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Steady Boundary Layer Flow under the Influence of Progressive Finite Amplitude Wave

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進行性 有限振幅波로 인한 定常性 境界層流

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Abstract

The problem of the formation of steady stream on flat bottom boundary is revisited by applying a progressive finite amplitude wave as an external flow. A solution for the boundary layer is found by expanding the boundary equation into double Fourier series. A vertical profile of the stream is obtained as a function of the ratio, h/L, where h and L are the water depth and the wave length. For the best applicable range of the external wave, it is shown that the boundary stream is independent of the fluid viscosity, but a function of the wave parameters and the water depth. The stream velocity of the steady boundary layer flow is proportional to the wave phase velocity and the square of the ratio, H/h, where H is the wave height. The magnitude of the velocity is insignificant when h/L is greater than 1/5.

要約 : 進行性 有限 振幅波가 垂平인 底部 境界面 위에 存在할때 이 波로 因하여 境界面에 인접해서 形成되는 定常流(steady stream)를 研究하였다. 이를 위하여 境界層 方程式이 使用되었으며, 이것을 二重 Fourier系別로 展開함으로써 그 解를 求하였다. 이 解의 垂直 構造를 水深과 波長의 比(h/L)의 函數로 表示하였다. 有限 振幅波가 가장 잘 適用될 수 있는 條件下에서 境界層의 定常流를 求해본 結果 이 定常流는 물의 粘性에는 無關하며 그 上部에 있는 有限 振幅波의 파라메타들, 즉 週期, 波長등과 水深의 函數임이 確認되었다. 또 이 境界層의 定常流의 속도는 波速과, 水深에 대한 波高의 比(H/h)의 제곱에 比例함이 밝혀졌으며, 이 定常流의 크기는 h/L 이 0.5보다 클때에는 아주 작아져서 無意味한 값이 된다.

INTRODUCTION

In water wave the particles of fluid possess two kinds of mass transport velocities. The first kind is the Stokes' drift in the interior layer of the fluid (Stokes, 1880). The drift which is a Lagrangian quantity is a net mass transport velocity in the direction of the wave propagation. The second is the steady stream which is developed on the bottom boundary due to the viscosity of the fluid.

The steady streaming near the bottom boundary has been also an interesting topic because it is clearly relevent to questions involving the movement of sediment and sand by wave action. In 1851, Stokes found a solution of the problem of an oscillating plane boundary in a fluid at rest at infinity on the assumption of perfect, non-viscous fluid. About a century later, Longuet-Higgins (1953) developed a theory of mass transport using small amplitude wave motion by taking account of the viscosity. His solution is markedly different from the perfect-fluid solutions with irrotational motion. Its chief characteristic is a strong forward velocity near the bottom. The mass transport velocity near the boundaries, however, does not depend critically on the ratio of the wave amplitude and the thickness of the boundary layer, but is determined by the first order motion and the local boundary conditions.

In the present paper the vertical structure of the steady stream is studied. In the presence of a progressive finite amplitude wave in the interior of the fluid, a more satisfactory physical and mathematical model of the phenomenon of steady stream near the bottom boundary will be developed. The finite amplitude wave theory is used here because the streaming velocity is the second order quantity. We also study the dependence of the stream velocity on the ratio of h/L, where h and L are the water depth and wavelength.

EQUATIONS AND BOUNDARY CONDITIONS

We consider a boundary layer flow on a plane bottom with x coordinate to the direction of the wave propagatin in the farfield from the boundary layer and z coordinate vertical to the bottom (Fig. 1.).

The propagating wave in the farfield is a Stokes' wave whose surface elevation H and the particle velocity U is as follows (Laitone, 1962)

$$H=b\cos\xi+\frac{\varepsilon^2\cosh kh}{4k\sinh kh}(2+\cosh 2kh)\cdot\cos 2\xi+0(\varepsilon^3) \qquad (1)$$

$$U=\varepsilon C\cosh[k(z+h)]\cos\xi+\varepsilon^2\frac{3C}{4}\cdot\frac{\cosh[2k(z+h)]}{\sinh^2 kh}\cos 2\xi+0(\varepsilon^3) \qquad (2)$$

here, $\xi = kx - \sigma t$, k the wavenumber ($=2\pi/L$, L is the wave length), σ the frequency ($=2\pi/T$, T is the wave period), C the phase velocity, b the amplitude of the first order term, h the water depth, and $\varepsilon = bk/\sinh kh$.

