CHAPTER 63

Coherent Structure of Tidal Turbulence in a Rotating System of Osaka-Bay

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Abstract

Coherent structures dominating in the tidal turbulence field inside the Osaka-Bay were detected by flow visualization through satellite image sensors. To obtain the hydrodynamical characteristics, scale down model experiments were done with the Froude/Rossby similarity law. The tidal residual circulations were reproduced on the ensemble mean turbulence field, which is made very similar to each instantaneous turbulence owing to the robustness of the coherent structure interlocked inside a closed vessel. The earth rotation effects were verified to dominate the turbulence processes in this closed vessel, and a hysteresis due to the moon aging was revealed.

Introduction

Hydrodynamical characteristics of turbulence structures interlocked inside the tidal flow field in Osaka-Bay was investigated by employing the coherent structure concept, satellite-based flow visualization and scale down model experiments performed in a rotating system. Figure 1(a) shows an example of the visualized flow pattern, in which the high gain visible data obtained with Mos-1/MESSR is enhanced to snapshot an instantaneous turbulence field at 1028, 23 December 1987.

The Osaka-Bay is an inland sea basin located in the middle part of Japan-Islands, which is enclosed by some populous and industrialized areas (Figure 1(b)). It is about 50km in size and about 50m in average depth, and is therefore 1,000 in the ratio of horizontal and vertical scales. The water quality of this bay, however, is not so seriously polluted owing to the tidal exchange through the two narrow channels connecting to adjoing sea areas; Akashi-Strait to the Harima-Sea and Tomogashima-Strait to the Pacific-Ocean. Further, tidal jets injected through these straits accelerate the transport process inside the bay feeding with its turbulence components.

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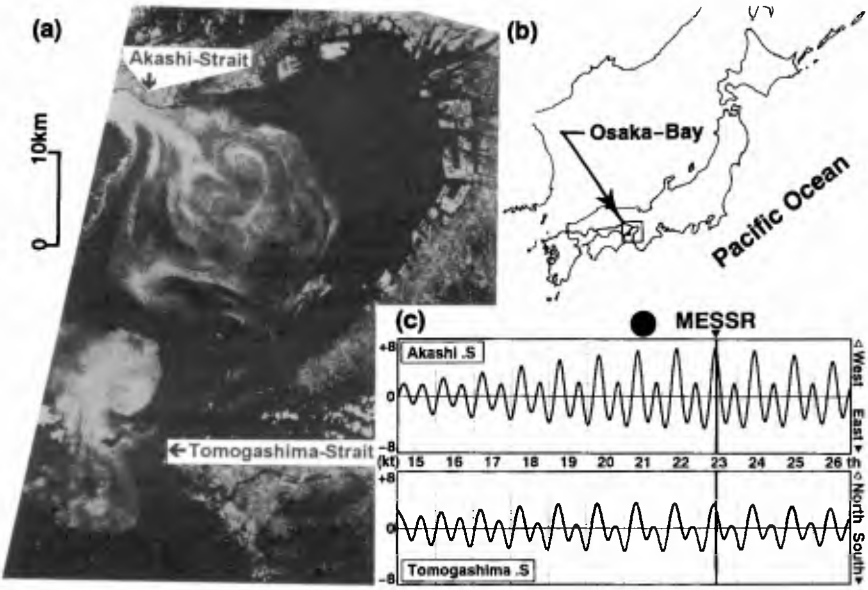
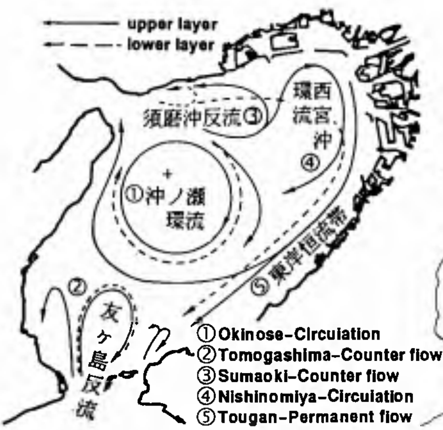


Figure 1. Tidal turbulence in the Osaka-Bay. (a) Flow visualization with Mos-1/MESSR high gain visible data at 1028, 23 December 1987. (b) Location of the site. (c) Tidal change showing with the running speed at Akashi and Tomogashima-Straits in 15-26 December 1987 (Source: forecasted value by the Maritime Safety Agency of Japan).



