MECモデルによる貯留物漏出シナリオ推定技術の実用化検討

Numerical estimation of the position and rate of CO_2 seepage at the seafloor

in the case of unexpected leakage of CO_2 purposefully stored in the sub-seabed geological formation

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概要

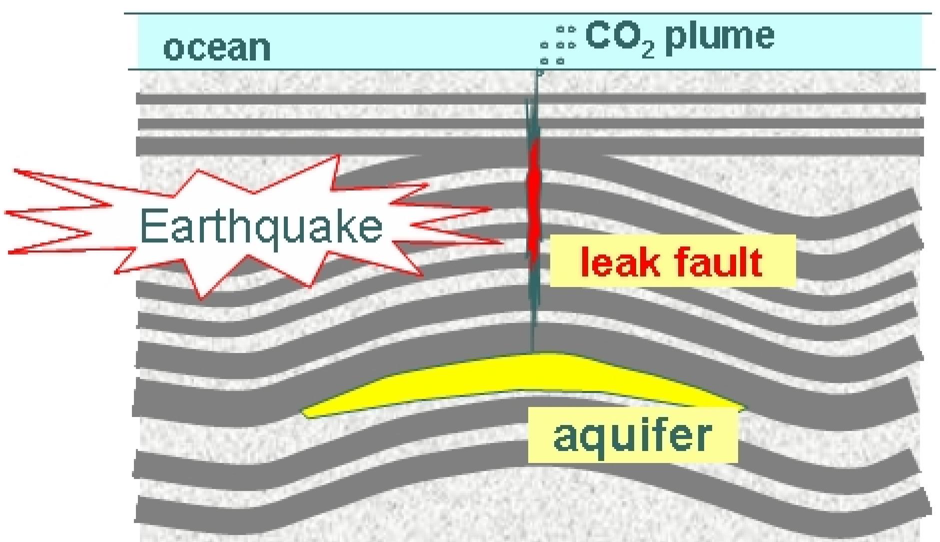
- CCSは温暖化対策技術の一つとして期待されている一方、海底下でCO_2が漏洩した場合の環境影響も懸念される。
- 万が一、海中への漏出が発生した際に、漏出位置と漏出量をいち早く探知することは重要である。
- そこで、アジョイント法を用い、限られた数の検知器のデータから漏洩情報を推定する解析手法を開発した。
- 本手法は、他の様々な海中物質のソース探知にも適用できる。

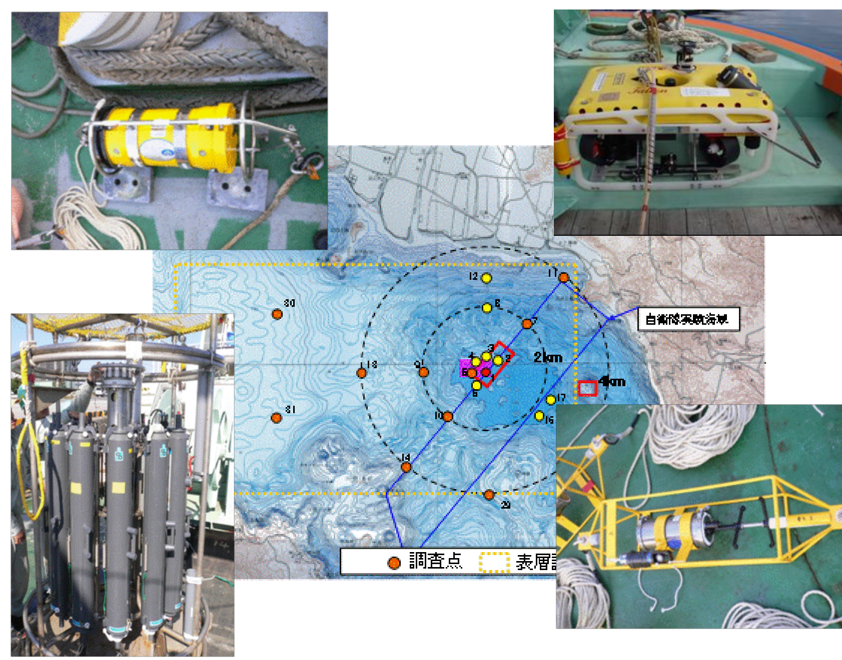
CO2 Leakage Risk

CCS (Carbon Capture and Storage) is catching attention to reduce extremely large amount of CO2.

However, there is a leakage risk although the probability of such a case is very low.

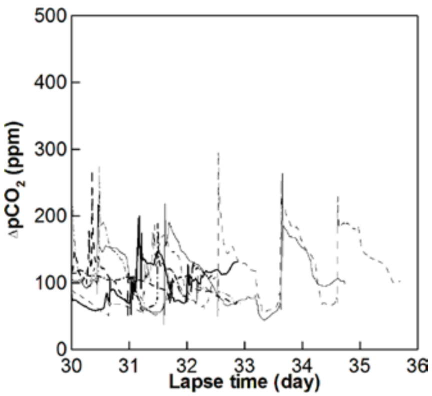
To obtain public acceptance, it is necessary to show the people the fact that environmental impact assessment techniques, such as monitoring and prediction methods, are available.