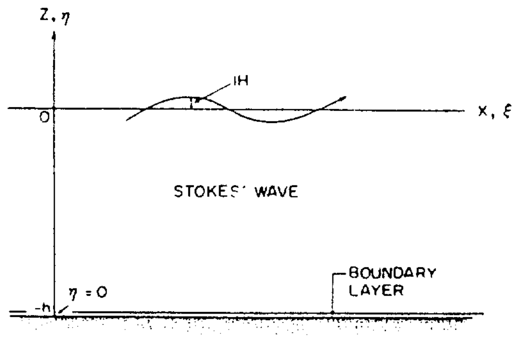

Fig. 1. The coordinate system.

For a bottom boundary layer, we need to stretch the vertical coordinate using the Reynolds number R ($=CL/\nu$, ν the kinematic viscosity) to see the clear structure of the stream. Under the normal ocean wave condition, the Reynolds number is large and the thickness of the bottom boundary layer is of the order $\sqrt{\nu T}$ (Schiliting, 1979; Stuart, 1976). The new vertical coordinate is

$$\eta=\sqrt{R/2\pi}\ k(z+h). \qquad (3)$$

The wave motion near the boundary exerts as an external forcing to the development of the boundary stream, thus, we need to find $U(z \to -h)$

$$U=U|_{z\to -h}=\varepsilon C\cos\xi+\varepsilon^2\frac{3C}{4\sinh^2 kh}\cos 2\xi+0(\varepsilon^3) \qquad (4)$$

For the boundary layer, Schlichting's (1979) boundary layer equation is used with the wave forcing terms at the righthand side.

$$\psi_{zt}+\psi_z\psi_{xz}-\psi_x\psi_{zz}-\nu\psi_{zzz}=U_t+UU_x \qquad (5)$$

The subscripts denote the derivatives with respect to each variable, and the stream function is defined $\psi(x,z,t)$ as

$$u=-\frac{\partial\psi}{\partial z},\quad v=\frac{\partial\psi}{\partial x} \qquad (6)$$

In the $\xi-\eta$ coordinate system, (5) becomes

$$-\phi_{\eta t}+\phi_{\eta}\phi_{\eta\xi}-\phi_{\xi}\phi_{\eta\eta}-\phi_{\eta\eta\eta} = (U_t+UU_x)/C^2k \quad (7)$$

where

$$\phi = (k/C)\sqrt{k/2\pi}\,\psi. \quad (8)$$

Near the bottom boundary $z \to -h$, the righthand side (= RHS) of (7) becomes

$$\text{RHS} = (a_1 - \frac{a_1a_2}{2C})\sin\xi + (a_2 - \frac{a_1^2+2a_1a_2}{2C})\cdot \sin 2\xi + (a_3 - \frac{a_1a_2}{C})\sin 3\xi \quad (9)$$

where

$$a_1 = \varepsilon$$

$$a_2 = \frac{3}{4}\varepsilon^2/\sinh^2 kh$$

$$a_3 = \frac{3}{64}\varepsilon^3(13-4\cosh^2 kh)/\sinh^4 kh.$$

The equation to be solved in $O(\varepsilon^3)$ is

$$-\phi_{\eta t}+\phi_{\eta}\phi_{\eta\xi}-\phi_{\xi}\phi_{\eta\eta}-\phi_{\eta\eta\eta} = \text{RHS} \quad (10)$$

We apply the non-slip boundary condition for the bottom boundary and assume that the particle velocity of the boundary oscillation matches that of the wave motion in first order when the particle is far enough from the bottom boundary.

$$\phi(\xi,0)=0,\quad \phi_{\eta}(\xi,0)=0, \quad (11a)$$

$$\phi_{\eta} = -\cos\xi \ \text{as}\ \eta\to\infty. \quad (11b)$$

METHOD OF SOLUTION

To solve equation (10) we shall expand ϕ (ξ,η) in a double Fourier series in the dimensionless variable ξ. The coefficients are functions of η and the parameter ε and each of these will be expanded in a power series in ε

$$\phi = \sum_{i=0}^{\infty}\varepsilon^i f_{0,i} + \sum_{i=1}^{\infty}\sum_{j=1}^{\infty}\varepsilon^{i+j}[f_{i,j}\cos j\xi + g_{i,j}\sin j\xi], \quad (12)$$

here, f's and g's are only function of η. Substituting (12) into (10) and collecting the lowest order terms, we get

$$f'''_{0,0} = 0, \quad (13)$$

$$f'''_{0,1} = 0. \quad (14)$$

$$f'''_{0,1} = \frac{1}{2}(g''_{1,0}f_{1,0} - g_{1,0}f''_{1,0}) \quad (15)$$

and

$$f'''_{0,3} = \frac{1}{2}(g''_{1,0}f_{1,1} - g_{1,0}f''_{1,1}) + \frac{1}{2}(g''_{1,1}f_{1,0} - g_{1,0}f''_{1,1}). \quad (16)$$

