

From an Ocean Model to an Operational Forecasting System

Introduction to Operational Ocean Forecasting

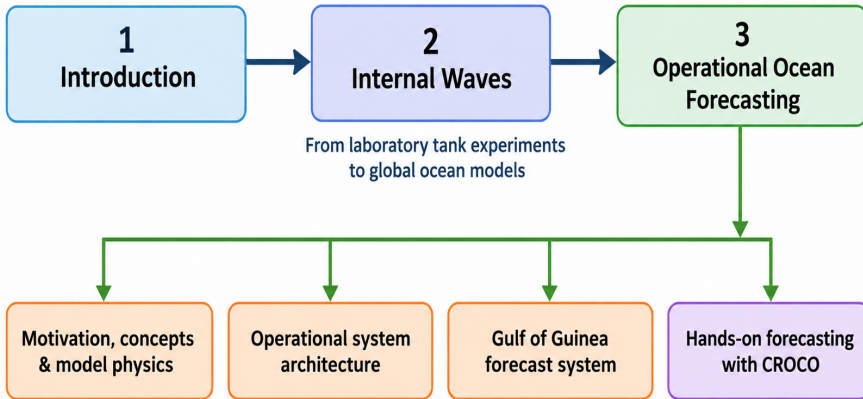
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UNESCO/IOC-ODC Training Course on Ocean Dynamics and Ocean Models
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Outline



Motivation, Concepts, and Forecast Variables.

The Physics Behind An Ocean Forecast Model.

From Governing Equations to Numerical Models.

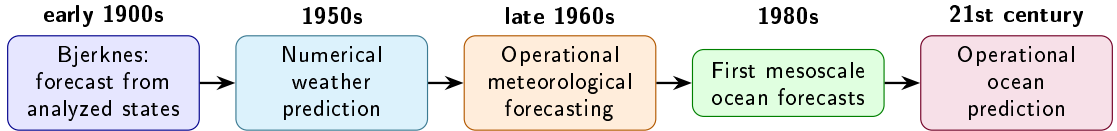
Learning Objectives

By the end of this session, you should be able to:

- explain what is meant by **operational ocean forecasting**;
- describe the physical equations underlying ocean models;
- explain the principal approximations used in ocean forecasting models;
- describe important dynamical balances in the ocean; and
- explain how the governing equations are transformed into a numerical ocean model.

A Brief History of Ocean Prediction

Ocean prediction grew out of the same scientific idea that shaped numerical weather prediction: use observations, physical laws, and computation to estimate future states of the fluid system.



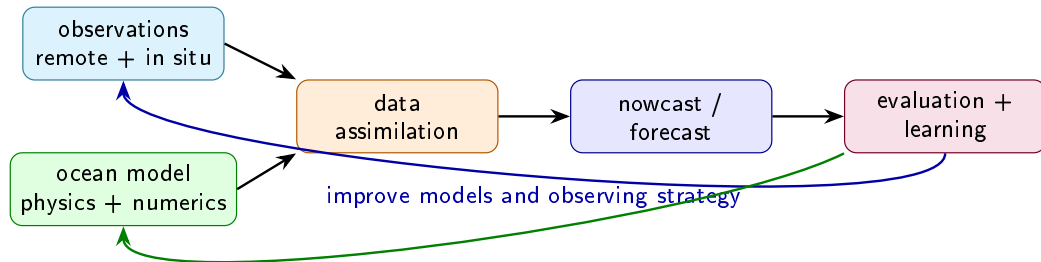
Takeaway

Ocean prediction is newer than operational weather prediction, but it follows the same core logic: observations + equations + computation + verification.

Based on Pinardi et al. (2017), *The Sea: The Science of Ocean Prediction*.

Modern Ocean Prediction Is an Integrated System

Modern ocean prediction combines observations and dynamical models through data assimilation, then evaluates the resulting estimates and forecasts against new observations.



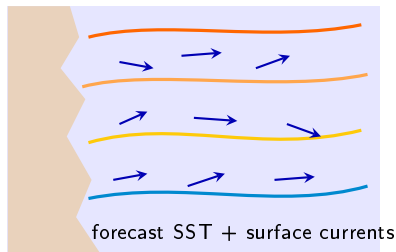
Key message

The science of prediction is not only running a model; it is the sustained combination of observations, models, data assimilation, computation, and testing.

What will the ocean look like tomorrow?

Operational forecasts ask, for example:

- Where will currents be strongest?
- How warm will the surface ocean be?
- How will sea level change?
- Where will drifting objects or pollutants move?
- Will conditions be safe for marine operations?



Operational Ocean Forecasting

The use of observations, numerical models, atmospheric forcing, and computational systems to estimate the present ocean state and predict its future evolution.

