# Numerical modeling of the slow-growing, motile harmful alga *Gymnodinium catenatum* in Inokushi Bay, a small inlet in southern Japan


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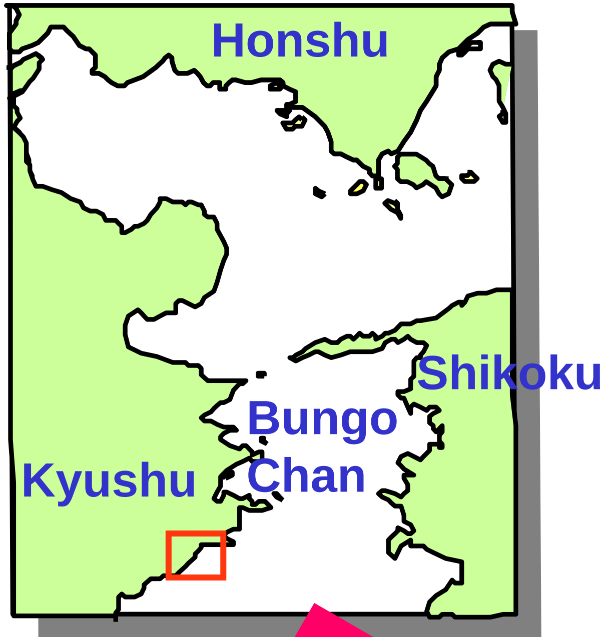
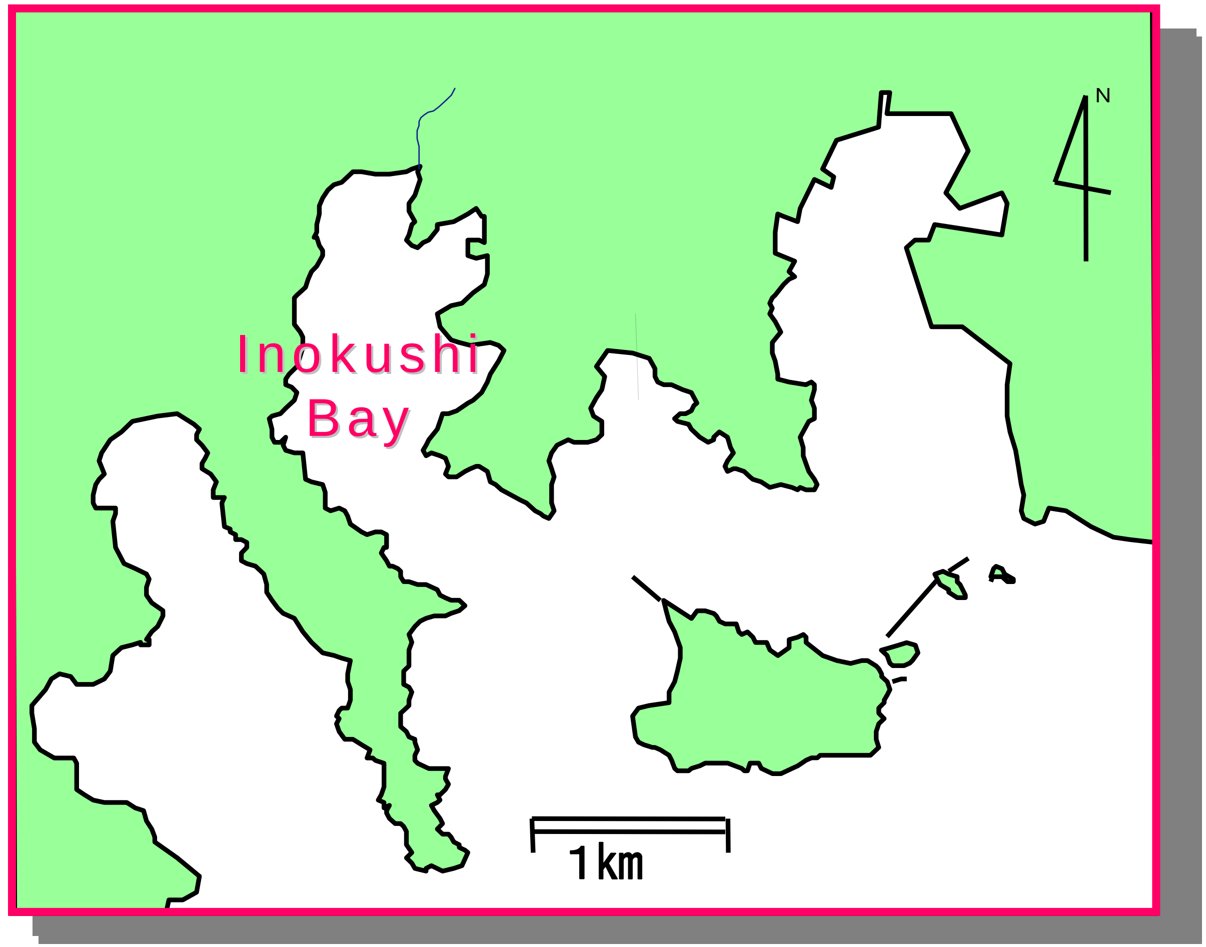
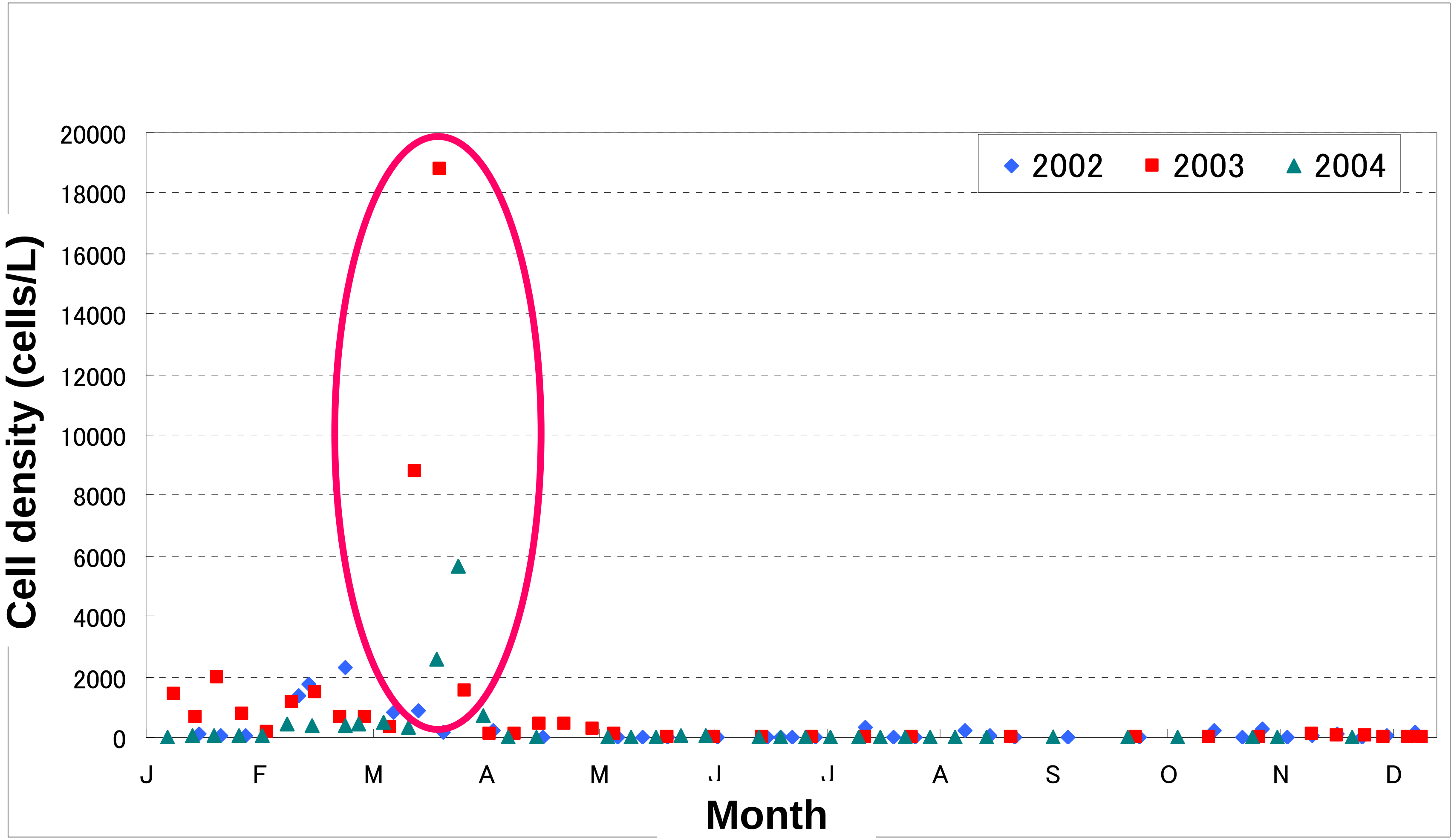
# Inokushi Bay, Japan