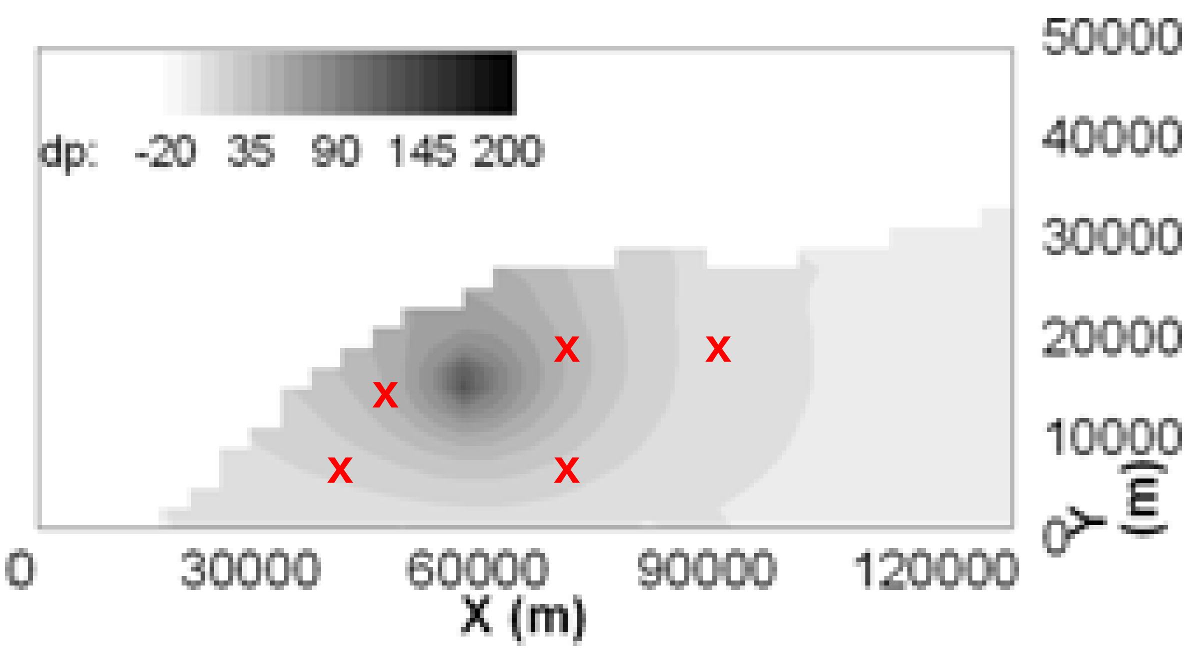




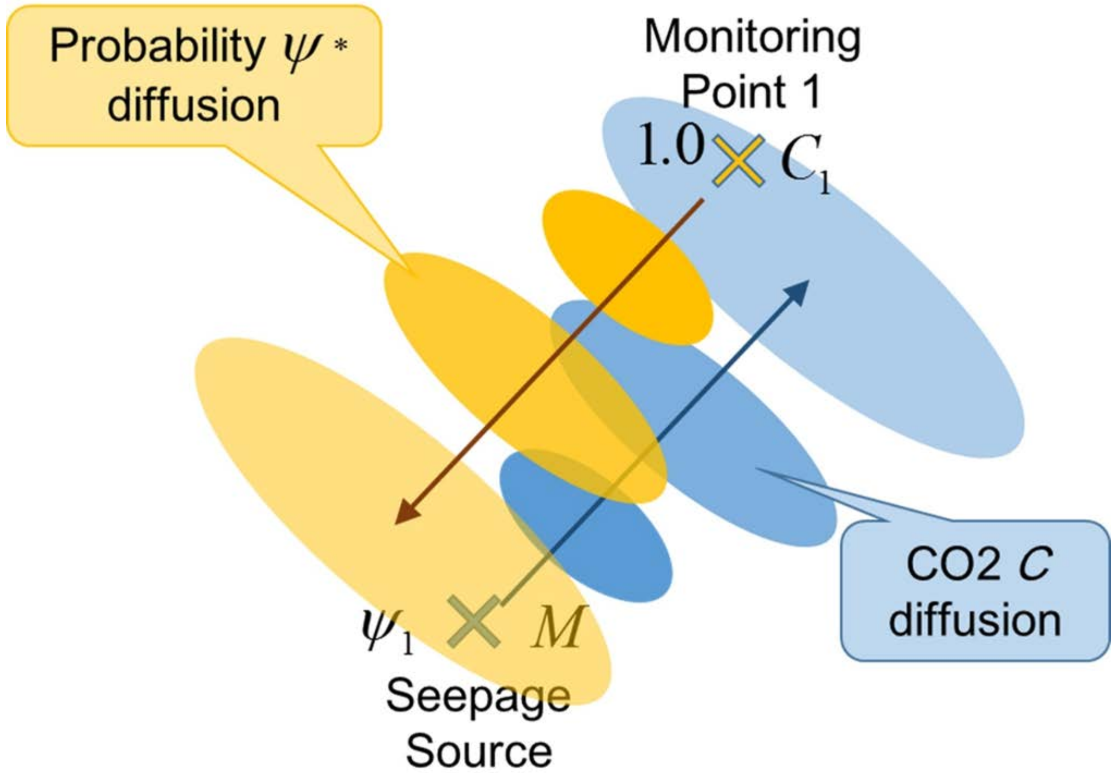
Seepage Position and Rate

If sensors detect unusually large CO2 concentration, we have to do find out the location and rate of CO2 seepage in the ocean. But, how?





Adjoint Marginal Sensitivity Method



Schematic images of the time-forward advection-diffusion of CO2 concentration C and the time-backward advection-diffusion of marginal sensitivity ψ^*. The seepage rates of C and ψ* are M and unity, respectively. The trajectory lines of C and ψ^*, which are parallel.

Adjoint Marginal Sensitivity Method

- Adjoint equation of an original model equation is solved in temporally inverse way.
- Viscosity in the adjoint equation is equal to the one in the original equation and, therefore, it is positive
- Adjoint methods are often used for data assimilation.

To solve the adjoint equation of the gradient of model variable against model parameter, that is marginal sensitivity ψ^*

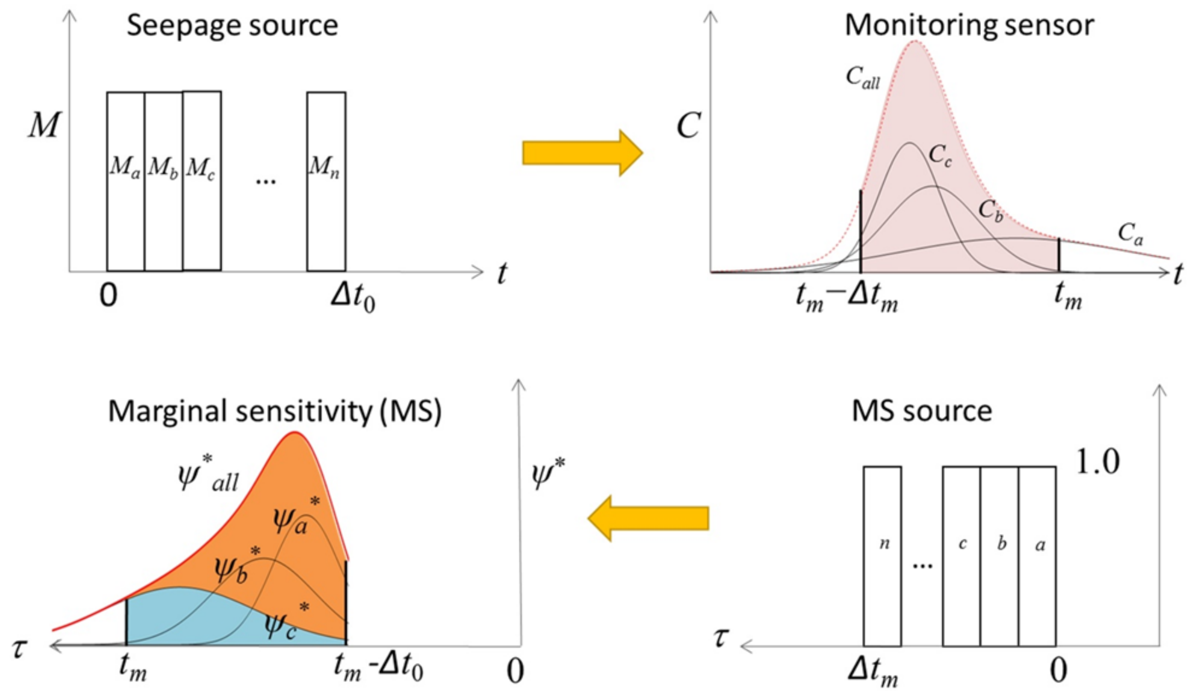
model equation

$$\frac{\partial C}{\partial t}+\frac{\partial V_j C}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\nu_C \frac{\partial C}{\partial x_j}\right]+\left(S_c+q_I C_I-q_o C\right)$$

adjoint equation

$$\frac{\partial \psi^*}{\partial \tau}-\frac{\partial V_j \psi^*}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\nu_C \frac{\partial \psi^*}{\partial x_j}\right]+\left(-q_o \cdot \psi^*\right)+\frac{\partial h}{\partial C}$$

Adjoint Marginal Sensitivity Method



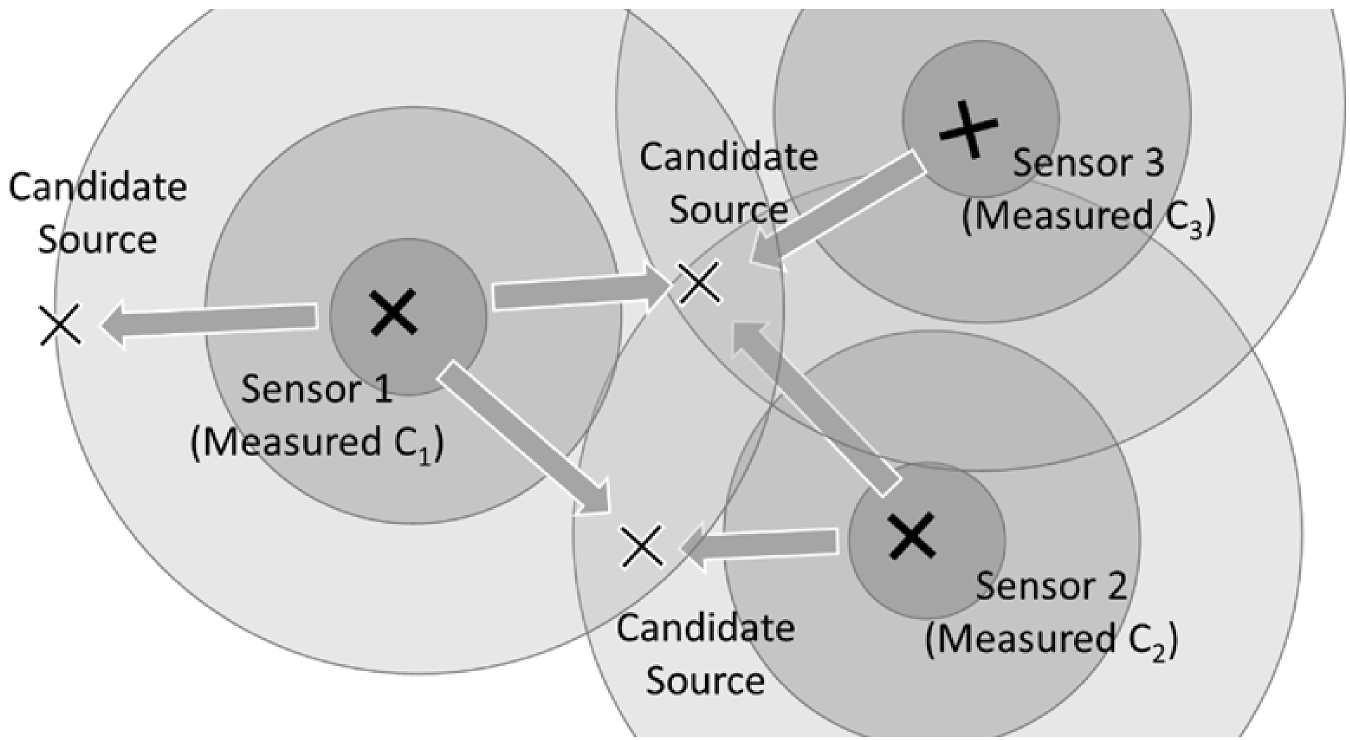
$$M = \frac{\int_{t_m-\Delta t_m}^{t_m} C(\mathbf{x}_m, t)\,dt}{\int_{t_m-\Delta t_0}^{t_m} \psi^*(\mathbf{x}_0, \tau)\,d\tau}$$

