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TECHNICAL COMMUNICATION

Vertical Mixing by Internal Wave Breaking at the Lutocline, Jiaojiang River Estuary, China

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ABSTRACT

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Field studies using acoustics, optics and current meters were undertaken of fluid mud entrainment in the extremely turbid Jiaojiang River estuary, China. The lutocline behaved as a density interface on which rode high-frequency internal waves. These waves were locally generated by the interaction of shear and buoyancy. Their breaking accounted for vertical mixing, however mixing events proceeded mainly upward, rather than downward, as a reason of the sediment-induced collapse of the turbulence in the lower layer. This asymmetry calls for a new parameterisation of vertical mixing in very turbid estuaries and coastal waters.

ADDITIONAL INDEX WORDS: Lutocline, internal wave breaking, turbulence collapse, vertical mixing, China.

INTRODUCTION

Mixing in estuaries and coastal seas is of great engineering and environmental importance because it has an effect on water quality, siltation patterns, benthic communities and fisheries. While the effect of horizontal mixing can often be parameterised by a scale-dependent eddy-diffusion coefficient (OKUBO, 1974), vertical mixing appears to be more difficult to parameterise because it is due to both boundary mixing (PHILLIPS *et al.,* 1986) and to the breaking of internal waves (TURNER, 1973, FISCHER *et al.,* 1979). Internal waves imply the presence of a vertical density gradient and such a gradient, together with the presence of a solid boundary generating boundary mixing, is present in most estuaries. The lutocline is a step structure in the vertical profile of the concentration of cohesive sediment in suspension. The lutocline was recognised from earlier experiments in the field (WOLANSKI *et al.,* 1988; WRIGHT *et al.,* 1988) and the laboratory (MEHTA and SRINIVAS, 1993) as essentially another parameter, together with temperature and salinity, generating a steep gradient in the water density. The effect of the lutocline on vertical mixing was then parameterised by its effect on the buoyancy, hence also on the Richardson number (WOLANSKI *et al.,* 1988; ROSS and MEHTA, 1989; SCARLATOS and MEHTA, 1993). More recently, it has been recognised from laboratory experiments (WOLANSKI *et al.,* 1989 and 1992) that the suspended mud does not just modify the density; it also modifies the turbulence. This has an effect directly on mixing, introducing an asymmetry in the turbulence which for equal energy inputs is stronger in the clear water above and weaker in the more turbid water below the lutocline.

The evidence for suspended mud inhibiting turbulence was apparently restricted to laboratory experiments. Here we present field evidence which demonstrates that this process is actually dominant in controlling the vertical mixing of suspended sediment in the very turbid Jiaojiang River estuary in China (Figure 1). Turbulence collapse by the fluid mud suspension is not parameterised in present models of vertical mixing in estuaries.

The Jiaojiang River estuary in China (Figure 1), is located 200 km south of the mouth of the Yangtze River. It is 35 km long, has a mean width of about 1.2 km and a mean water depth of about 3–5 m. It faces the shallow, muddy Taizhou Bay. Semi-diurnal, macro-tides prevail with a mean tidal range of 4 m and a maximum tidal range of 6.3 m.

METHODS

A ship-borne ASSM acoustic meter was used for 12 h at site M1 in the Jiaojiang River estuary. The meter sampled at 0.6 sec interval and had a vertical resolution of 5 cm. At half hourly intervals vertical profiles of suspended sediment, salinity and temperature were also collected using a ship-born CTD-nephelometer as described by WOLANSKI *et al.* (1988).