**Toxification of noble scallops and other shellfish**

# Cell density of *G. catenatum* in Inokushi Bay, Japan




Oita Pref. Fish. Res. Inst.

# Purpose

**$\mu_{max}$=0.31/day (25$^{o}$C, 30 psu)**

**(Yamaguchi, pers. comm.)**

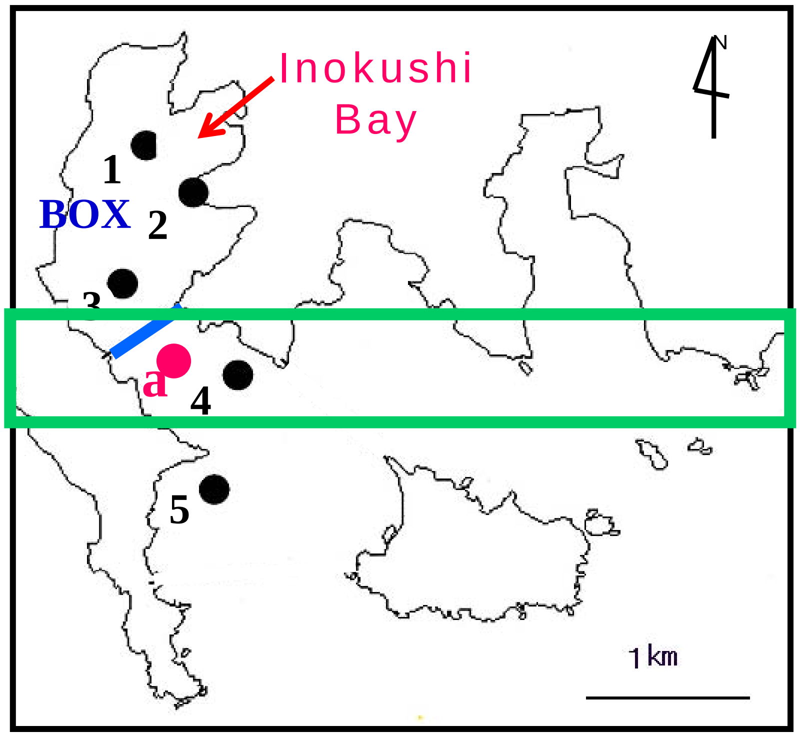
**Question:**

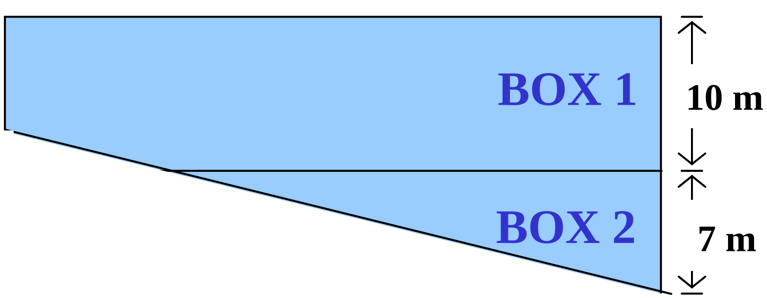
**Why is this species able to form blooms in Inokushi Bay with such a low growth rate?**

**To understand the bloom forming mechanisms of *G. catenatum* in Inokushi Bay using a numerical model**

# Methods

## Arrangement of boxes




**<Observation>** 25 Nov 2003-12 Apr 2004

| **<Parameters>** | **<Stations>** |
|---|---|
| Temperature<br>Salinity<br>Nutrients<br>Cell density | ● St.1-5 |
| Current velocity | ● St.a |

