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A DRIVING MECHANISM OF THE TSUSHIMA CURRENT

By Masaki TAKEMATSU* and Tsugio KITA†

Using a simple laboratory model on a turntable rotating anti-clockwise, we demonstrate that differential cooling of the Japan Sea induces a considerable amount of inflow through the Korea/Tsushima Strait and outflow through the Tsugaru Strait. The model consists of a cylindrical Perspex basin of constant depth placed centrally in a larger tank; the inner basin ('the Japan Sea') is connected with the outer tank through two shallow passages on the "western" and "eastern" side of the basin. The fluid motion in the model is produced by cooling the "northern" portion of the basin's sidewall. It is observed by a dye technique that the localized sinking of cold water along the "northern" sidewall, combined with the deflection effect of the (constant) Coriolis force, gives rise to an intense "western" boundary current in the basin and an inflow through the "western" passage. A feature of the buoyancy-driven inflow is that its volume transport tends to concentrate in the "northern" part of the passage.

In some experiments the "eastern" passage is closed to mimic the Mediterranean Sea with the Strait of Gibraltar. In this case, the differential cooling induces a surface inflow underlain by a compensating outflow through the single opening on the "western" side of the basin.

***Key words*:** Inflow/Outflow, Japan Sea, Mediterranean Sea, Differential cooling, Experiment.

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1. Introduction

A major feature of the current system in the Japan Sea is the inflow of the Tsushima Current through the Korea/Tsushima Strait and the outflow through the Tsugaru Strait. This in- and outflow phenomenon in the Japan Sea is generally thought to be caused by the pressure (sea-level) difference associated with the Kuroshio current system in the North Pacific Ocean (cf. Minato & Kimura[1], Toba et al.[2], Sekine[3] and Fang et al.[4]). As noted by Minato & Kimura[1], however, the pressure difference in the open ocean is merely one of probable factors causing the in- and outflow of the marginal sea : Differential cooling and wind forcing over the Japan Sea are among other promising factors. Indeed, a previous laboratory work (Takematsu[5]) has suggested that sinking of cold water due to differential cooling might strongly affect the in- and outflow process through openings (an opening) of a marginal sea. It is this suggestion that has motivated the present laboratory study.

The laboratory model employed is a conceptually simple one on an f-plane, consisting of a cylindrical basin of constant depth which is connected with "an open ocean" through two shallow passages. The fluid motion is driven by applying a uniform cooling at a portion (1/4) of the basin's sidewall as in the previous experiment[5] : Sidewall cooling is much easier to control than the more realistic way of cooling from above, and that it can cause a localized sinking of cold (dense) water similar to that in real oceans. The resulting convective circulations in the model are observed by a dye technique over a period of 'stratification time scale'.

On an f-plane, unlike on a β-plane, there is no definite rule for introducing cardinal points. One natural and meaningful way of doing so may be to regard the cooled portion of the basin as "north" for anti-clockwise (northern hemisphere) basic rotation. Other directions are then automatically determined. In what follows, directions thus introduced to the model ocean will be distinguished by attaching quotation marks " " like "west" or "east". In most experiments one passage is made on the "west" side of basin and the other is on the "east" side. If the "eastern" passage is closed, the model mimics the Mediterranean Sea with the Strait of Gibraltar. Experiments are carried out also for this model with a single passage to see the possible effect of deep sinking in the Mediterranean Sea on the water exchange processes through the Strait of Gibraltar.

2. Experiment

A top view of the laboratory model is schematically shown in Fig. 1. The model consists of a plexiglass cylindrical container (40 cm in diameter) placed centrally in another container (60 cm in diameter). The inner basin is connected to the outer one through two shallow passages whose width is 5 cm (about 5 time the internal radius of deformation). A portion (1/4) of the annulus region between the two cylindrical containers is partitioned by two insulated vertical

