Introduction to Marine Ecosystem Modeling

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Mathematical Modeling

A mathematical model is a description of a system using mathematical concepts and language.

The process of developing a mathematical model is termed mathematical modeling.

Mathematical models are used in the natural sciences (such as physics, biology, earth science, chemistry) and engineering disciplines (such as computer science, electrical engineering), as well as in the social sciences (such as economics, psychology, sociology, political science).

A model may help to explain a system and to study the effects of different components, and to make predictions about behaviour.

Source: Wikipedia

Marine Ecosystem Modeling

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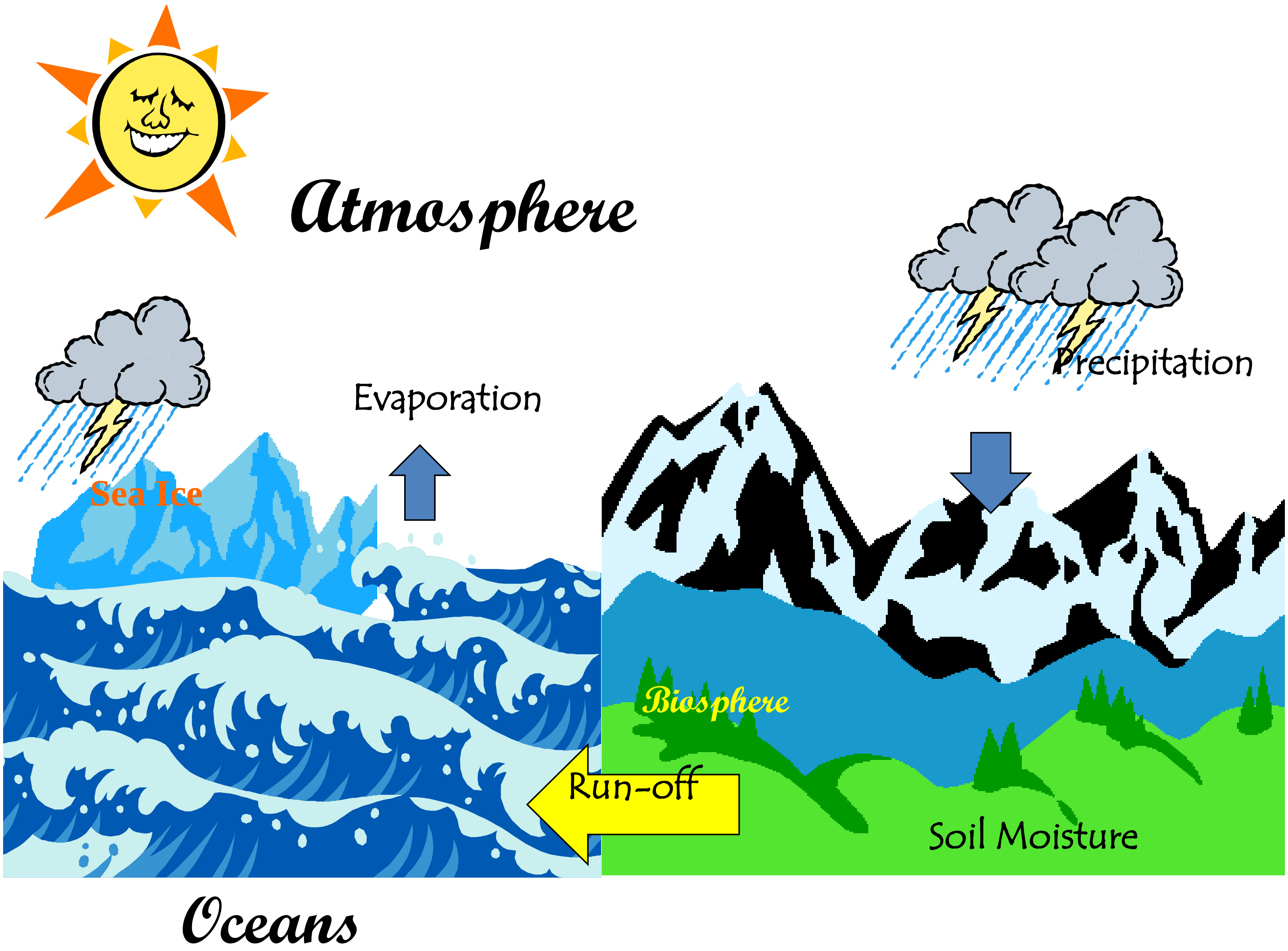
- Ocean models have a unique ability to integrate our empirical and theoretical understanding of the marine environment.

