Coastal dispersal of urban treated wastewater in semi-enclosed estuaries

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ABSTRACT

Anthropogenic land-derived materials in urban wastewater in semi-enclosed, partially stratified estuaries (Osaka Bay and Harima Nada, Japan) are investigated with a triple-nested high-resolution ocean model. The dispersal and dilution of effluent released from the subsurface nearshore outfall of Tarumi Sewage Treatment Plant near Akashi Strait is considered. The effluent dispersal in the northeastern Osaka Bay is two-layered and highly reversible in the upper and lower layers due to stratification influenced by freshwater input mainly from Yodo River. The overall effluent load is in the dominant circulation direction of Seto Inland Sea encompassing the two estuaries, substantially controlled by Kuroshio.

KEY WORDS: oceanic downscaling; ROMS: The Regional Oceanic Modeling System; urban wastewater effluent; buoyancy plume

INTRODUCTION

Osaka Bay and Harima Nada located off the densely populated Kobe and Osaka areas are encompassed in the northeastern part of Seto Inland Sea, Japan (**Fig. 1**). Complex shoreline topography with over 3,000 islands in Seto Inland Sea (SIS) and riverine inflows play an essential role in formation of quite complicated tidal and estuarine circulations. Uchiyama *et al*. (2012) reported that the overall circulation in Seto Inland Sea is strongly affected by the seasonally varying Kuroshio path. The water quality, coastal marine ecosystem and aquatic resources in these estuaries are significantly influenced by anthropogenic sewage effluent and river discharges (*e.g.*, Abo *et al*., 2012). Therefore, for a rigorous hydrodynamic and associated material dispersal modeling for these shallow estuaries, it is necessary to precisely account for boundary conditions to convey the SIS circulations to Osaka Bay and Harima Nada, forcing conditions such as tides, river inputs, and surface wind, and the lateral topography and bathymetry as exactly as possible. To this end, in the present study, we develop an oceanic downscaling system in a triple nested configuration to conduct a high-resolution forward modeling of Osaka Bay and Harima Nada with lateral grid spacing of 200 m. A particular attention is paid to dispersion of sewage effluent released from the subsurface nearshore outfall of Tarumi Sewage Treatment Plant (TSTP) near Akashi Strait (**Fig. 1 middle**) that is considered to be a potential source of nutrient loads to the inner Osaka Bay attributed to the clockwise predominant current in Seto Inland Sea. The modeling system is similar to the one developed for Santa Monica Bay and San Pedro Bay, California, USA (Uchiyama *et al*., 2014) while the area of the previous study is rather at an open coast, differing to the tidally-driven, semi-enclosed, connected estuaries considered in the present study.

REGIONAL CIRCULATION MODEL

The triple nested regional ocean circulation model for Osaka Bay and Harima Nada relies on a state-of-the-art regional ocean model, ROMS (Shchepetkin and McWilliams, 2005; 2008). The outermost boundary condition is provided by JCOPE2 (Miyazawa *et al*., 2009), an eddy-resolving, assimilative oceanic reanalysis product with a horizontal grid resolution, dx, of 1/12º ($dx \approx 10$ km) to bring offshore signals inclusive of influences of Kuroshio into the ROMS-L1 model at dx = 2 km (**Table 1**). The triply nested configuration (**Fig. 1 left**) based on ROMS successively refines the grid spacing from dx = 600 km (L2) to 200 m (L3). The L3 model consists of 800 × 560 horizontal grids with 32 bottom-following, stretched vertical σ-layers. The intermediate L1 and L2 results described in Uchiyama *et al*. (2012) are exploited for the lateral boundary conditions of the innermost L3 model with a bihourly update to account for high frequency tidal signals. One-way, offline nesting approach (Mason *et al*., 2010) is used to accurately reproduce internal tides as in the previous studies (*e.g.*, Buijsman *et al*., 2012). The L3 grid relies on the high-resolution (at dx = 50 m) dataset of the topography and the coastal embankments compiled by Japan's Cabinet Office. We make use of the hourly GPV-MSM reanalysis product (JMA) for surface wind stresses and the COADS climatology for the other surface forcing. Monthly climatology of freshwater inputs from the 10 major rivers in L3 is taken into account. The computational period is chosen for the four-month period from Aug. 1, 2009 to Nov. 29, 2009.

