Ocean Prediction for Aquaculture: 
An Interview-based system

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Abstract. Interviews with scallop aquaculturists were conducted using the Grid Evaluation Method to evaluate the information most valuable to them. The interviews suggested that low-salinity nearshore water, which can increase the mortality of cultured scallop in the nursery stage, is a major concern in spring. Here, we show that a coupled land–ocean,
high-resolution model predicted springtime maps of the low-salinity nearshore water and its interannual variations in the specific enclosed bay with aquafarms. The proposed visualization for simultaneous display of low-salinity water, snow cover, and river runoff may be preferable to provide helpful information. The predicted salinity around aquafarms can provide essential information to help reduce mortal risks.

Keywords: Real-time prediction, Coupled land–ocean simulation and visualization, Evaluation Grid Method, Funka Bay, Aquaculture, Scallop, Low-salinity nearshore water

1. Introduction

State-of-the-art ocean simulations with high spatiotemporal resolution have practical applications to ship routing, rescue operations, flooding or surges forecasts, [1], and smart fishing [2, 3]. Overall, many real-time ocean predictions (forecasts and hindcasts) can provide a large amount of data on velocity, temperature, sea-level, and other quantities to the general
The predicted results should be interpreted to provide information for stakeholders such as fishers [4].

Aquaculture is operated mainly in semi-enclosed bays or inland seas [5], and currently contributes approximately 48% of the aquatic animal food destined for human consumption [6]. Information from the prediction system is required to effectively inform fishers in enclosed bays with aquafarms. Before distributing the predictions, we need to know which predicted properties are beneficial to effective aquaculture operation.

The objective of the present study is to answer the question: which prediction system and visualization are necessary to provide the information required by aquaculturists? To address this question, we attempted to interview aquaculturists using the Evaluation Grid Method (EGM) [7] and employed an ocean prediction system that can be used during various periods, from several days to interannual timescales [8].

We selected Funka Bay in northern Japan (Hokkaido; Figure 1), as the pilot study area. Funka Bay is a typical enclosed bay and produces vast amounts of scallop around the coastal ocean every year [9].

Figure 1: (a-d) Nested domains of our prediction system and bathymetries (color). (e) Map of the study area showing watersheds (colors) and aquafarm (black blocks) around Funka Bay. Broken line denotes the boundary of the bay. Contours indicate the topography in meter. Open blue circles represent river observation stations with emphasis on four major watersheds (solid lines). Red dots denote the Automated Meteorological Data Acquisition System (AMeDAS) stations. The eight capital letters (T, D, Y, K, O, N, and S) are the abbreviations for the major rivers (Torizaki, Nodaoi, Yurappu, Kunnu, Oshamanbe, Nukibetsu, and Osaru Rivers, respectively).
2. Interviews by Evaluation Grid Method (EGM)

2.1. Overview

The EGM [7] is an efficient interview method that extends the Repertory Grid Method [10] based on personal construct theory [11]. Here, the term "construct" represents a unit of understanding that includes a pair of opposing concepts. When humans recognize an event such as "the ocean current is fast/slow" or "the operation is easy/difficult", their overall cognition can be composed of a group of "constructs". An essential feature of the EGM is that it can selectively elicit only constructs relevant to the evaluation by asking the examinees why something (e.g., goods, information) is preferable based on their own judgments or requirements. Here, the constructs concerning the evaluation are called "evaluation items".

Each evaluation item should be related by causality, e.g., "the operation is difficult because the ocean current is fast". The overall system is composed of many evaluation items, and their causalities are referred to as the "evaluation structure", which can be finally clarified by the EGM. The evaluation structure can be expressed by a hierarchical network composed of abstract items at higher levels such as "the operation is easy/difficult" and concrete items at lower levels such as "the ocean current is fast/slow" [12]. The higher/lower level of the evaluation items can be elicited by the "laddering" method [13] conducting leading questions and systematically summarized in an evaluation structure.