- Ecosystem Modeling is a key scientific technique by which we can elucidate the mechanism of the marine system and predict its evolution in both short and long term.

- Coupled physical-biological models, thus, become a useful tool to study biogeochemical and ecological responses to physical forcing.

- The fundamental modeling technology for operational forecast, climate change science and environmental risk assessment is of high strategic importance.

The Climate System



Source: Basics of numerical oceanic and coupled modelling by Antonio Navarra & Simon Mason

Numerical Models: Atmosphere

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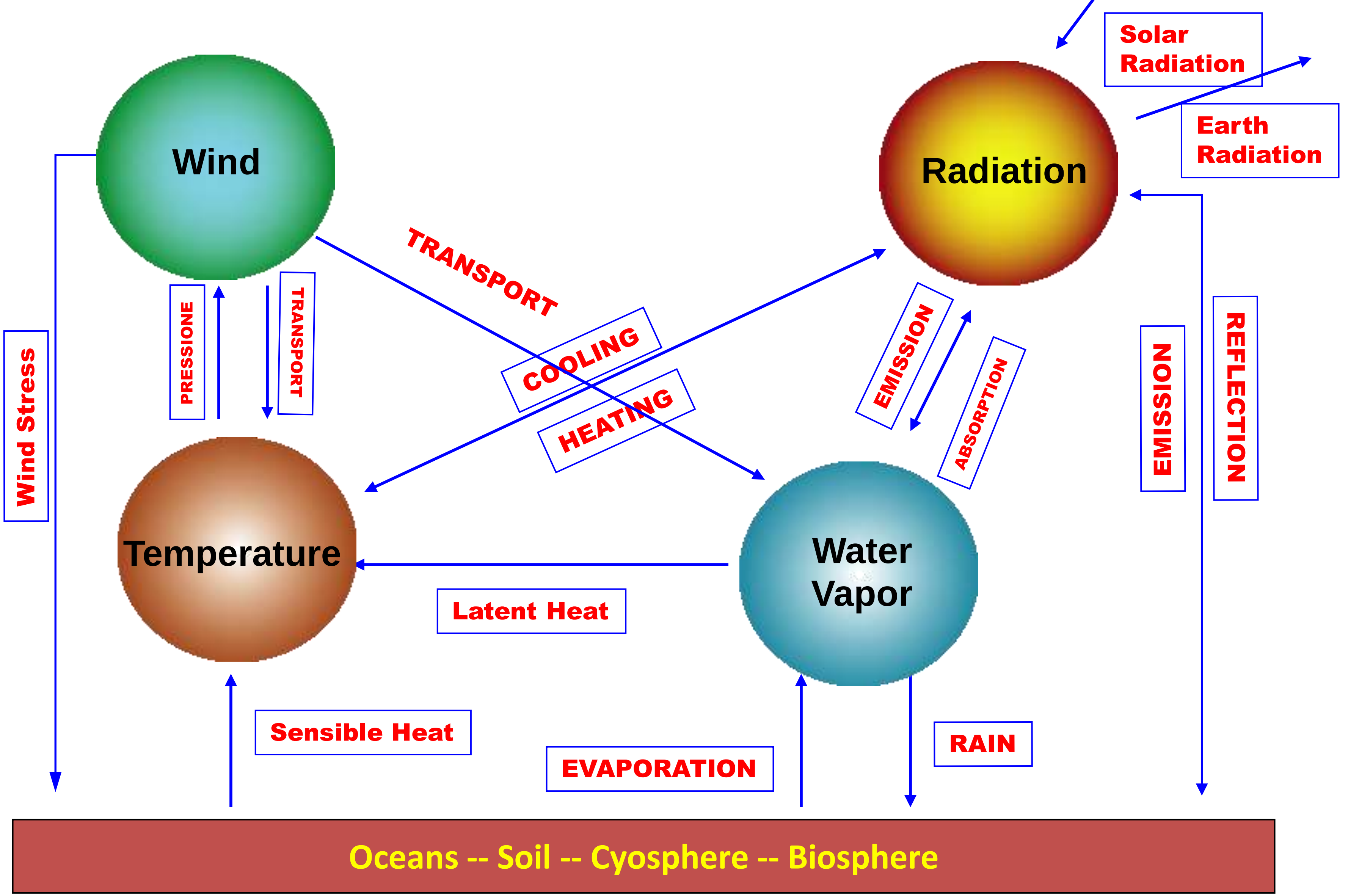
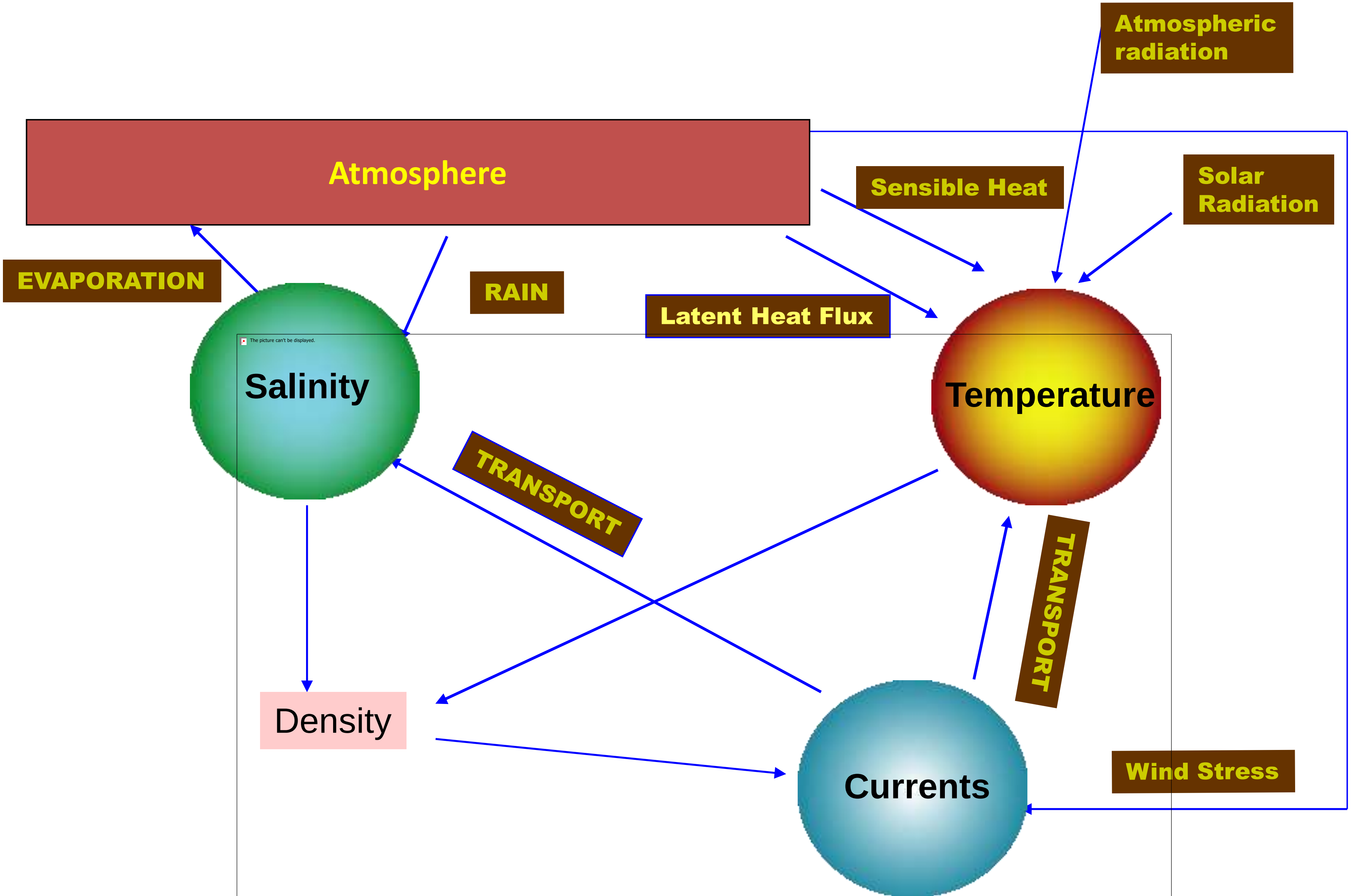