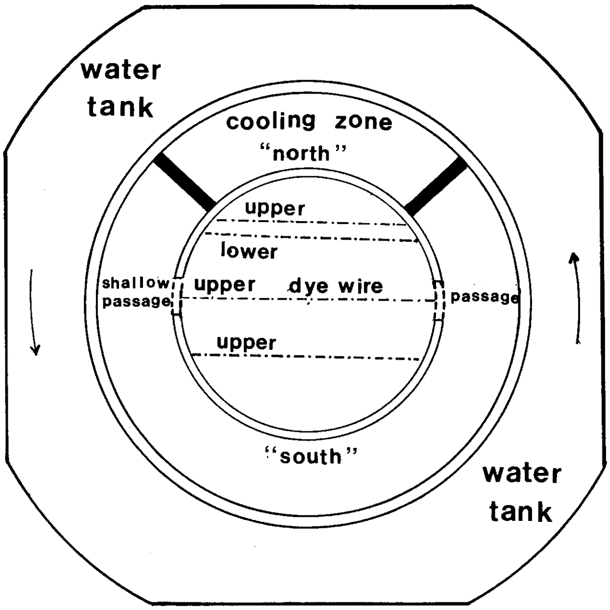


Fig. 1 Top view of the experimental set-up on a turntable

plates so that the water temperature in this section can be varied independently of the remainder. The working fluid then occupies the remaining portion (3/4) of the annulus region and the inner basin to a constant height (mostly 8 cm). These working basins are further set in a larger water tank (80 cm in diameter) to minimize the effect of change in room temperature on the working fluid; otherwise, the sidewall of the outer basin is directly exposed to the temperature change, which readily gives rise to unwanted convective motions in the annulus region and then in the inner basin. Initially all the water temperatures in the apparatus are set at a fixed value, say T_0, and the top of the working basin is covered with a lucite plate to prevent the air from exerting a stress on the free surface of the working fluid. The whole apparatus is mounted on a turntable and set rotating in the counterclockwise direction about its vertical axis of symmetry. After the working fluid attains a complete solid-body rotation (this is confirmed by releasing dye lines), the water temperature in the partitioned (1/4) portion of the annulus region is lowered, by ΔT_0 say, by adding chilled water to the "northern" section and is kept at the lowered value ($T_0 - \Delta T_0$) throughout the duration (about 3 hours) of each experimental run, while the outer surfaces of the sidewall and the bottom of the working basins are kept at the initial temperature T_0. This provides a well-controlled local cooling to the sidewall of the inner working basin. Experiments are conducted only when the room temperature is slightly higher (by less than 0.5°C) than the water temperature

T_0; otherwise, the top cover of the working basin gets opaque. Then the working fluid is subjected to heating from above. Repeated checks by dye lines show that the uniform heating from above alone induces no appreciable motion in the basin.

The convective motion thus induced in the basin is observed by a dye technique. Then a diluted solution of thymol blue (a pH indicator) is used as the working fluid and several electrodes of 0.005 cm platinum wire are stretched horizontally across the basin at desired locations and depths. A movable vertical electrode of 0.05 cm copper wire is also used to survey the vertical profile of the flow. When a d.c. potential (15V) is applied across the electrodes, blue dye is swept off each electrode by the flow. Resulting dye patterns are photographed by a camera mounted on the turntable. The temperature of the working fluid is measured by a thermistor at the foot of the cooled ("northern") sidewall.

The controllable external parameters are the basic rotation rate Ω, the applied temperature difference ΔT_0 and the height of the working fluid H. Values of the parameters in the present study are

$$\Omega = 0.1 \sim 0.5\,\mathrm{rad/s}, \quad H = 8\,\mathrm{cm}$$
$$\Delta T_0 = 0.5 \sim 1.5^\circ\mathrm{C} \quad (\text{for } T_0 = 15^\circ\mathrm{C} \text{ typically}).$$

Here it should be noted that the effective temperature difference imposed on the working fluid is much smaller than ΔT_0 due to highly insulating nature of the sidewall material (0.8 cm-thick plexiglass); temperature measurements show that it is about one third of ΔT_0. Then we will use

$$\Delta T = \Delta T_0/3$$

rather than ΔT_0 itself as a measure of the thermal forcing. In terms of these external parameters, a propagation speed of the density difference, the internal radius of deformation and the buoyancy frequency are given respectively as

$$c = \sqrt{g \cdot \alpha \cdot \Delta T \cdot H}, \quad \lambda = c/2\Omega$$

and $$N = \sqrt{g \cdot \alpha \cdot \Delta T/H},$$

where g is the gravitational acceleration and α the thermal expansion coefficient (which depends on T_0).