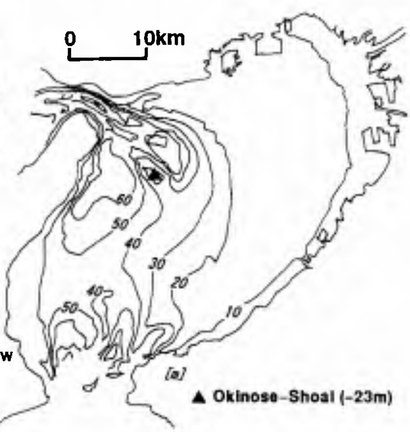


Figure 2. Schema of tidal residual circulations in the Osaka-Bay. (by Fujiwara, 1989)

Figure 3. Topography of the rotating closed vessel of the Osaka-Bay.

Flow visualization of coherent structure

On the MESSR image, we detect a coherent structure in the tidal turbulence, which is fed by the tidal jet and is interlocked inside this closed sea basin. Figure 1(c) shows the tidal change indicated with running speed at the two straits. When the MESSR data were received, north tide of about 3 knots in speed is flowing into the bay through the Tomogashima-Strait. On the satellite image, we identify a dipole of a cyclone and an anticyclone is now growing through the inverse cascade of turbulent eddies, which are injected riding on the northward tidal jet. Near the Akashi-Strait, we find another dipole. Through the strait, however, the west tide is discharging out of the bay with about 6 knots in speed. Here, we identify the dipole with that formed by the east tides in the past, which transported the turbulent eddies into the bay. The most impressive is that the dipoles are not independent, but interconnect to organize a coherent structure interlocked in the whole basin. The cyclones and anticyclones are rotating so smoothly just like the gears interlocked in a machine gear box.

Morphology and scales of coherent structure

Tide curves forecasted at the two straits are the time series index of the input of turbulence energy into the Osaka-Bay. The dominant frequency components are those of semidiurnal, diurnal and of half a month due to the moon aging. The coherent structure is equipped with three stages of morphology. The first one is the 3-dimensional turbulent eddies, which are injected into the bay riding on the tidal jets. The time and space scales are minutes and 10 meters, respectively. The second stage relates to the 2-dimensional dipoles near the straits, which is formed through the inverse cascade of injected turbulece. The scales are hours and kilometers. The third stage is the 2-dimensional coherent structure filling the whole bay, which is formed through the inverse cascade of 2-dimensional dipoles. The scales are days and 50km.

Tidal residual circulation

The coherent structure hadn't been so explicitely recognized until the satellite based flow visualization was realized. From surface surveys performed in the past, however, we can extract some onsite information implicitely indicating the physics of turbulence. Figure 2 shows the schema of tidal residual circulations compiled by Fujiwara (1989). The most dominant one is the anticyclonic circulation near the Akashi-Strait, the Okinose-Circulation named after a shallow shoal locating there.

Comparing it with the MESSR image, we find a geometrical similarity. The key of this similarity is in the topographical boundary of this closed vessel (Figure 3). If the vessel interlocked tight the coherent structure, then we would gain ensemble mean turbulence quite similar to each sample of instantaneous turbulence. Here, we identify the tidal residual circulations with the ensemble mean of coherent structure dominating in this rotating closed vessel. To observe the turbulence processes, however, the satellite survey has some disadvantage; such a large period of repetitive observation and so frequent cloud covering against the sequential observation.

