Why **phenology** is important?

The study of the timing of periodic biological events

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**Tight linkage** to the peak abundance in grazers [Longhurst, 2007]

**Match-mismatch hypothesis**
[Cushing, 1990]
Global ocean (for subpolar regions)

[Bloom initiation](#)

- Net heat flux > 0
- Mixed layer depth shoaling
- Mixed layer PAR increases

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[Introduction](#)

[Cole et al., 2015](#)
The East Sea/Sea of Japan

Period: 1982~2002
1. Using Gaussian curve

2. Spring bloom initiation
   $\propto$ average wind speed in February and March

3. Spring peak timing
   $\propto$ $1$/stratification strength

[Yamada and Ishizaka, 2006]
**Key Questions**

- **Is there any significant relationship between bloom timing metrics?**

- **What physical drivers influence the relationship between bloom timing metrics?**

※ bloom timing metrics: bloom initiation, peak timing, duration, termination, peak magnitude
**Definition**

*Feature extraction using shifted Gaussian Curve*

- **B(t)** = \( B_0 + \beta \times t + h \times \exp \left( \frac{-(t-t_m)^2}{2\sigma^2} \right) \)

- **\( t_i \)** = \( t_m - (-2 \times \log 0.2)^2 \times \sigma \)
  = \( t_m - 1.76 \times \sigma \)

- **\( t_d \)** = \( 2 \times (t_m - t_i) \)

- **\( t_t \)** = **\( t_i \) + **\( t_d \)

- **\( t_p \)** = \( B_0 + \beta \cdot t + h \)

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**Bloom timing metrics of Gaussian Curve**

- \( B(t) \) = shifted Gaussian function
- \( B_0 \) = background value of chl
- \( \beta \times t \) = additive linear term
- \( h \) = amplitude of bloom
- \( \sigma \) = width of chl peak
- \( t \) = time

- \( t_i \) = time when chl \( (B(t) - (B_0 + \beta \times t)) \)
  reaches 20% of bloom amplitude
- \( t_m \) = time when bloom peaks
- \( t_t \) = time when chl(“”) decreases to 20% of bloom amplitude
- \( t_d \) = period from initiation to termination
- \( t_p \) = peak intensity

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Zhai et al., 2011
### Data Sources

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chlorophyll a</strong>&lt;br&gt;(CHL[mgm⁻³])</td>
<td>Oc4v6 merged data (SeaWiFS &amp; MODIS Aqua)</td>
</tr>
<tr>
<td><strong>Sea Surface Temperature</strong>&lt;br&gt;(SST[°C])</td>
<td>NOAA AVHRR-OI SST data</td>
</tr>
<tr>
<td><strong>Net Heat Flux</strong>&lt;br&gt;(NHF [W m⁻²])</td>
<td>ECMWF shortwave radiation + longwave radiation + latent heat flux + sensible heat flux data</td>
</tr>
<tr>
<td><strong>Photosynthetically Available Radiation</strong>&lt;br&gt;(PAR[W m⁻²])</td>
<td>SeaWiFS &amp; MODIS Aqua PAR data</td>
</tr>
<tr>
<td><strong>Wind Stress</strong>&lt;br&gt;(WND τ[Nm⁻²])</td>
<td>ECMWF wind U/V component data</td>
</tr>
<tr>
<td><strong>Eddy Kinetic Energy</strong>&lt;br&gt;(EKE[m²s⁻²])</td>
<td>AVISO U/V component data</td>
</tr>
</tbody>
</table>
Result & Discussion

Annual mean

- CHL [mg m$^{-3}$]
- SST [°C]
- NHF [W m$^{-2}$]
- PAR [W m$^{-2}$]
- MND [m$^{2}$ m$^{-2}$]
- EKE [m$^{2}$ s$^{-2}$]

**Average in Feb and Mar**
- Increase max
- Decrease max

**Average in Sep and Oct**
- Turn positive
- Turn negative
Spatial distribution: climatological mean

<table>
<thead>
<tr>
<th>Initiaton</th>
<th>Peaktiming</th>
<th>Duration</th>
<th>Termination</th>
<th>Peakmagnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_i$</td>
<td>$t_m$</td>
<td>$t_d$</td>
<td>$t_t$</td>
<td>$p_i$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(yearday)</th>
<th>(yearday)</th>
<th>(yearday)</th>
<th>(yearday)</th>
<th>(mg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>Autumn</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Latitude

Longitude

byelggi@kiost.ac.kr
Interannual variability

Weak trend

$t_i_{Spring}$
$P=0.05$

$t_m_{Spring}$
$P=0.20$

$t_d_{Spring}$
$P=0.06$

$t_t_{Spring}$

$t_p_{Spring}$

Spring

Autumn

Results & Discussion
Result & Discussion

Relationship between bloom timing metrics

Spring

- $t_m$ vs. $t_i$: $Cor = 0.86^{***}$
- $t_d$ vs. $t_i$: $Cor = -0.74^{***}$
- $t_i$ vs. $t_m$: $Cor = 0.73^{***}$

