Environmental influence prediction of discharged water from ocean thermal energy conversion plant in Kume-Island by numerical simulations

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Introduction

Introduction: OTEC plant

What is OTEC :

A renewable energy technology that exploits the thermal difference between surface seawater and deep seawater to generate electric power.

Suitable area :

Tropical and subtropical oceans.

Categorization :

Closed-cycle, open-cycle and hybrid cycle.

Principle of Closed-cycle :

→ vaporized into vapor by surface water
→ drive the turbine to work
→ cooled by the deep ocean water
→ recycled in the system
→ used surface water and DOW will be discharged.

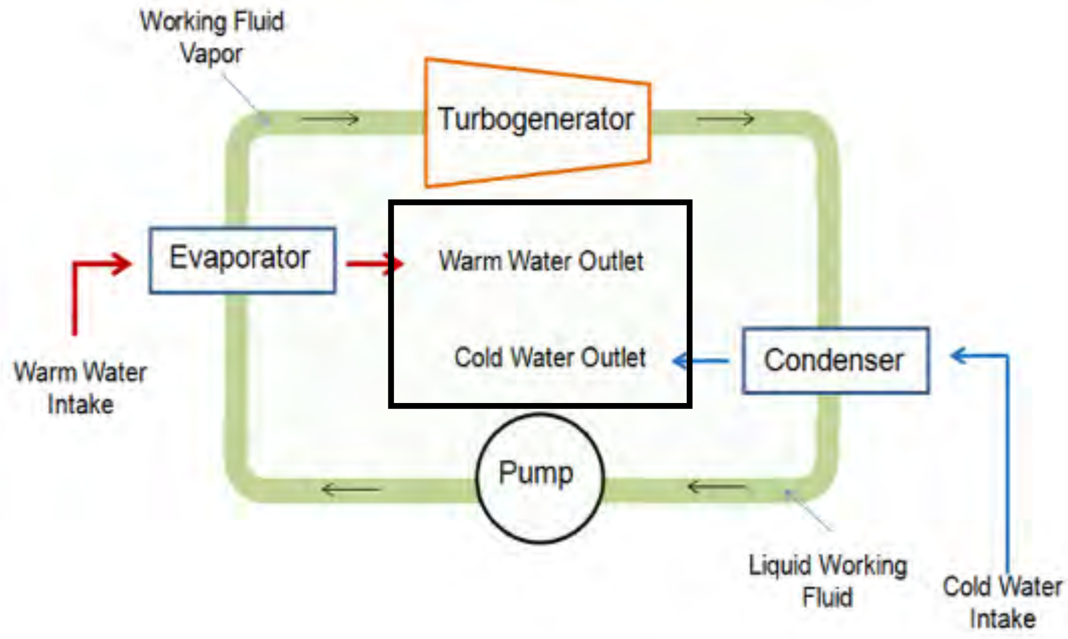


Fig.1. Schematic diagram of closed-cycle OTEC power plant [1].

Introduction: environmental issues

Properties of Deep Ocean Water (DOW):

- Cleanness, uniformity, enormous reservation, fast renewability.
- Low temperature, high nutrient concentrations.

Environmental influence :

Benefit

Enhance primary productivity
Create fish ground.

Issues

Alter local marine environment
Cause a phytoplankton bloom.
Perturb natural population of marine organisms.

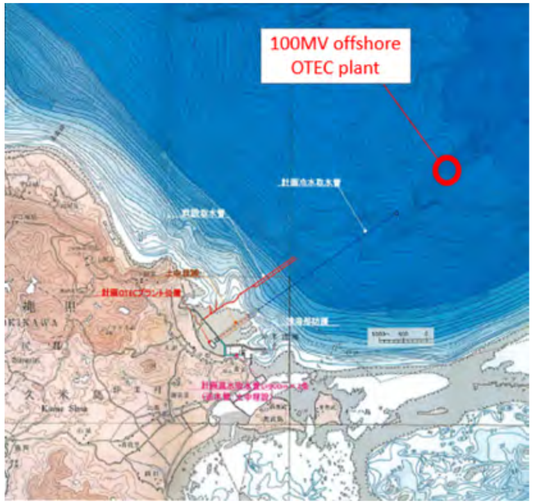
Fig.2. 50 kW OTEC plant on Kume-Island [2].

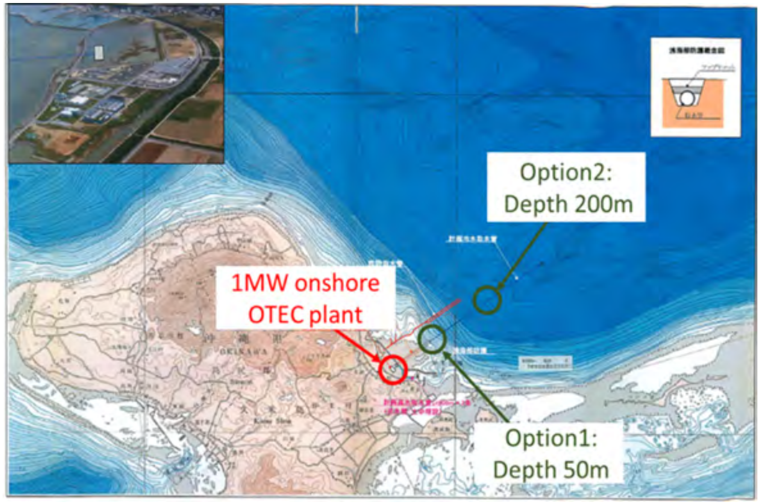
Project of OTEC plant:

In 1974, OTEC study in Japan started with launch of Sunshine Project.
In 2013, a 50 kW OTEC pilot plant was constructed on Kume-Island and performing stable.
Now, commercial scales of 1MW~100MW OTEC plants are in the plans.