When $\Delta t_0 \rightarrow 0$ ($\Delta t_0 = \Delta t_{cmp}$ in a numerical simulation)
and $\Delta t_\mathrm{m} \rightarrow 0$ ($\Delta t_\mathrm{m} = \Delta t_{cmp}$ in a numerical simulation

$$M = \frac{C(\mathbf{x}_m, t = t_m)}{\psi^*(\mathbf{x}_0, \tau = t_m)}$$

Adjoint Marginal Sensitivity Method

When estimating seepage rate Mi at an arbitrary point x at an arbitrary time τ from multiple sensors i (= 1, 2, …, n), the following holds at the correct seepage point and time



$$M_1(\mathbf{x},\tau=t_m)=M_2(\mathbf{x},\tau=t_m)=\cdots=M_n(\mathbf{x},\tau=t_m)\Leftrightarrow\frac{C_{m1}}{\psi^*{}_1(\mathbf{x},\tau=t_m)}=\frac{C_{m2}}{\psi^*{}_2(\mathbf{x},\tau=t_m)}=\cdots=\frac{C_{mn}}{\psi^*{}_n(\mathbf{x},\tau=t_m)}$$

Adjoint Marginal Sensitivity Method

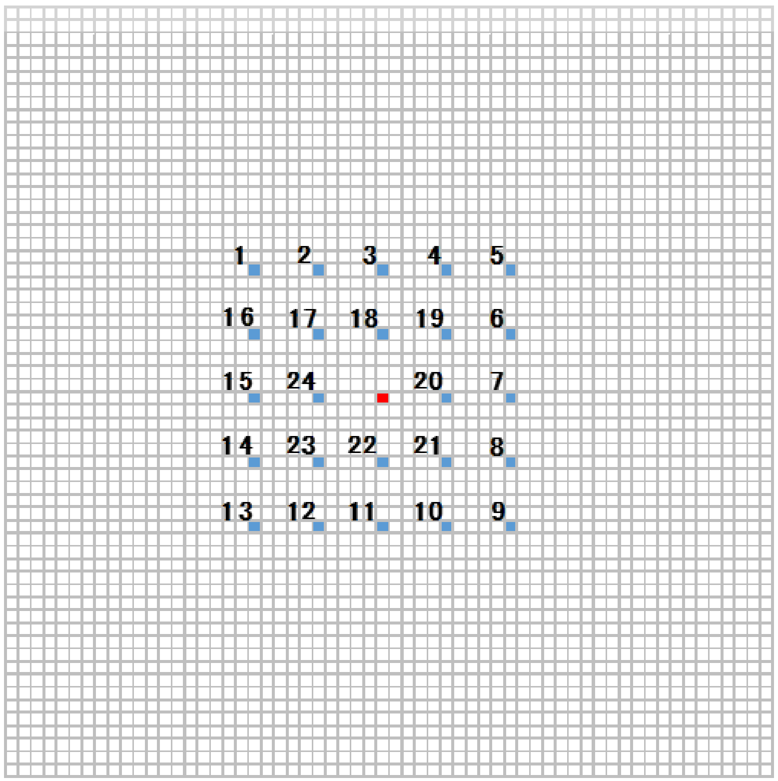
Because there are always some errors in numerical simulations, we cannot expect Eq. (37) exactly. Here, we define an index to evaluate the difference among *Mi* and to estimate x0:

$$F(\mathbf{x}, \tau = t_m) = \frac{\sqrt{\sum_{i=1}^{n}\sum_{k=1}^{n}\left[(M_i(\mathbf{x}, \tau = t_m) - M_k(\mathbf{x}, \tau = t_m))^2 / (M_i(\mathbf{x}, \tau = t_m) + M_k(\mathbf{x}, \tau = t_m))^2\right]}}{n(n-1)}$$

Even if we do not know the instantaneous seepage time t = 0 or τ = tm, it can be assumed that the minimum F is obtained at t = 0 and, therefore, we can estimate the time of seepage by examining the F values at all the points at all the time steps. In other words, none of position, rate, and time of instantaneous seepage is necessary for prediction using the proposed method, with evaluating the minimum value of the following F:

$$F(\mathbf{x}, \tau) = \frac{\sqrt{\sum_{i=1}^{n}\sum_{k=1}^{n}\left[(M_i(\mathbf{x}, \tau) - M_k(\mathbf{x}, \tau))^2 / (M_i(\mathbf{x}, \tau) + M_k(\mathbf{x}, \tau))^2\right]}}{n(n-1)}$$

2D Test – unsteady homogeneous flow field



$$u = u_0 \times \cos(2\pi t / T_P)$$
$$v = u_0 \times \cos(2\pi t / T_P + \pi)$$

Computational conditions

Grid: 60×60×1 (1000m×1000m×20m each grid)

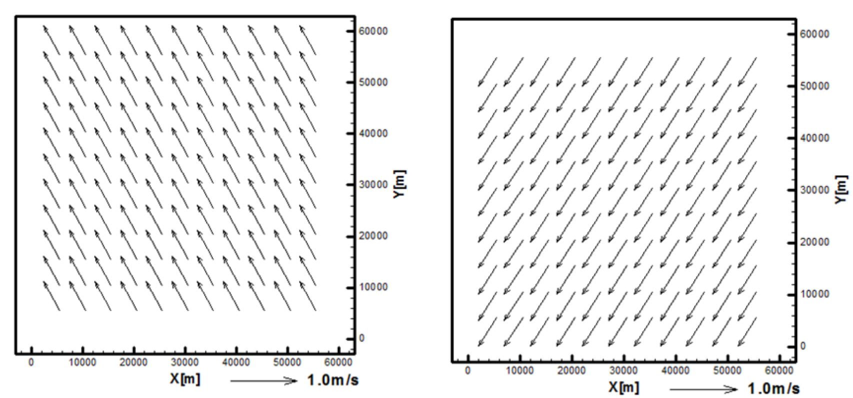
Time: 150,000s (1.0s/step)

Seepage rate : 1.0 kg/m^2/s

Seepage Location : (30, 30) (Red dot)

Seepage start time : t_0 = 200,000s

Blue dot: CO_2 sensors (24 sensors, 5 km interval)



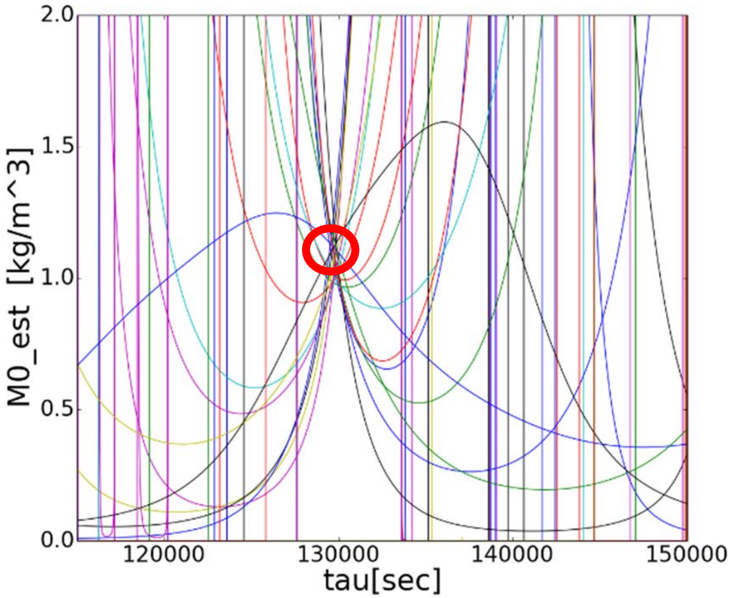
t=30000 s (left) and 60000 s (right)