The primes above denote the derivatives with respect to η. It is easy to solve (13) and (14). After applying the boundary conditions (11), we get

$$f_{0,0} = 0 \quad (17)$$

and $f_{0,1} = 0$. (18)

In order to solve the differential equation (15) we have to wait until we determine $f_{1,0}$ and $g_{1,0}$. Collecting the coefficients of $\cos\xi$ and applying (17) and (18), we obtain three lowest order equations,

$$O(\varepsilon):\ f'''_{1,0}+g'_{1,0}=0 \quad (19)$$

$$O(\varepsilon^2):\ f'''_{1,1}+g'_{1,1}=0 \quad (20)$$

$$O(\varepsilon^3):\ f'''_{1,2}+g'_{1,2}=g''_{1,0}f_{2,0} - g_{1,0}f''_{2,0}/2 + (f'_{1,0}g'_{2,0} - f'_{2,0}g'_{1,0})/2 + (-f''_{0,2}g_{1,0} - f''_{1,0}g_{2,0}/2 + f_{1,0}g''_{2,0}/2). \quad (21)$$

Similarly we obtain the equations for the coefficients of $\sin\xi$ as follows

$$O(\varepsilon):\ f'_{1,0}-g'''_{1,0} = -1 \quad (22)$$

$$O(\varepsilon^2):\ f'_{1,1}-g'''_{1,1} = 0 \quad (23)$$

$$O(\varepsilon^3):\ f'_{1,2}-g'''_{1,2} = 3/4\sinh^2 kh - [g_{1,0}g''_{2,0} - g_{2,0}g''_{1,0}/2] + f_{0,2}f''_{1,0}/2 - f_{2,0}f''_{1,0}/2 + f''_{0,2}f_{1,0} + (g'_{1,0}g'_{2,0} - f'_{0,2}f'_{2,0} - 3f'_{1,0}f'_{2,0})/2. \quad (24)$$

By solving (19) and (22) for $f_{1,0}$ for $g_{1,0}$ we obtain the solution after application of the boundary conditions (11),

$$f_{1,0}=1/\sqrt{2}-\eta-(p-q)/\sqrt{2}, \tag{25}$$
$$g_{1,0}=(1-p-q)/\sqrt{2} \tag{26}$$

where p and q are defined as follows for simplicity,

$$p=e^{-\eta/\sqrt{2}}\cos(\eta/\sqrt{2}), \tag{27a}$$
$$q=e^{-\eta/\sqrt{2}}\sin(\eta/\sqrt{2}). \tag{28b}$$

Now, we can determine $f_{0,2}$ (see equation (15)) using (25) and (26). It leads to the steady streaming flow to the direction of wave propagation

$$f_{0,2}=\frac{3}{8}\sqrt{2}-\frac{3}{4}\eta+\frac{1}{4\sqrt{2}}e^{-\eta/\sqrt{2}}-\frac{1}{\sqrt{2}}(p-2q)$$
$$-\frac{1}{2}\eta p. \tag{28}$$

Let's look at the second order terms. We can solve for $f_{1,1}$ and $g_{1,1}$ by matching (20) and (23). The required boundary conditions (Eq. 11) forced them to be zero.

$$f_{1,1}=0, \tag{29}$$
$$g_{1,1}=0. \tag{30}$$

Here, we used

$$\frac{\partial f_{1,1}}{\partial\eta}\to 0 \quad \text{as} \quad \eta\to\infty, \tag{31}$$

$$\frac{\partial g_{1,1}}{\partial\eta}\to 0 \quad \text{as} \quad \eta\to\infty. \tag{32}$$

The equations (29) and (30) give the solution of (16) immidiately

$$f_{0,3}=0. \tag{33}$$

We, however, can not determine $f_{1,2}$ and $g_{1,2}$ until we find $f_{2,0}$ and $g_{2,0}$. Let's look at the second harmonics. We collect the $O(\varepsilon^2)$ and $O(\varepsilon^3)$ coefficients of cos 2ξ.