Introduction: study cases

	100 MW offshore OTEC plant	1 MW onshore OTEC plant
Location	9km away from northeast coast.	northeast of Kume-Island
Discharge depth	15 m	50 m, 200 m
Discharge amount	1,480,000 t/h	22,100 t/h
Water temperature	16.9° C	18.7° C
Nitrate concentration	9.541×10^{-6}μmol/L	8.44×10^{-6}μmol/L





Introduction: previous work

Marine Environmental influence :

Construction, presence, operation of the OTEC plant;

↓

Discharge and withdraw of the seawater.

Quinbyhunt (1987)

↓

One of the most prominent environmental concern is the potential for upwelled nutrients.

Binger (2003)

Numerical simulations :

100 MW OTEC plant in Hawaii :

EFDC model was adopted to simulate the discharged plume and clarified the nitrate concentration around OTEC plant.

Patrick Grandelli (2011)

1MW OTEC plant in Tarawa, Kiribati :

EFDC and CFD was adopted to identified the dispersion characteristics of discharged water.

Hwang-Ki Lee (2016)

↓

Most of the paper focuses on **Physical Field**.

Few papers concerns about **Ecosystem Response**.

Introduction: objectives

This research focuses on

Environmental influence prediction of the discharged water from the 100MW offshore OTEC plant and the 1MW onshore OTEC plant in Kume-Island.

This research aims at :

- Clarifying the behavior of discharged water;
- Predicting the distribution of the water qualities and planktons;
- Investigating possible ways to control the environmental influence.

Methodology

Methodology: MEC-NEST model

Model

1. Calculation of hydrodynamic process [3]

Navier-Stokes equation:

- $\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + fv + A_M\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(K_M\frac{\partial u}{\partial z}\right)$ (1)
- $\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} - fu + A_M\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(K_M\frac{\partial v}{\partial z}\right)$ (2)
- $0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$ (3)

Continuity equation:

- $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$ (4)

Advection-diffusion equations of the temperature and salinity:

- $\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = A_c\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(K_c\frac{\partial T}{\partial z}\right)$ (5)
- $\frac{\partial S}{\partial t} + u\frac{\partial S}{\partial x} + v\frac{\partial S}{\partial y} + w\frac{\partial S}{\partial z} = A_c\left(\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2}\right) + \frac{\partial}{\partial z}\left(K_c\frac{\partial S}{\partial z}\right)$ (6)

Density equation:

- $\rho = \rho^*(p, T, S)$ (7)

t time;

g gravitational acceleration;

ρ_0 standard value of seawater density;

f Coriolis parameter;

A_M Horizontal eddy viscosity coefficient;

K_M Vertical eddy viscosity coefficient;

A_C Horizontal eddy diffusivity coefficient;

K_C Vertical eddy diffusivity coefficients.

Methodology: Low-trophic ecosystem model

2. Calculation of low-trophic ecosystem model

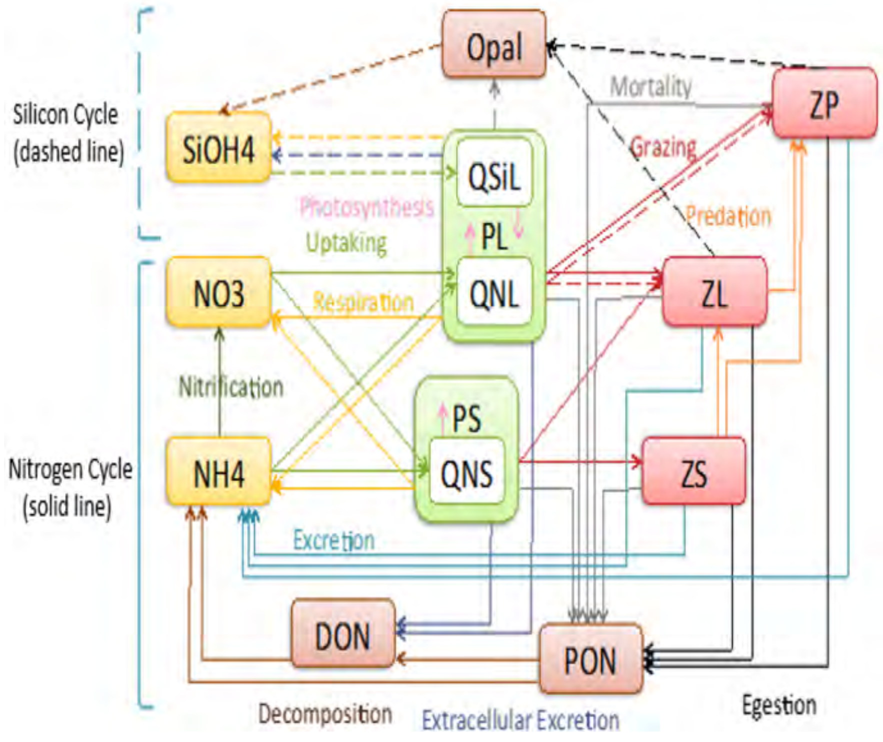


Fig.4 Low-trophic ecosystem model [4].