The EGM has been used by many researchers for product development and design appraisal (e.g., interior accessories, domiciliary environments, and interface designs for electronic devices) [14]. The EGM has the following advantages. 1) It allows the user requirements to be accessed without special skills. 2) The outcome can be presented as a hierarchical network diagram that is comprehensible to researchers and users. 3) The systematic interview procedure can minimize errors and distortions subjectively induced by the interviewers. The EGM can be both practical and efficient and can avoid outcome redundancy.

2.2. Methodology

The procedures of the EGM consist of three steps as follows (Figure 2):

**STEP 1: Prepare "elements"

The "elements" made by various media, formats, and styles should be prepared for cross-comparison (e.g., via color pictures, brochures, and schematics). A card containing words that the examinees know well can be an element; in this case the examinees' memory can also be the element [7].

**STEP 2: Extract "evaluation items" by comparing "elements"

The interviewer asks the relative merits of a pair of elements, e.g., "Why do you think the chosen ocean information is preferable to other information?" The reasons expressed by examinees are recorded as the original evaluation items. If finding out the evaluation items from the examinees is difficult, the interviewer should move to another pair of elements.

**STEP 3: Extract hierarchy of "evaluation items" by "laddering"

After extracting the original evaluation items in STEP 2, the leading questions (laddering questions) are asked for each evaluation items to elicit higher/lower levels [13,15] by conducting a "ladder-up/down" analysis. The questions for the "ladder-up" are of the type "Why..."
do you think that the chosen ocean information is profitable?" and for the "ladder-down" of the type, "What is preferable for you about this ocean information?" Finally, the evaluation structure can be assembled using the causality of evaluation items clarified by ladderings.

2.3. Examinees

We targeted four fishers who are engaged in scallop aquaculture in the homeports of Yakumo, Abuta, and Date, which are fishery harbors in Funka Bay. The fishers use ocean information daily. The interviews were conducted on April 4 and June 18, 2013.

2.4. Procedures

The interviews followed STEPS 1–3. However, the elements used in STEP 1 mainly referred to the examinees’ memories and hence were called "virtual" elements [7] because presenting the vast array of ocean information as real elements is unrealistic and inefficient. We prepared several sample images representing the ocean information that the examinees could easily remember. The prepared images fell into the following categories: 1) ocean observational results (e.g., surface and interior seawater temperature) conducted by research bodies such as the prefectural fisheries research institute, 2) images derived by satellites (e.g., chlorophyll-$a$ distributions), and 3) ocean predictions browsed via personal computers. What is important is that these images, which provide a sense of affinity to the examinees, were used to remember the ocean information used in daily fishery operation. We started the laddering in STEP 3 when the first evaluation item was elicited in STEP 2. If the evaluation items did not emerge, we returned to STEP 2. Thus, we alternated STEPS 2 and 3 to achieve more efficient interviews [16]. The interview times per person were 0.5–1 hour to suppress errors, distortion, and repeating of answers due to fatigue. However, to avoid errors, we stopped the laddering when the examinees exhibited puzzled reactions to answers.

Figure 2: Schematics of three step procedures of the EGM.
2.5. Results

The evaluation structure derived by the EGM (Figure 3) shows that aquaculturists prioritize four items at the highest level: 1) mortal risk, 2) productivity of scallop, 3) safety, and 4) efficiency of operations. These items closely relate to the ocean properties (water temperature, nearshore salinity, chlorophyll-a, waves, flow fields in aquafarms) clarified by the evaluation items in the lowest level. The ocean information used by the examinees varies seasonally and is different in the growth stages of the scallop. For example, the lowest items indicate "Chlorophyll-a maps in aquafarm in spring can be clarified", which can be important in spring as an index of the phytoplankton amount fed on by scallop. The examinees’ interests in the floating larvae maps of scallop are limited in early summer (April–May) because the examinees can decide the "Timing to set-up gears catching scallop larvae in aquafarm" based on the larvae maps. These items exhibit a single relationship toward the upper level and relate to "Fishery yields can be expected" and hence the improvement of operation efficiency and increase of production. The evaluation structure indicates that aquaculturists paid attention to the vertical profile of water temperature, which is related to mortal risk for the scallop from early spring to fall. The examinees check water temperatures in the aquafarm to see if the temperature are high enough (23–24°C) to cause mass mortality. The information on waves and current speeds in aquafarms is also important to suppress the risk of mass mortality because scallop can drop out from the aquafarm due to strong waves and currents. Thus, the evaluation items and their relationships (evaluation structure) for aquaculturists were systematically elicited using the EGM. The priorities of the items depend on the season.