Autumn

- $t_i$ vs. $t_d$: $Cor = 0.89^{***}$
- $t_d$ vs. $t_i$: $Cor = -0.81^{***}$
- $t_i$ vs. $t_m$: $Cor = 0.68^{**}$

***: $P < 0.001$
Result & Discussion

**The effect of physical factors**

- Spring
  - $W_{ND2-3}$ [N m$^{-2}$]: $Cor = 0.67^*$
  - $NHF_{2-3}$ [W m$^{-2}$]: $Cor = -0.53^*$
  - $EKE_{2-3}$ [m$^{-2}$ s$^{-2}$]: $Cor = -0.56^*$

- Autumn
  - $PAR_{decrease_{max}}$ [yearday]: $Cor = 0.32$
  - $SST_{9-10}$ [$^\circ$C]: $Cor = 0.52^*$
  - $NHF_{9-10}$ [W m$^{-2}$]: $Cor = 0.45$

* $P < 0.05$
<table>
<thead>
<tr>
<th>Summary</th>
</tr>
</thead>
</table>

- **Temporal Trend**

<table>
<thead>
<tr>
<th>Season</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>Weak trend</td>
</tr>
<tr>
<td>Autumn</td>
<td>No remarkable trend</td>
</tr>
</tbody>
</table>

- **Q1. Relationship between bloom timing metrics**

<table>
<thead>
<tr>
<th>Season</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>$t_i \propto \frac{1}{t_d}$, $t_i \propto t_m$</td>
</tr>
<tr>
<td>Autumn</td>
<td>$t_t \propto t_d$, $t_t \propto t_m$</td>
</tr>
</tbody>
</table>

- **Q2. Influence of physical forcing**

<table>
<thead>
<tr>
<th>Season</th>
<th>Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>$t_i$, $t_m \propto WND_{2-3}$, faster and strong stratification: earlier blooms?</td>
</tr>
<tr>
<td>Autumn</td>
<td>weak correlation, The biotic impact is more important?</td>
</tr>
</tbody>
</table>
Further thought

✓ Why does the earlier bloom tend to be longer lasting?

✓ We expected that if the bloom initiation is advanced, the peak magnitude is lower. But, why is there no relationship between them?

✓ Is the wind stress in Feb and Mar really going to decrease? If not, how can we explain the trend of bloom initiation in the East Sea?
Thank You!!
Ephemeral periods of deep convection → positive buoyancy (in the absence of stratification)

Turbulence below a certain threshold

Shutdown of deep convection

Restratification (reduction of turbulence mixing, mesoscale features: eddies and fronts, even in the absence of net positive heat input)

[Lindemann and John, 2014]

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**Data & Methods**

**Analysis flow**

- **SeaWIFS**
- **MODISA**

**Creating merged data (oc4v6)**

**Spatial binning**

**Parameters**
- $t_i$, $t_m$, $t_d$, $t_t$, $t_p$
  - $t_i$: bloom initiation
  - $t_m$: peak timing
  - $t_d$: bloom duration
  - $t_t$: bloom termination
  - $t_p$: peak magnitude

- using shifted Gaussian Curve

- (spatial: interval value using mean (horizontally, vertically, diagonally), n ≥ 4)

- (chl<50, mean-1.96•sd≤x≤mean-1.96•sd, n≥3)

95% of all observations

**Spatial filtering**

[Racault et al., 2014]
# Data & Methods

## Description of physical metrics

<table>
<thead>
<tr>
<th>Physical driver</th>
<th>Metric name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>$SST_{2-3}$</td>
<td>The SST average in Feb and Mar</td>
</tr>
<tr>
<td></td>
<td>$SST_{\text{increase_max}}$</td>
<td>The date of largest increase rate in SST between the beginning of the annual cycle and the maximum SST</td>
</tr>
<tr>
<td></td>
<td>$SST_{9-10}$</td>
<td>The SST average in Sep and Oct</td>
</tr>
<tr>
<td></td>
<td>$SST_{\text{decrease_max}}$</td>
<td>The date of largest decrease rate in SST between the maximum SST and the end of the annual cycle</td>
</tr>
<tr>
<td>NHF</td>
<td>$NHF_{2-3}$</td>
<td>The NHF average in Feb and Mar</td>
</tr>
<tr>
<td></td>
<td>$NHF_{\text{turnp}}$</td>
<td>The first date when NHF turns from zero into positive value</td>
</tr>
<tr>
<td></td>
<td>$NHF_{9-10}$</td>
<td>The NHF average in Sep and Oct</td>
</tr>
<tr>
<td></td>
<td>$NHF_{\text{turnn}}$</td>
<td>The first date when NHF turns from zero into negative value</td>
</tr>
<tr>
<td>PAR</td>
<td>$PAR_{2-3}$</td>
<td>The PAR average in Feb and Mar</td>
</tr>
<tr>
<td></td>
<td>$PAR_{\text{increase_max}}$</td>
<td>The date of largest increase rate in PAR between the beginning of the annual cycle and the maximum PAR</td>
</tr>
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<td></td>
<td>$PAR_{9-10}$</td>
<td>The PAR average in Sep and Oct</td>
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<td></td>
<td>$PAR_{\text{decrease_max}}$</td>
<td>The date of largest decrease rate in PAR between the maximum PAR and the end of the annual cycle</td>
</tr>
<tr>
<td>WND</td>
<td>$WND_{2-3}$</td>
<td>The WND average in Feb and Mar</td>
</tr>
<tr>
<td></td>
<td>$WND_{9-10}$</td>
<td>The WND average in Sep and Oct</td>
</tr>
<tr>
<td>EKE</td>
<td>$EKE_{2-3}$</td>
<td>The EKE average in Feb and Mar</td>
</tr>
<tr>
<td></td>
<td>$EKE_{9-10}$</td>
<td>The EKE average in Sep and Oct</td>
</tr>
</tbody>
</table>
Result & Discussion