$$0(\varepsilon^2):\ f'''_{2,0}+g'_{2,0}=-[g''_{1,0}f_{1,0}+f''_{1,0}g_{1,0}]/4$$
$$+g'_{1,0}f'_{1,0}/2 \tag{34}$$
$$0(\varepsilon^3):\ f'''_{2,1}+g'_{2,1}=0. \tag{35}$$

Similarly the coefficients of sin 2ξ are

$$0(\varepsilon^2):\ f'_{2,0}-g'''_{2,0}=-(g_{1,0}g''_{1,0}-f_{1,0}f''_{1,0})/4$$
$$+(g'_{1,0}g'_{1,0}-f'_{1,0}f'_{1,0})/4$$
$$0(\varepsilon^3):\ f'_{2,1}-g'''_{2,1}=0. \tag{37}$$

It is possible to solve (34) and (36) for $f_{2,0}$ and $g_{2,0}$ using (25) and (26). We obtain the following by applying the boundary conditions,

$$f_{2,0}=C_{20}(1-p-q)-\frac{3}{8}\eta/\sinh^2 kh-\frac{1}{2}\eta p$$
$$-\frac{1}{16\sqrt{2}}\eta^2(p+q) \tag{38}$$

$$g_{2,0}=C_{40}(1-p-q)-\frac{1}{16}\eta q-\frac{1}{16\sqrt{2}}\eta(p+q) \tag{39}$$

where $C_{20}=\frac{3\sqrt{2}}{16}/\sinh^2 kh+1/2\sqrt{2}$

and $C_{40}=-\frac{1}{8\sqrt{2}}(1+3/\sinh^2 kh)$.

Similarly, from (35) and (37) we get

$$f_{2,1}=0, \tag{40}$$
$$g_{2,1}=0. \tag{41}$$

We may write

$$\phi=\varepsilon(f_{1,0}\cos\xi+g_{1,0}\sin\xi)$$
$$+\varepsilon^2(f_{0,2}+f_{2,0}\cos 2\xi+g_{2,0}\sin 2\xi)$$
$$+0(\varepsilon^3). \tag{42}$$

The x-direction particle velocity in the order of ε^1 approaches to $-\cos\xi$ in the farfield from the bottom.

The steady stream is

$$U_\ell=-\varepsilon^2 C\frac{\partial f_{0,2}}{\partial\eta}=\varepsilon^2 C\{\frac{3}{4}+\frac{1}{4}e^{-\sqrt{2}\eta}$$
$$-(p-q/2)+\eta(p+q)/2\sqrt{2}\}. \tag{43a}$$

This streaming velocity is a function of η, and independent of the viscosity ν. It is totally a function of the wave parameters. When η approaches to infinity, the steady streaming velocity in dimensional form in the order of ε^2

is

$$U_l = U_l|_{\eta\to\infty} = \frac{3}{4}Cb^2k^2/\sinh^2 kh. \qquad (43b)$$

This result exactly agrees with what Longuet-Higgins (1953) has found by using small amplitude wave motion.

RESULTS AND DISCUSSIONS

A steady flow is developed in the boundary layer of a flat bottom. This second order streaming flow is purely driven by the interaction between the oscillatory motion of the water body at the outside of the boundary layer and the viscous effect along the bottom boundary. The direction of this streaming is the direction of wave propagation and its magnitude is independent of the viscosity ν. Equation (43a) is the profile of the steady stream. This is plotted in Fig. 2 as a function of h/L. As is seen here, the magnitude of the stream velocity increases with decreasing h/L. The streaming velocity becomes insignificant when h/L is greater than 1/5. The detailed structure of the present solution is somewhat different from the Longuet-Higgins' (1953). The peak value of the steady stream for a fixed h/L is about 20% larger than the farfield steady stream velocity, U_l. This tendency also appeared on the results of the Longuet-Higgins, but his maximum value is only about 10% larger than the U_l. This discrepancy seems to be due to the wave theories used. The higher order finite amplitude wave theory is used for the present study, but the small amplitude theory is used by Longuet-Higgins. When η goes to infinity, the steady flow in the boundary layer can be reduced to the same equation (43b) that Longuet-Higgins has found. This implys that the two solutions correspond each other in the lowest order.

