of breaking was required to allow for the existence of air flow separation, supporting the results of Banner and Melville (1976).

Garrett and Smith (1976) have reconsidered Hasselmann's (1971) analysis of the "maser" mechanism. They derived the following result for short, dissipative (breaking) surface waves riding on a long wave: the long wave momentum grows according to

$$\frac{dM_\ell}{dt} = k_\ell a_\ell < - k_\ell S_s \sin \theta + \tau_s \cos \theta >$$

where a_ℓ, k_ℓ are the amplitude and wavenumber of the long wave ($a_\ell k_\ell$ is the long wave steepness), S_s is the short wave radiation stress, τ_s is the rate of transfer of momentum to the short waves from the wind, θ is the long wave phase ($\theta = k_\ell x - \omega_\ell t$) and $< >$ denotes a phase average over the long wave.   The implications of this result are that since the first term in $< >$ is generally negligible compared with the second, long waves can grow if short wave generation is correlated with the long wave orbital velocity.   Even though the mechanism is limited by the long wave slope, Garrett and Smith infer that a significant momentum flux to the long waves can occur, but that this mechanism is unlikely to account for all the momentum input to the long waves. They stress the need for experimental determinations of the variation of wind stress and short wave amplitude along the long wave profile.

Clearly this work does not treat the full wind-wave problem but does provide a useful formalism once the distribution of τ_s is known.

Longuet-Higgins (1976) presents arguments for expecting the localization of wind stress at the crests of steep gravity waves.   He cites recent work in Marseille which showed the presence of high frequency waves having the same phase speeds as a lower frequency carrier wave.   He hypothesizes various possible distributions of tangential stress resulting from these observations and estimates that the energy transferred to the carrier wave via the high frequency phase-locked waves could make a significant contribution to the growth of the carrier wave.

Generally, at the time these papers were submitted for publication, none of the authors were aware of the results of Banner and Melville (1976).   These provide a concrete mechanism for the various variable stress mechanisms suggested by the authors.

4   CONCLUSIONS

This is the current status of this problem.   The evidence points to the potential importance of wind momentum transfer to long waves via shorter, small-scale breaking waves superimposed on the long waves. It remains to quantify the magnitude of this effect. Further developments in this direction, should they occur, will be reported at the conference.

"maser" mechanism in which it is envisaged that the small-scale equilibrium wave dynamics is of little direct significance in energizing the swell but their kinematic effect of creating a distribution of localized pockets of separated air flow moving relative to the swell appears to be significant. The efficacy of this mechanism in feeding momentum from the wind to the swell depends clearly on the asymmetry induced in the air-flow above the swell. Initial experiments I have conducted indicate that the asymmetry in the mean velocity and pressure fields is appreciable.   It is hoped to be able to present the detailed results of my work currently under progress at the conference.

3.   THEORETICAL AND NUMERICAL WORK

A few relevant publications have appeared very recently.   Gent and Taylor (1976a) have proposed a numerical model for the air flow above water waves. They closed their equations using an isotropic eddy viscosity, claiming that their results were 'insensitive' to the details of the closure assumption.

5   ACKNOWLEDGMENT

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