2D Test – unsteady homogeneous flow field

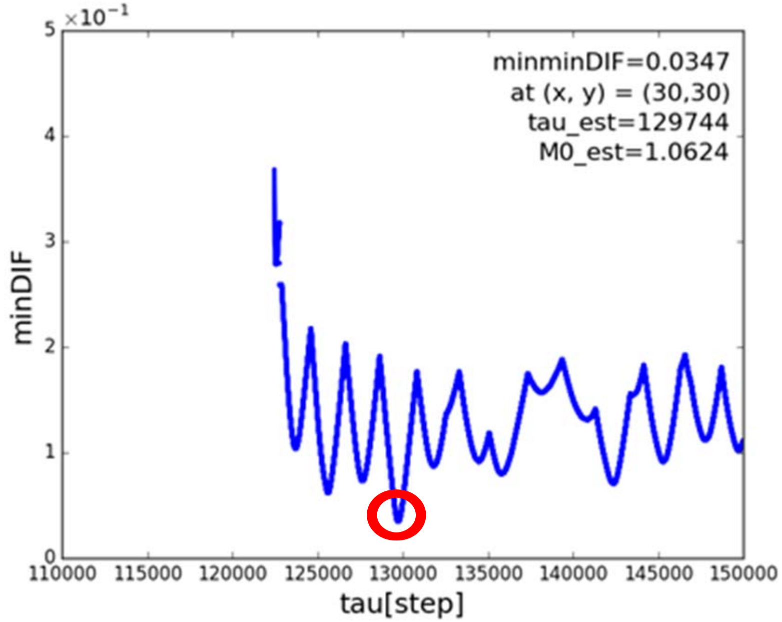
Instantaneous Seepage and Instantaneous Measurement

$$M = \frac{C(\mathbf{x}_m, t = t_m)}{\psi^*(\mathbf{x}_0, \tau = t_m)}$$

$$F(\mathbf{x},\tau) = \frac{\sqrt{\sum_{i=1}^{n}\sum_{k=1}^{n}\left[(M_i(\mathbf{x},\tau) - M_k(\mathbf{x},\tau))^2 / (M_i(\mathbf{x},\tau) + M_k(\mathbf{x},\tau))^2\right]}}{n(n-1)}$$



Temporal trends of seepage rates *Mi* estimated by all 24 sensors at the original seepage grid position (30, 30).

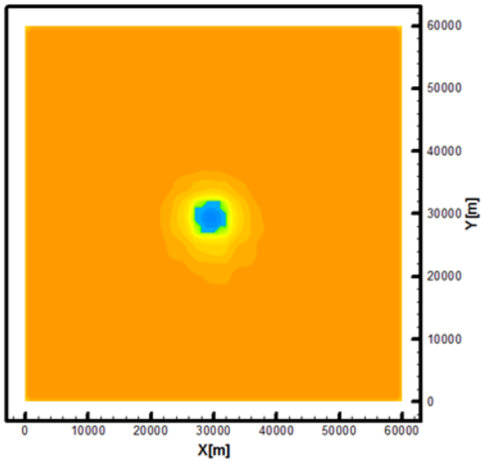


Time change of the smallest *F* in the whole domain when excluding sensors at which $C_i/\max(C_i)$ was below 0.01.

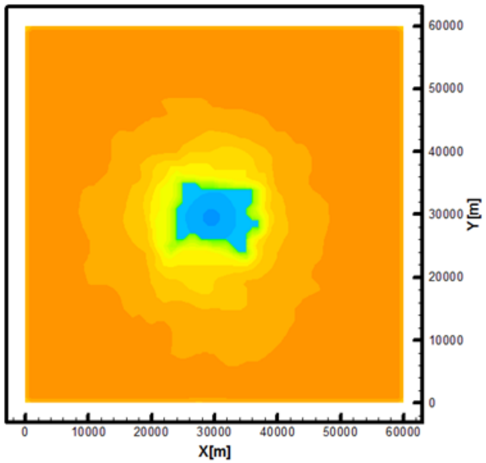
2D Test – unsteady homogeneous flow field

Continuous Seepage and Instantaneous/Continuous Measurement

Instantaneous Measurement



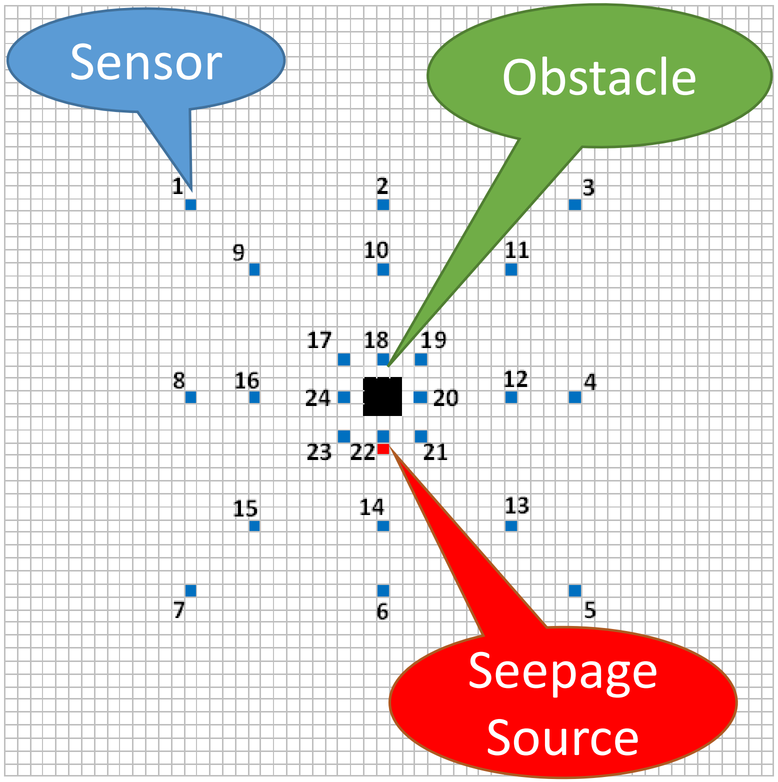
Continuous Measurement



Instantaneous Measurement	Correct	Continuous Measutement
M_0=1.638(Error = 63.8%) t=61,665(t =88,335) (x, y) = (30, 30)	M_0=1.0kg/m^{3}s t_0=20,000 (t =130,000) (x, y) = (30, 30)	M_0=0.982(Error =1.8%) t_0= 21,532 (t =128,468) (x, y) = (30, 30)

Considering numerical error treatment, seepage rate was estimated more accurately with continuous measurement method.

2D Test – steady heterogeneous flow field



$$u = (j-50)(2\times 360/447142)$$
$$v = (i-50)(2\times 360/447142)$$

Computational conditions

Grid: 100×100×1 (1000m×1000m×20m each grid)

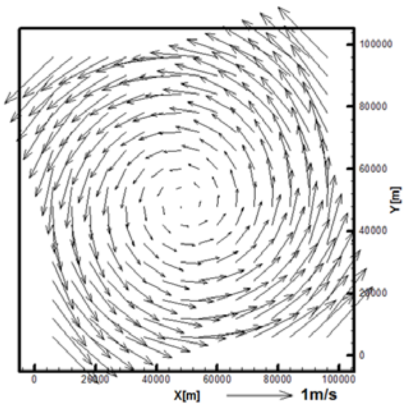
Time: 1,500,000s (10.0s/step)

Seepage rate : 1.0 kg/m^2/s

Seepage Location : (50, 46) (Red dot)