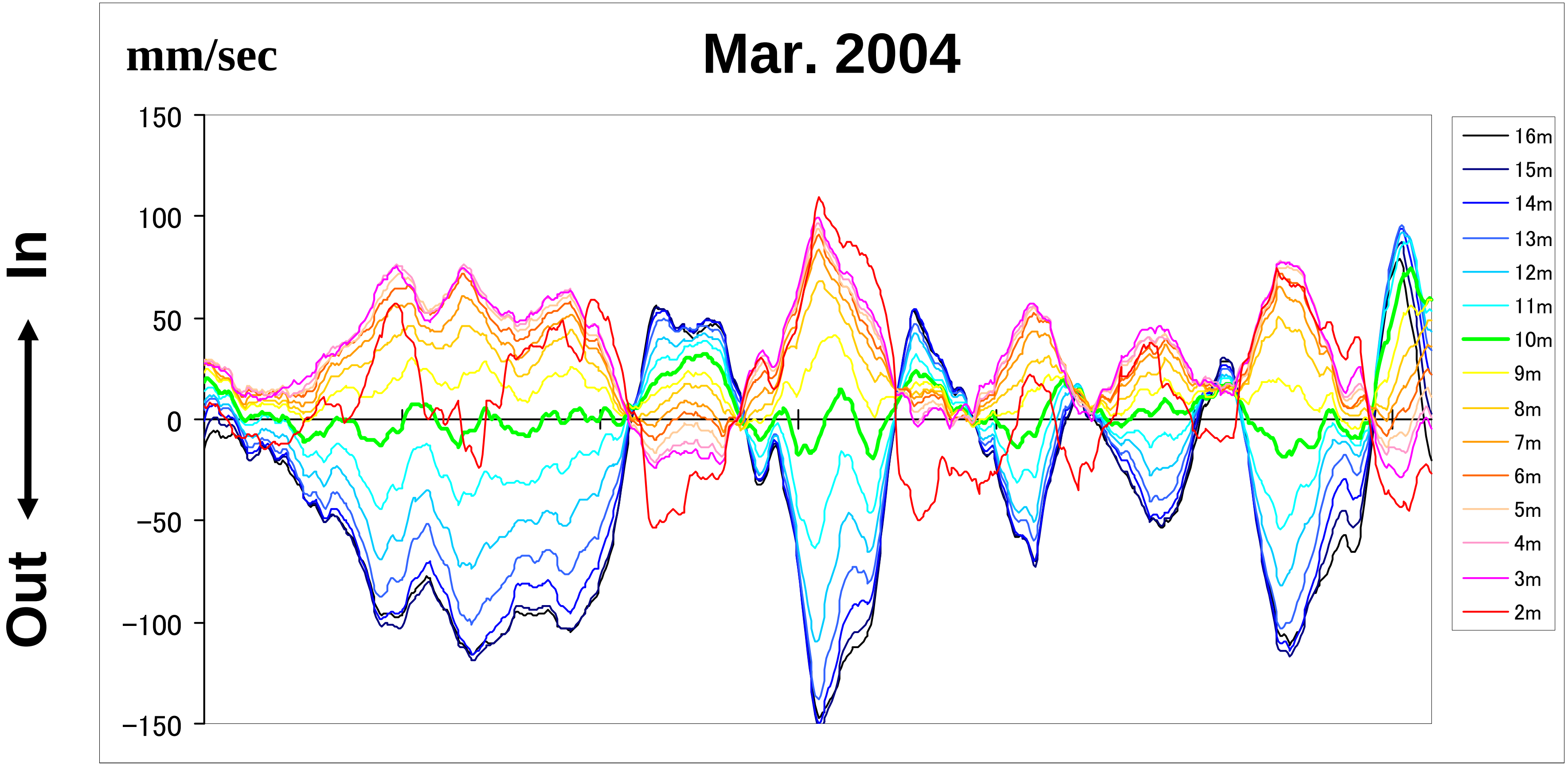
## BOX sizes

| | BOX 1 (upper) | BOX 2 (lower) |
|---|---|---|
| Surface area | 1.94 $km^2$ | 1.36 $km^2$ |
| Depth | 0-10 m | 10-17 m |
| Area of cross section | 5,600 $m^2$ | 3,920 $m^2$ |

# Current velocity

●St.a, Doppler Current Meter Abo (pers. comm.)

Running mean of 25 hrs.




**When the water comes in to the upper layer (0-10 m), the water of lower layer (10 m-B) is pushed out of the bay.**

# Meteorological data used

**Light** **1 Jan 1989-31 Dec 2002** **(Fukuoka Met. Agency)**

$$Ic=0.5 \cdot I_0 \cdot exp(-k \cdot Dc)$$

**Precipitation** **25 Nov 2003-12 Apr 2004**

**(Nobeoka Met. Agency)**

**Evaporation** **25 Nov 2003-12 Apr 2004**

**(Nobeoka Met. Agency)**

**Daily temp., wind vel., vapor pressure**

$$E(m^3/day) = 130(E_s - E_a)W \cdot A$$

*Es*: saturated vapor pressure at the water temp. (mb)
*Ea*: atmospheric vapor pres. (mb)
*W*: wind vel. (m/s)
*A*: surface area ($km^2$)

$$E_s = \exp(-3.863098 \times 10^{-9} T^4 + 1.18177 \times 10^{-6} T^3 - 3.00388 \times 10^{-4} T^2 + 0.00726612 \; T + 1.8095)$$

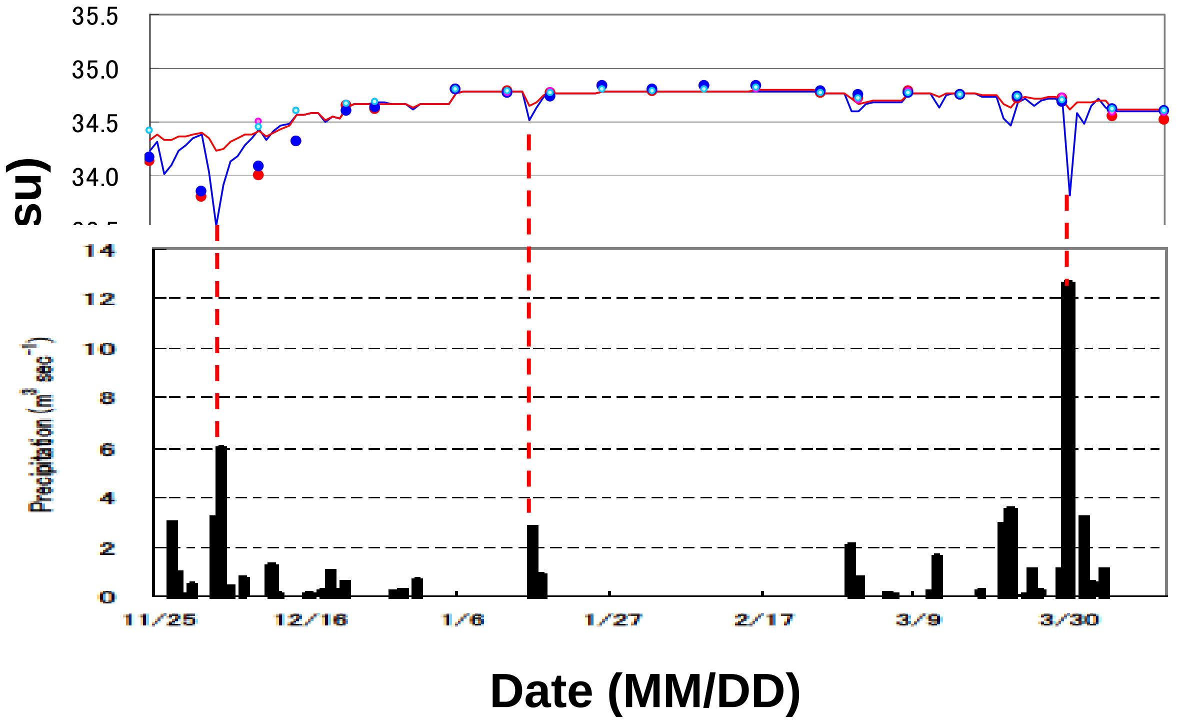
Kurata and Okada (1984)