EFFLUENT POINT SOURCE SUBMODEL

Sewage effluent is applied in L3 at the location of TSTP (**Fig. 1 right**) as a bottom-released fresh (buoyant) plume at the monitored hourly volume rate with a Gaussian initial dilution submodel to avoid undesirable non-hydrostatic effects (Uchiyama *et al*., 2014). Eulerian passive tracer is additionally released at TSTP to track the effluent.

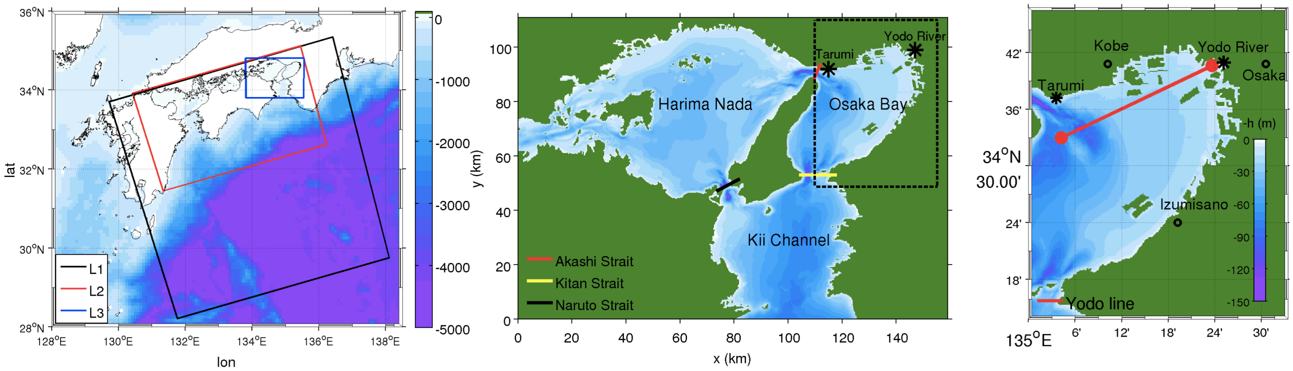

Fig. 1. (Left) ROMS-L1, L2 and L3 domains, (middle) ROMS-L3 domain, (right) blow-up of Osaka Bay and Yodo Line (red line).

Table 1. The configlations for the triple nested ROMS model.

	ROMS-L1	ROMS-L2	ROMS-L3
Horizontal grids	320× 320 (× 32 vertical)	800× 480 (× 40 vertical)	800 ×560 (× 32 vertical)
Horizontal resolution	2.0 km	600 m	200 m
Surface wind stress	JMA GPV-MSM (hourly)	JMA GPV-MSM (hourly)	JMA GPV-MSM (hourly)
Other surface flux	COADS（monthly）	COADS (monthly)	COADS (monthly)
Major river discharge	29 rivers (monthly)	27 rivers (monthly)	10 rivers (monthly)
Lateral boundary condition	JCOPE2 (daily)	L1（daily）	L2 (two-hourly)
Tides	N/A	Barotropic tides at the open boundaries using TPXO7.0 (Egbert *et al*., 1994)	Barotropic and baroclinic tides at the open boundaries with high-frequency B.C. update
Topography	SRTM30 + JEGG500	JEGG500 (500 m)	Japan Cabinet Office (50 m)