Can We Forecast the Ocean Like the Weather?

Weather forecasting asks:

What will the **atmosphere** be like tomorrow?

Ocean forecasting asks:

What will the **ocean** be like tomorrow?

Both require:

- observations;
- mathematical equations;
- numerical models;
- initial conditions;
- forcing;
- high-performance computing; and
- forecast verification.

But the ocean presents some additional challenges.

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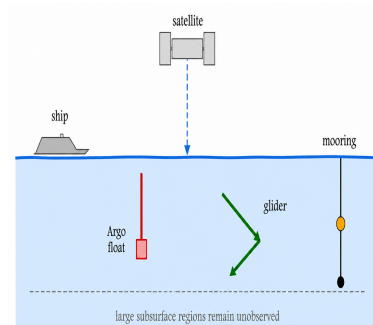
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Why Is Ocean Forecasting Challenging?

The ocean is

- rotating and strongly stratified;
- forced by the atmosphere and tides;
- constrained by complex bathymetry and coastlines;
- characterized by many interacting scales; and
- much less densely observed than the atmosphere.



The Fundamental Challenge

We must predict a complex three-dimensional fluid even though we never observe its complete state.

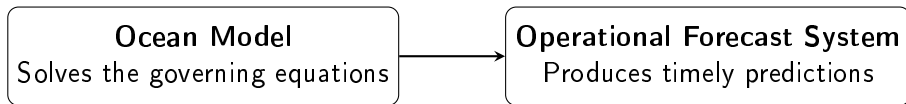
Why Forecast the Ocean?

Operational ocean forecasts support:

- maritime safety;
- shipping and navigation;
- search and rescue;
- fisheries;
- coastal management;
- port operations;
- offshore energy;
- oil-spill response;
- harmful algal bloom prediction;
- marine heatwave monitoring;
- storm and coastal hazards;
- scientific field campaigns.

Forecast information must arrive before it is needed.

Ocean Modelling Is Not Ocean Forecasting



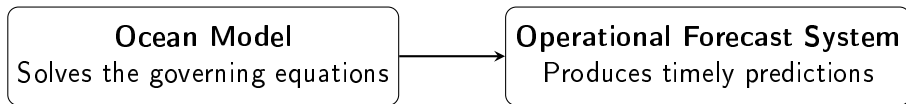
An ocean model can be used for:

- process studies;
- sensitivity experiments;
- climate simulations;
- hindcasts; or
- idealized experiments.

An **operational forecast system** must additionally be:

repeatable, timely, automated, monitored, and quality controlled.

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The Forecasting Problem

Suppose we know the ocean state at time t_0 :

$$x(t_0) = x_0.$$

The numerical model can be represented schematically as

$$\frac{dx}{dt} = \mathcal{M}(x, F, B),$$

where

- x is the ocean state;
- $\mathcal{M}$ represents the ocean model;
- F represents external forcing; and
- B represents boundary information.

The forecasting problem is therefore:

$$x(t_0) \longrightarrow x(t_0 + \Delta t)$$

What Is the Ocean State?

A basic ocean state vector contains

$$\mathbf{x} = \begin{bmatrix} u \\ v \\ T \\ S \\ \eta \end{bmatrix},$$

where

- u zonal velocity,
- v meridional velocity,
- T temperature,
- S salinity,
- η sea surface elevation.

From these variables we can calculate many other quantities of interest.

What Can We Forecast?

Direct model variables

- temperature;
- salinity;
- sea surface height;
- zonal velocity;
- meridional velocity.

Derived forecast products

- current speed and direction;
- mixed-layer depth;
- ocean transport;
- stratification;
- upwelling indices;
- particle trajectories;
- marine heatwave indicators.

From Model Variable to Forecast Product

A model produces numerical fields.

Users generally need **information**.

$(u, v) \longrightarrow$ current speed and direction

$T \longrightarrow$ SST maps / marine heatwave indicators

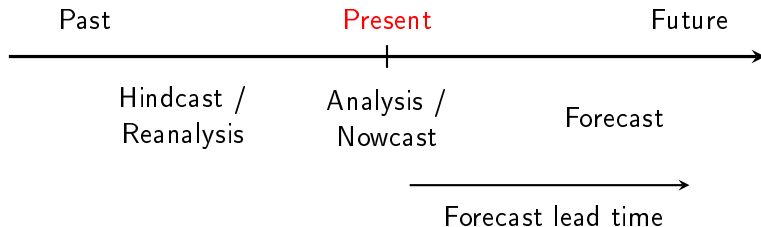
$\eta \longrightarrow$ sea-level information

$(u, v, T, S) \longrightarrow$ search-and-rescue / drift predictions

Important

Operational forecasting does not end when the model finishes running. Model output must be transformed into useful forecast products.