The most interesting structure (red lines and squares) shows that aquaculturists care about the low-salinity nearshore water located in front of their scallop farms because "Mortal risk of scallop can be reduced" at the highest level. Nearshore sea water is pumped up to the nursery scallop house, but scallop cannot survive or grow under low-salinity (<30‰) conditions. The total production of scallop depends on the amount of nursery scallop in spring. Therefore, aquaculturists also pay attention to the snow cover, "Yukishiro" in the mountains and heavy rainfall that can generate high snowmelt runoff from the rivers to the aquafarms. The snowmelt runoff produces large freshwater discharges and forms low-salinity water along the coastal oceans. Using accurate predictions of nearshore salinity, aquaculturists can decide "to stop drawing seawater into nursery scallop house" to suppress the mortal risk to scallop from low-salinity nearshore water.

Our interview research clarified that an ocean prediction system should implement a predictive ability for land-surface conditions and river runoffs to tackle the nearshore low-salinity prediction required by aquaculturists.

To date, studies to predict water temperature and chlorophyll-a on the bay-scale have often been conducted and have gradually improved their predictability. In particular, the seasonal prediction of the vertical profile, water mass, and water temperature in Funka Bay has been in practical use [4,8]. In this study, focusing on the low-salinity nearshore water affecting scallop production, we propose the prediction and visualization of low-salinity nearshore water and analyze its spatiotemporal variation.
Figure 3: Evaluation structure derived by the EGM.
3. Prediction System Overview

To predict land-surface conditions and river runoffs in addition to ocean properties, a coupled land–ocean model was employed in this study. The model consists of both the Hydrometeorological and multi-Runoff Utility Model (HaRUM) [17] (Figure 4) and a three-dimensional Oceanic General Circulation Model (OGCM) developed at Kyoto University [18].

The river discharges can be predicted using the distributed tank model based on the radiation, heat budget, and water mass budgets (Figure 4) by calculating physical components: the solar insolation ($S_{\downarrow}$), the downward longwave radiation flux from the atmosphere ($L_{\downarrow}$), the latent heat flux ($H$), the surface ground temperature ($T_s$), the evapotranspiration ($E$), and the snowmelt ($M$) (see [17] for the detailed physical formulae to calculate the physical components). These budgets can be calculated using the five meteorological properties (rainfall: $P$, air temperature: $T_a$, wind speed, cloud cover, relative humidity) provided by the Grid Point Value datasets of the Meso-Scale Model (GPV-MSM) provided by the Japan Meteorological Agency on an hourly basis. The total river discharge $Q_t$ generated by the net water input ($P+M-E$) can be predicted in each grid of the distributed tank model. The model has three serial tanks represented as $n = 1-3$ and 10 model coefficients ($A_n$, $B_n$, and $Z_n$) for the side outlets ($Q_n$), the bottom outlets ($L_n$), and the water levels ($S_n$), respectively, in each tank (see [17] for the parameter calibrations and model validations). If snow covers the ground surface (Figure 4) and the snow surface temperature $T_{snow} < T_a$, snowmelt $M$ can occur based on radiation and the heat balance. The HaRUM was designed to minimize the calculation cost for ocean forecasts.