Seepage start time : t_0 = 30,000s

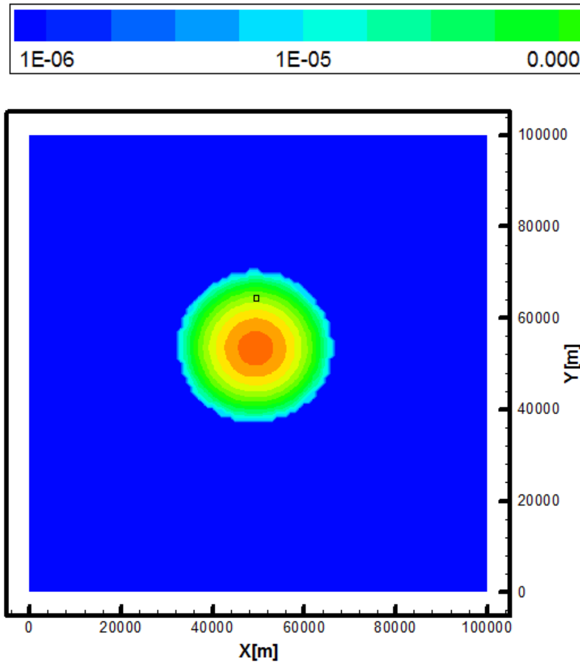
Blue dot: CO_2 sensors (24 sensors)



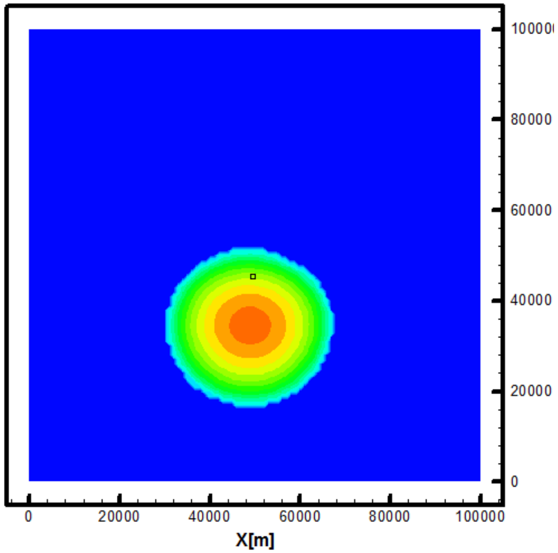
2D Test – steady heterogeneous flow field

Instantaneous Seepage and Instantaneous Measurement

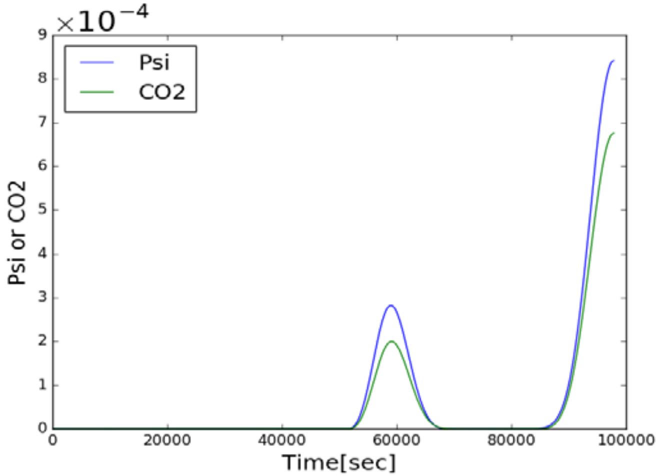
Without Obstacle



C



ψ^*



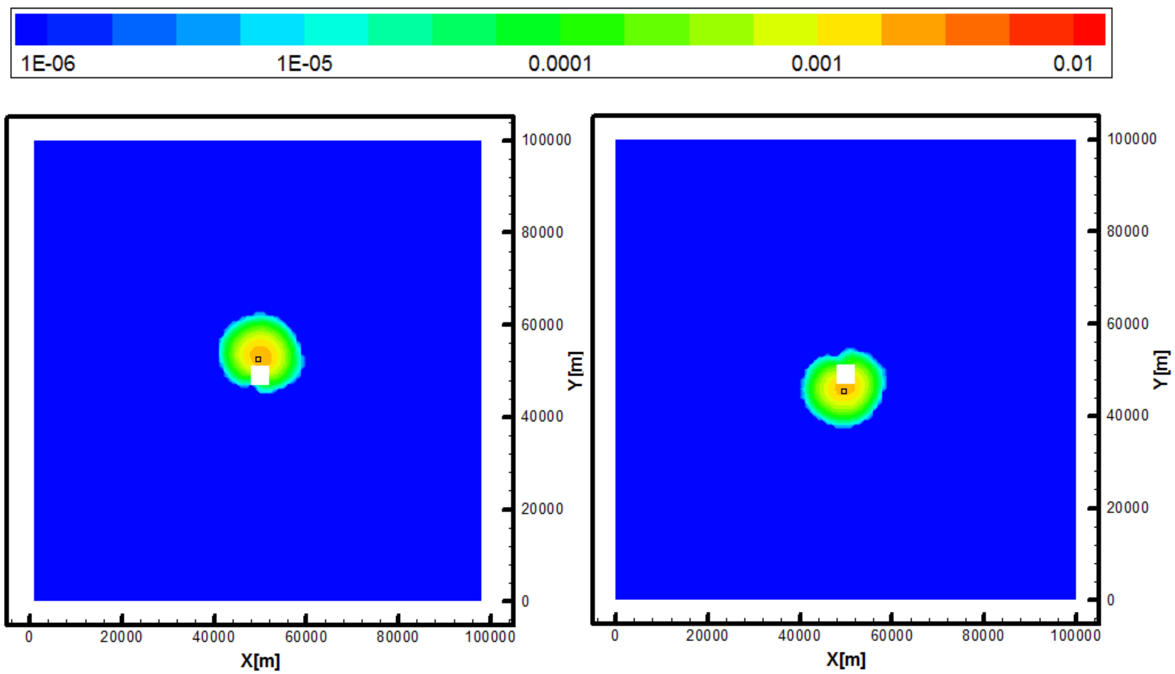
C: Measured at sensor

ψ^*: Measured at seepage source

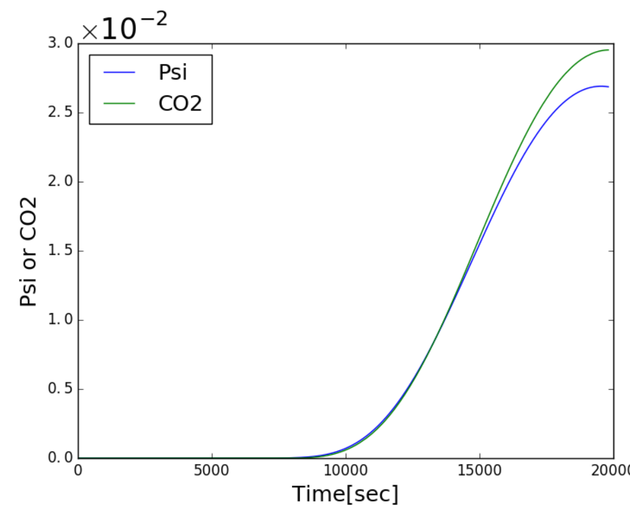
2D Test – steady heterogeneous flow field

Instantaneous Seepage and Instantaneous Measurement

With Obstacle



C ψ^*



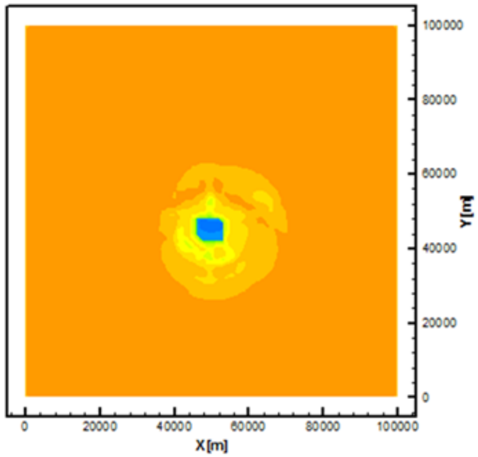
C: Measured at sensor

ψ^*: Measured at seepage source

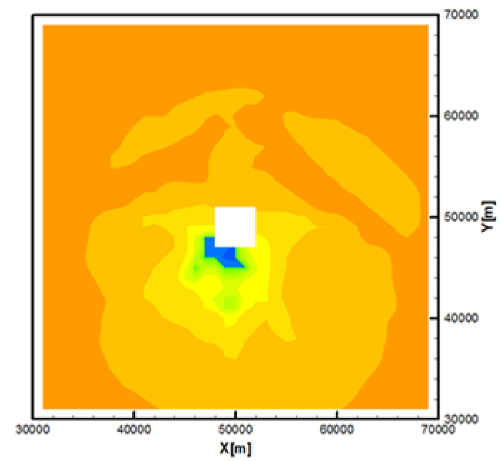
2D Test – steady heterogeneous flow field

Instantaneous Seepage and Instantaneous Measurement

Without Obstacle



With Obstacle



Without Obstacle	Correct	With Obstacle
M_0=0.970(Error =3.0%) t=29,959 (t =120,041) (x, y) = (50, 46)	M_0=1.0kg/m^{3}s t_0=20,000 (t =130,000) (x, y) = (50, 46)	M_0=0.882(Error =11.8%) t= 20,636 (t =119,364) (x, y) = (50, 46)

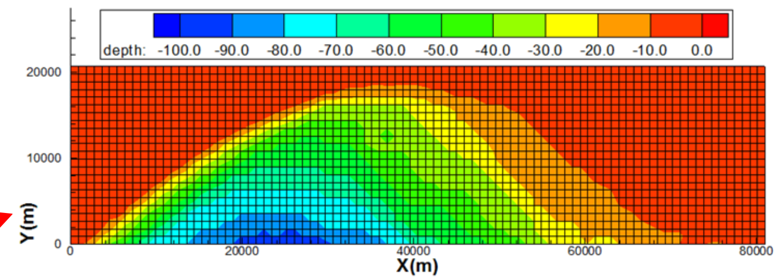
Obstacle decreased the accuracy of seepage rate estimation.