Interannual variability

In the East Sea
Interannual variability: Spring
(h > 0.8 mg m⁻³)
Interannual variability: Autumn
(h > 0.2 mg m\(^{-3}\))

Time [yearday]
Interannual variability of annual mean

CHL

[mg m\(^{-2}\)]


0.65 0.60 0.55

SST

[\degree C]


13.4 13.4 13.4 13.4 13.4

NHF

[W m\(^{-2}\)]


-40 -50 -60 -70 -80

PAR

[W m\(^{-2}\)]


30 28 26 24 22

WND

[N m\(^{-2}\)]


0.078 0.075 0.072 0.069 0.066

EKE

[m\(^{2}\) s\(^{-1}\)]


0.01 0.008 0.006 0.004 0.002
Spatial distribution: linear trend

Initiation $t_i$

Peaktiming $t_m$

Duration $t_d$

Termination $t_t$

Peakintensity $p_i$

Spring

Autumn
Result & Discussion

Spatial distribution: climatological mean

- SST
- NHF
- PAR
- WND(τ)
- EKE
Result & Discussion

Spatial distribution: linear trend

<table>
<thead>
<tr>
<th>SST</th>
<th>NHF</th>
<th>PAR</th>
<th>WND(τ)</th>
<th>EKE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(℃ year⁻¹)</td>
<td>(W² year⁻¹)</td>
<td>(W m² year⁻¹)</td>
<td>(N m² year⁻¹)</td>
<td>(m² s⁻² year⁻¹)</td>
</tr>
</tbody>
</table>

Images show spatial distributions for SST, NHF, PAR, WND(τ), and EKE for different periods (Feb+Mar, Sep+Oct).
Spatial distribution: trend relationship

$t_i$ vs. $t_m$

$t_i$ vs. $t_d$

$t_i$ vs. $t_p$

$t_m$ vs. $t_t$

$t_d$ vs. $t_t$

Spring

Autumn
Result & Discussion

Correlation

Spring
Initiation

Autumn
Termination

SST  NHF  PAR  WND  EKE

Latitude
45°N
40°N
35°N

Longitude
130°E 135°E 140°E
Result & Discussion

Spatial distribution: trend relationship

Spring

- $t_m$ vs. $t_i$ [yearday]: $Cor = 0.83$***
- $t_d$ vs. $t_i$ [yearday]: $Cor = -0.87$***
- $t_d$ vs. $t_i$ [yearday]: $Cor = 0.61$***

Autumn

- $t_m$ vs. $t_i$ [yearday]: $Cor = 0.86$***
- $t_d$ vs. $t_i$ [yearday]: $Cor = 0.89$***
- $t_d$ vs. $t_i$ [yearday]: $Cor = -0.57$***

***: $P<0.001$
Result & Discussion

**Relationship between bloom timing metrics**

- If the bloom initiation ($t_i$) advanced, the peak timing ($t_m$) tends to be advanced.
- If the bloom termination ($t_t$) advanced, the peak timing ($t_m$) tends to be advanced.
- If the bloom initiation ($t_i$) advanced, the bloom tends to last longer ($t_d$).
- If the bloom termination ($t_t$) advanced, the bloom tend to last shorter ($t_d$).
Result & Discussion

Correlation

![Graph showing correlation for Spring and Autumn years from 1998 to 2014. The x-axis represents the years, and the y-axis represents the data values. The graph compares two sets of data, denoted by different colors and markers.](image-url)
Further study

**Why does the earlier bloom tends to be longer lasting?**

*Phytoplankton community respond differently to physical forcing!*

- Deriving phytoplankton groups using bio-optical models and HPLC pigments
- Analysis of relationship between phytoplankton bloom feature and physical forcing

[Edwards & Richardson, 2004]

**How about the spatial distribution?**

Description of spatial differences in phytoplankton phenology patterns
- using K-means clustering