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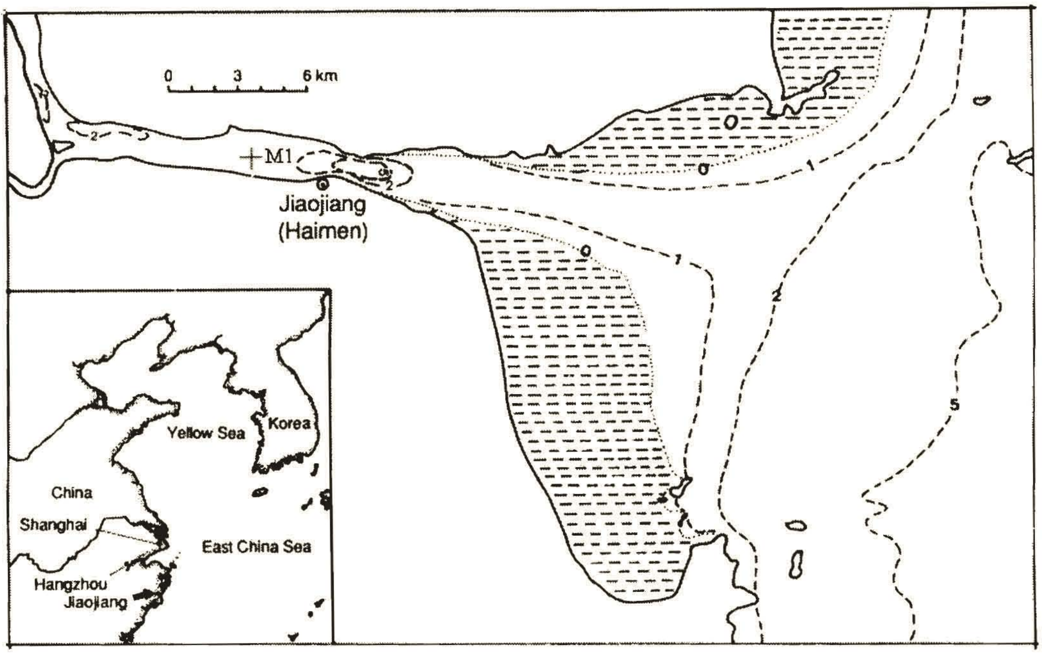

Figure 1. Location map of the Jiaojiang River estuary, China, depth in m below lowest astronomical tides.

A mooring was also deployed at that site, it had six self-logging nephelometers and a S4 InterOcean current meter attached to a frame 2.5 m high. The moored instruments logged data at 10 min intervals. Propeller-type current meters were suspended from the ship to obtain a continuous profile of the horizontal velocity; this string of meters was deployed at the level of the lutocline.

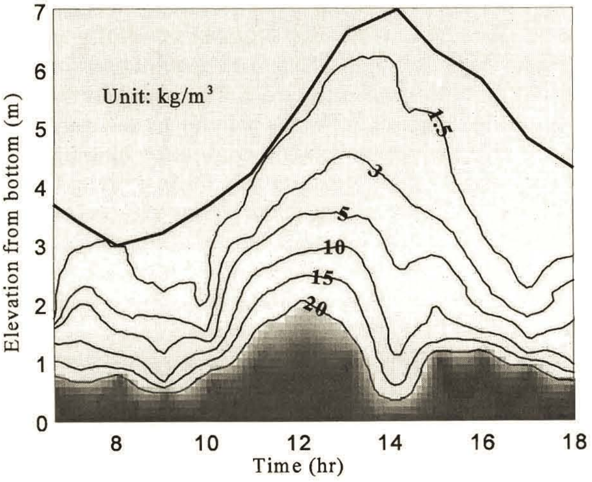

Figure 2. Time series plot of the suspended sediment concentration (in kg m^{-3}) at the study site, November 15, 1995. The waters with concentration > 20 kg m^{-3} are shaded. The nephelometer used to measured the concentration saturates at about 50 kg m^{-3}. Calm weather conditions prevailed, there were no surface waves.

The ASSM data were collected in series of 1800 sampling profiles. Each profile lasted 1080 seconds. Following THORNE *et al.* (1994), the suspended sediment concentration, c, was calculated from the ASSM reading, F, from the relation

$$c = F^2 (h+a)^\alpha \exp(\beta h) \quad (1)$$

where h is the depth below the acoustic probe, a, α and β are empirical constants. The location of the largest vertical gradient of F was taken as the depth A(t) of the lutocline where t is the time. The datum was the bottom.

RESULTS

Using the data from the CTD and the moored instruments, LIXIAN *et al.* (1997) found that the Jiaojiang River estuary was extremely turbid with near-bottom suspended sediment concentration often exceeding 10 kg m^{-3}; the waters were always highly stratified in suspended sediment concentration, particularly near slack high and low tides, this lutocline was present throughout the tidal cycle and its mean elevation changed by about 1–2 m during a tidal cycle (Figure 2). Sediment was resuspended and settled with the reversing tidal currents.

The ASSM signals (Figure 3a) showed the lutocline as a number of dark lines. Low-frequency internal waves riding on the lutocline were quite apparent (Figures 3a). These internal waves had amplitude of up to 0.5 m peak to trough. A visual examination of the acoustic data suggests that the low-frequency waves simply rode on the lutocline without breaking and generating vertical mixing.