The OGCM implemented the hybrid $\sigma$–$z$ vertical coordinate system to better simulate free surface motion of the ocean within the hydrostatic and the Boussinesq approximations using realistic bottom topography. To further enhance the representation of upper ocean circulation, this model adopted some sophisticated parameterizations such as a turbulence closure scheme for the mixed layer, horizontal advection, and isopycnal mixing [18]. To reproduce more realistic salinity distributions around the coastal ocean or aquafarm in Funka Bay, we employed a three-step nesting or downscaling method (Figure 1), which implemented a large-scale, 4-Dimensional VARIational Data Assimilation system (4DVAR DA) model [18].

The 4DVAR DA model (NEST0) covers the western half of the North Pacific with horizontal resolutions of 1/6° and 1/8° in longitude and latitude, respectively, and provides accurate boundary conditions for two nested models embedded in the western region. The first nested model (NEST1) covers the northwestern North Pacific centered on the mixed water region with a medium-range resolution of 1/18° and 1/24°. The second nested inner model (NEST2) has a horizontal resolution of 1/54° and 1/72° to reproduce small-scale physical features within coastal zones. The 78 vertical levels are placed from 4 m near the sea surface to 500 m at the bottom. The boundary conditions used in each nested model are provided from the upper-level (larger-scale) model results using the nesting technique [19]. The assimilated elements in our study are satellite-derived SST and sea surface height (SSH) data, and in-situ observation data of temperature and salinity (see [18] for more details). The river runoff derived from HaRUM is converted to freshwater flux and input in the grids closest to the coast in Funka Bay. The freshwater flux is reflected in a decrease in salinity as the water be-
came elevated by riverine volume inputs in the water column at each surface grid. The high-resolution ocean simulation in NEST 2 is conducted using the initial condition and the spin-up calculation following Ref. [18]. The system runs once a day from a previous day to a projected 5 days from the beginning of 2008.

Reanalysis and predicted meteorological data sets NCEP and GPV-MSM are used as input to the coupled model. These are the mean hourly air temperature, precipitation, cloud cover, relative humidity, and wind speed. The coupled model was validated using observational data, and showed both quantitative and qualitative reproducibility of the temporal variations in the bay after several calibrations [17, 18]. The analysis period was chosen to be from 2008 to 2011 because significant contrasts of snow cover and river runoff in spring were observed during the period, which should have influenced the nearshore salinity in the bay.

4. Results

4.1. Preferable visualization of the predicted results

Figure 5 shows a proposed visualization to concurrently represent the low-salinity near-shore water (red areas) in the bay, river runoffs into the bay, and snow cover areas simulated by the coupled model. The levels of runoff volume transport are depicted by red to blue through the white colors along the river paths. For example, many river paths are visible in red in March 2008, but the number of paths decreased in May and paled in color, indicating that the runoff volumes in March were larger than in May. The snow cover in the mountain was more than that along the coast in March, and the snow cover almost disappeared in May. A similar tendency was found in 2009 and 2011, although the snow cover occupying the mountain in March 2009 and 2011 was more than that in 2008. However, the visible rivers and red colored paths in May 2010 were more than in other years, indicating that the runoff
volumes in 2010 were greater than in other years. Furthermore, the snow cover in March 2010 was more than in other years; the snow in May 2010 still remained on the mountain.

The low-salinity water (<30) shown by the red areas in the bay (Figure 5) often appeared around the river mouths in May 2009 under the condition of the inflow of the saline water to the bay. However, the low-salinity water regions were unclear in 2008 and 2011. Large areas of low-salinity water were widely found along the coast in May 2010, forming the counterclockwise circulation in the bay. The counterclockwise circulation in May 2008 and 2010 was generated by the inflow of the low-salinity Oyashio water in early and late March, respectively. However, the velocity fields in 2009 and 2011 indicated clockwise or inflow patterns because the Oyashio inflows in 2009 and 2011 were much smaller than in 2008 and 2010.