# Diffusion coefficients

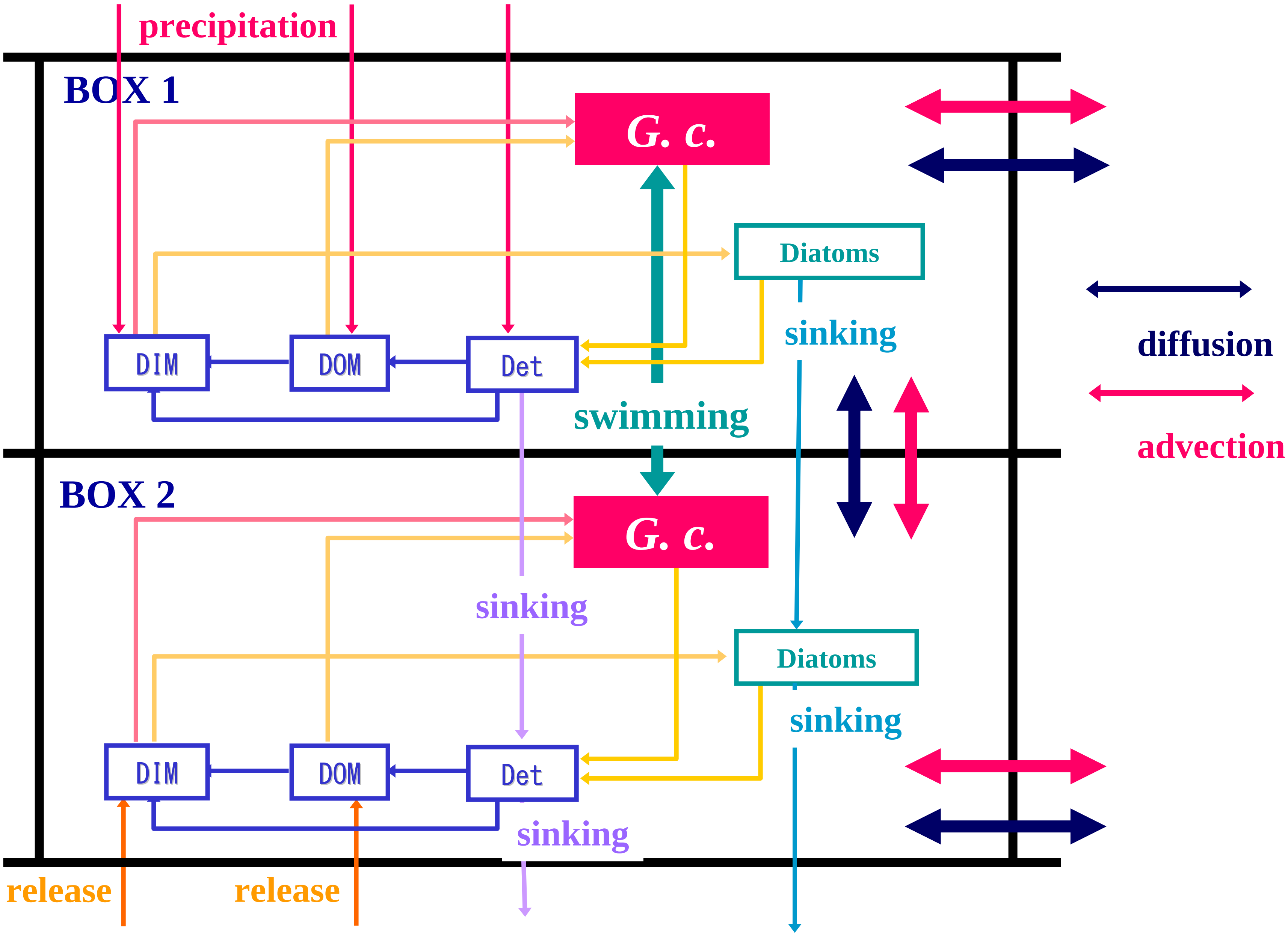
$$V_1 \frac{S_{1a} - S_1}{dt} = Kh_1 \times \frac{S_{1out} - S_1}{X_1} \times Ah_1 + Kv \times \frac{S_2 - S_1}{Z} \times Av - Vh_{1adv} \times Ah_1 \times Sh_1 - Vv_{adv} \times Av \times Sv - (P - E) S_1$$

$$V_2 \frac{S_{2a} - S_2}{dt} = Kh_2 \times \frac{S_{2out} - S_2}{X_2} \times Ah_2 + Kv \times \frac{S_1 - S_2}{Z} \times Av - Vh_{2adv} \times Ah_2 \times Sh_2 + Vv_{adv} \times Av \times Sv$$

**Horizontal dif. coef. 1.0～1.0×$10^3$ $m^2$ $sec^{-1}$**
**Vertical dif. coef. 1.0×$10^{-5}$～1.0×$10^{-3}$ $m^2$ $sec^{-1}$**



# Framework of ecosystem model



# Mass balance (P, upper layer)

## Time change in DIP

$$V_{1U}\frac{dDIP_{1U}}{dt} = -V_{1U}\left(\rho_{Ud}PHYd(P)_{1U} + \rho_{Ugdip}PHYg(P)_{1U} - C_1PP(P)_{1U} - D_1DOP_{1U}\right)$$

$$-V_{adv}\times DIP_{1U} + V_{adv}\times DIP_{1L} - AH_{1U}\frac{KH_{1U}}{X_{1U}}(DIP_{1U} - DIP_{OU}) - AV_1\frac{KV_1}{Z_1}(DIP_{1U} - DIP_{1L})$$

## Time change in DOP

$$V_{1U}\frac{dDOP_{1U}}{dt} = -V_{1U}\left(\rho_{Ugdop}PHYg(P)_{1U} - C_2PP(P)_{1U} + D_1DOP_{1U}\right)$$

$$-V_{adv}DOP_{1U} + V_{adv}\times DOP_{1L} - AH_{1U}\frac{KH_{1U}}{X_{1U}}(DOP_{1U} - DOP_{OU}) - AV_1\frac{KV_1}{Z_1}(DOP_{1U} - DOP_{1L})$$

## Time change in Det-P

$$V_{1U}\frac{dDetP_{1U}}{dt} = +V_{1U}\left(A_{3Ud}PHYd(P)_{1U} + A_{3Ug}PHYg(P)_{1U} - C_1DetP(P)_{1U} - C_2DetP(P)_{1U}\right)$$

$$-AV_1Sink_{PP}DetP(P)_{1U} - AH_{1U}\frac{KH_{1U}}{X_{1U}}(DetP_{1U} - DetP_{OU}) - AV_1\frac{KV_1}{Z_1}(DetP_{1U} - DetP_{1L})$$

$$-V_{adv}\times DetP_{1U} + V_{adv}\times DetP_{1L}$$

## Time change in PHYg (*G. catenatum*)

$$V_{1U}\frac{dPHYg_{1U}}{dt} = V_{1U}\left(\mu_{Ugdip}PHYg_{1U} + \mu_{Ugdop}PHYg_{1U} - A_{Ug}PHYg_{1U}\right) - AV_1Swim_{Pg}PHYg_{1U}$$

$$-V_{adv}\times PHYg_{1U} + V_{adv}\times PHYg_{1L} - AH_{1U}\frac{KH_{1U}}{X_{1U}}(PHYg_{1U} - PHYg_{OU}) - AV_1\frac{KV_1}{Z_1}(PHYg_{1U} - PHYg_{1L})$$