Table.1. Compartments in the low-trophic ecosystem model

Symbol	Compartment	Unit
PS	Small Phytoplankton	μmolN/L
PL	Large Phytoplankton	μmolN/L
ZS	Small Zooplankton	μmolN/L
ZL	Large Zooplankton	μmolN/L
ZP	Predatory Zooplankton	μmolN/L
NO_3	Nitrate	μmolN/L
NH_4	Ammonium	μmolN/L
$Si(OH)_4$	Silicate	μmolSi/L
PON	Particulate Organic Nitrogen	μmolN/L
DON	Dissolved Organic Nitrogen	μmolN/L
Opal	Particulate Silicon	μmolSi/L
SQNS	Cell Quota of Small Phytoplankton Nitrogen	μmolN/L
SQNL	Cell Quota of Large Phytoplankton Nitrogen	μmolN/L
SQSiL	Cell Quota of Large Phytoplankton Silicon	μmolSi/L

Methodology: Low-trophic ecosystem model

Suppose *B* as the variable of each compartment in the ecosystem model.
Q_{Bi} represents the biological & chemical process concerning each compartment.

$$\frac{\partial B_i}{\partial t}+u\frac{\partial B_i}{\partial x}+v\frac{\partial B_i}{\partial y}+w\frac{\partial B_i}{\partial z} = A_c\left(\frac{\partial^2 B_i}{\partial x^2}+\frac{\partial^2 B_i}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(K_c\frac{\partial B_i}{\partial z}\right)+Q_{Bi} \quad (8)$$

$$Q_{PLn} = GppPLn - ResPLn - MorPLn - ExcPLn - GraPL2ZLn - GraPL2ZPn \quad (9)$$

Gpp represents the production rate due to photosynthesis.
Mor represents mortality rate.
Exc represents extracellular secretion rate.
Res represents respiration rate.

$$GppPLn\,(NO_3, NH_4, Si(OH)_4, Temp, I, PLn) = V_{maxL}\min\left\{\frac{SQNL}{SQNL+QNL0}, \frac{SQSiL}{SQSiL+QSiL0}/RSiN\right\}$$
$$\exp\left(k_{GppL}Temp\right)\int_{-H}^{0}\frac{I}{I_{optL}}\exp\left(1-\frac{I}{I_{optL}}\right)dz\cdot PLn \quad (10)$$

Parameters in the model were picked up from Shiokari (2012), the experiment about the effect of DOW on fertilization in sea area around Oshima.

Model validation

Introduction :

Due to the shortage of local data around area of OTEC plant, I chose the data available in other sea area.

Takumi facility:

Applied density current generator for artificial upwelling.

Mechanism :

Pump in deep ocean water and surface ocean water, mix and discharge in surrounding sea area.

Effect :

Enhancing marine primary productivity by taking advantages of DOW.

Location :

Sagami bay, Kanagawa Prefecture

Observational data source:

Experiment on the effect of Takumi was carried out in 2006.

In the experiment, **uranine** solution was used as the tracer to track the hydrodynamic motion of sea water around Takumi facility.

Results of the **tracer concentration** at the observational spots was acquired and reported by Marinoforum21.

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Results were used to validate MEC-NEST model.

Model validation

Computational Domain:

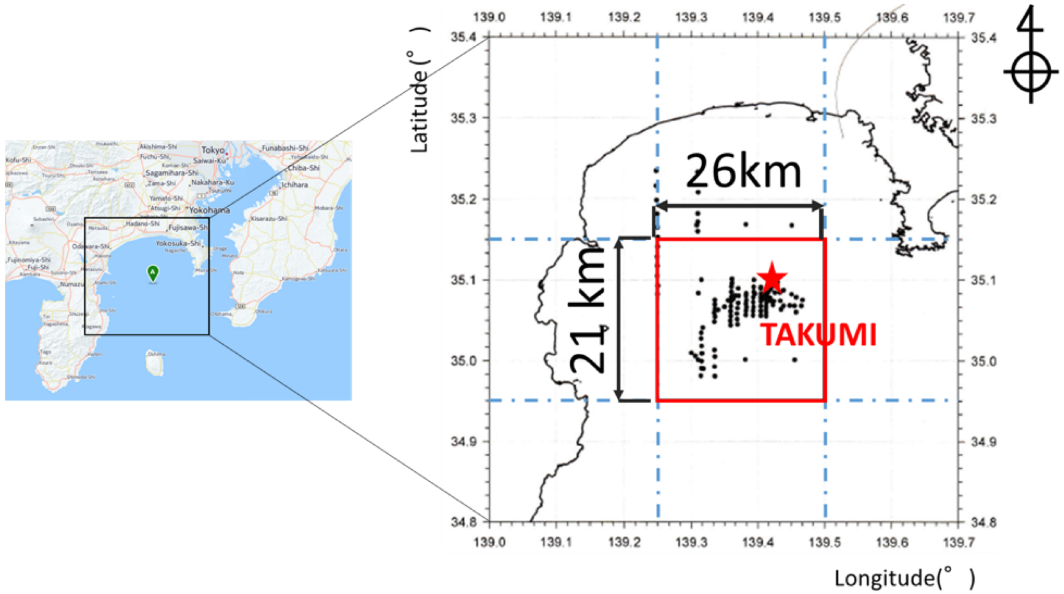


Fig.5. Location and computational domain of Takumi facility.

- Red box is computational domain.
- Black dots are the places where the observation experiment was conducted.

Grid :

Length : 1000m

Number : 26×21×26

Data source:

Meteorological data : JMA

Water quality data: JODC, WOA13

Topographic data : Sasaki (2005)

Experiment data : Marinoforum (2007)

Comparable Approach :

1. Observational data which has clear values are chosen.
2. Tracer concentration of each spots was picked up from the calculation and observation data.