Hydrodynamical experiments in a rotating system

Some laboratory experiments were performed by employing the scale down model of prototype turbulence. Figure 4 outlines the experimental arrangements and methods. The 3-dimensional model of Osaka-Bay was set on a turntable of 2 meter in diameter. Horizontal scaling ratio is 1/50,000, which is determined by the diameter of table. Vertical scaling ratio is set as 1/1,000 to make the surface tension effects negligible. With the Froude's similarity law, the scaling ratio for the time is calculated at 1/1,581. Employing the Rossby's similairty law, the rotation period of the turntable is set as 98 seconds. Under these conditions, topographical β-effect is satisfied.

The tide was generated by two plunger-type tide generators installed outsides of the two straits, which are computer-controlled to reproduce the forecasted tide curves at the two straits. The flow field is visualized with floating fine particles of aluminum powder, and the movement was recorded sequentially by a VTR camera.

Daily-mean velocity and vorticity fields

The sea surface velocity vector distribution was estimated in every hour by applying the pattern matching method to sequential VTR image frames sampled with a certain time interval. Through the time averaging, daily-mean velocity fields were obtained. Taking a spatial differential, the daily-mean vorticity fields were calculated.

Figure 5 shows the daily-mean velocity and vorticity fields in the model basin corresponding to the MESSR image obtained on 23 December 1987. On the velocity field, we detect the tidal residual circulations quite similar to the prototype ones shown in Figure 2 compiled by Fujiwara (1989). The vorticity field looks much like the prototype eddy patterns interpreted on the MESSR image shown in Figure 1.

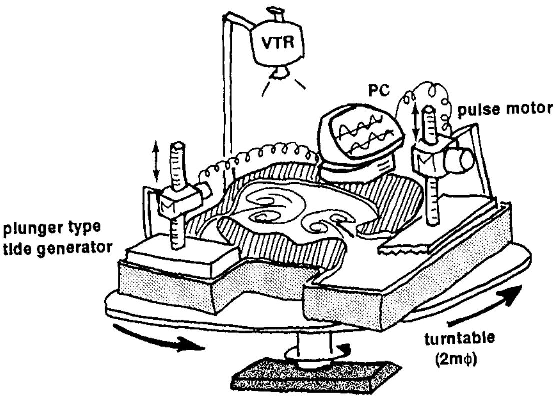


Figure 4. Experimental apparatus and methods for the hydrodynamical experiments on the tidal turbulence of Osaka-Bay. The diameter of turntable is 2 meter.

Earth rotation effects on turbulence

The present model is characterized by the Rossby's similarity law. For the experimental limitation, the model is one order smaller in size, and one order larger in the distortion ratio than the existing models. Table 1 indicates the comparison of some parameters for the present model to those for existing two model basins, which had been also driven for the physical simulation of the tidal flow field in Osaka-Bay. These two models are those designed with the Froude's similarity law alone. The sizes were set one order larger than the present model in order to simulate the bottom friction, but the earth rotation effects on the turbulence were assumed negligible.

For the comparison, the earth rotation effects on the tidal turbulence inside Osaka-Bay was estimated here using the present model. Figure 6 shows one of the experimental results, which were obtained on the stationary table. We see that this Froude model fails to simulate the prototype coherent structure. The vorticity fed through the Akashi-Strait diffuse into the whole basin, and the bay is dominated by a basin scale anticyclonic tidal residual circulation. In the traditional design of physical models, the earth rotation effects were usually neglected for the sea basin of less than 100km in size. There, the bottom friction was estimated as the dominant parameter, and the Reynolds number was made as close as possible to the prototype to take the similarity in the turbulence mixing. Refering to the experiments on geophysical coherent structure, however, the turbulent eddies is made of higher coherence when it is in a rotating system (Nihoul, 1989). Comparing the turbulent fields in Figures 5 and 6, it is shown that the earth rotation effects should be put the first priority in the physical modelling of tidal turbulence in Osaka-Bay of 50km in size.