However (see events a and b in Figure 3b) there were also high frequency waves (period < 10 sec). These high-frequency waves were asymmetric with sharp crests (events a in Figures 3 b and c) and flat troughs (events b in Figure 3 b and c). This finding is similar to that observed in laboratory experiments of turbulent mixing across a density step structure (TURNER, 1973; WOLANSKI and BRUSH, 1975). However in these laboratory experiments fluid was entrained both downward and upwards, while in the Jiaojiang River estuary downward entrainment of light fluid was practically never observed. Indeed, in the Jiaojiang River estuary mixing was asymmetric, it commonly occurred as a patch of fluid entrained upwards in a filament from the wave crests (events c in Figures 3 b and c). These events appear similar to those observed in laboratory experiments of mixing across a density interface, the dense fluid being entrained in filaments swept from wave crests by eddies in the upper fluid (event c in Figure 3c). In the laboratory, turbulent jets are generated by turbulent eddy pairs in the upper layer, these also impinge on the density interface and generate two filaments which wrap into each other (event d in Figure 3c). Such a feature is recognisable also in the Jiaojiang River ASSM data (event d in Figure 3b). Presumably just like in the laboratory experiments these filaments of muddy water do not fall back to the lutocline, instead they are mixed by the turbulence in the upper layer.

These high-frequency waves affected the energy spectrum of the lutocline elevation. In each of the 18 min long acoustic surveys, the slope of this spectrum decreases with the power $-5/3$ as characteristic of a Kolmogorov turbulent spectrum (TURNER, 1973). These waves were presumably responsible for a local peak in the spectrum of the lutocline elevation (shown by a vertical arrow in Figure 4) which was present in all the time series and corresponded to a period of 2 to 3 seconds.

The filaments are entrained and mixed upward and not downward. The turbulence in the Jiaojiang River is thus asymmetric, it is larger above the lutocline and smaller below the lutocline. As a result mixing is also asymmetric, fluid is entrained only upward and the lutocline is eroded downward. Laboratory experiments (WOLANSKI *et al.*, 1989 and 1992) suggest that the likely candidate for this asymmetry is the suspended mud itself collapsing the turbulence at suspended sediment concentration > 10 g l^{-1}. The fluid mud below the lutocline is not diluted with clear water from above. Only the addition of new mud eroded from the bottom can prevent a downward movement of the lutocline elevation.

During this study the waters were vertically well-mixed in salinity and temperature and only the suspended sediment contributed to the buoyancy gradient. Because the CTD casts were taken at half-hourly intervals, we assumed that the CTD cast taken during each of the five 18-min long ASSM time series was typical of that period. This enabled us to calculate the vertical profile of buoyancy from the suspended sediment concentration. The local Richardson number was calculated from the buoyancy profile and from the profile of velocity as determined by the string of current meters. We also computed the cumulative spectral energy density, S, of the lutocline elevation for periods < 30 sec, neglecting the low-frequency fluctuations (period > 30 sec), since these could readily have been generated elsewhere. This was justified because in our ASSM time series, the high-frequency waves accounted for 75 to 85% of the total energy, implying that the low-frequency waves (period > 30 sec) were not energetic. No correlation was found (not shown) between S and the bottom stress. This essentially ruled out bottom-generated turbulence events such as bursting as being responsible for mixing in the Jiaojiang River estuary. Instead S was found (Figure 5) to depend on the local Richardson number, Ri, the higher the value of Ri the smaller the internal waves, this finding replicates those from laboratory experiments (WOLANSKI and BRUSH, 1975). The scatter in Figure 5 could not be explained (not shown) in terms of a simple parameterisation of the external energy input such as the interfacial shear or the upper or lower layer velocity. The correlation between S and Ri implies that the internal waves were locally generated by the interaction of the velocity shear and the buoyancy.

CONCLUSION

Current meters, CTD profiles and acoustic profiles in the Jiaojiang River estuary reveal that mixing across the lutocline was not controlled by bursting generated at the bottom. Instead it was determined by the breaking of high-frequency (period < 5 sec) internal waves riding on the lutocline. Their height was controlled by the Richardson number. Mixing over lutocline proceeded mainly upward in events whereby the dense fluid was entrained as a filament into the upper layer. Mixing was thus asymmetric. This is contrary to classical fluid mechanics when the fluid is stratified in salinity and temperature, where mixing proceeds both upward and downward if there is turbulence in both layers. The apparent reason for that was the collapse of the turbulence in the dense fluid though it was not stagnant but had velocity ranging from a minimum of 0.39 to a maximum of 0.76 m s^{-1} and thus potentially able to produce turbulence. The high values (> 20 kg m^{-3}) of suspended sediment concentration in the bottom layer can account for this collapse of the turbulence.