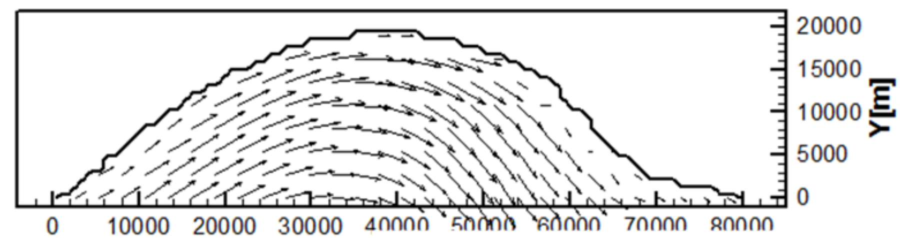
3D Test – off Tomakomai

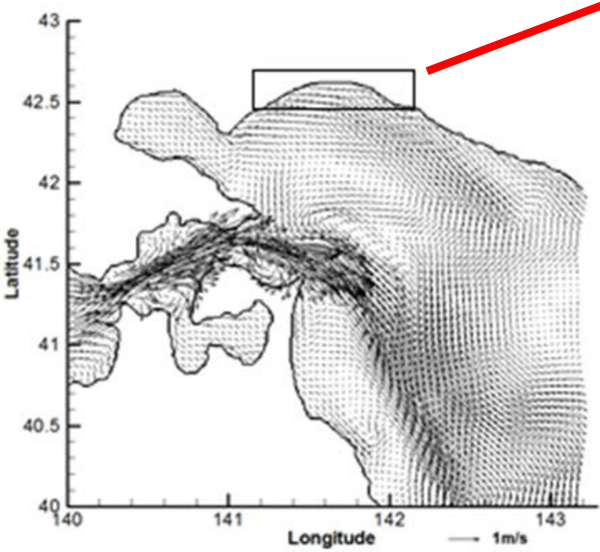
Time-forward calculation

Grid: 90×23×32 (900m×900m×2 or 5m)
Time: 2016/04/20 ~ 05/10 (10.0s/step)

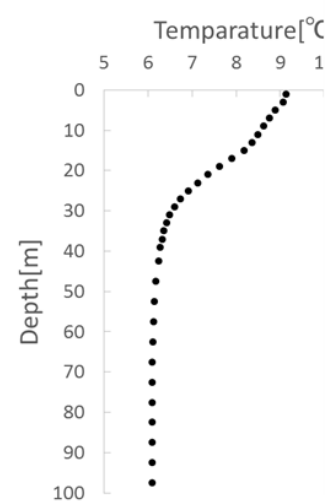
Ocean current results of ROMS was forced on the tidal current calculation of MEC Model.

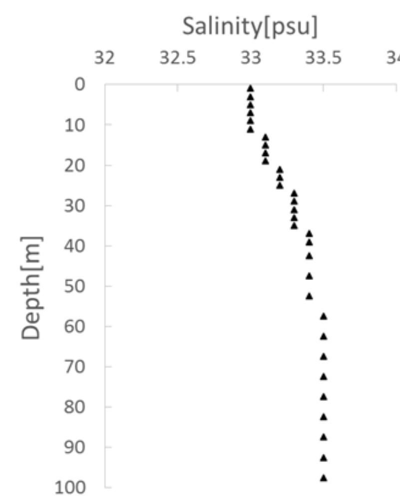






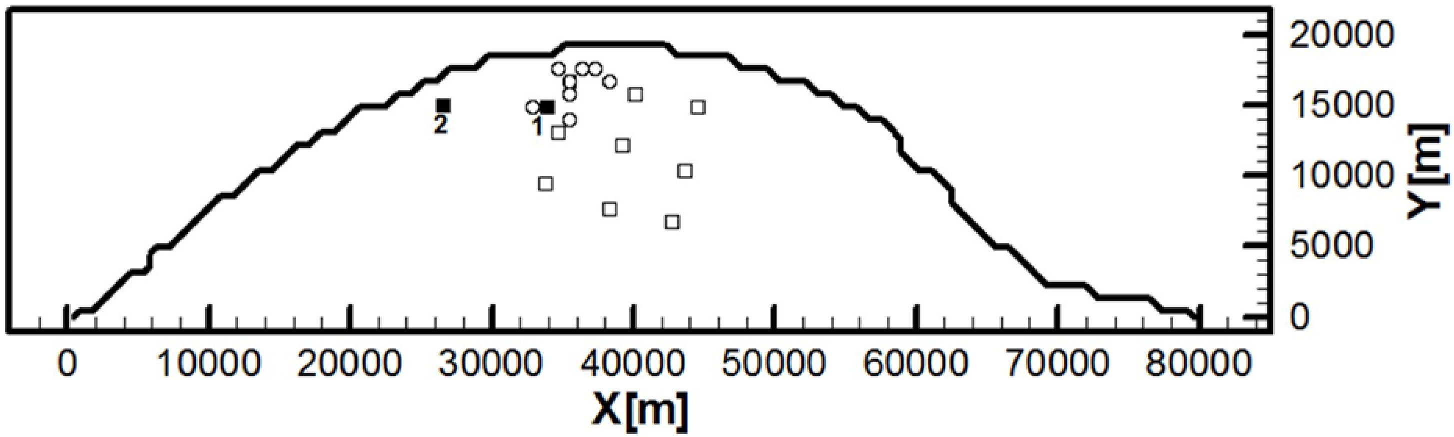
Ocean current calculated by ROMS





3D Test – off Tomakomai

Time-forward calculation



Seepage rate : M_0 = 9.57E-07 kg/m^3/s

Seepage position :

Case 1 (x_0, y_0, z_0) = (33750m, 14850m, 39m)
Case 2 (x_0, y_0, z_0) = (26550m, 14850m, 31m)

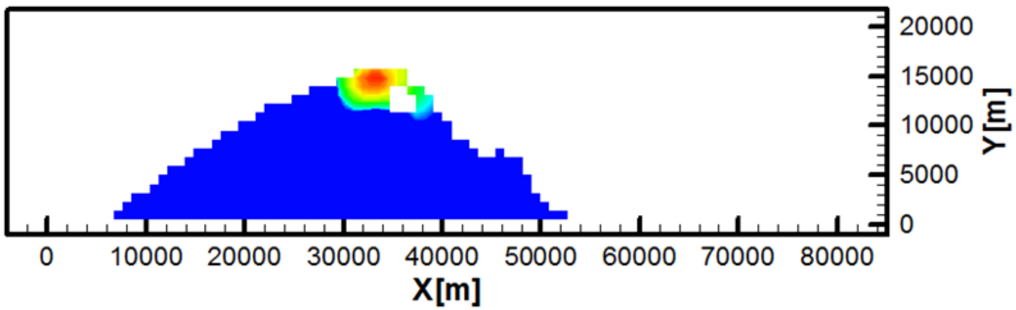
Seepage start time : t_0 = 950,400sec (τ_0 = 777,600sec)

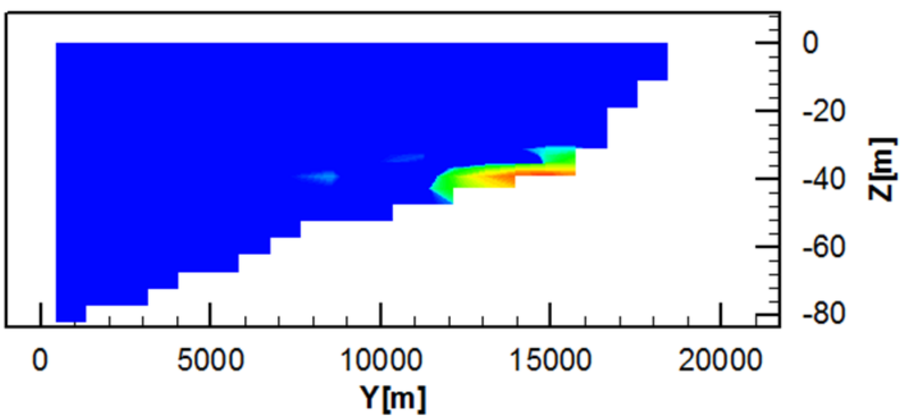
2 cases for seepage positions (black squares).
48 sensors at 3 depths at the 16 white squares.