The near-field initial dilution submodel of Uchiyama *et al.* (2014) is employed in the present study. Given an input pollutant concentration in the outfall pipe C_p [kg/m^3] with volume flux $Q_p(t)$ [m^3/s], we force a normalized tracer concentration equation by an equivalent source P [1/s]

$$\frac{\partial c}{\partial t} + \nabla \mathbf{u} c = P \tag{1}$$

Here the unit of c is pollutant concentration normalized by C_p (unlike salinity which is a mass fraction of seawater), and $\mathbf{F} = \mathbf{u}c$ (+ $\mathbf{F}_{sgs}$) is the advection-mixing flux associated with the flow and subgrid-scale (sgs) parameterizations. The source P is

$$P(x,y,z;t) = P_s(t)A(x,y)H(z) \tag{2}$$

with A and H are specified spatial functions mimicking the outcome of unresolved nearfield mixing above the outfall diffusers; their values are non-dimensional and close to one in the source region and zero outside it. They have integrals equal to the effective source area and depth,

$$\iint A\,dx\,dy = A_s; \quad \int H\,dz = H_s \tag{3}$$

with A_s the horizontal area, H_s the vertical size, and $V_s = A_sH_s$ the volume. P_s is determined from integrated tracer equivalence between the model source and the pipe inflow by the relation, $P_s = Q_p/V_s$. For our simulations we use outfall data for $Q_p(t)$, and we could multiply by a mean concentration value C_p for any particular pollutant species (e.g., CDOM) to translate from our c fields. There is an analogous forcing source in the model's salinity S equation, $R = R_sAH$, by the freshwater flow out of the pipe, where integral balance implies that $R_s = -S_oQ_p/V_s$ with $S_o = 35$ PSU the mean oceanic salinity.

The wastewater effluents are specified as hourly freshwater volume fluxes of $Q_p = 1.018 \pm 0.0364$ m^3/s. The nearfield vertical mixing of the buoyant effluent occurs on a scale smaller than our grid resolution, and as a hydrostatic model ROMS is ill-suited for the large local vertical velocities associated with the freshwater discharge from the bottom-mounted pipes. Therefore we assume the outcome of the nearfield initial mixing and dilution by imposing the prescribed spatial distributions of A and H in (2).

$A = 1$ in the horizontal grid cells that tile the diffuser pipe sections and zero elsewhere. So $A_s = N_sdx^2$, where N_s is the number of tiling cells and $dx^2 = 2.25 \times 10^4$ m^2 is the cell area. For TSTP, $N_s = 9$ for the bottom-mounted nearshore outfall pipe. We fit a Gaussian shape function to H with parameters guided by nearfield buoyant plume