Model validation

Fig.6. Uranine observation line.

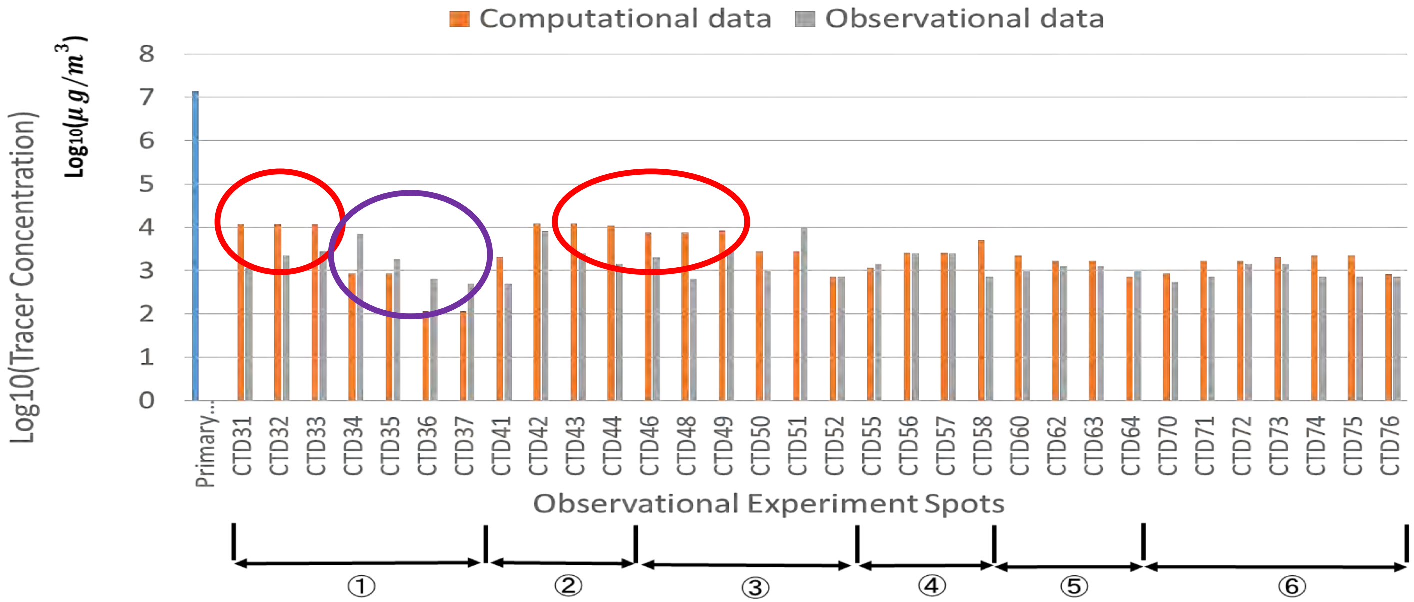


Fig.7. Comparison between observation data and computational data.

In farther area, computational data agree with the observation data.
In closer area, some incorrespondence occurs.

Local current is not completely taken into consideration.

Validation of MEC-NEST model is accomplished to some extend.

Methodology: conditions

<u>Computational domain :</u>

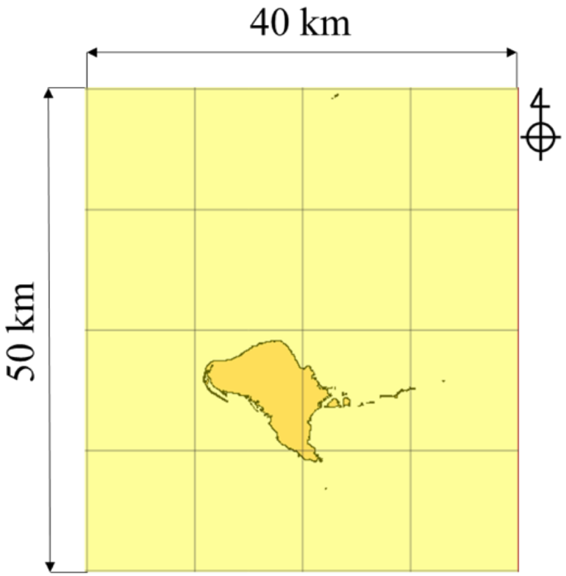


Fig.8. 100MW offshore OTEC plant.

<u>Grid arrangement :</u>

Finer grid system
→ Enhance the resolution and precision of results.

In the horizontal plane :

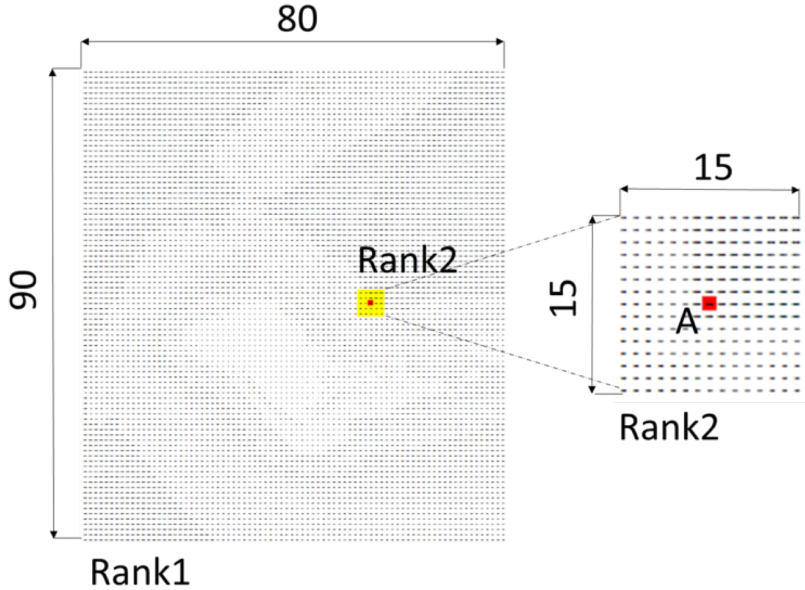


Fig.9. Grid system of the 100MW offshore OTEC plant.