Present models of vertical mixing in density-stratified fluids and applied to estuaries do not account for the suspended sediment collapse brought upon by the suspended sediment.

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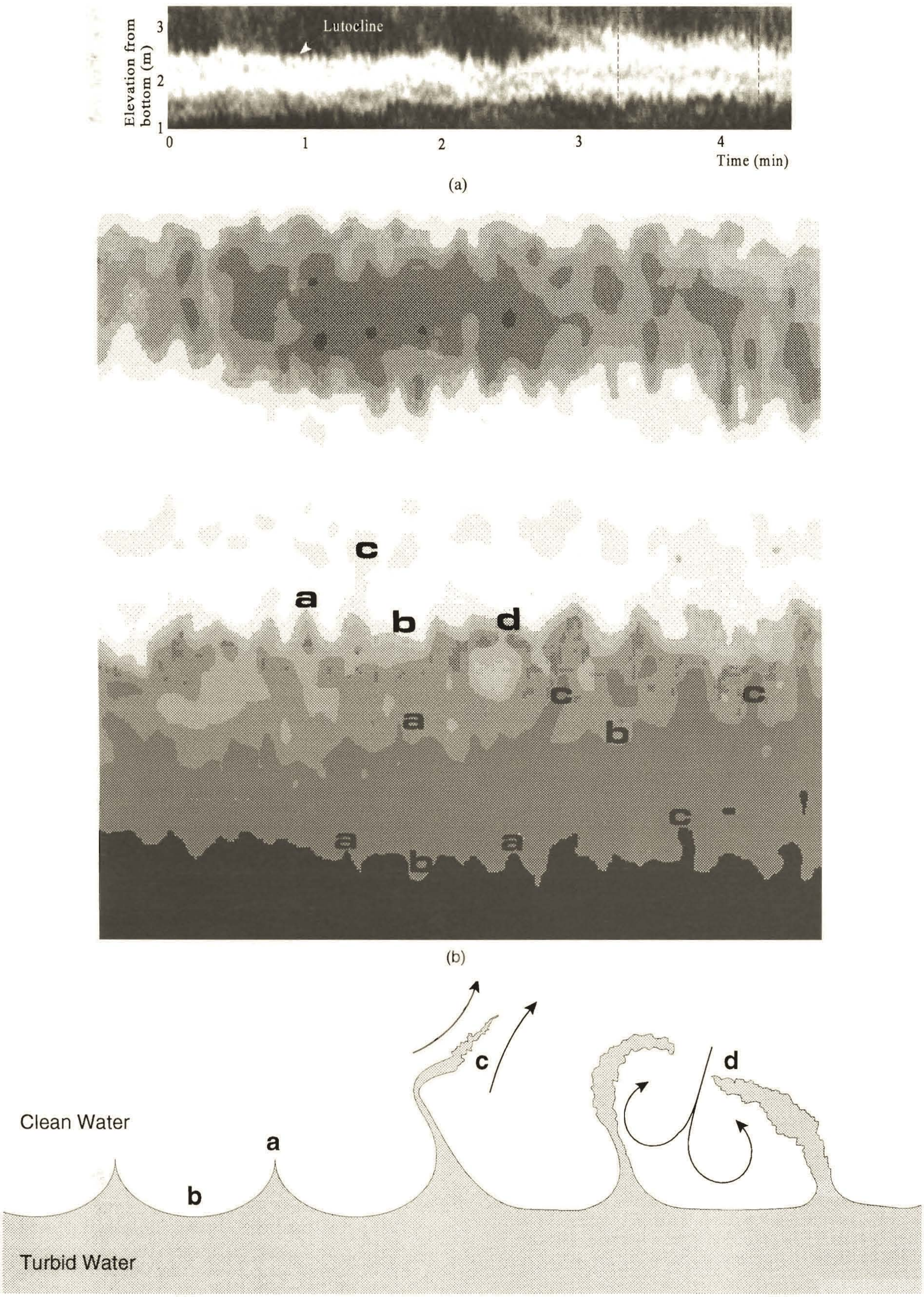
Figure 3. (a) and (b) are typical time-series of acoustic profiling at 0.6 sec intervals at the study site in the Jiaojiang River estuary, (a) over a period of 4.5 min and (b) close-up over a 1 min period. (c) is a sketch of mixing events observed in the laboratory when turbulence is generated by oscillating grids above a density interface (adapted from TURNER, 1973, WOLANSKI and BRUSH, 1975 and WOLANSKI *et al.*, 1988). In (b) the depth below the acoustic probe was 3.5 m. A number of events are visible a = sharp crest, b = flat trough, c = upward entrainment of a filament entrained by a turbulent eddy in the upper layer, d = entrainment of two filaments by a turbulent jet impinging on a density interface. The water below the lutocline was not stagnant but had a velocity > 0.39 m s^{-1}, *i.e.* always sufficient to generate turbulence; the lack of downward entrainment suggests there was no turbulence in the bottom layer.