3D Test – off Tomakomai

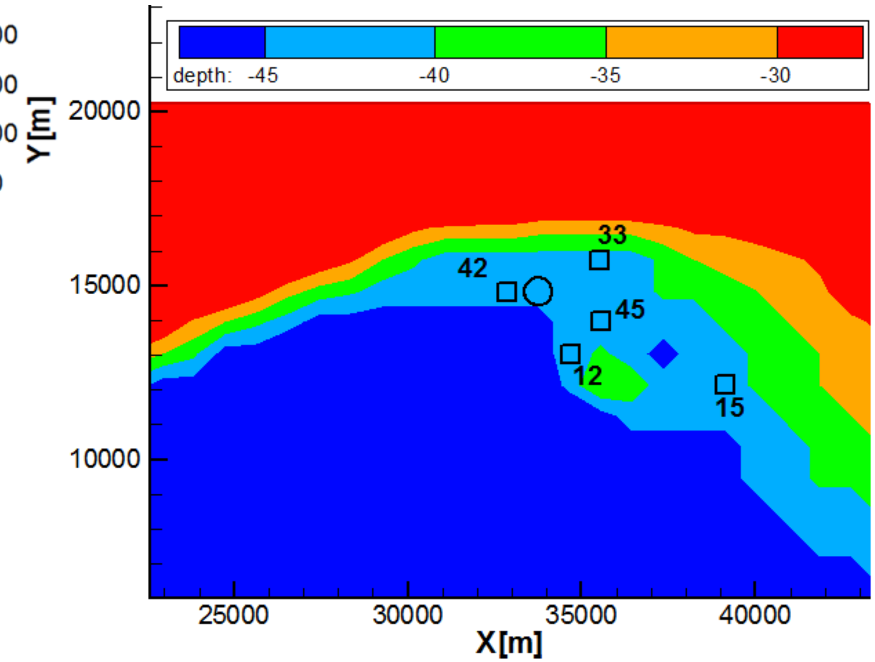
Time-forward calculation

Case 1





Distribution of CO2, which seeped continuously at the seepage position 1 (Case 1), resulted from the time-forward calculation.

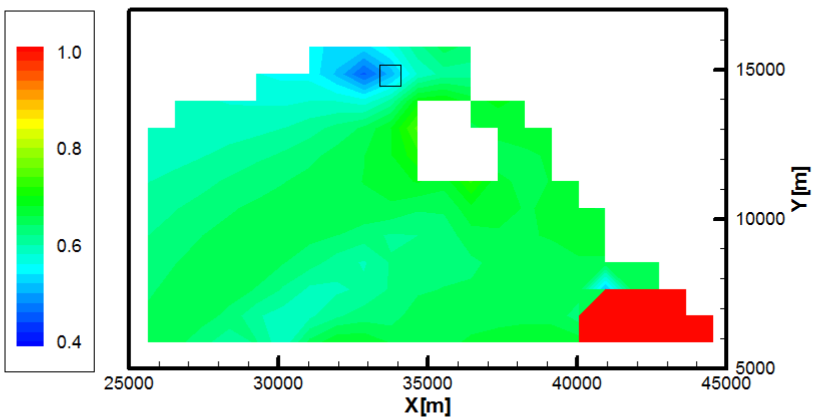


After applying a threshold,
$Ci/\max(Ci)=0.01$,
5 sensors survived.

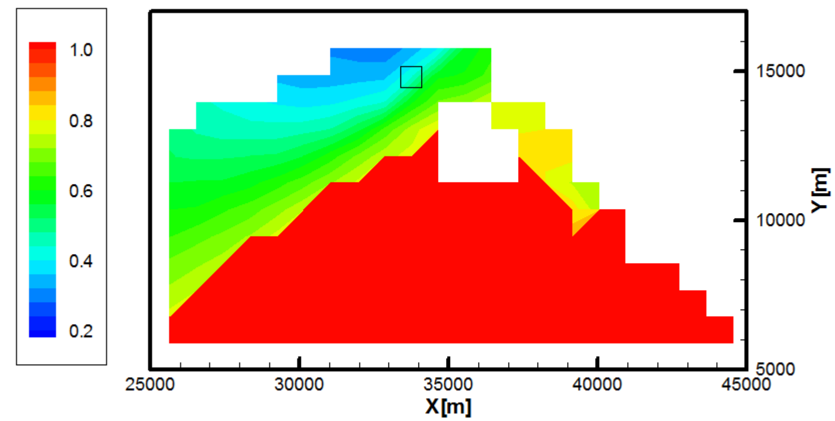
3D Test – off Tomakomai

Case 1

Instantaneous Measurement



Continuous Measurement



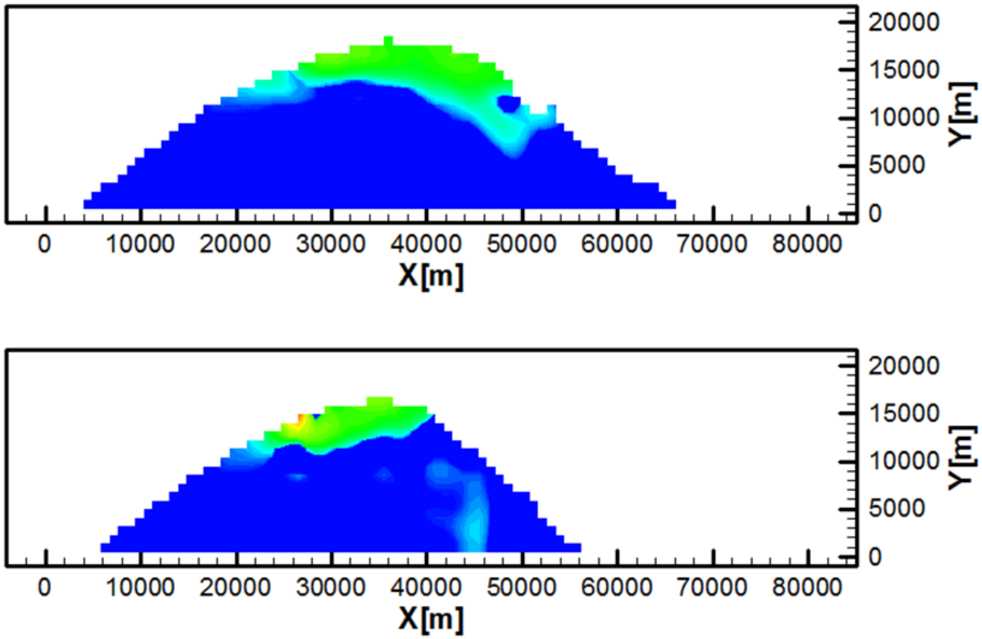
Instantaneous Measurement	Correct	Continuous Measurement
M_0=3.85E-07 (Error =59.8%) t =1,295,530sec (32850m, 14850m, 39m) (Error=0.9 km)	M_0=9.57E-07 kg/m^{3}sec τ_0 = 777,600sec (33750m, 14850m, 39m)	M_0=6.83E-07 (Error =28.6%) t =714,540sec (32850m, 15750m, 39m) (Error=1.3 km)