In the vertical plane :

Multi-level layers (z-coordinate)

<u>Meteorological condition</u>

Japan Meteorological Agency (JMA)

<u>Oceanographic condition</u>

- Tide :
  Tide Model NAO99b
- Water quality:
  Japan Oceanographic Data Center (JODC)
  World Ocean Atlas 2013

Grid system verification

Necessity :

Verification of the finer grid system is also necessary to ensure the precision of the results.

Approach :

Calculation on nesting3 grid system was conducted and compared with the nesting2 and nesting1.

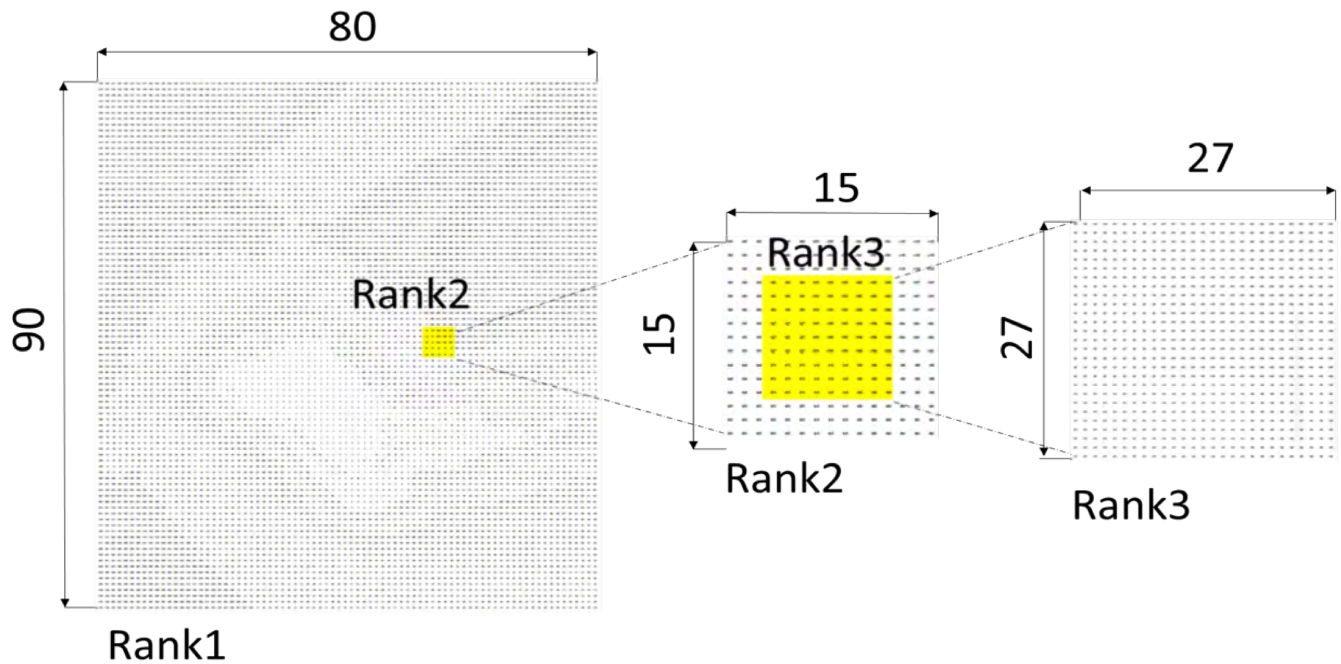


Fig.9. Grid system of nesting 3

Grid system verification

<u>Results :</u>

The amount of water mass of which water temperature drops 0.1℃ ~ 1℃ was calculated.