Source: Basics of numerical oceanic and coupled modelling by Antonio Navarra & Simon Mason

Numerical Models: Oceans



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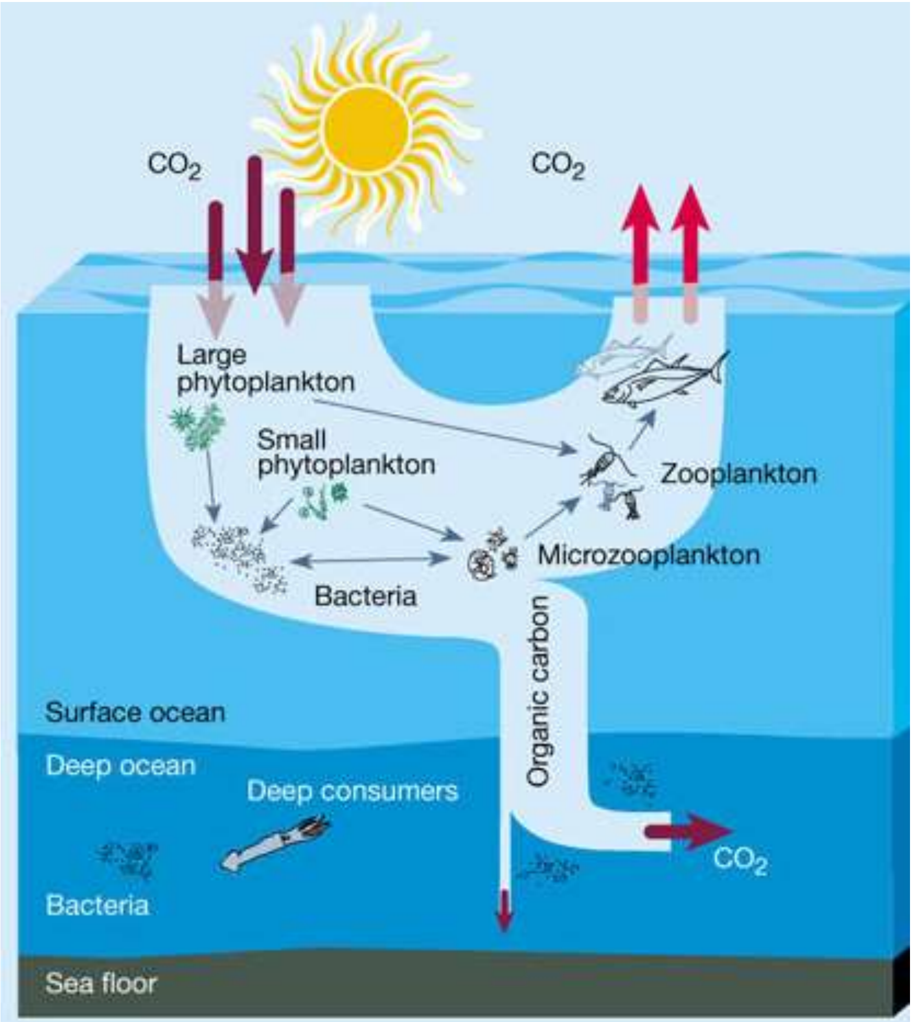
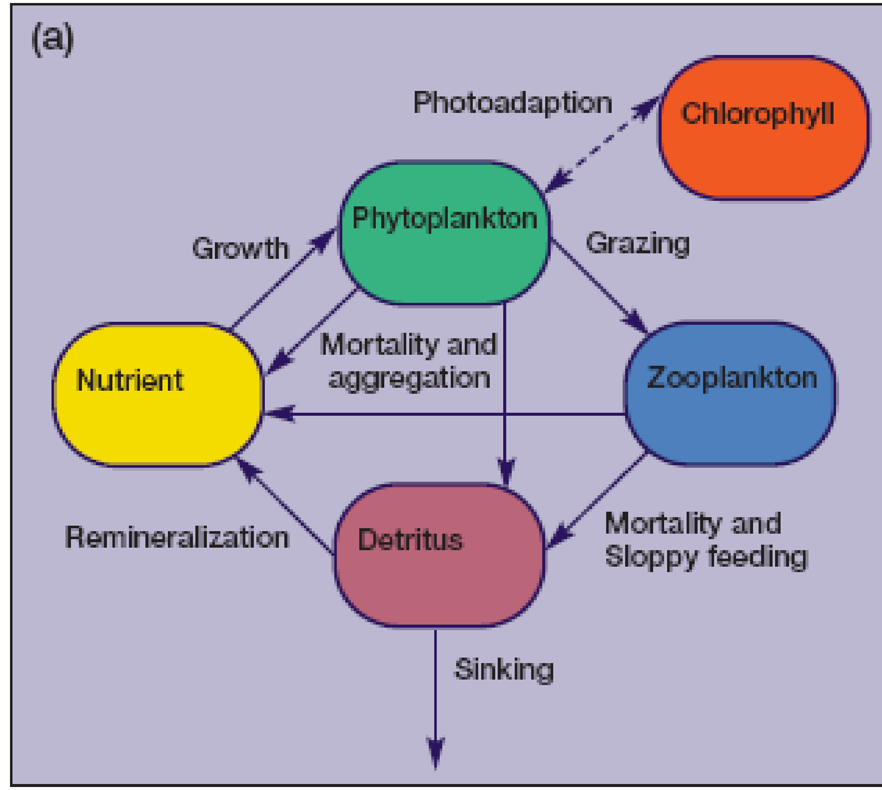
Simple Coupled Physical-Biogeochemical Models of Marine Ecosystems





Formulating *quantitative* mathematical models of *conceptual* ecosystems

Courtesy: John Wilkin

Ocean Processes

- Biological:
  - Growth
  - Death
  - Photosynthesis
  - Grazing
  - Bacterial regeneration of nutrients

- Physical:
  - Mixing
  - Transport (by currents from tides, winds …)
  - Light
  - Air-sea interaction (winds, heat fluxes, precipitation)

Mathematical Formulation

$$V\frac{d}{dt}C_n = sources_n - sinks_n + \sum_j transfer_{n,j}$$

e.g. inputs of nutrients from rivers or sediments

e.g. burial in sediments

e.g. nutrient uptake by phytoplankton

C is the concentration of any biological state variable

The key to model building is finding appropriate formulations for transfers, and not omitting important state variables.