Table 1 Scale down model experiments and parameters.

	horizontal scale	vertical scale	distortion ratio	Reynolds number	Froude's similarity	Rossby's similarity
Ishikawa(1979)	1/2,000	1/159	12.5	1×10^5	+	
Imamoto(1988)	1/5,000	1/500	10.0	3×10^4	+	
Present model	1/50,000	1/1,000	50.0	1×10^4	+	+

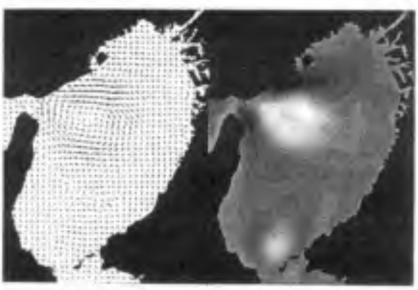


Figure 5. Daily-mean velocity and vorticity fields in the Froude/Rossby model.

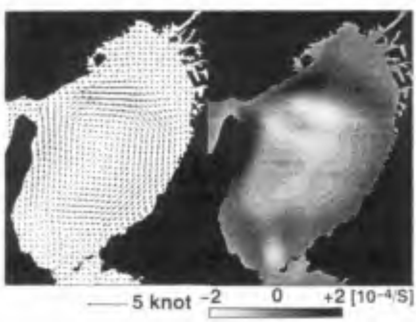


Figure 6. Daily-mean velocity and vorticity fields in the Froude model.

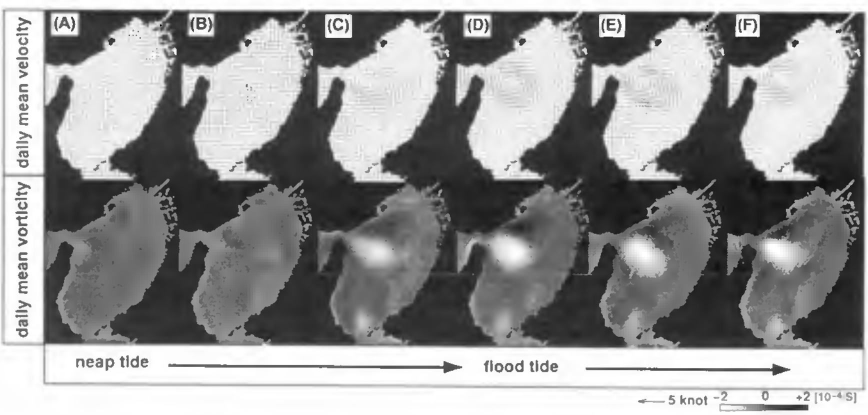
Hysteresis with moon aging

An impressive phenomenon in this Froude/Rossby model is the hysteresis detected in the process of coherent structures. Figure 7(a) shows the daily-mean turbulence fields, which were gained at some representative phases of moon aging; neap tide, flood tide and transient phases. Figure 7(b) shows the modelled tide curve at the Akashi-Strait, which corresponds to the prototype in the December 1987, when the MESSR image shown in Figure 1(a) was obtained.

In the case (A) of the neap tide, little trace of the coherent structure is found. In the cases (C)~(E) at the flood tide, the coherent structure is formed, which is similar to the MESSR image and to the schema of tidal residual circulation. By the detailed inspection, we see that the coherence of eddy structure and the similarity to the prototype are both made higher as the moon ages.

The remarkable difference is observed in the transient phases of the moon aging. Comparison between the daily-mean turbulence fields in the cases (B) and (F) denotes a hysteresis in the turbulence processes due to the aging of moon. In the transient phase (B) from neap tide to flood tide, we scarecely find any coherent structures. In the transient phase (F) from flood tide to neap tide, we find a coherent structure, which was established by the preceding flood tides. Although the strength of tide is same, the coherent structure in the bay is much more robust in the decreasing phase of the tide than in the increasing phase. The time scale of this hysteresis phenomenon is estimated at days, which is comparable to the earth rotation.

(a)



(b)

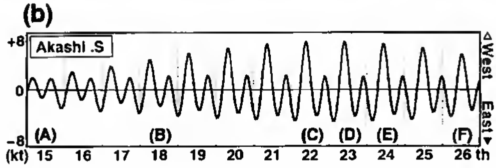


Figure 7. Hysteresis in the process of coherent structure in the Froude/ Rossby model of Osaka-Bay.
(a) Daily-mean turbulence fields.
(b) Tide curve at Akashi-Straits.