Thus, the graphics include all necessary information on the low-salinity water related to the snowmelt runoffs as revealed by the EGM to reduce mortal risk. Aquaculturists can browse the predicted nearshore low-salinity water and its temporal variation on the Web site based on the proposed visualization. For example, the system can show that low-salinity nearshore water was significant in early May in 2009 and 2010. Aquaculturists can judge a rough period to stop pumping seawater by knowing the spatial distribution of the low-salinity water. The map of the snow cover can quantitatively inform the possibility of substantial snowmelt runoffs. The many river paths colored red in the snowmelt season (March–May) can indicate large snowmelt runoffs into the nearshore waters around the aquafarm.

4.2. Emergence of low-salinity nearshore water

Figure 6 shows Hovmöller diagrams of the daily mean nearshore salinity along the coast of the bay. The nearshore salinity in the spring of 2008 started to decrease in mid-March. The emergence of low-salinity water started from late March but was limited to the areas near the river mouths (N, O, Y, D, and T), which became less saline in April. The inflow of the Oyashio water was recognized in late March, but the decrease in salinity in the nearshore water was unclear because the salinity of the Oyashio water (~32) was close to the nearshore salinity. The salinity in early spring (February–March) in 2011 generally ranged between 32 and 33, less than in other years, but the low-salinity water regions were not clear in the snowmelt season.

The decrease in nearshore salinity in the spring of 2009 also started from mid-March, but the inflow of the Oyashio water in the spring was unclear. The Oyashio inflow was small, as evidenced by Ref. [8]. The emergence of low-salinity water was found in April, May, and August, suggesting that the decrease in nearshore salinity could be mainly induced by the large snowmelt or heavy rainfall.
Figure 5: Examples of visualization of the simulated current velocity, low-salinity areas (purple color), snow cover (water equivalent of the snow cover: W.E.S.C), and river run-off in March and May in each year.
The marked low-salinity nearshore water was more visible in 2010 in contrast to other years. The gradual decrease in nearshore salinity was clearly found in early March 2010, indicating the marked inflow of the Oyashio water. The propagating speed (5–7 cm s\(^{-1}\)), as shown by the solid line on the diagram, was comparable to the typical speed of the coastal Oyashio, indicating advection of the low-salinity water from the original Oyashio region. After the inflow of the Oyashio water in 2010, marked low-salinity water (<30) regions were emergent from early April due to the snowmelt runoffs and continued to occupy most of the nearshore ocean, in particular near the large river mouths (Y, N, and S) until late August, in

Figure 6: Hovmöller diagrams of the daily mean nearshore salinity along the coast of the bay from February to August in 2008–2011. The eight capital letters (T, D, Y, K, O, N, and S) are the abbreviations for the mouths of the major rivers (Torizaki, Nodaoi, Yurappu, Kuninui, Oshamanbe, Nukibetsu, and Osaru Rivers, respectively).
contrast to other years. Thus, the emergence of low-salinity nearshore water can be induced by snowmelt runoff under the conditions of the Oyashio inflow in 2010 (Figure 6).

Figure 7 shows the interannual variations of the total observed precipitations, snow depths, and runoffs of four major rivers (Figure 1) averaged from winter to summer, which were quantitatively consistent to those simulated in Ref. [17]. The snow depth and total rainfall in 2010 was largest in the period from 2008 to 2011, therefore the largest snowmelt runoff occurred in 2010. In particular, the Yurappu and Nukibetsu Rivers were swollen in 2010. These snowmelt runoffs were closely related to the snow depth in the mountain areas, rather than the averaged snow depth.

The total number of days when low-salinity water was emergent in nearshore areas (Figure 8) ranged from 5 to 25 days in 2008, 2009, and 2011. However, the number of days was 50 to 125 in 2010. The amount of snow cover (or averaged snow depth) in 2010 was more than that in 2008 and 2009. The amount of snow cover in 2011 was comparable to that in 2010 (Figure 7), although the maps of the snow cover were locally different between 2010 and 2011. The snow cover in the northeastern (southwestern) mountain was more (less) in 2010 than in 2011, which was consistent with the snow observations (Figure 7). Notably, the total number of days of emergent low-salinity water in 2011 was least among all years, such that the inflow of the Oyashio water was unclear (Figure 5).