Mathematical Formulation

Rate of change of phytoplankton = uptake − grazing − mortality

$$\frac{dP}{dt} = \frac{V_m N}{k+N} f(I_o) P - GZ - \epsilon P$$

Rate of change of nutrients = − uptake + regeneration + input

$$\frac{dN}{dt} = -\frac{V_m N}{k+N} f(I_o) P + (1-\gamma) GZ + \epsilon P + aZ + \; + m(N_o - N)$$

Rate of change of zooplankton = growth − mortality

$$\frac{dZ}{dt} = \gamma GZ - aZ$$

V_m	=	maximum nutrient uptake rate
k	=	half-saturation constant for nutrient uptake
$f(I_o)$	=	incoming solar radiation
G	=	grazing rate
ϵ	=	death rate of phytoplankton
γ	=	grazing efficiency
a	=	death rate of zooplankton
m	=	mixing rate
N_o	=	nutrient concentration beneath the mixed layer

Coupling to physical processes

Advection-diffusion-equation:

physics

$$\frac{\partial}{\partial t}C + \nabla \cdot \vec{v}\, C - D\Delta C = gain(C) - loss(C)$$

advection

turbulent mixing

Biological dynamics

C is the concentration of any biological state variable

A Conceptual Ecosystem

A model of a food web might be relatively complex

- Several nutrients
- Different size/species classes of phytoplankton
- Different size/species classes of zooplankton
- Detritus (multiple size classes)
- Predation (predators and their behavior)
  - Multiple trophic levels
- Pigments and bio-optical properties
  - Photo-adaptation, self-shading
- 3 spatial dimensions in the physical environment, diurnal cycle of atmospheric forcing, tides

What's a ROMS?

Regional Ocean Modeling System (ROMS)

ROMS is an ocean general circulation model that can be used on a variety of scales. It has been designed to excel in coastal applications but has been successfully implemented on larger scales.

Like other OGCM's it solves some approximation of the time-evolving three-dimensional equations for water motion in the ocean.

ROMS is much more than a hydrodynamics code. It has biology, sediment, sea ice, etc. (ROMS > start)

Steps to Create an Application (Standalone ROMS)

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Create input files (also can be generated analytically by Fortran code)

- Grid
- Forcing (atmospheric, river etc.)

] Independent from vertical coordinates

- Boundary Condition (BC) - if domain has open boundaries
- Initial Condition (IC)
- Climatology - if nudging and/or relaxation are activated

] create these files after vertical coordinates changed

Create configuration file (*.h)

- A set of CPP option must be defined such as advection, mixing, flux calculation etc.

Create namelist file (*.in)

- User needs to edit namelist file based on the created application (additional namelist file exist for ICE model).