## Time change in PHYd (Diatoms)

$$V_{1U}\frac{dPHYd_{1U}}{dt} = V_{1U}\left(\mu_U PHYd_{1U} - A_{3U}PHYd_{1U}\right) - AV_1Sink_{Pd}PHYd_{1U}$$

$$-V_{adv}\times PHYd_{1U} + V_{adv}\times PHYd_{1L} - AH_{1U}\frac{KH_{1U}}{X_{1U}}(PHYd_{1U} - PHYd_{OU}) - AV_1\frac{KV_1}{Z_1}(PHYd_{1U} - PHYd_{1L})$$

# Biological processes

## □Temp. & Sal.

***G. catenatum***

$$\mu_{st} = 1.2842 - 0.2767 \times T + 0.016 \times T^2 - 0.0004 \times S^2 + 0.0023 \times T \times S - 0.0003 \times T^3 - 0.00004 \times T^2 \times S$$

(Yamaguchi, pers. comm.)

**Diatom (*S. costatum*)**

$$\mu_t = -0.004 \times T^2 + 0.165 \times T - 0.766$$

$$\mu_s = -0.003 \times S^2 + 0.132 \times S - 0.226$$

(Tsuruta et al., 1985)

## □Light

***G. catenatum***

$$\mu_i = \mu'_{\max} \times \frac{I - 10}{I - 3.2}$$

(Yamamoto et al., 2002)

**Diatom (*S. costatum*)**

$$\mu_i = \mu'_{\max} \times \frac{I - 5.43}{(60.8 - 5.43) + (I - 5.43)}$$

(Langdon ,1987)

## □Nutrient uptake

***G. catenatum*** **Diatom (*S. costatum*)**

$$\rho = \rho_{\max} \times \frac{S}{S + K_S}$$

(Dugdale, 1967)

$$\mu_e = \mu'_{\max}(1 - Q_{\min} / Q_e)$$

(Droop, 1973)

$$Q_{\max} = \left(\frac{\mu'_{\max}}{\mu'_{\max} - \mu_{\max}}\right) \times Q_{\min}$$

(Morel,1987)

$$\rho_{\max} = \rho^{hi}_{\max} - \frac{(\rho^{hi}_{\max} - \rho^{lo}_{\max}) \times (Q - Q_{\min})}{(Q_{\max} - Q_{\min})}$$

$$\rho^{lo}_{\max} = \mu'_{\max} \times (Q_{\max} - Q_{\min})$$

(Grover, 1991)

# Biological processes (cont'd)

## □Growth rate

***G. catenatum***

$$\mu = \mu'_{\max} \times \min(f(e), f(i)) \times \frac{\mu_{st}}{\mu'_{\max ST}}$$

**Diatom (*S. costatum*)**

$$\mu = \mu_e \times \frac{\mu_t}{\mu_{\max\ t}} \times \frac{\mu_s}{\mu_{\max\ S}} \times \frac{\mu_i}{\mu_{\max\ i}}$$