Analysis, Nowcast, and Forecast



Forecast lead time is commonly expressed as

$$T + 6 \text{ h}, \quad T + 24 \text{ h}, \quad T + 48 \text{ h}, \quad T + 72 \text{ h}.$$

Forecast Lead Time

Let the forecast begin at t_0 .

The forecast at lead time τ is

$$x_f(t_0 + \tau).$$

For example:

$$\tau = 0 \quad \rightarrow \quad T + 0,$$

$$\tau = 24 \text{ h} \quad \rightarrow \quad T + 24,$$

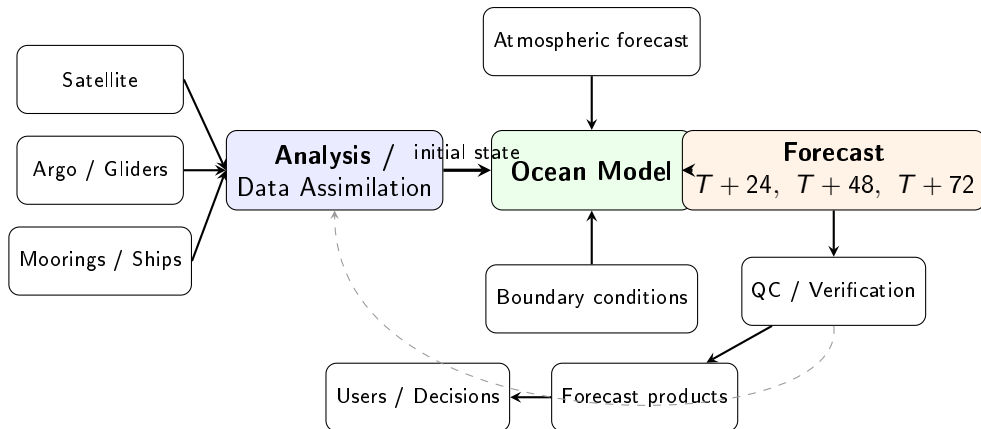
$$\tau = 48 \text{ h} \quad \rightarrow \quad T + 48,$$

$$\tau = 72 \text{ h} \quad \rightarrow \quad T + 72.$$

In general,

forecast uncertainty tends to increase with lead time.

A First Look at the Forecast Cycle



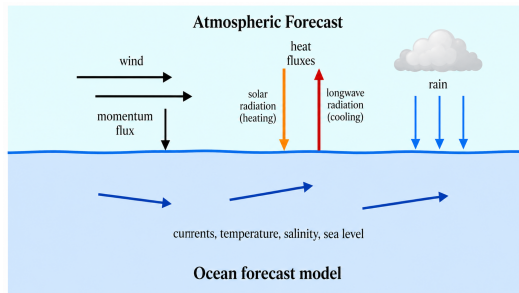
Operational forecasting is a complete system, not just a model run.

Where Does the Atmospheric Forecast Enter?

The ocean is forced strongly by the atmosphere.

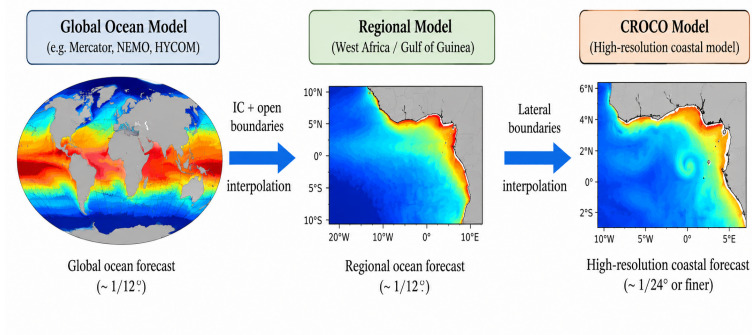
Atmospheric forcing may include

- wind stress;
- air temperature and humidity;
- precipitation;
- atmospheric pressure;
- shortwave radiation; and
- longwave radiation.



Where Does the Larger Ocean Enter?

A regional ocean model does not exist in isolation.



Global product → Regional ROMS/CROCO forecast

A Forecast Is an Initial-Value Problem

The ocean model solves an initial-value problem.

At the initial time,

$$x(t_0) = x_0.$$

The model then integrates forward:

$$x(t_0) \rightarrow x(t_1) \rightarrow x(t_2) \rightarrow \cdots \rightarrow x(t_f).$$

But this raises a fundamental question:

What equations determine how the ocean state evolves?

