Introduction to the modeling of marine ecosystems
Why Interdisciplinary Study?

The physical processes in the ocean regulate, for example, nutrients availability and many organisms distributions which cannot be described by biology alone.
Why do we need models?

To develop and enhance understanding (e.g. do experiments with modeling that we can otherwise only observe in the state at the time of the observation).

To quantify descriptions of processes,

To synthesize and consolidate our knowledge (e.g. synthesis of sparse observations).

To establish interaction of theory and observation,

To simulate scenarios of past and future developments (e.g. to use predictive potential for environmental management).
Concepts of Coupled Modeling of Biological and Physical Oceanography

- Physical Model
  - Sets of differential equations which describe the motion of ocean + numerical implementation to solve these equations in computer

- Biological Model
  - Synonymously for theoretical descriptions in term of sets of equations which describe the food web dynamics of marine systems + numerical implementation to solve these equations in computer
Physical Model:

Equations:

1: Momentum equation
2: Mass conservation equation
3: Heat conservation equation
4: Salinity conservation equation
5: Turbulent energy equation

\{ \text{A closed system} \}

Time- and space-dependent variables to be obtained:

1. Velocities of ocean flow
2. Temperature and salinity (therefore, density) of sea waters
3. Turbulence conditions
Atmospheric fluxes (winds, heat, fresh water)

Ocean Model
Eqs. For $\mathbf{V} (u,v,w)$, density ($T,S$),
mass conservation ($\eta$, surface elevation),
turbulent mixing, parameterization

Numerical algorithms

Lateral flux (e.g. remote forcing)

Programming

Execution in computer

Model Data Processing and analyzing
Biological Model:

Equations (Simple Model, e.g. NPZD):

1: Equation of nutrients
2: Equation of phytoplankton
3: Equation of zooplankton
4: Equation of detritus

Time- and space-dependent variables to be obtained:

1. Nutrients concentration
2. Phytoplankton concentration
3. Zooplankton concentration
4. Detritus concentration

A closed system which contains pathways of chemical biological processes from different trophic levels to nutrients through respiration, excretion and dead organic material.

Model should be as simple as possible and as complex as necessary to answer specific questions.
Chemical Biological-Models

• To describe, understand and quantify fluxes of biochemical process through food web and interactions with the atmosphere and sediments.
Fundamental laws of biogeochemical model:

Conservation of mass of the chemical elements needed by the plankton cells (e.g. carbon or nitrate, i.e. as ‘model currency’)

\[ M \text{ (mass of all chemical elements)} = \sum_{n=1}^{\text{nth chemical elements}} C_n V \]

\( C_n \) is a concentration (biomass per unit volume, e.g. mmol/m\(^3\)) for nth chemical variable
Conservation of mass of the chemical elements

Change of mass of nth chemical elements

\[ V \frac{dC_n}{dt} = \text{sources}_n + \text{sinks}_n \pm \text{transfers}_{n-1,n+1} \]

V is the volume of water
$V \frac{dC_n}{dt} = \text{Sources (gains) of } n\text{th of element (e.g. external nutrient inputs by river discharge and sediments)}$

$+ \quad \text{Sinks (losses) of } n\text{th of element}$

$+ \quad \text{The propagation of nutrients through different elements (driven by biological processes, e.g. nutrient uptake during primary production or by microbial conversion).}$

$+ \quad \text{Transfers by turbulent processes}$
\[ V \frac{dC_n}{dt} = \text{Local change of } VC_n + \text{advection of } VC_n \text{ by oceanic current} \]

i.e. \( C_n \) can be predicted

Example: Let \( C1 = S \), \( C2 = P \) and

\[
\begin{array}{c}
S \\
\end{array} \rightarrow \begin{array}{c}
P \\
\end{array}
\]
The conservation of mass in the absence of external sources or sinks is given by:

\[
\frac{dS}{dt} = -kS
\]

\[
\frac{dP}{dt} = kP
\]

The change in the sum of S and P is:

\[
\frac{d(S + P)}{dt} = 0
\]

Therefore, the sum of S and P is constant:

\[S + P = \text{const}\]

P can be expressed as:

\[P = S_0 - S\]

S and P concentrations are assumed to decrease at the same rate as the product increase (more complex relation can be applied in real case).

At \(t=0\), \(S=S_0\), \(P=P_0=0\).
Nutrient Limitation:

• The law of minimum: If only one of the essential nutrients becomes rare then growing of plants is no longer possible.

• For example: In N-limit case, if N become rare, the growing will stop.

• Molar ratio of carbon to nitrogen to phosphorous, C:N:P=106:16:1.
In the modeling, we can focus on only those one or two nutrients which are exhausted first and hence are limiting the further biomass development.
Nutrients control the rate of phytoplankton:

N: a nutrient concentration (dissolved inorganic nitrogen)
P: phytoplankton biomass concentration

\[
\frac{dP}{dt} = r_{\text{max}} f(N) P
\]

\( r_{\text{max}} \): the maximum rate, which constitutes intrinsic cell properties at given light and temperature;

\( f(N) \): uptake function
\( f(N) = 1 \), when the nutrient is plentifully available maximum rate or P’s change is not affected by N

\[
f(N) = \frac{N}{k_N + N}
\]

One of the option for uptake function \( f(N) \). It is obtained from empirical relationship. More options are presented in figure 2.4.
Figure 2.4: Four different choices of functions with limiting properties plotted for half saturation constant $k_N = 0.1 \text{ mmol/m}^3$ (solid), $k_N = 0.3 \text{ mmol/m}^3$ (dash dot), $k_N = 0.5 \text{ mmol/m}^3$ (dash).
For a set of arbitrary $r_{max}$ and $f=N/(K_N+N)$, $N$ and $P$ behave as Fig. 2.5

\[
\frac{dN}{dt} = -r_{max} f(N) P
\]

\[
\frac{d(N + P)}{dt} = 0
\]

for any $t$

Figure 2.5: Nutrient and plankton dynamics for a nutrient limiting the growth rate.
Recycling: Phytoplankton back to nutrients.