Satellite based verificaion of the hysteresis

For the physical reasoning of the hysteresis phenomenon, we should remark the three stages of the coherent structure and two stages of inverse cascade processes. Figure 8 shows a Landsat/TM image of the neap tide flow field inside the Osaka-Bay. Although the dipoles are formed near the two straits, the coherent structure in the third stage is not yet organized. In this case, the second stage of inverse cascade fails to proceed, and we can scarecely expect the tidal residual circulations.

Figure 9 shows a Landsat/MSS image in the final phase of flood tide. On the image, we can interpret three dipoles, which were produced through the inverse cascade from the 3-dimensional turbulence injected by the eastward tidal jets of preceding flood tides. They are labelled as A, B and C respectively on the Landsat/MSS image and on the tide curve at the Akashi-Strait. These dipoles are riding on the anticyclonic Okinose-Circulation formed by the preceding flood tides.

Here, we notice that the central part of the set of dipoles is composed of three anticyclones, which would strengthen the Okinose-Circulation feeding it with the anticyclonic vorticity. In the decreasing phase from flood tide to neap tide, such an inverse cascade proceeds effectively, and the tidal residual circulation is maintained to gain the robustness. In the increasing phase, on the other hand, this process is scaresely expected because of the absence of existing Okinose-Circulation. This difference in the second stage inverse cascade cause the hysteresis in the coherent structure with moon aging.

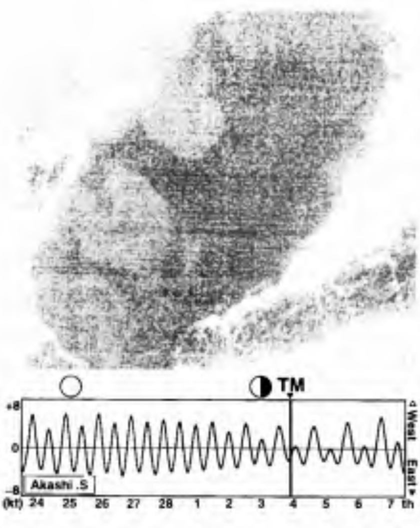


Figure 8. Landsat/TM image of the neap tide flow field on 4 March 1986.

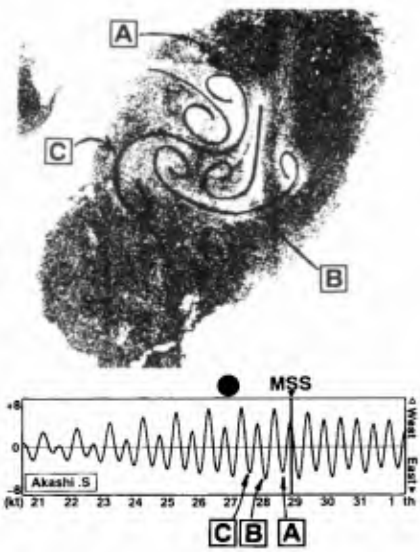


Figure 9. Landsat/MSS image of the flood tide flow field on 29 August 1984.

Inverse cascade of 3-dimensional tidal jets

Based on past research, it is well known that a pulse-like 3 dimensional jet injected into a vessel forms a compact dipole when it is in a rotating system (Nihoul, 1987). Figure 10 shows an experimental verification of the earth rotation effects on the inverse cascade of 3-dimensional tidal jet. To abstract the process, the topography of Osaka-Bay is simplified to a rectangular basin with a single strait and a flat bottom as shown in Figure 10(b). This 2-dimensional model is intended to compare with the Froude model of tidal residual circulation by Yanagi (1976) with 5 times larger size. The tide generator was driven to generate a sinusoidal tide curve at the strait.