Elevation from bottom (m)
3
2
1
Lutocline
0
1
2
3
4
Time (min)
c
a
b
d
a
c
b
c
c
a
b
a
Clean Water
a
b
c
d
Turbid Water

(a)

(b)

(c)

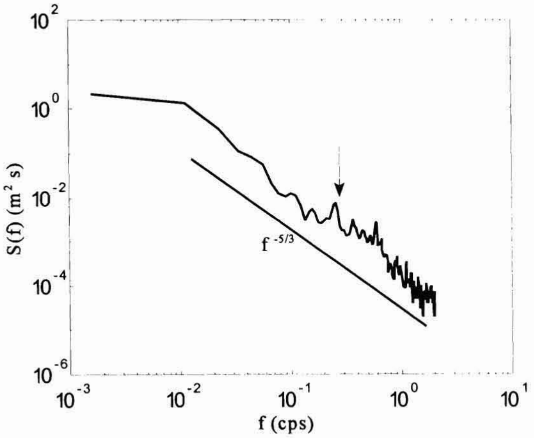


Figure 4. Typical spectrum of the lutocline elevation from a 18 min period sampled at 0.6 sec intervals. f = frequency. The vertical arrow points to a local maximum found in all the time series with a period between 2 and 3 seconds.

They rely on computing a Richardson-number dependent vertical eddy diffusivity coefficient (DYER, 1988; ROSS and MEHTA, 1989; SCARLATOS and MEHTA, 1993; MEHTA and SRINIVAS, 1993; WOLANSKI *et al.,* 1988). Mixing can then occur both upward and downward. Downward mixing at the lutocline was not observed in the Jiaojiang River estuary though the velocity below the lutocline was always > 0.39 m s^{-1} and peaked at 0.7 m s^{-1} during the ASSM surveys. In the absence of fluid mud this velocity is sufficient to generate turbulence in the bottom layer. Turbulence collapse is not parameterised in present models of vertical mixing in estuaries.

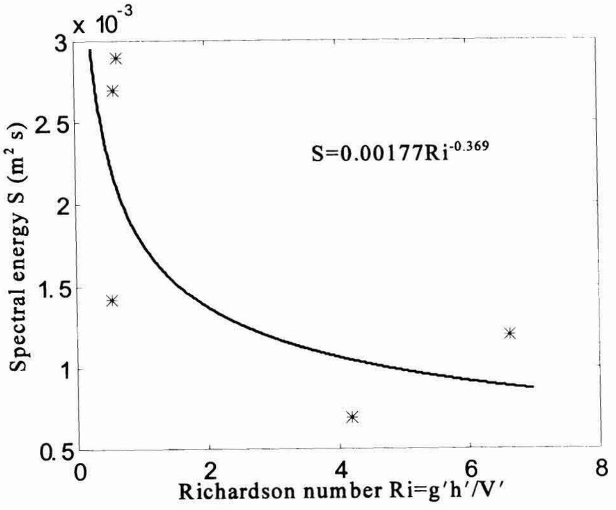


Figure 5. Relationship between the Richardson number Ri and the high-frequency component S of the lutocline elevation spectrum, where g' is the reduced gravity, V' the velocity difference across the lutocline, h' is the mixed layer depth.

The collapse of the turbulence in the fluid mud is important because the lutocline is only entrained upward. The lack of downward entrainment means that the fluid mud is not diluted by mixing with the clear water above.

The collapse of the turbulence also helps to decrease the bottom friction coefficient in very turbid estuaries by enabling the upper layer of clear water to slip over the fluid mud (KING and WOLANSKI, 1996; LIXIAN *et al.,* 1997).

We conclude that a new parameterisation of vertical mixing in mud-stratified estuaries is needed that takes into account the collapse of turbulence in the fluid mud.

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