Values of these quantities are typically (for $\Delta T_0 = 1.0^\circ\mathrm{C}$, $T_0 = 15^\circ\mathrm{C}$, $\Omega = 0.3\,\mathrm{rad/s}$)

$$c = 0.6\,\mathrm{cm/s}, \quad \lambda = 1\,\mathrm{cm}, \; N = 0.081/\mathrm{s}.$$

Related controllable non-dimensional quantities are the Ekman number E, the Burger number S and the Rayleigh number Ra, which are respectively defined as

$$E = \nu/2\Omega H^2,$$
$$S = (N/2\Omega)^2 \cdot (H/L)^2 = (\lambda/L)^2,$$

and

$$Ra = g\alpha\Delta T H^3/\nu\kappa,$$

where L is the diameter of the working basin, ν the kinematic viscosity and κ the thermal diffusicity. Most experiments are conducted under the following conditions:

$$\begin{cases} E = 10^{-4}\sim10^{-3}, \quad S = 10^{-4}\sim10^{-3}, \\ Ra = 10^{6}\sim10^{7}. \end{cases}$$

After the onset of the differential cooling, the resultant convective motion seems to evolve on three time-scales. The shortest time-scale is $\tau_1 = L/c$, which is of the order of 1 min in the present experiment. The phenomenon under consideration is a typical 'filling-box' process (Turner[6]). An important time-scale for general 'filling-box' problems is the time required to pump all the working fluid through vertical boundary layers along cooled (or heated) sidewalls (see, e.g., Worster & Leitch[7] and Condie[8]). This 'stratification' or 'heat-up' time is given for the present configuration as

$$\tau_2 = LH/\kappa Ra^{1/4},$$

and takes values of order 1 hour: In real oceans this time-scale may be equivalent to a mean residence time for water mass, of order 100 years. The longest time-scale is the thermal diffusion time

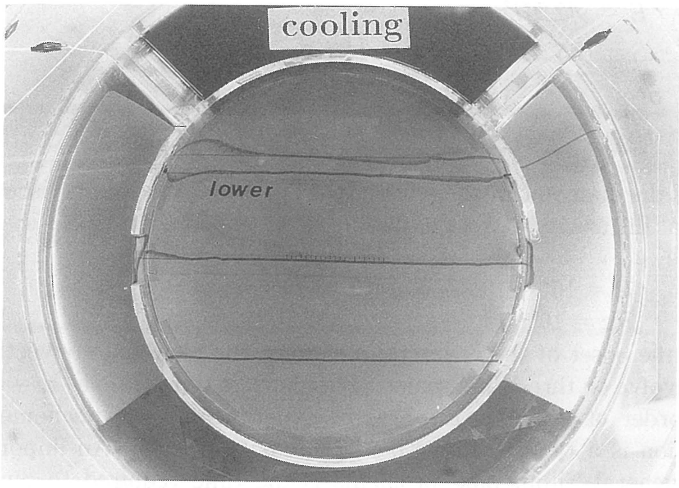
$$\tau_3 = H^2/\kappa,$$

which is about 12 hours in the present case. The duration of each experiment is about 3 hours ($\sim 2\tau_2 < \tau_3$).

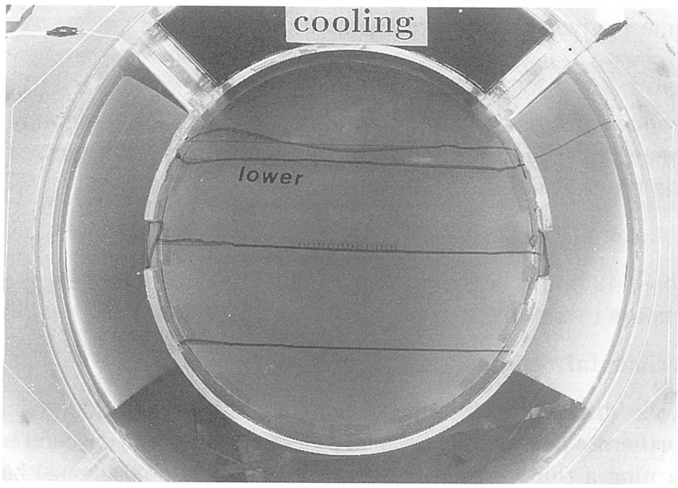
3. Experimental results

When the differential cooling is applied, working fluid adjacent to the cooled ("northern") portion of the basin's sidewall begins to descend towards the bottom, forming a thin vertical boundary layer. The cold (dense) bottom fluid then flows away from the source region towards "south" in a density current. Under the rotational constraint, the density current is readily deflected to the right and results in a deep boundary current along the "western" sidewall. Thus, localized sinking in the "northern" part of the basin, combined with the (constant) Coriolis force, produces a "western" intensified boundary current in the lower layer. What is of interest here is the compensatory motion in the upper layer of the basin with two openings and the associated in-and outflow through the openings; the buoyancy-driven motion in the absence of opening was described in a previous paper[5].