## □Motality rate

$$A_3 = M_{po} \exp(k_{MP} T)$$

## □Decomposition rate of PP to DIP and DOP

$$C_1 = V_{PI} \exp\left(k_{VPI}\ T\right)$$

$$C_2 = V_{PO} \exp\left(k_{VPO}\ T\right)$$

## □ Decomposition rate of DOP to DIP

$$D_1 = V_{DIP} \exp\left(k_{VDI}\ T\right)$$

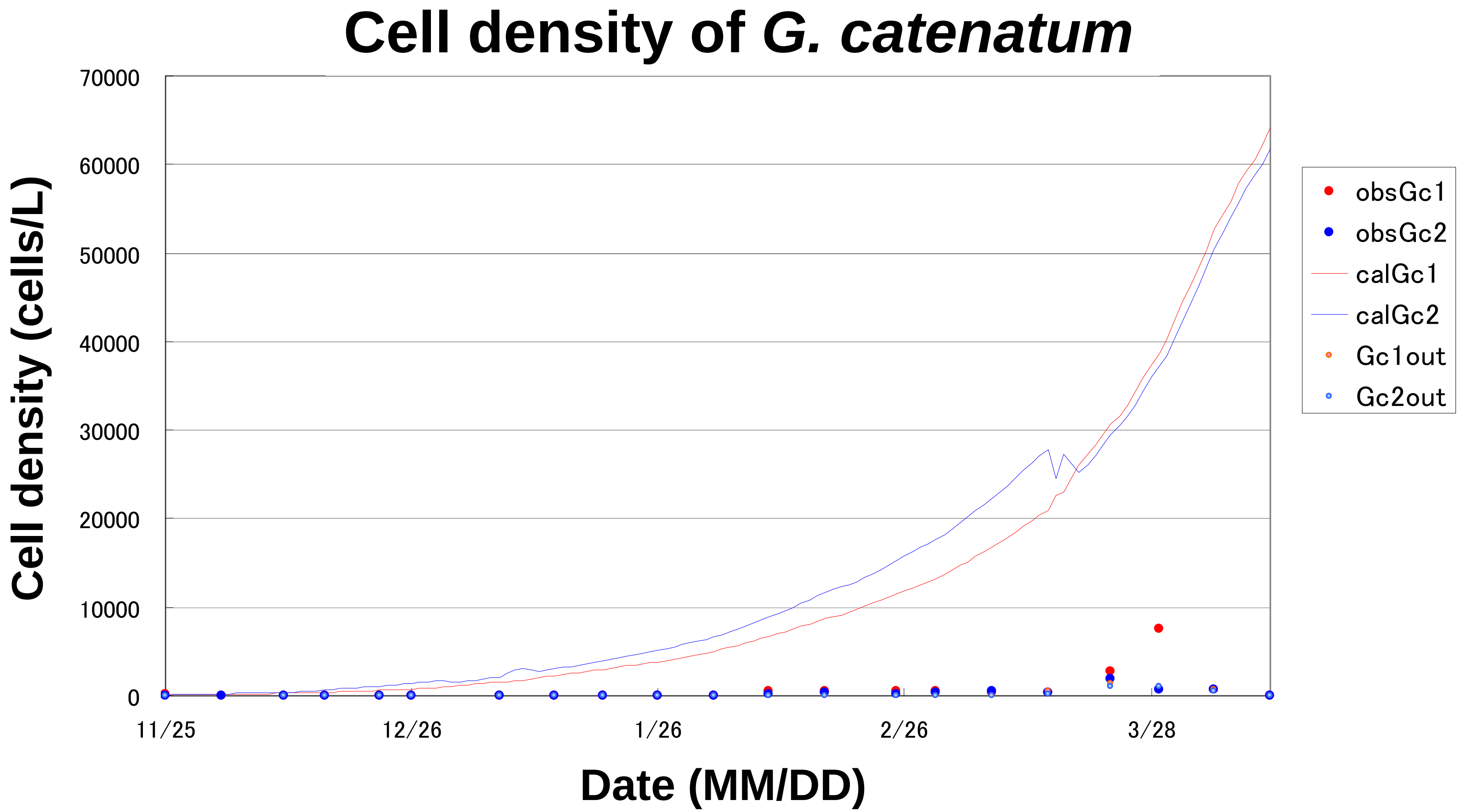
# Parameters used in this model

| symbols | values | unit | references |
|---|---|---|---|
| *Gymnodinium catenatum* | | | |
| $\mu_{max}$ | 0.31 | $d^{-1}$ | Kann (2000) |
| $\mu'_{max(P)}$ | 0.53 | $d^{-1}$ | yamaguchi |
| $K_{s\,(DIP)}$ | 3.4 | μM | Kataoka (2001) |
| $K_{s\,(DOP)}$ | 7.61 | μM | Oh(2002) |
| $\rho_{max}^{hi}{}_{(DIP)}$ | 1.42 | $pmol\ cell^{-1}\ h^{-1}$ | Kataoka (2001) |
| $\rho_{max}^{hi}{}_{(DOP)}$ | 13.38 | $pmol\ cell^{-1}\ h^{-1}$ | Oh(2002) |
| $\rho_{max}^{lo}{}_{(P)}$ | 0.15 | $pmol\ cell^{-1}\ h^{-1}$ | *1 |
| $Q_{0\,(P)}$ | 1.44 | $pmol\ cell^{-1}$ | yamaguchi |
| $Q_{max\,(P)}$ | 3.43 | $pmol\ cell^{-1}$ | *2 |
| $W_{(dinoflagellate)}$ | 14.88 | $m\ day^{-1}$ | Anderson and Stolzenbach(1985) |
| *Skeletonema costatum* | | | |
| $\mu_{max}$ | 0.96 | $d^{-1}$ | yamaguchi |
| $\mu'_{max(P)}$ | 1.25 | $d^{-1}$ | tarutani and yamamoto(1994) |
| $K_{s\,(DIP)}$ | 0.68 | μM | tarutani and yamamoto(1994) |
| $\rho_{max}^{hi}{}_{(DIP)}$ | 0.038 | $pmol\ cell^{-1}\ h^{-1}$ | tarutani and yamamoto(1994) |
| $\rho_{max}^{lo}{}_{(P)}$ | 0.02 | $pmol\ cell^{-1}\ h^{-1}$ | *1 |
| $Q_{0\,(P)}$ | 0.004 | $pmol\ cell^{-1}$ | tarutani and yamamoto(1994) |
| $Q_{max\,(P)}$ | 0.02 | $pmol\ cell^{-1}$ | *2 |
| Sinking | 0.7 | $m\ day^{-1}$ | Smayda(1970) |

*1: calculate with $\mu'_{max} = \rho_{max}^{lo} / (Q_{max} - Q_0)$

*2: calculate with $Qmax = \mu' max \times Qmin / (\mu' max - \mu max)$

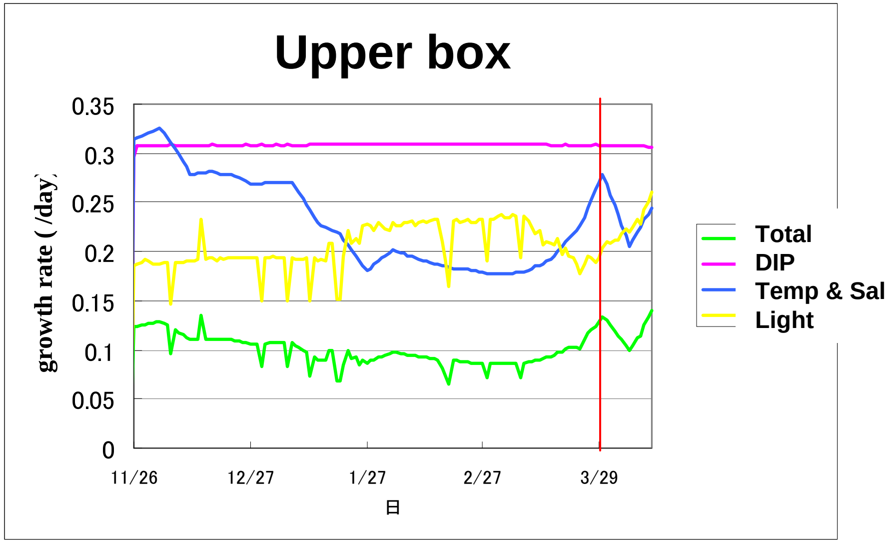
# Results – primary calculation: with no physical processes