Figure 10(a) shows the daily-mean velocity and vorticity fields. In the Froude model (A), the flow field similar to Yanagi(1976) was gained, in which the Okinose-Circulation was formed inside the whole bay similar to the 3-dimensional model shown in Figure 6. In the Froude/Rossby model (B), it was made compact near the strait like the 3-dimensional model shown in Figure 5. For the physical model of the first stage inverse cascade, however, this model is oversimplified. As the topography was made 2-dimensional from the first, the turbulence injected into the bay is composed of 2-dimensional line vortices, which is well known to inverse cascade easily in nature. In order to simulate the inverse cascade from 3-dimensional tidal jets,

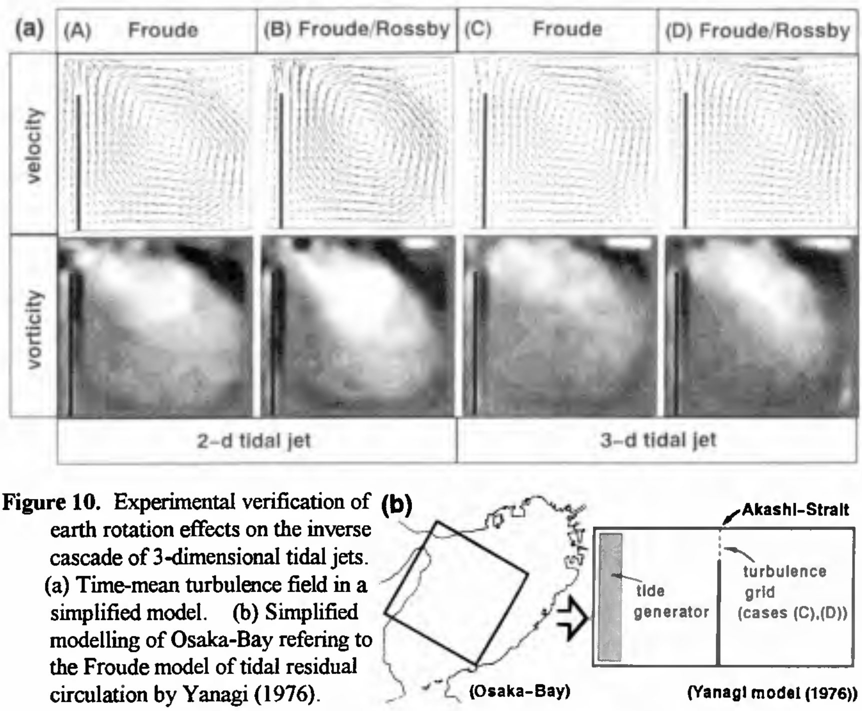


Figure 10. Experimental verification of earth rotation effects on the inverse cascade of 3-dimensional tidal jets. (a) Time-mean turbulence field in a simplified model. (b) Simplified modelling of Osaka-Bay refering to the Froude model of tidal residual circulation by Yanagi (1976).

the last two experiments were done installing a turbulence grid at the Akashi-Strait. In the Froude model (C), the inverse cascade didn't proceed so efficiently as in the case of 2-dimensional tidal jets. In the Froude/Rossby model (D), a more compact Okinose-circulation is formed near the strait.

Earth rotation, roughness and 2-dimensionality of turbulence

In the numerical modelling of tidal flow fields, the earth rotation effects are usually formulated with the Coriolis term. On the simplified physical model, however, the eddy viscosity is also influenced in the rotating system significantly. Then, some turbulence characteristics are expected only from the physical model, however, it is under an experimental limitation from the size of available turntable. As shown in Table 1, the distortion ratio of Froude/Rossby model is 5 times higher than the representative Froude model used by Ishikawa(1979), which has been practically applied to the assessments of physical influence due to reclamations. The higher the distortion rate is set up, it enhances more the 3-dimensionality of the turbulence in the model, and the first stage inverse cascade is relatively underestimated. Figure 11 shows the experimental estimation of the balance of hydrodynamical effects of earth rotation and 2-dimensionality of turbulence, in which the daily-mean turbulence on 23 December 1987 are compared. Case (A) shows the model of 50 in the distortion ratio, which has been examined here in detail. In the Froude/Rossby model, the prototype coherent structure was well simulated excepting some deviations found in the location