Fig. 2 a), b) show a typical horizontal circulation pattern in the basin with



2 a)



2 b)

Fig. 2 A basin-wide circulation and an in-and outflow through the two openings induced by the sidewall cooling: $\Omega = 0.140$rad/s, $\alpha \Delta T = 0.30 \times 10^{-4}$. The lower dye wire is at 1.5 cm above the bottom and others are at the mid-depth. Interval between dye pulses is 1min.
a) 30 min b) 90 min

two openings at two different times after the onset of differential cooling. The localized sinking in the "northern" area causes a considerable amount of inflow through the "western" passage and an equal amount of outflow through the "eastern" passage as well as a basin-wide circulation with "northward" "western" boundary current in the upper layer of the inner basin; the major flow features in the inner basin are essentially similar to those described in a previous paper[5]. A distinctive feature of the buoyancy-driven inflow is that its volume transport is concentrated in the "northern" part of the passage. The maximum speed of the inflow is nearly identical to that of the "western" boundary current. Dye lines from a vertical (movable) electrode show that both the inflow and the outflow are almost barotropic although they have slight vertical shears decreasing downwards. Therefore the volume transport of the in-and outflow can be estimated from dye profiles across the passage at its mid-depth (by graphically integrating the prafiles.) For the case in Fig. 2 b), the estimated volume transport is of the same order of magnitude as the total rate of sinking along the "northern" boundary which can crudely be estimated by $\pi/4 \cdot \kappa L\ Ra^{1/4}$ (see, e.g., Condie[8]).

Fig. 3 shows a similar horizontal circulation pattern for a different rotation rate $\Omega=0.419$ rad/s. Note that the widths of the inflow, "western" boundary current and bottom counter current are all smaller than the corresponding widths in Fig. 2 b) for $\Omega=0.140$ rad/s. This variation in current width seems to be related to that in the internal radius of deformation λ : Indeed, values of λ in Fig. 3 and Fig. 2 b) are 0.7 cm and 1.7 cm respectively. A width of the inflow is about 3 λ.

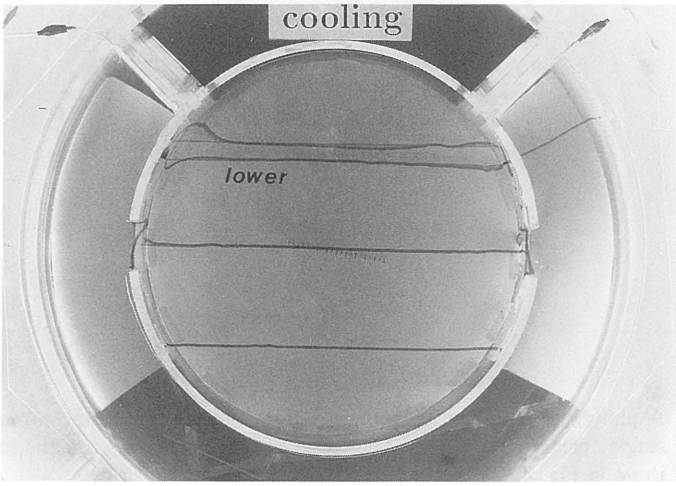


Fig. 3 A basin-wide circulation and an in-and outflow at 150 min for a different rotation rate: $\Omega=0.149$rad/s, $\alpha\Delta T=0.30\times10^{-4}$. Dye interval, 1.5 min.

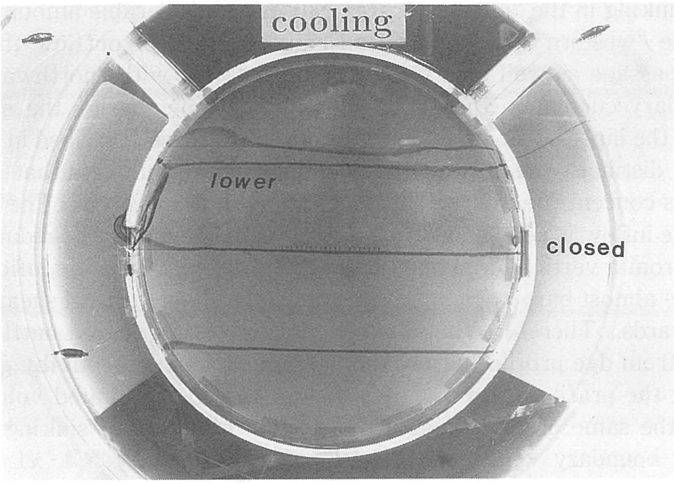


Fig. 4 A surface inflow and a compensatory outflow in the lower layer through the single "western" opening: $\Omega=0.140$rad/s, $\alpha\Delta T=0.67\times10^{-4}$