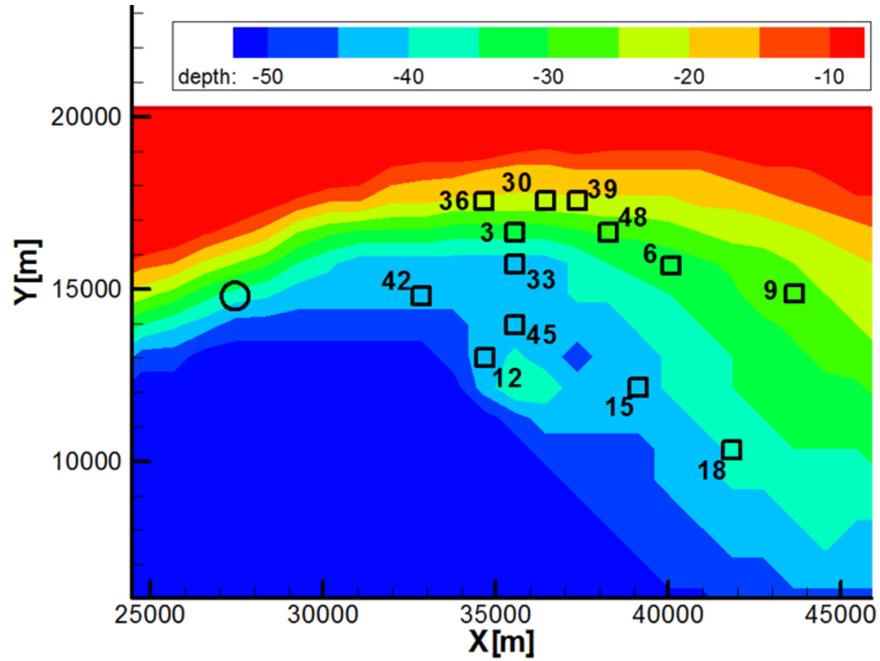
Seepage rate: Continuous measurement gave better estimation.
Seepage Source: Almost accurately estimated.

3D Test – off Tomakomai

Time-forward calculation

Case 2





Distribution of CO_2, which seeped continuously at the seepage position 2 (Case 2), resulted from the time-forward calculation at depths of 3 m (upper) and 6 m (lower).

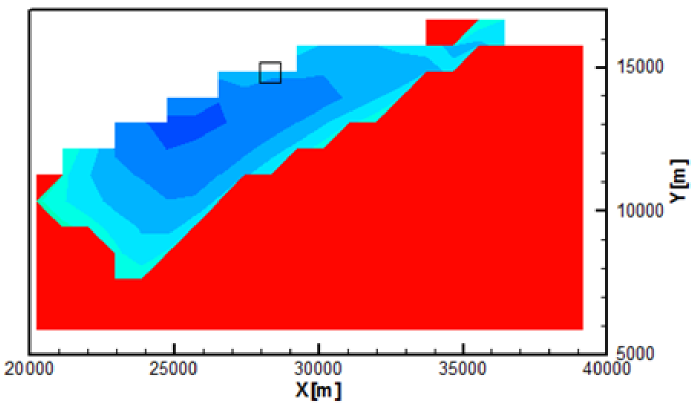
After applying a threshold $C_i/\max(C_i)=0.1$, 8 sensors survived.

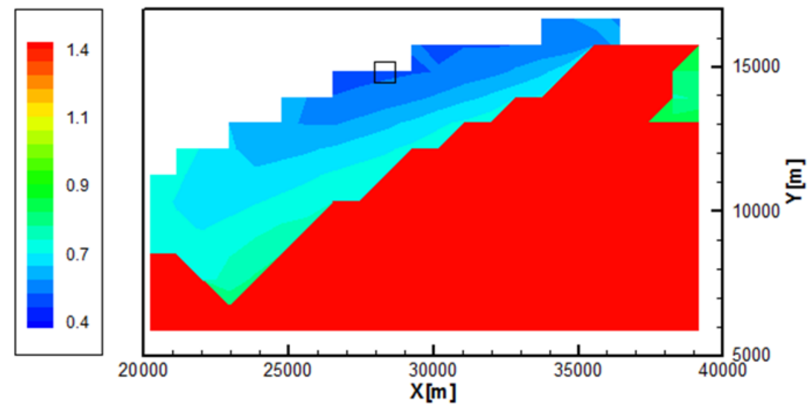
3D Test – off Tomakomai

Case 2

Instantaneous Measurement

Continuous Measurement





Instantaneous Measurement	Correct	Continuous Measurement
M_0=17.40E-07 (Error =81.8%) (25650m, 13950m, 37m) (Error=1.3 km)	M_0=9.57E-07 kg/m^{3}sec (26550m, 14850m, 31m)	M_0=7.24E-07 (Error =24.3%) (26550m, 14850m, 31m) (Error=0.0 km)

Seepage rate: Continuous measurement gave better estimation.
Seepage Source: Very accurately estimated.

Conclusions

- A numerical method, which estimates seepage information from data of a limited number of sensors was developed.
- Adjoint marginal sensitivity method was generalized to estimate the source information of marine pollutants.
  - This makes it possible to clearly define the relationship between time periods of seepage and measurement.
- 2D test simulations and 3D simulations with the realistic topography to obtain knowledge of the procedures of the method.

地球シミュレータコードの開発

- Sakaizawa et. al (2018)の計算に用いた海流入りMECコード（オリジナル）をもとに、OpenMPによるマルチコア並列化とベクトル化を行った。
- まずOpenMP化をワークステーションで行い、そのコードを地球シミュレータでベクトル化によるチューニングを行った。
- OpenMPによる並列化しか行っていないので、地球シミュレータではS系バッチジョブの1ノードでの計算となった。

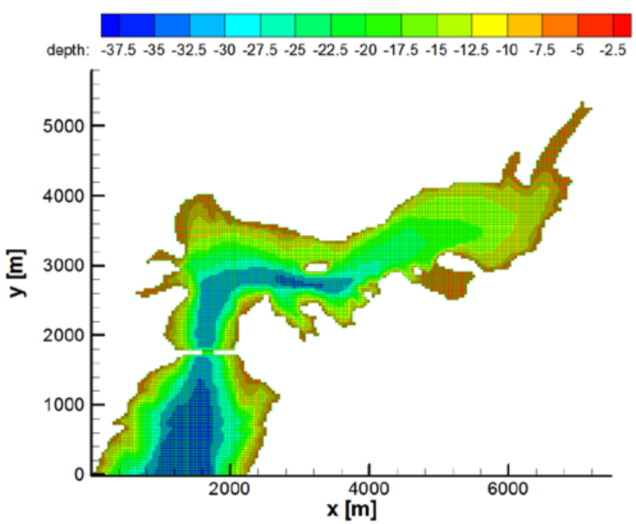
実行環境

・ワークステーション
OS：Ubuntu 17.10 (GNU/Linux 4.13.0-32-generic x86_64)
CPU：Intel Xeon E3-1246 v3, 3.5MHz, 4コア8スレッド（ピーク224.0GFLOPS）

・地球シミュレータ
S系バッチジョブで1ノード使用
ベクトル性能：256GF

大船渡

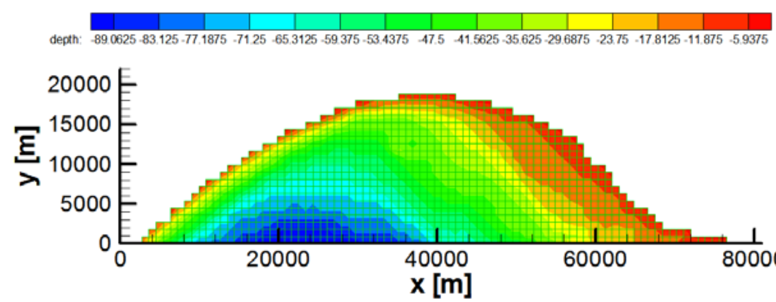
- 海流計算なし
- メッシュサイズ：I=185, J=140, K=12
- 2200000step（実時間で約1ヶ月）



コード	計算機	実行時間
オリジナル	ワークステーション	16時間20分
並列版	ワークステーション	9時間11分
並列・ベクトル版	地球シミュレータ	8時間30分

苫小牧

- 海流計算あり
- メッシュサイズ：I=90, J=23, K=32
- 561600step
- Sakaizawa et. al (2018)の2012年2月



コード	計算機	実行時間
オリジナル	ワークステーション	6時間42分
並列版	ワークステーション	2時間36分
並列・ベクトル版	地球シミュレータ	3時間50分

境界条件の設定するサブルーチンのベクトル化率が低いことが、速度が上がっていない原因。苫小牧では開領域が広く、海流情報の処理もあるため、処理時間がかかっている。

このサブルーチンの処理で、実行時間の15%が使用されている。改善の余地あり。