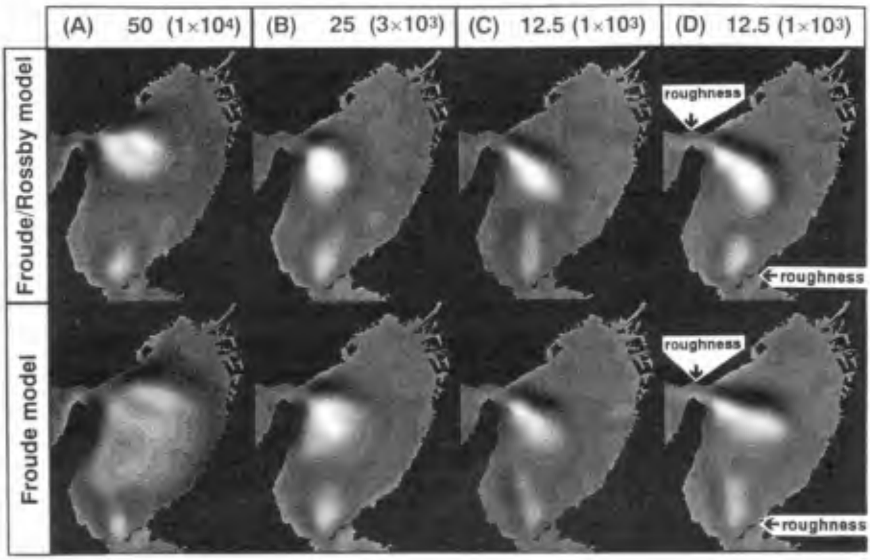


Figure 11. Experimental estimation of the balance of hydrodynamical effects of earth rotation and 2-dimensionality of turbulence. The parameters are distortion ratio (Reynolds number) of the 3-dimensional model. The representative length and speed are the mean depth and maximum speed at the Akashi-Strait.

of the Okinose-Circulation. Case (B) shows the results in a model basin of 25 in distortion ratio. Owing to the improvement in the 2-dimensionality of tidal jet, the similarity of Froude/Rossby model is made higher. Here, we also notice that the difference due to the earth rotation is made smaller. In the case (C), the distortion ratio was set at 12.5, same to the representative Froude model for the practical use. As the 2-dimensionality of tidal jet is improved further, the Okinose-Circulation is made positioned nearer to the Okinose-Shoal in the Froude/Rossby model. In the same time, the difference caused by the earth rotation effects are made much smaller.

Here, we should mention that the Reynolds number of the third model is two order less than that of the representative Froude model, and four order less than in the prototype Osaka-Bay. The turbulence energy injected into the model basin is underestimated in this model. To simulate the first stage inverse cascade of tidal jet in the last Case (D), some artificial roughness were attached at the narrowest part of the straits of Akashi and Tomogashima. On the Froude/Rossby model, the Okinose-Circulation is made positioned exactly overhead the Okinose-Shoal. On the Froude model, however, the reproducibility is made less than in the case without roughness, as the first stage inverse cascade of 3-dimensional turbulence scarcely proceeds.

Concluding remarks

From the viewpoint of a turbulence interlocked inside a rotating closed vessel, the physics of the tidal flow field in Osaka-Bay was examined. Through the flow visualization by Mos-1/MESSR, a coherent structure very similar to the tidal residual circulation was detected, which is interlocked tight inside the bay. The morphology and scales of the coherent structure are revealed. To discuss the turbulence processes, laboratory experiments were done using a hydrodynamical model of 1/50,000 in scaling ratio with the Froude/Rossby similarity law. A hysteresis in the turbulence processes was detected, and was verified through the hydrodynamical interpretation of Landsat images. Based on a simplified model experiments, it was shown that the earth rotation accelerates the inverse cascade of 3-dimensional tidal jet. Using four types of scale down models with some difference in distortion ratio and surface roughness, the hydrodynamical balance of earth rotation, bottom friction and 2-dimensionality of turbulence were estimated experimentally.

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