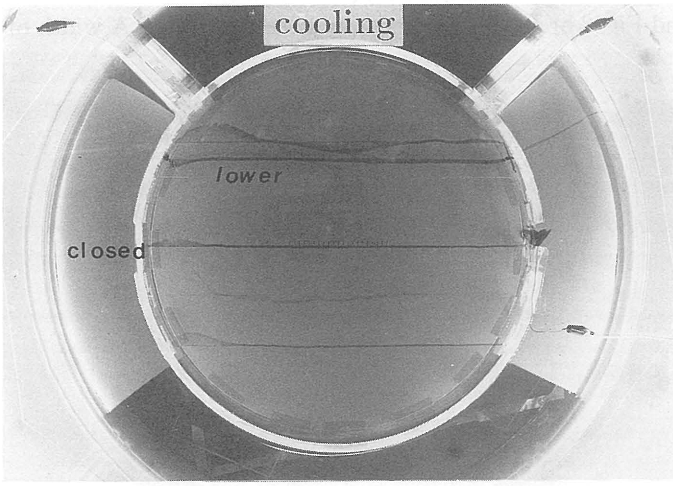


Fig. 5 A photograph illustrating the absence of an in-and outflow through the single "eastern" opening. The experimental conditious are the same as those in Fig. 4.

Experiments with one passage closed are also suggestive. Figure 4 illustrates a feature of the flow through the "western" passage when the "eastern" one is closed (a configuration relevant to the Mediterranean Sea). Dye patterns released from a vertical electrode at the center of the passage show that the flow through the single passage has a strong vertical shear ; an inflow similar to those in Figs. 2 and 3 occurs only in the upper layer and the surface inflow is replaced by a lower-layer outflow from the inner basin. For comparison, a typical example of flow patterns in the basin with the "western" passage closed is presented in Fig. 5. The dye released at the "eastern" passage is only lingering around its source region, indicating that no appreciable in-and outflow occurs through the "eastern" passage if the "western" passage is closed. Thus we see that the "eastern" passage plays only a passive role in the buoyancy-driven in-and outflow process. The "northern" sinking gives rise to a suction force along the "western" boundary of the basin, in particular in its upper layer, and it is this suction force that drives the surface inflow in Fig. 4 as well as the nearly barotropic inflows in Figs. 2 and 3. The suction force is expected to get stronger as the distance from the sinking region decreases. Figure 6 shows an inflow through the "north-western" opening. It is noticeable that the volume transport of the in-and outflow is much larger than that through the "western" opening in Fig. 2 b).

In an additional experiment the water temperature of the cooling zone is raised, rather than lowered. A resulting horizontal circulation pattern is shown in Fig. 7, where the heating zone is regarded as "south". The localized rising of

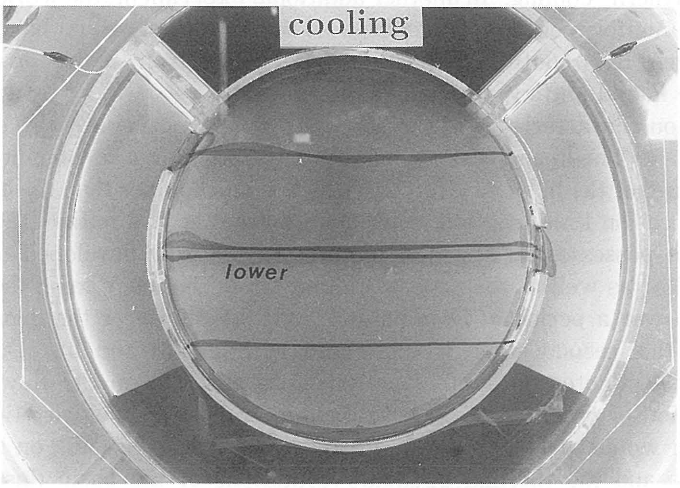


Fig. 6 An intense inflow through a "western" opening located very near to the sinking region. The experimental conditions are almost the same as those in Fig. 2 b). Interval between dye pulses is 0.75 min (45sec).