The long period of low-salinity nearshore water in 2010 was attributable to the early inflow of the Oyashio water, in addition to the large snowmelt runoff caused by the deeper snow depth on the mountain than in other years. The broad emergence of the low-salinity nearshore water could depend on the timing of the Oyashio inflow; preferable timing would occur in early March.

The ratio of the runoff (Figure 8) indicated that the averaged runoff associated with high snow cover in 2010 was highest among all years, as evidenced by the observations (Figure 7). The averaged runoff in 2011 was less than that in 2010, despite the higher snow cover on the southern mountain in 2011. The highest runoff in 2010 can be caused by rainfall runoff in addition to the snowmelt runoff.

Figure 7: Interannual variations of the total observed precipitations, averaged snow depths, and averaged runoffs of 4 major rivers from November in a previous year to August. The precipitations and snow depths were observed by the Automated Meteorological Data Acquisition System (AMeDAS) in their stations (Figure 1). The runoffs were observed at the river observation stations (Figure 1).
5. Conclusion and Discussion

This study showed that coupled land–ocean models are essential to predict the low-salinity nearshore water around aquafarms. The proposed visualization concurrently exhibits low-salinity water, the Oyashio inflow, snow cover/melt, and river runoffs to effectively inform aquaculturists. It can provide helpful information and reduce the risk of scallop death in the nursery stage.

The remarkable low-salinity nearshore water in 2010 was induced by the large snowmelt runoff under the precondition of low saline Oyashio water inflow from early March. To date, the Oyashio inflow has been generally referred to as a useful phenomenon for scallop aquaculture because it transports nutrients and phytoplankton into the bay. However, we found that the early Oyashio inflow can induce the frequent emergence and endurance of low-salinity nearshore water from spring through summer.

The outcome from our interviews suggested that the prediction of low-salinity water can be emphasized in the nursery stage of the scallops (March–May), as well as the predictability of water temperature affecting the scallop production growth [9] in June–October. The simu-
lated low-salinity nearshore water has shown interannual differences in its distribution. The low-salinity nearshore water can be widely distributed along the coast and continue over 6 months, for example, in 2010. The spread of the low-salinity nearshore water may be important for other fishery productions (e.g., Japanese trout: *Plecoglossus altivelis altivelis*, chum salmon: *Oncorhynchus keta*, oyster: *Crassostrea gigas*). From the viewpoint of the coastal environment, aquatic plants (e.g., eelgrass: *Zostera marina*) useful for water purification can also be influenced by the low-salinity nearshore water [20]. Meanwhile, framework to observe the low-salinity nearshore water will need to be established in a future study because its validation has not been conducted in this study.

Japanese kelp can also be affected by the snowmelt runoffs. For example, the kelp harvests in 2009 (e.g., 55 tons at Yakumo and 19 tons at Mori) were less than in 2008 (e.g., 93 tons at Yakumo and 43 tons at Mori). Such a clear contrast of kelp production between 2008 and 2009 might be induced by land–ocean conditions in the bay. Intrusion of the Tsugaru Warm water and Oyashio water in 2008 was observed, but both were minimal in 2009 [8], leading to poor nutrients throughout the bay in 2009. However, the decreases in the kelp production in 2009 were 44% and 59% of the production in 2008 at Mori and Yakumo, respectively. These productions could be attributed to the nutrients supplied by the snowmelt runoff. Indeed, the snowmelt runoff was higher in 2009 than in 2008 (Figure 7). The decrease for Muroran, located in the northern part of the bay, was 67%. The clockwise circulation might transport the nutrients northward and suppress the decrease in kelp production. The submarine groundwater discharge induced by the snowmelt runoff can be also considered a main source of nutrients for both phytobenthos [21] and kelp.

If dams are constructed on the upstream rivers, their controls will affect the low-salinity nearshore water and should be important to treat the whole water circulation in the coastal areas. Land–sea coupled models and visualization are an essential tool when developing integrated coastal engineering practices.

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**References**