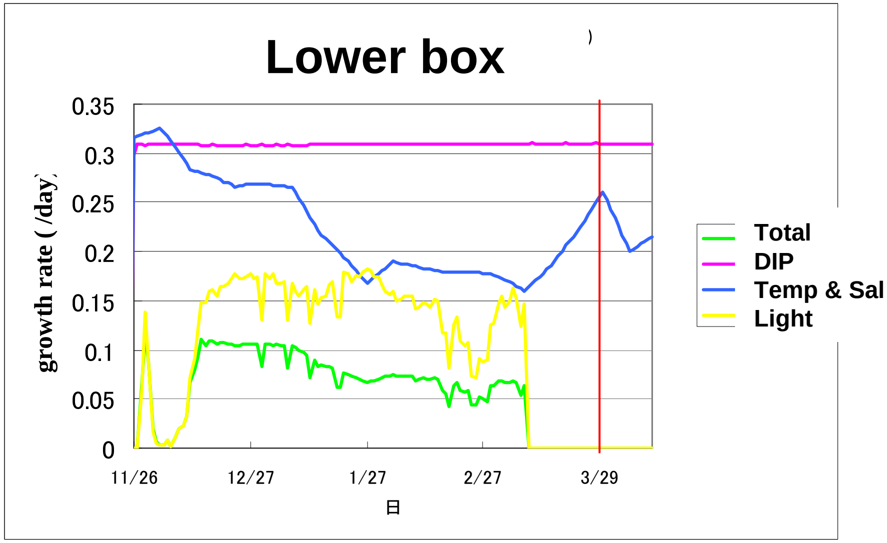



1. **High growth potential/no extinction**
2. **Timing of the bloom**

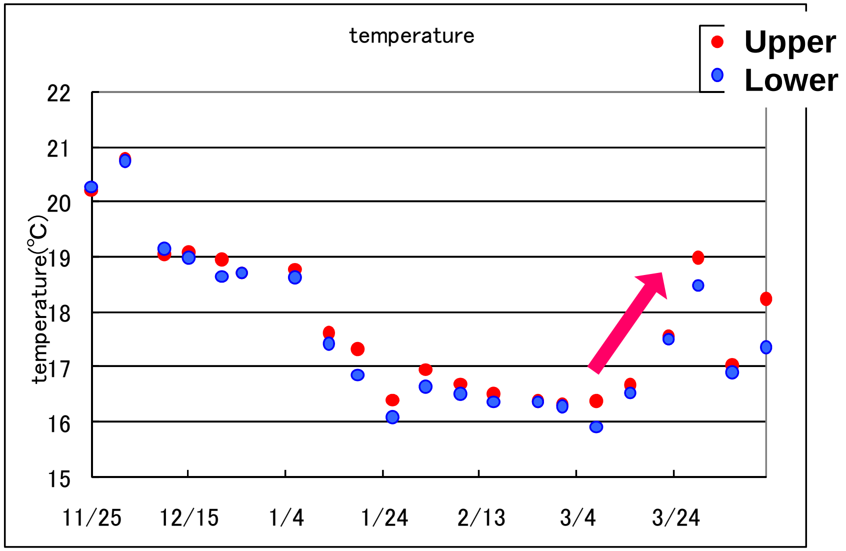
# Examination of biological factors

## Growth rate of *G. catenatum*



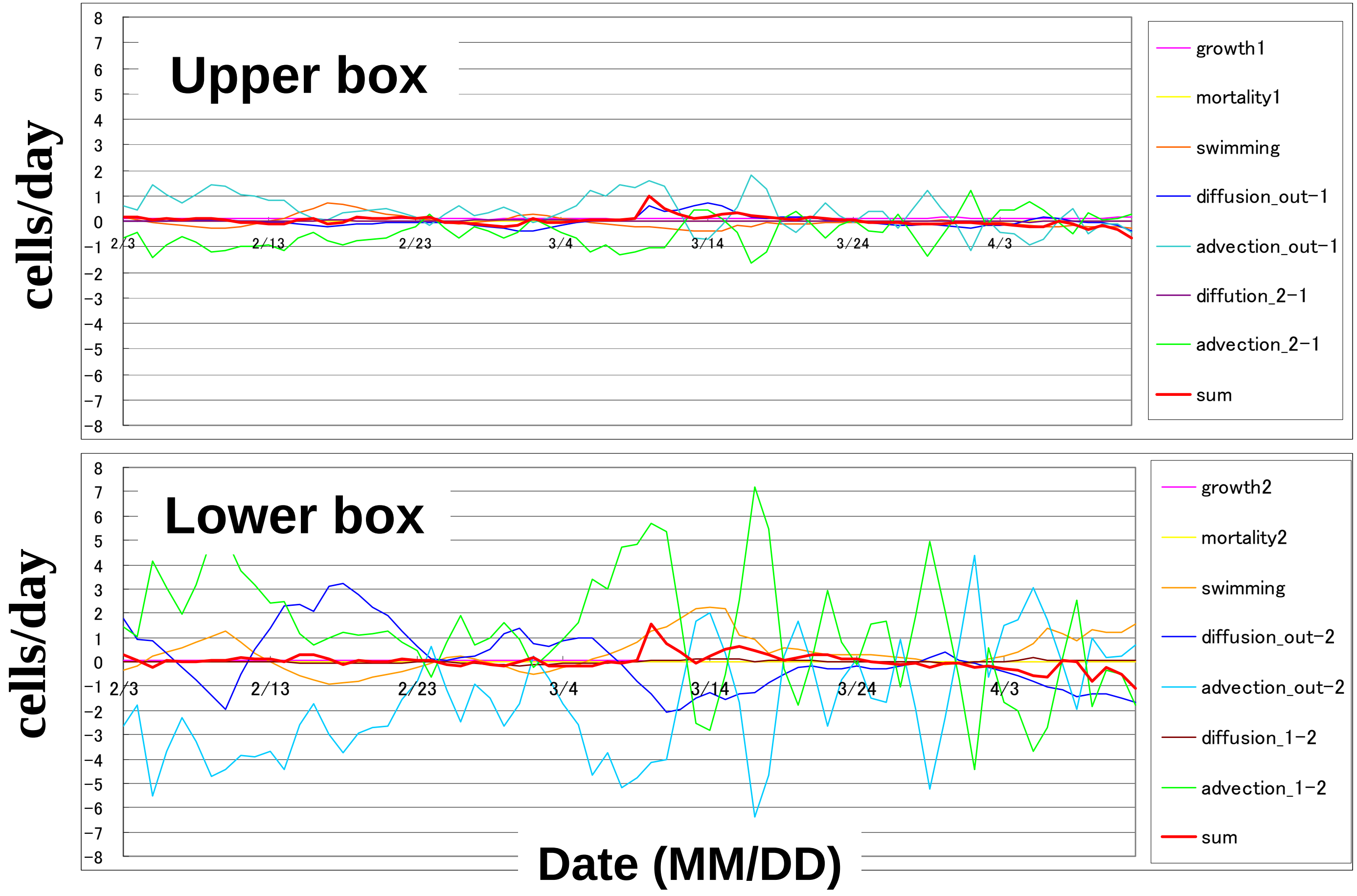

## Temperature




**16.5℃→19.0℃**

**Temperature is possible**

# Examination of biological/physical factors

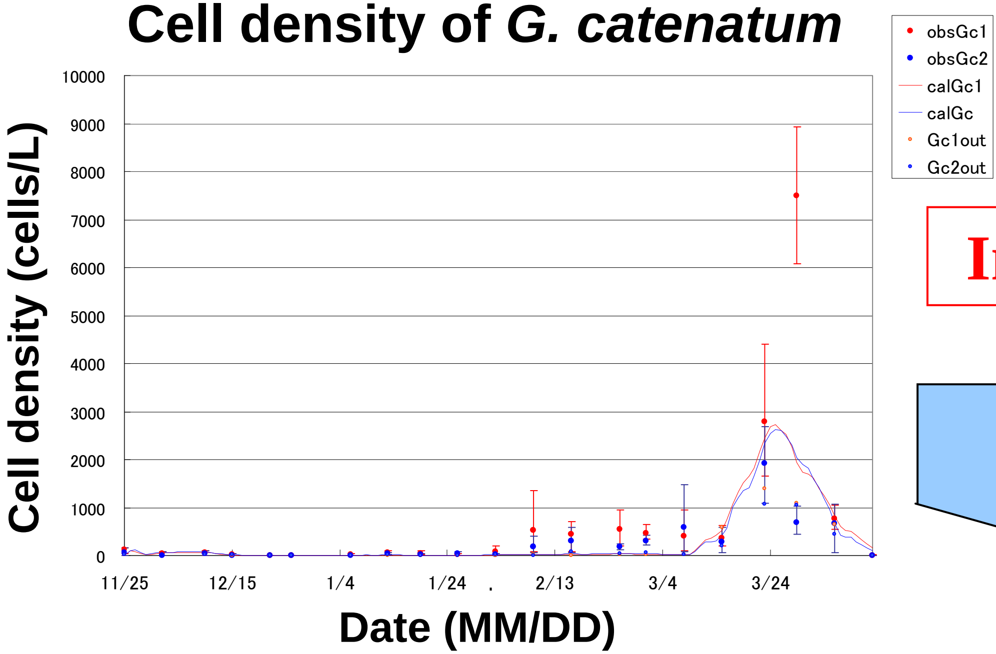


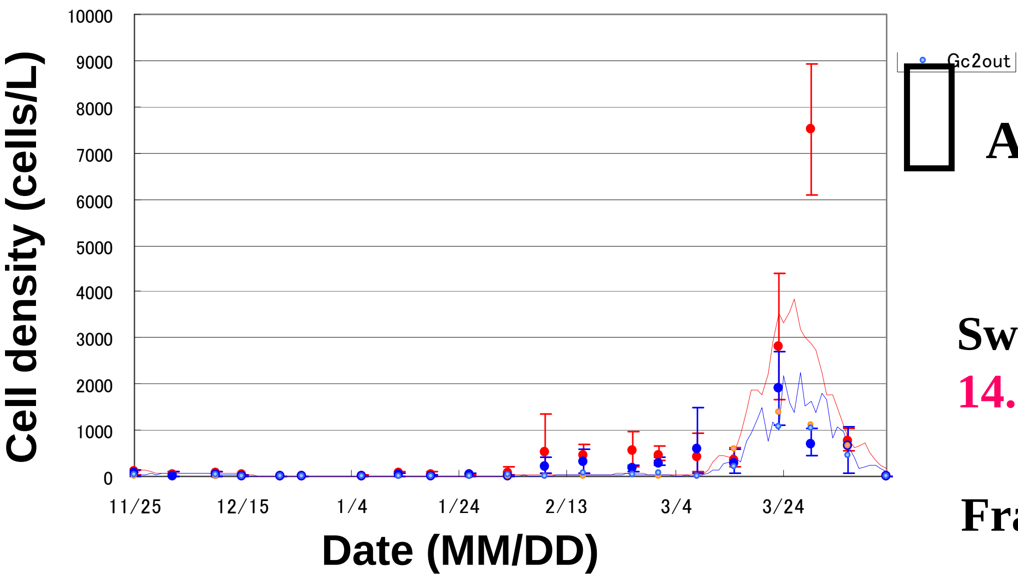

Changing rate ($day^{-1}$)=flow (cells/day)/cell density($cells/m^3$)/box volume($m^3$)

1. Physical factors (advection and diffusion) are deterministic,
2. Motility (swimming) is the second effective.

# Comparison of with/without motility

## Cell density of *G. catenatum*

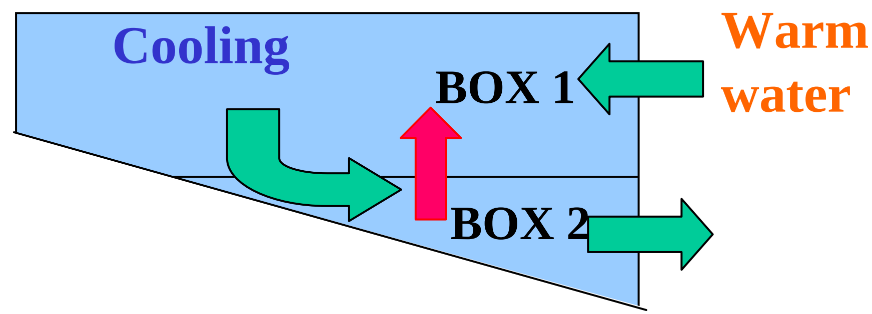