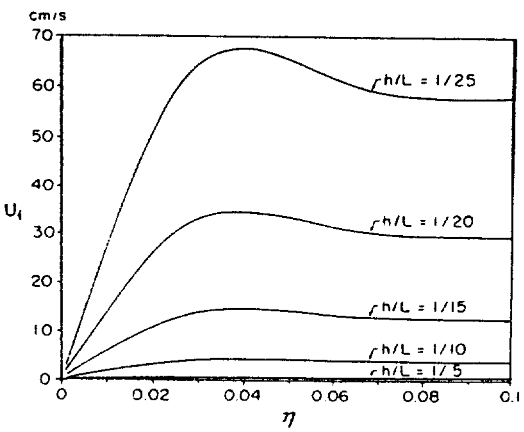

Fig. 2. Profiles of the steady stream velocity (U_l) at each h/L as a function of η. (Wave height = 1 m; Wave period = 8 seconds)

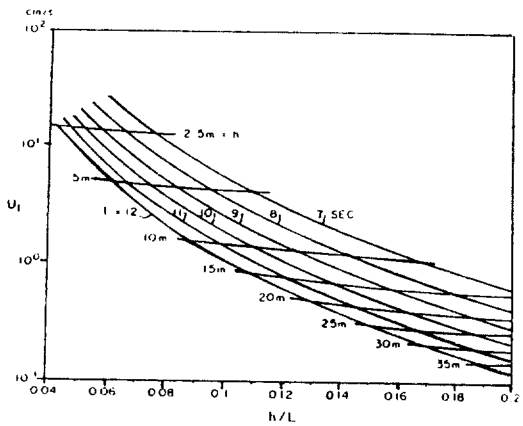

Fig. 3. Farfield steady stream (U_l) at each wave period as a function of h/L (Wave height = 1 m)

The steady stream velocities for the external waves of 7 to 12 seconds period are plotted in Fig. 3 as a function of h/L. The solid horizontal lines denote the constant water depths. For a fixed period wave, the velocity decreases as h/L increases. For a fixed depth, the shorter period wave induces slightly slower stream than the longer period waves.

Let's consider a range in which a Stockes' wave applys best. We consider the wave in intermidiate depth $0.04 < h/L < 0.5$. We elliminate the depth range which is too shallow to apply the theory. We also do not consider the case which is too deep to take the bottom boundary layer into account. For small kh, we expand $\sinh^2 kh$ of U_l and take the first term only, and get the steady flow as follows

$$U_l \cong \frac{3}{16}\left(\frac{H}{h}\right)^2 C\{1+\frac{1}{3}e^{-\sqrt{2}\eta}-\frac{4}{3}e^{-\eta/\sqrt{2}}$$
$$(\cos\ \eta/\sqrt{2}-\frac{1}{2}\sin\ \eta/\sqrt{2})\ -\frac{\sqrt{2}}{4}e^{-\eta/\sqrt{2}}$$
$$(\cos\ \eta/\sqrt{2}+\sin\ \eta/\sqrt{2})\} \tag{44}$$

When η increases, the last three terms in the braces becomes much smaller as compared to 1, thus, the velocity in shallower region is approximated as follows

$$U_l = \frac{3}{16}\left(\frac{H}{h}\right)^2 C \tag{45}$$

Here, we notice that the speed of the farfield stream is proportional to the phase speed of the wave and the square of H/h. where h and H are the water depth and the wave height.

A weak point of the present solution is that the steady stream velocity (43b) does not agree with the Stokes drift when $z \rightarrow -h$. In order to avoid this velocity jump of the steady streams, we have to find a way that the two velocities could be matched smoothly. This suggests that there may be another boundary layer which will match the two velocities. The study about this problem is presently going on.

CONCLUSIONS

We tried to clarify the profile of the steady stream near the bottom boundary in the presence of a progressive wave of finite amplitude in the interior of the fluid. The inner boundary layer is developed by the Reynolds stresses due to the wave action above and viscosity at the bottom. In this layer, a steady stream is developed in the direction of the wave propagation and its magnitude is a second order quantity. The stream velocity we have found is independent of the viscosity, ν, but it depends on the wave parameters and the water depth. The velocity of the steady boundary layer flow is proportional to the wave phase velocity and the square of the ratio of wave height to water depth, H/h. The magnitude of the steady stream velocity diminishes rapidly as h/L increases, and it becomes insignificant at h/L>1/5. For a place of fixed depth, the shorter period waves induce a slower steady stream, U_l, than the longer period waves. The maximum speed of the steady stream is about 20% larger than the speed U_l. This is somewhat larger than the value that Longuet-Higgins (1953) has found.