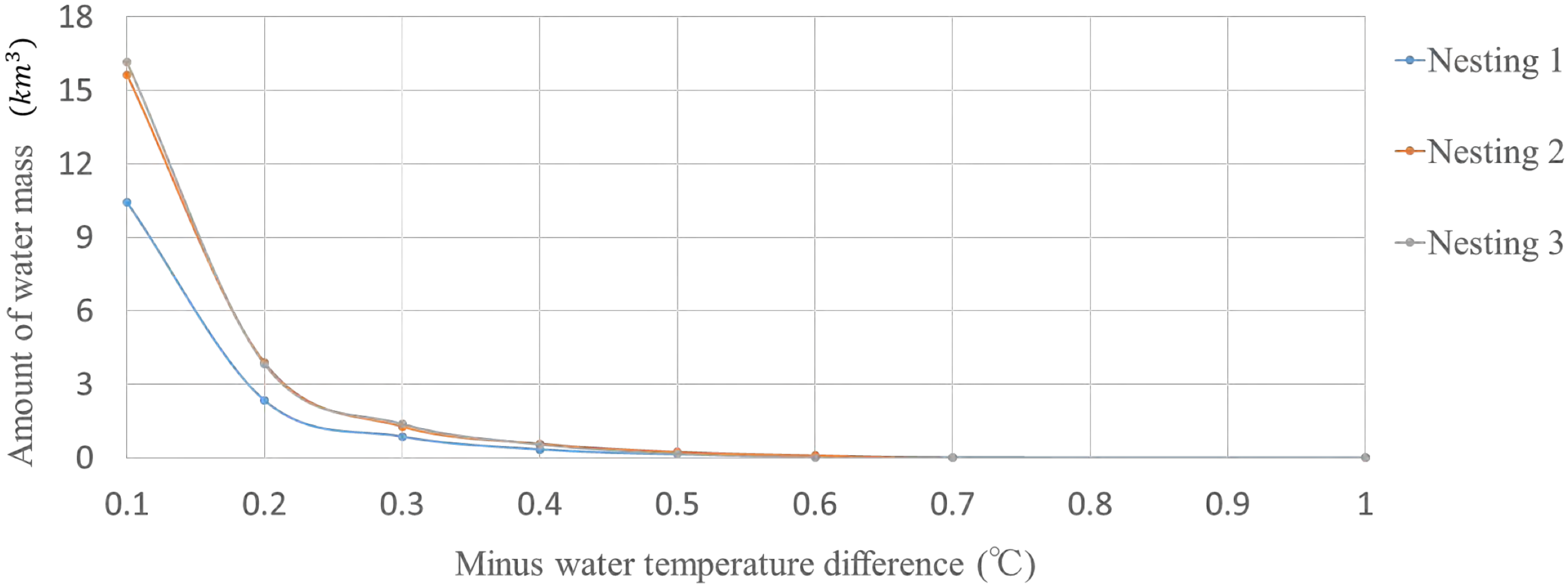


Fig.10. Amount of water mass of which the water temperature drops.

The results verify that the precision of the nesting2 is enough for the analysis and prediction.

Results & Discussion

Results & Discussion

Results of 100MW offshore OTEC plant :

- Results of 60 days in calculation period are used when the variation of water quality (temperature, nutrients, salinity), and phytoplankton are stable.
- From the figure, only a little difference can be identified.

Subtraction :

After OTEC installation

–

Before OTEC installation

=

Change due to OTEC installation

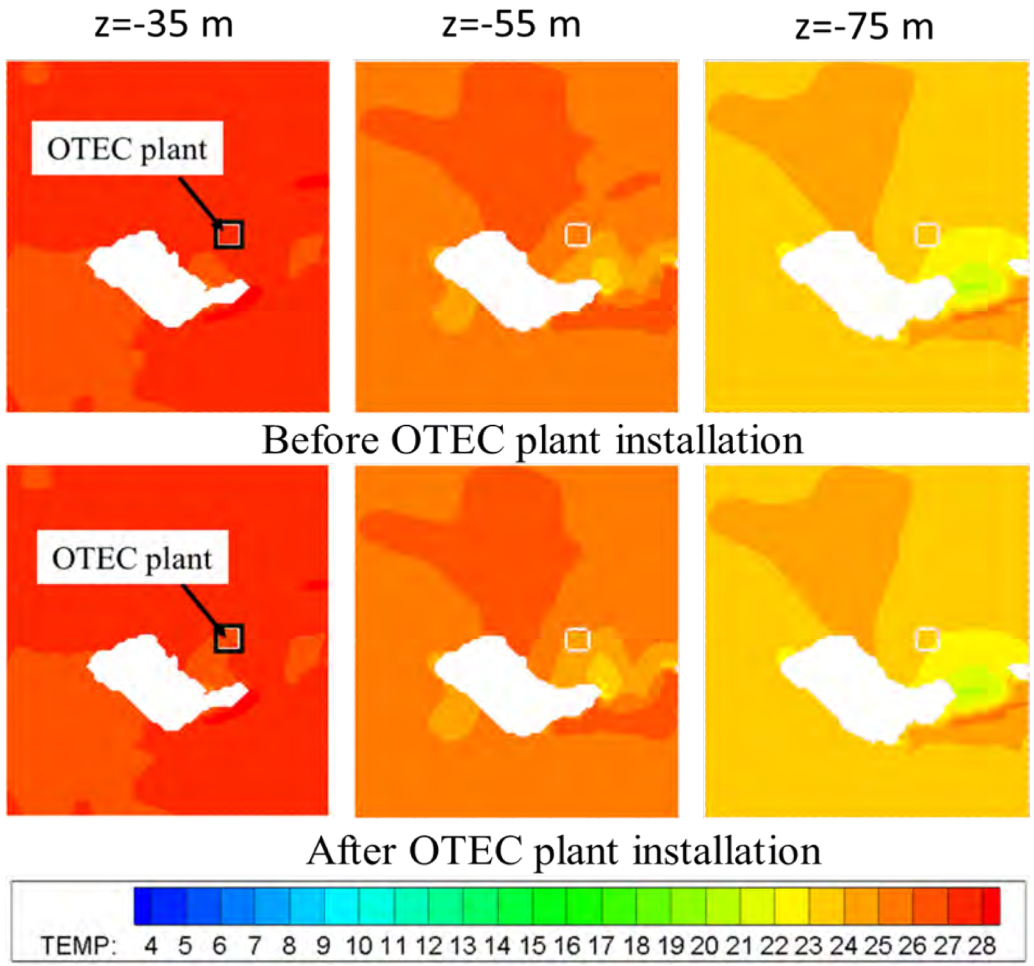
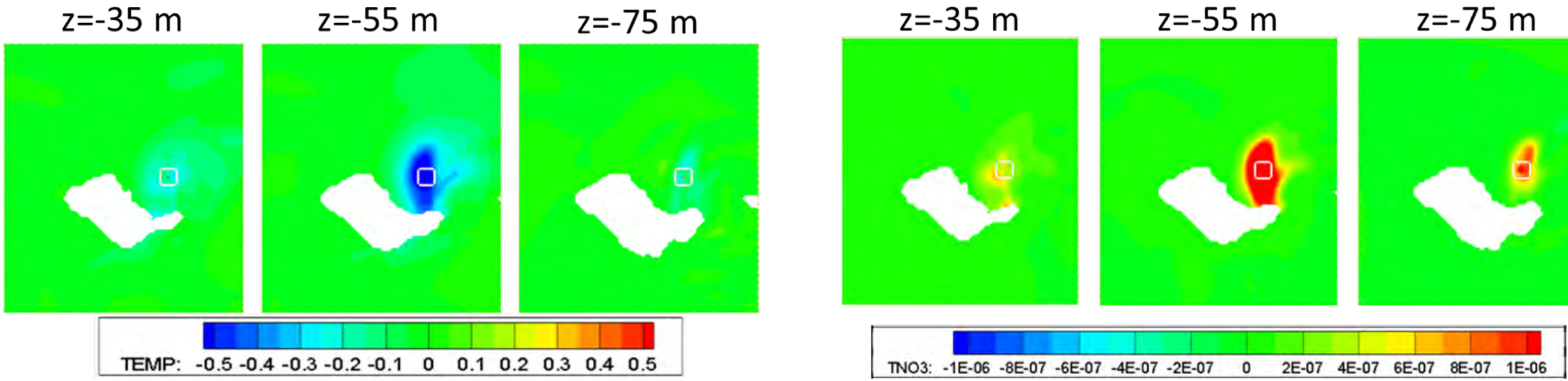