## Flow pattern in winter

**Inverse estuarine circulation**

**Abo and Miyamura (2005)**




**Avg adv velocity ca. 10 m $day^{-1}$**

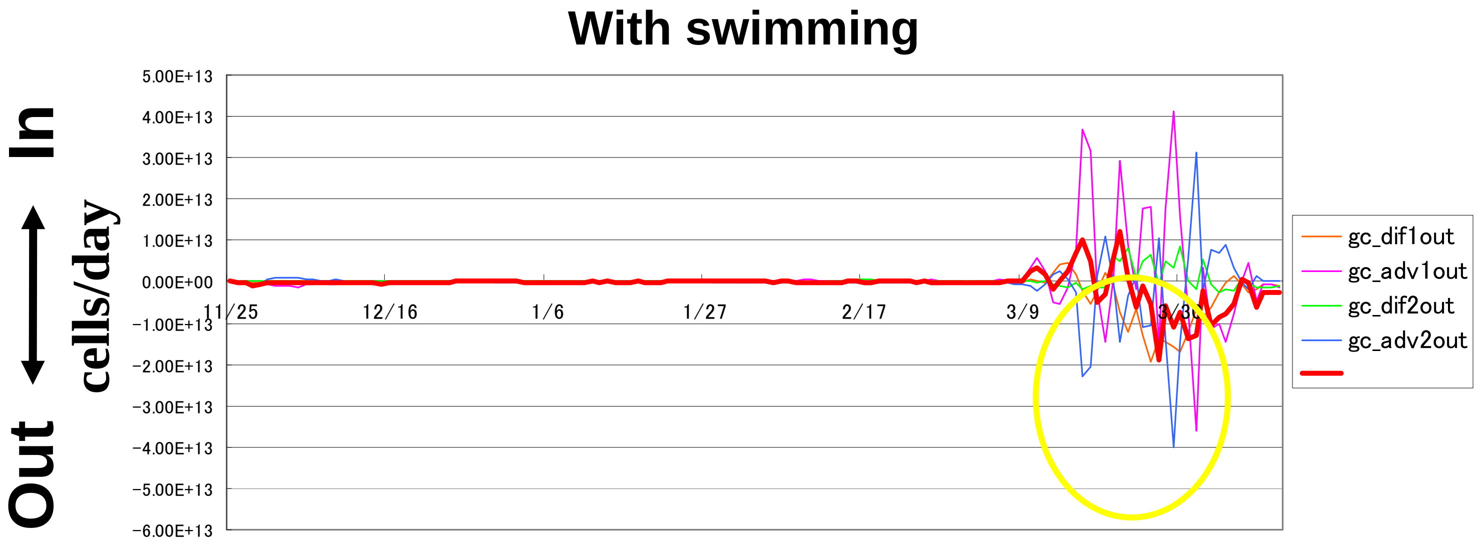
∧

**Swimming speed of *G.catenatum***

**14.88 m $day^{-1}$ (Anderson and Stolzenbach, 1985)**

**Fraga et al. (1988), Fermin et al. (1996)**
**Ria de Vigo, Spain**

# Examination of motility


**Upward swimming behavior of *Gc* plays an important role to decrease the loss of cells from the lower box to out.**

# Conclusions

1. **Temperature is a possible factor to accelerate a growth rate at the time of the bloom.**

2. **Physical processes are the most effective to determine the bloom formation/dissipation of *G. catenatum* in Inokushi Bay.**

3. **Swimming behavior is likely to be important for *G. catenatum* to maintain their cell density during the period of "inverse estuarine circulation".**

# Acknowledgements

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