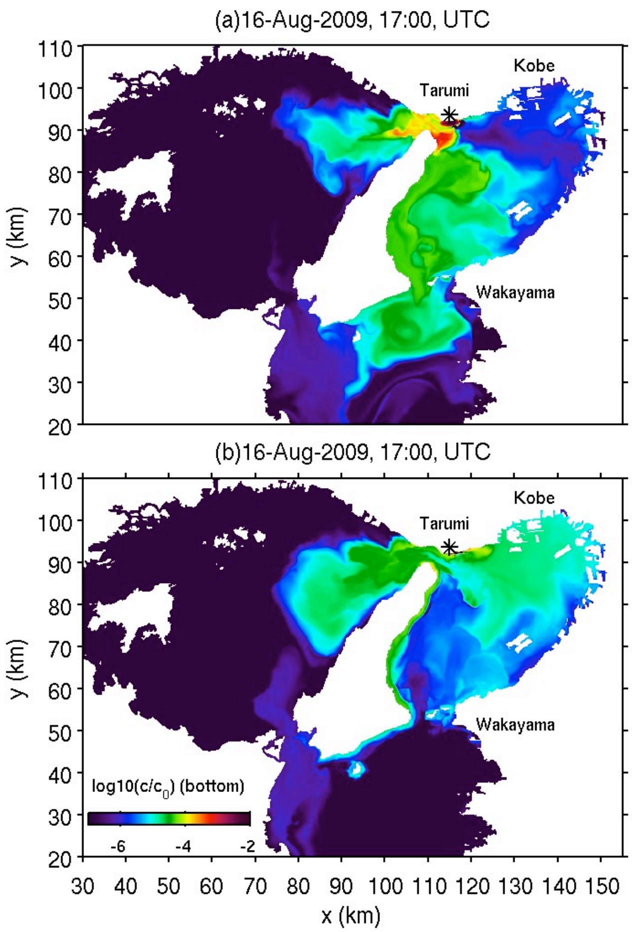

Fig. 2. Snapshots of the $\log_{10}$-based normalized passive tracer concentration on Aug. 16, 2009, in (a) surface and (b) bottom layers.

solutions obtained by the model of Roberts *et al*. (1989) with measured currents near the outfall:

$$H(z) = \exp\left[-\frac{(z - z_s)^2}{d_s^2}\right] \tag{4}$$

where z_s is the plume center height, and d_s is its vertical scale. A half-space integral of this $H(z)$ is 0.5 $d_s\sqrt{\pi}$. For the TSTP outfalls, we presume that the plume penetrates the stratification and rises up to the surface: z_s = 0. We further choose d_s = 10 m, hence H_s = 8.9 m neglecting the bottom boundary limit.

A feasible future generalization of this nearly-steady effluent source is to use monitored $Q_p(t)$ and run the nearfield buoyant plume model with modeled local currents. This would contribute additional variability to the effluent distributions seen in the present solutions.

EFFLUENT DISPERSAL

Significant differences between the bottom and the surface layers are observed in the passive tracer concentration (*i.e.*, wastewater effluent) released from TSPT. Initially, the tracer in the surface layer (the top-most s-layer) is mainly transported toward Osaka Bay and spread southward, whereas the prevailing transport occurs eastward in the bottom layer (the bottom-most s-layer). On the 16th day, the tracer begins to emerge in the surface layer in the inner part of Osaka Bay near the month of Yodo River and to subsequently flow westward (Fig.2a). Meanwhile the near-bed tracer has reached the inner bay (Fig.2b). This would be caused by an upwelling associated with an estuarine recirculation in the inner bay near Yodo River that has the largest freshwater input to Osaka Bay. Once surfaced, the effluent is dispersed over the entire Osaka Bay due to the mean near-surface flow in the WSW direction. This suggests that the estuarine recirculation is substantial to form a two-layered structure in the inner Osaka Bay that plays a key role in three-dimensional effluent dispersion.

VERTICAL STRUCTURE

Figure 3 (top panels) shows the monthly-averaged offshore (southwestward) velocity along the Yodo Line (**Fig.1**). As anticipated in the preceding subsection, the lateral velocity in the northeastern Osaka Bay is two-layered and reversible in the upper and the lower layers due to stratification (not shown) induced by the freshwater input. The interface between the offshore-directed surface current and the shoreward subsurface current is located approximately at 3-5 m deep, corresponding to the mixed layer depths computed with the KPP model (Durski *et al.*, 2994). This recirculating reversal clearly leads to the upwelling of the near-bed effluent at the inner Osaka Bay (**Fig. 3 bottom**). In week 1 of Aug., 2009, the tracer distributes in the vertical near the release site crossing the pycnocline to deeper than 40 m. In weeks 2 and 3, subsurface intrusion into the lower layer occurs off Kobe with onshore transport of the concentration maxima, and continuously disperses towards the inner bay. In weeks 3 and 4, the tracer surfaces by the upwelling associated with the estuarine recirculation, and then drifts back to the southwest in the upper layer.

TRACER FLUX BUDGET

A tracer flux budget analysis is conducted at the three straits (*viz.*, Akashi, Kitan and Naruto). Predominant effluent transport is found to occur westward to HN at Akashi Strait, while in the southward direction to the Pacific at Kitan and Naruto Straits. The cumulative normalized tracer fluxes for the four-month period are 1.04×10^6 m^3 at Akashi, 1.63×10^6 m^3 at Kitan, and 2.28×10^5 m^3 at Naruto Strait, respectively. The estimated inventory reveals that 75% and 8% out of the total amount of the released sewage water in the four months are accumulated in Osaka Bay and Harima Nada, albeit the rest (about 17%) disperses towards the Pacific Ocean through Kii Channel.