Fig.11. Horizontal plane of temperature distribution at each depths.

Results & Discussion



Water temperature | Nitrate concentration

Fig.12. Changes of temperature distribution and nitrate concentration distribution in horizontal plain due to discharged water from 100MW OTEC plant.

Water temperature, Nutrient concentration (NO_3) :

- Depth of 35m is not affected very much.
- Depth where affected most is around the depth of 55m.

Results & Discussion

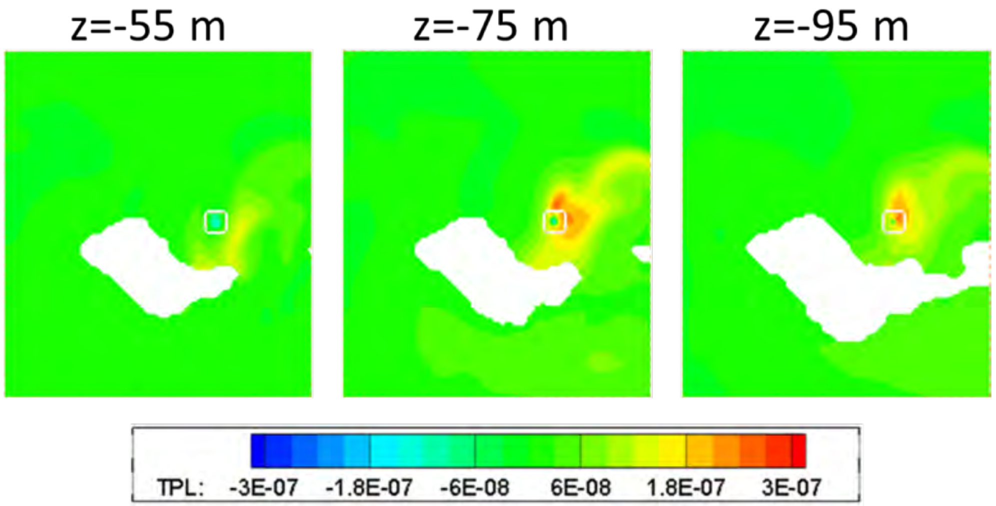


Fig.13. Changes of phytoplankton distribution in horizontal plain due to discharged water from 100MW OTEC plant.

Large Phytoplankton :

- Phytoplankton concentration **increases** at the **depth around 75m** .
- Phytoplankton concentration **does not change in vicinity of OTEC plant** but increases a little far.

Discussion :

- Instead of dispersing at the depth where the discharged water is released, discharged water will first flow downward, while the density changes at the same time. When it reaches the depth where the density is the same with itself, it disperses horizontally.
- Phytoplankton increases under the influence of water temperature and nutrients concentration.

Effect of difference in discharge scheme

Effect of difference in discharge scheme

Different depth :

Calculation on 4 different discharge depth is attempted.

Table.2. water temperature and density of the background.

depth (m)	water temperature (℃)	density (kg/m^3)
discharged water	16.9	1025.2
7.5	28.6	1021.8
15	28.3	1021.9
25	27.7	1022.1
55	25.7	1022.9
205	17.6	1025.2