Two pathways:
1: fast direct release of nutrients through respiration and extra-cellular release.
2: slow mineralization (microbial conversion) of dead cells.

The 2 will require taking into account a new variable, the detritus, and form a NPD-model.
In the N-limit case

- $\text{N}$ uptake + solar radiation
- $\text{P}$ respiration
- $\text{D}$ mineralization
- $\text{D}$ mortality
\[
\frac{dN}{dt} = -r_{\text{max}} f(N) + l_{PN} P + l_{DN} D
\]
\[
\frac{dP}{dt} = r_{\text{max}} f(N) - l_{NP} P - l_{PD} P
\]
\[
\frac{dD}{dt} = l_{PD} P - l_{DN} D
\]

\(r_{\text{max}}\) is depends on light and temperature

\(l_{PN}\): loss by respiration

\(l_{PD}\): mortality

\(l_{DN}\): Mineralization
\[ \frac{d(N + P + D)}{dt} = 0 \]

Conservation of mass is fulfilled

For a steady state, i.e. N, P and D do not vary with time, then

\[ 0 = -r_{\text{max}} f(N)P + l_{PN} P + l_{DN} D \]

\[ 0 = r_{\text{max}} f(N)P - l_{NP} P - l_{PD} P \]

\[ 0 = l_{PD} P - l_{DN} D \]
From steady state equations, it can be found an equilibrium among N, P and D can be reached for certain nutrient level

\[ N^* = \frac{k_N}{r_{\text{max}} - l_{PN} - l_{PD}} \left( l_{PN} + l_{PD} \right) \]

when

\[ f(N) = \frac{N}{k_N + N} \]
Sensitivity of N, P and D to different choices of the rate-parameters, $l$.

- The time to steady state ratios of $P/D = l_{DN}/l_{PD}$.
- The time scale at which the steady state is reached depends on the mineralization rate, $l_{DN}$, which corresponds to the longest pathway in the mode cycle.

Figure 2.7: Dynamics of nutrients, $N$ (solid), phytoplankton, $P$ (dashed), and detritus, $D$ (dash-dotted) for different choices of the loss parameters. Top panel: $l_{PN} = 0.50d^{-1}$, $l_{PD} = 0.05d^{-1}$, and $l_{DN} = 0.06d^{-1}$; middle: $l_{PN} = 0.10d^{-1}$, $l_{PD} = 0.06d^{-1}$, and $l_{DN} = 0.05d^{-1}$; bottom: $l_{PN} = 0.10d^{-1}$, $l_{PD} = 0.10d^{-1}$, and $l_{DN} = 0.5d^{-1}$. Note that the steady state nutrient level is small but nonzero.
Zooplankton Grazing:

The consumption of phytoplankton by zooplankton.

The new variable $Z$ is introduced and phytoplankton is a limiting resource for $Z$ growth, it becomes

$$\frac{dZ}{dt} \propto g(P)Z$$
$G(P)$ is a grazing rate which quantifies the ingestion of phytoplankton and is often defined by so-called Ivlev function. One of the option is

$$g(P) = g_{\text{max}} \frac{P}{I_v^{-1} + P}$$

**Maximum grazing rate** \[ \text{Iv: an Ivlev parameter} \]

**NPZD model**
A simple NPZD-Model:

In the N-limit four component model

- N (Nitrogen) uptake + solar radiation
- P (Phosphorus) respiration
- D (Dissolved organic matter) mineralization
- Z (Zooplankton) grazing

N → P
P → Z
Z → N
N → D
D → Z
Z → P

uptake → respiration → mineralization → grazing
\[ \frac{dN}{dt} = -r_{\text{max}} f(N)P + l_{PN} P + l_{DN} D + l_{ZN} Z \]
\[ \frac{dP}{dt} = r_{\text{max}} f(N)P - l_{NP} P - l_{PD} P - g(P)Z \]
\[ \frac{dD}{dt} = l_{PD} P - l_{DN} D + l_{ZD} Z \]
\[ \frac{dZ}{dt} = g(P)Z - (l_{ZD} + l_{ZN})Z \]
A simple NNPZD-Model:

In the N (Nitrate)-limit five component model

- **N** (Nitrate) uptake
- **NH4** (Ammonium) nitrification, remineralization
- **D** (Dissolved) respiration, metabolism
- **P** (Phosphorus) respiration
- **Z** (Zooplankton) grazing

**Processes:**
- Uptake
- Nitrification
- Remineralization
- Respiration
- Metabolism
- Grazing

**Connections:**
- Uptake from N to P
- Nitrification from NH4 to D
- Remineralization from D to NH4
- Respiration from D to NH4
- Metabolism from NH4 to D
- Grazing from Z to P
Oregon example (NNPZD): Response to upwelling flow
NSCS example (NPPZD with small and large D): Response to upwelling flow

Velocity at s=30 on day 30 (max. magnitude: 0.89808 m/s)

nitrate concentration at s=30 on day 30 (millimole m-3)

Salinity at s=30 on day 30 (PSU)

phytoplankton concentration at s=30 on day 30 (millimole m-3)
Zooplankton > 1 mmol m\(^{-3}\)
Phytoplankton > 2 mmol m\(^{-3}\)
NO\(_3\) > 4 mmol Nm\(^{-3}\)