SUMMARY

Anthropogenic land-derived materials in urban wastewater have been recognized to influence on the water quality and the marine ecosystem in Osaka Bay and Harima Nada, Japan. Towards a rigorous environmental assessment of these two semi-enclosed estuaries, a triple-nested high-resolution oceanic modeling framework based on ROMS is developed to investigate the dispersal and dilution of treated swage water effluent released from the subsurface nearshore outfall of Tarumi Sewage Treatment Plant near Akashi Strait. The effluent dispersal in the northeastern Osaka Bay is two-layered and highly reversible in the upper and lower layers due to stratification influenced by freshwater input mainly from Yodo River. The overall effluent load is in the dominant circulation direction of Seto Inland Sea encompassing the two estuaries, substantially controlled by Kuroshio. The estimated cumulative tracer flux for a four-month period is found to accumulate by about 75% in Osaka Bay, while merely 17 % exits towards the Pacific Ocean.

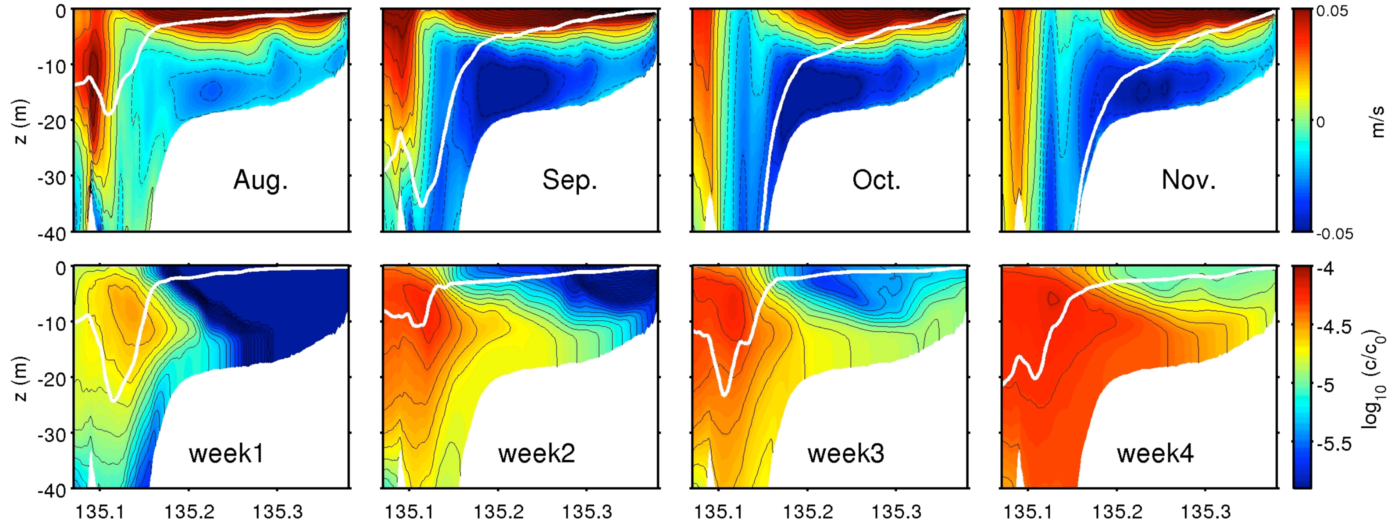

Fig. 3. Cross-sectional plots of the monthly-averaged offshore (to the SW) velocity (top panels) and of the weekly-averaged normalized tracer concentration in Aug., 2009 (bottom panels). The while curves indicate the corresponding mixed layer depths.

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