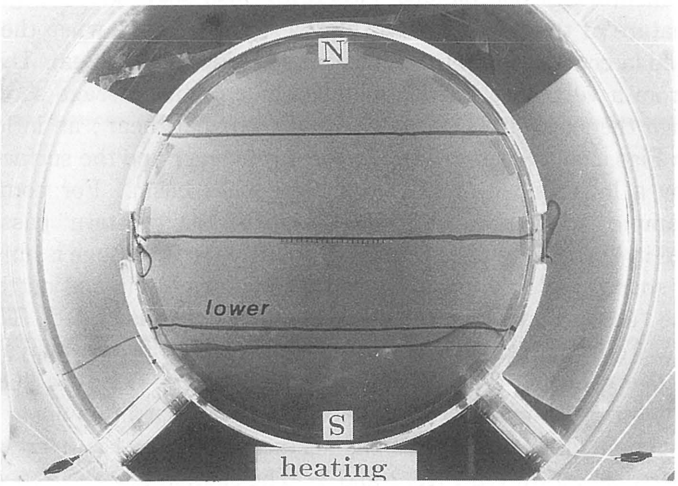


Fig. 7 An in-and outflow through the two openings induced by heating a "southern" portion of the basin's sidewall:
$\Omega=0.419$rad/s, $\alpha\Delta T=0.63\times10^{-4}$ (heating). Dye interval, 1.5min.

warm fluid along the heated sidewall causes a basin-wide anti-clockwise circulation in the inner basin and an in-and outflow through its two passages. It is remarkable that the inflow occurs again through the "western" passage as in the case of "northern" cooling. In another additional experiment, the working basin subjected to uniform cooling from above as the Japan Sea would be during the last Ice Age. It is confirmed that uniform cooling from above produces no appreciable in-and outflow through the openings.

Evolution characteristics of the buoyancy-driven motion are also examined in some detail. The in-and outflow manifests itself within a few minutes ($\sim 5\tau_1$) after the onset of the buoyancy forcing, which is much faster than the characteristic stratification time τ_2. The convective motion at this initial stage is still weak, but it possesses all essential features of the fully developed one. The in-and outflow as well as the general circulation in the inner basin then gradually evolve over a period of 90 minutes ($\sim\tau_2$). Evolution of the general flow pattern at this second stage is illustrated in Figs. 2 a) and b). During the subsequent 90 minutes no appreciable chang is observed in the flow pattern. After a period of order τ_3, the density field as well as the velocity field in the entire basin would attain a certain steady state, which depends on the room temperature and the thermal boundary conditions of the basin (insulated or isothermal).

4. Conclusions and discussion

The laboratory experiments on an f-plane with the northern hemisphere rotation have shown that deep sinking in a "northern" area of the basin produces not only a basin-wide circulation with a "western" boundary current but also an inflow from an open ocean if there is a passage on the "western" side of the basin. The convective flow manifests itself very soon ($\sim 5\tau_1$) after the onset of differential cooling and gradually evolves on longer timescales (τ_2 and τ_3). The volume transport of the inflow depends on the location and geometry of the passage as well as on the total rate of sinking: In most cases, however, the volume transport has been the same order as the sinking rate. More detailed study of the quantitative aspects of the in-and outflow is now under way. For ease of observation the experiments have been performed mainly within the laminar-flow regime, but some tentative experiments with larger ΔT_0 have indicated that a similar in-and outflow occurs also in turbutent-flow cases.

The buoyancy-drivern inflow process demonstrated herein may be oceanically relevant. We have in mind the winter-time deep sinking in the northern part of the Japan Sea or of the Mediteranean Sea. Such a sinking may induce a nearly barotropic inflow through the Tsushima Strait or a surface inflow through the Gibraltar Strait. Since the deep sinking is intermittent in reality, the resultant inflow and the compensatory outflow may also be intermittent. In this respect it should be recalled that the inflow phenomenon responds very soon (within a period $5\tau_1$ or so) to the change in the thermal forcing. In real marginal seas τ_1 may be of the order of 10 days. Then the experiments suggest that the in-and outflow processes may feel the seasonal change in the rate of sinking.

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