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彙 報

韓國海洋學會 創立 20周年 記念 심포지움 要約

한국 근해의 해류와 해수 특성

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이제까지 알려진 동해, 황해 및 동지나해를 흐르는 해류의 구조와 시간적 변화상은 주로 정선 관측자료에 근거하였다. 일시적 또는 2 개월 간격으로 수집된 자료의 분포로부터 유추된 해류는 정상류를 전제로 하는 반면에, 해류는 계절적으로 뿐만 아니라, interannual variation에서 inertial period에 이르기까지 다양한 주기를 갖고 변할 수 있으므로, 극히 제한된 시간적 변화상만이 파악되었을 뿐이다. 해류의 공간적 구조 역시 최근 이용되기 시작한 인공위성 사진에서 볼 수 있듯이, 다양한 eddy의 출현으로 이제까지 알려진 것보다 훨씬 복잡함에 틀림이 없다.

해류의 변화를 예측하여 이를 인간의 삶에 활용함이 물리해양학의 궁극적 목표라 한다면, 이를 위하여 일차적으로 해류의 시공간적 변화 실상을 밝히는 것이 앞서며, 필연적으로 해류의 유체역학적 규명이 따라야 한다. 동시에 적절한 측정 기기 및 방법의 선정, 자료수집의 극대화(optimization of sampling)을 위하여 가능한 현상을 예측함이 매우 중요하다. 이와 같이 자료의 수집, 자료의 분석 및 해석, 이론적 규명의 세가지 요소가 유기적 관계를 맺을 때에 비로소 궁극적 목표에 접근할 수 있음은 자명하다. 부족한 연구 인력이 각종 기관에 흩어져 있고, 또한 아직도 본연의 해양학 연구를 위한 자원이 미약한 국내 여건에서 위의 목표를 달성하려면 연구자 및 기관들이 서로 긴밀하게 협동함이 절실하다. 1981년 Japan and East China Seas Study Workshop 이후 외국인 학자들의 한국 주변 해역에 대한 조사 및 연구가 더욱 활발함을 간과해서는 안될 것이다.

창간호 이후 최신호까지 한국해양학회지에 게재된 81편의 물리 해양학 관계 논문들을 분류하면, 대한해협을 포함하는 동해의 해류 (29편), 제주해협 및 남해, 황해, 동지나해의 제반 현상 (14편), 조석·조류 및 해면 변화 (10편), 수온·염분변화, 파랑, 하구 해수유동 등의 기타 (28편)로 대별할 수 있다. 이에 비추어 앞으로도 대한해협과 제주해협을 관련하는 종합적 연구가 기대된다.

韓國近海의 水塊와 漁業資源生物의 分布, 移動

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韓半島와 그 隣接海域의 主要水系 및 水塊의 配置를 檢討하고 이곳을 生活環境區로 하는 主要漁業資源生物의 分布限界를 규정하는 要因을 究明하였다.

1. 東海 및 東支那海 北部에 分布域을 갖인 꽁치는 Okaba의 Pelagic 群集에 속하며 冬季에는 緣邊北西太平洋 中央水 (Tm′), 春季에는 對馬暖流中 核水, 夏季에는 東海北西部 表面水 (Ls) 그리고 秋季에는 Ls와 Tm′ 間의 水塊에 分布하고 東支那海에서의 分布 西側限界는 鹽分不連續帶이다.

2. 고등어는 Okaba의 Pelagic 群集에 속하나 꽁치보다 適温範圍를 넓게 갖이므로 東支那海, 黃海 및 東海의 大部分의 暖水域을 生活環境區로 하고 東海의 下層水와 黃海中部 底層冷水塊를 除外한 水塊에 分布가능하다.

3. 참조기는 Okaba와 Taraba 群集의 中間的 位置에 있고 東支那海 및 黃海의 中·底層에 生活環境區를 갖인다. 참조기는 東支那海에서는 黑潮 및 對馬暖流와 中國沿岸水間의 混合水域에 그리고 黃海에서는 黃海冷水塊, 對馬暖流 및 韓國, 中國沿岸水塊間의 混合水域에 分布한다. 이 種의 分布 東側 限界는 高温, 高鹽의 暖流水域이다. 참조기의 季節回遊 過程에서는 性的成熟群과 未熟群 사이에 分離가 일어나는 것 같다.

4. 청어는 대표적인 Taraba 群集에 속한다. 東