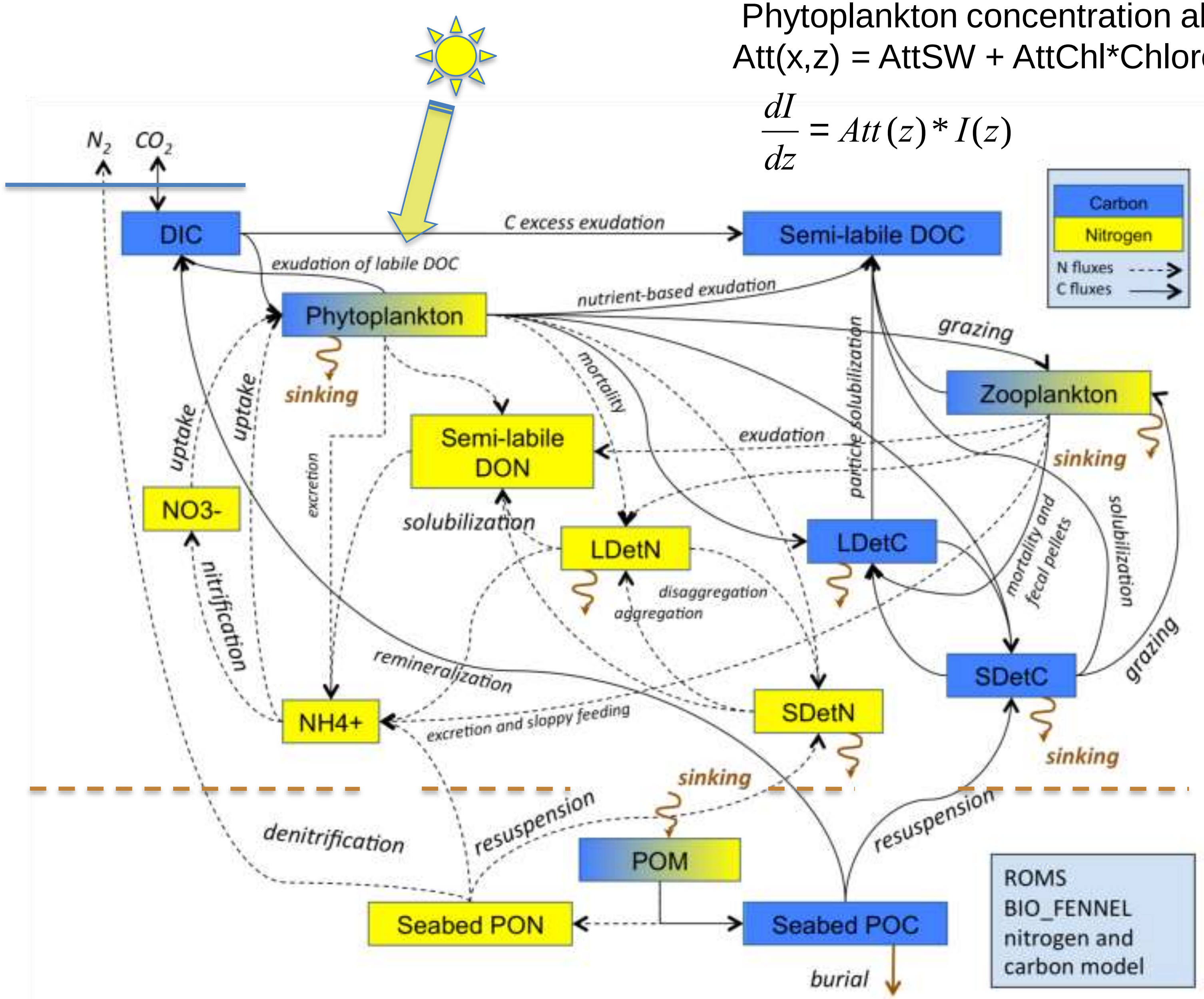
Run

- Edit machine specific definitions (Build/*.mk and build.sh)
- Run the model

Schematic of ROMS Fennel Ecosystem Model

Phytoplankton concentration absorbs light
Att(x,z) = AttSW + AttChl*Chlorophyll(x,z,t)

$$\frac{dI}{dz} = Att(z) * I(z)$$



End-to-End Modeling Approach

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ECOSYSTEM MODELS

Population/Concentration-Based Model

$$\frac{dP}{dt} = \frac{V_m N P}{k_s + N} e^{k_{ext} z} - R_m (1 - e^{-\Lambda P}) Z - mP$$

$$\frac{dZ}{dt} = (1 - \gamma) R_m (1 - e^{-\Lambda P}) Z - g Z^n$$

$$N = N_T - P - Z$$

Franks et al, 1986

Implemented in ROMS

EcoSim
NEMURO
NPZD Franks
NPZD Powell
Fennel

Individual-Based Models

Time dependent-Growth for Mackerel (fish)