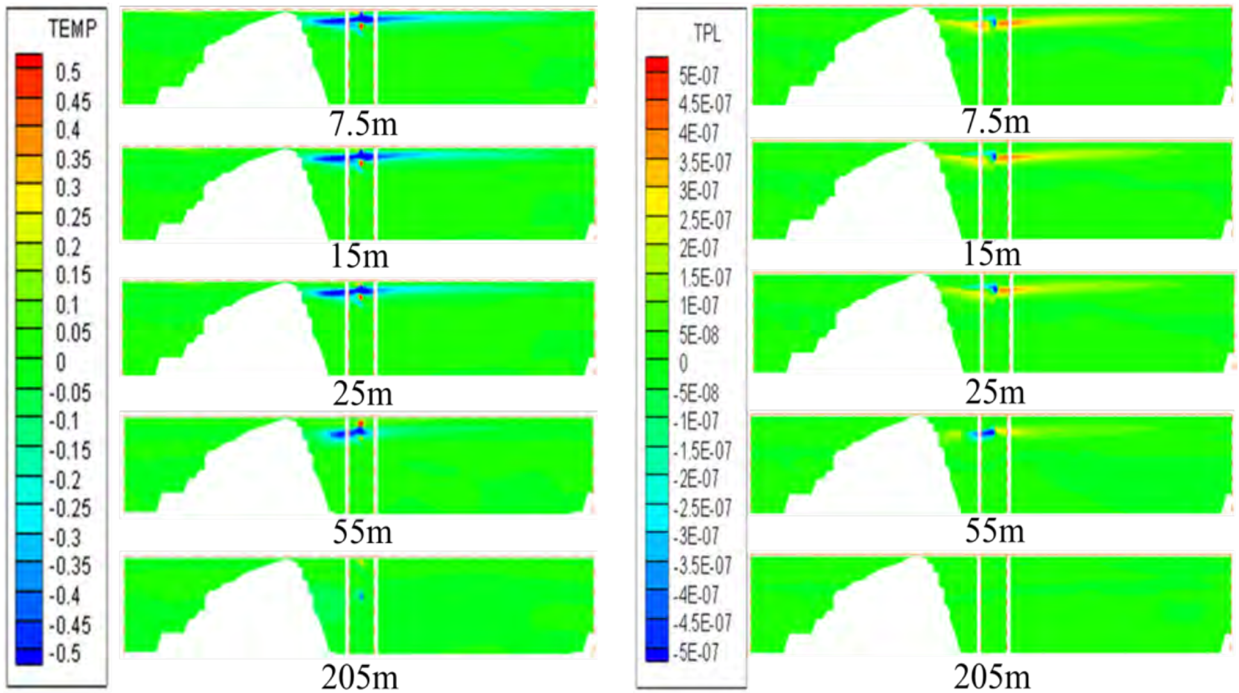


Fig.14. Distribution of temperature and phytoplankton concentration change of different discharge depth.

Schemes of discharge depth 7.5m, 15m, 25m have little changes.
Scheme of discharge depth 55m, affected area is smaller.
Scheme of discharge depth 205m, affected area is limited.

Effect of difference in discharge scheme

Different proportion of the deep sea water and surface water :

Amount of the DOW was not changed to maintain the efficiency of the OTEC plant.
By increasing the surface water, the proportion is changed

Table.2. water temperature and density of the different proportion.

Ratio (Surface : Deep)	1:1	1.5:1	2:1
Amount of discharged water (t/h)	2.88×10^{6}	3.5×10^{6}	4.2×10^{6}
Temperature (℃)	16.9	19.1	20.63
Density (kg/m^3)	1025.2	1024.6	1024.2

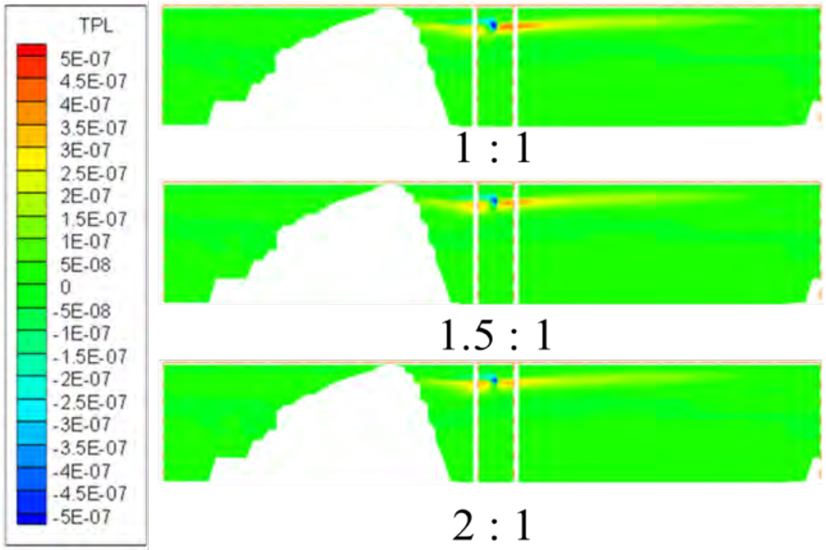


Fig.14. Distribution of phytoplankton concentration change of different water proportion.

Changing the proportion of the discharged water will not effectively change the influence.

Adjustment of the discharge depth is an effective way to control the water quality factors.

Conclusion

Conclusion

Accomplished achievement :

- **Behavioral characteristics** of the discharged water from 100MW offshore OTEC plant and 1MW onshore OTEC plant were analyzed by using the three-dimensional numerical model MEC-NEST. The discharged water will spread at the **equilibrium depth** horizontally instead of spreading right after released.
- The **variation of the nutrients and phytoplanktons** is predicted by combining the low-trophic ecosystem model.
- **Changing discharge depth** can be an effective way of controlling the environmental influence.

Future tasks :

- In the present calculation, I did not take the **ocean currents** into consideration. But in reality, there are still some ocean currents around Kume-Island.
- Ecosystem model and parameters that I used in the present model are applicable to the **middle latitude of North Pacific Ocean**. Since Kume-Island is located in subtropical area, the model and parameters need to be **adjusted according to the observational data**.

Thanks for your attention !