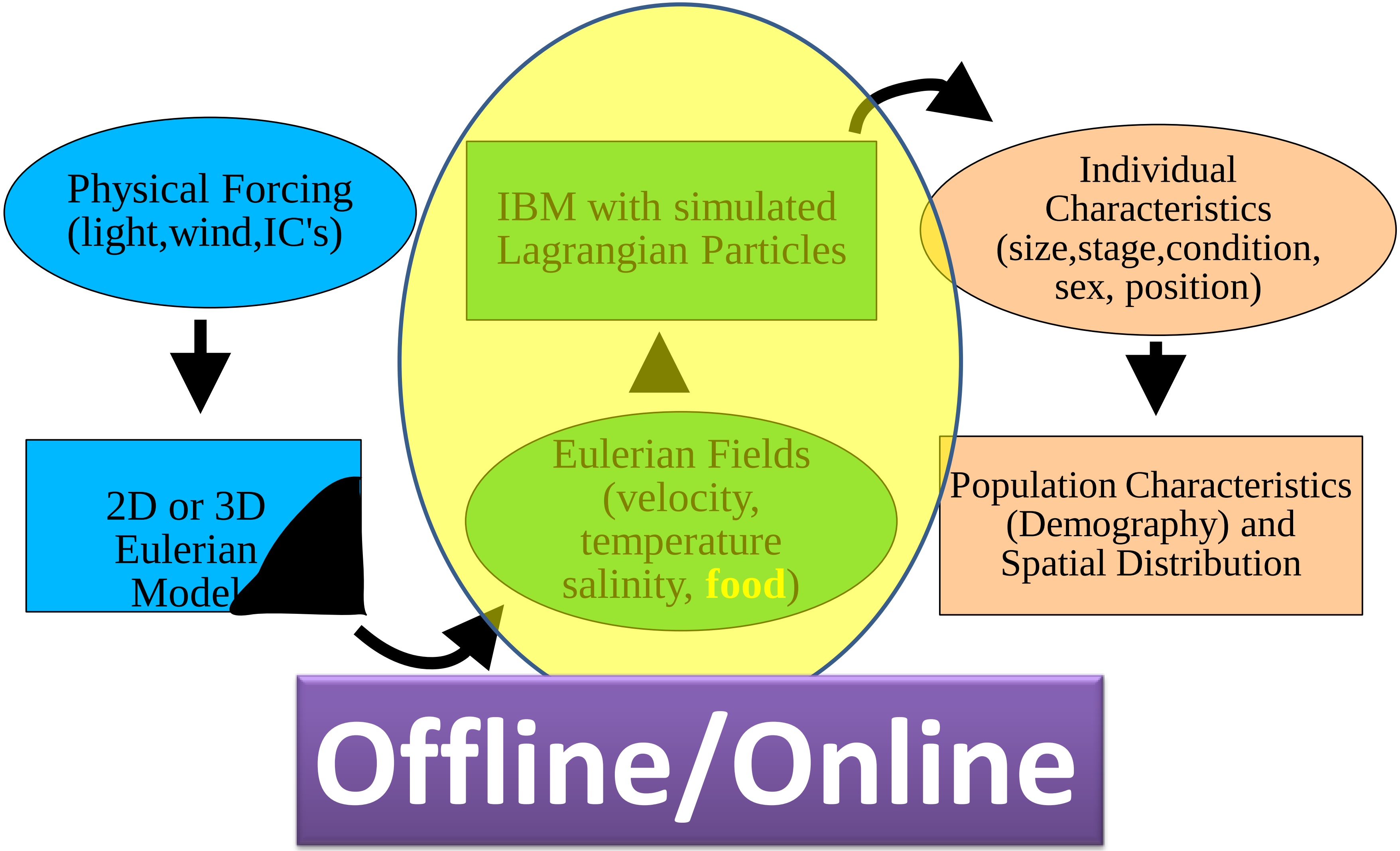
$$\frac{dS}{dT} = \frac{3}{2} \cdot a \cdot P_T \cdot t^{0.5}$$

$$P_T = 1 - (T - T_{opt})^2 / g, \text{ for } \Delta T = |T - T_{opt}| < 10°C$$

Bartsch & Cooms, 2001

End-to-End Modeling Approach

Eulerian-Lagrangian Coupling



Thank you for your attention!