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From Forecasting to Ocean Dynamics

To predict tomorrow's ocean, we must describe today's ocean mathematically.

The foundation is provided by conservation laws:

- 1 conservation of mass;
- 2 conservation of momentum;
- 3 conservation of heat;
- 4 conservation of salt.

These lead to the governing equations used by numerical ocean models.

Physics $\rightarrow$ Equations $\rightarrow$ Numerical Model $\rightarrow$ Forecast

Think Before We Continue

Question

Suppose you have been asked to produce a three-day forecast of coastal currents. What information would you need before you could run the forecast?

Possible answers:

- the present ocean state;
- atmospheric forcing;
- boundary conditions;
- bathymetry and coastline;
- tides and rivers, where relevant;
- a numerical ocean model;
- computational resources.

We now examine the physics inside that numerical ocean model.

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The Physics Behind An Ocean Forecast Model.

The Physics Behind an Ocean Forecast

An ocean forecast is ultimately a numerical solution of the **governing equations of ocean circulation**.

These equations express fundamental conservation laws:

Conservation law	Ocean variable
Mass	Velocity / continuity
Momentum	Ocean currents
Heat	Temperature
Salt	Salinity

Together with an equation of state,

$$\rho = \rho(T, S, p),$$

they describe the evolution of the three-dimensional ocean.

Conservation of Momentum

Newton's second law applied to a fluid parcel gives

$$\text{mass} \times \text{acceleration} = \text{sum of forces.}$$

For ocean circulation, the important contributions include

- local acceleration;
- advective acceleration;
- pressure-gradient force;
- gravity;
- Coriolis force;
- friction and turbulent mixing.

These processes form the basis of the momentum equations solved by ocean circulation models.

Momentum Equation in a Rotating Frame

In vector form, the momentum equation can be written schematically as

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} + 2\mathbf{\Omega} \times \mathbf{u} = -\frac{1}{\rho} \nabla p + \mathbf{g} + \mathbf{F}$$

where

$\mathbf{\Omega}$ Earth's rotation vector,

p pressure,

$\mathbf{g}$ gravitational acceleration,

$\mathbf{F}$ frictional and other forces.

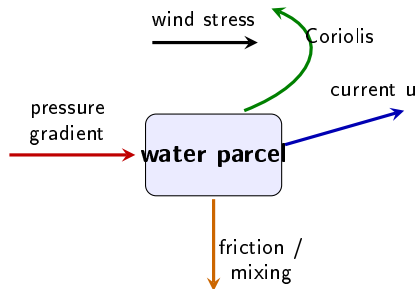
This is the starting point for the momentum equations used in large-scale ocean modelling.

What Accelerates an Ocean Current?

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} + 2\mathbf{\Omega} \times \mathbf{u} = -\frac{1}{\rho} \nabla p + \mathbf{g} + \mathbf{F}.$$

Each term represents a physical process:

- local and advective acceleration;
- pressure-gradient force;
- Earth's rotation (Coriolis);
- gravity;
- friction and turbulent mixing.



The model calculates how currents evolve from the forces acting on the ocean.

Standard Approximations

The **primitive-equation** framework retains the physics required for large-scale and regional ocean circulation while making the problem computationally tractable.

The major assumptions include

- continuum approximation;
- rotating reference frame;
- Boussinesq approximation;
- incompressibility;
- hydrostatic approximation;
- parameterization of unresolved mixing.

Horizontal Momentum Equations

After the standard approximations, the horizontal momentum equations have the schematic form

$$\frac{Du}{Dt} - f_v = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + F_u$$

and

$$\frac{Dv}{Dt} + f_u = -\frac{1}{\rho_0} \frac{\partial p}{\partial y} + F_v.$$

These equations determine the evolution of the horizontal ocean currents.

Currents respond to pressure gradients, rotation, advection, and mixing.

Conservation of Heat

Temperature evolves through

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \mathcal{D}_T + Q_T$$

where

- $\mathbf{u} \cdot \nabla T$ represents advection;
- $\mathcal{D}_T$ represents mixing and diffusion;
- Q_T represents heating and cooling.

Important surface heat exchanges include

- shortwave radiation;
- longwave radiation;
- latent heat flux;
- sensible heat flux.

Conservation of Salt

Salinity evolves approximately according to

$$\frac{\partial S}{\partial t} + \mathbf{u} \cdot \nabla S = \mathcal{D}_S + Q_S$$

where

- $\mathcal{D}_S$ represents mixing and diffusion;
- Q_S represents freshwater-related effects.

Processes affecting surface salinity include

- evaporation;
- precipitation;
- river discharge;
- sea-ice processes where relevant.

Temperature and Salinity Control Density

Seawater density depends primarily on

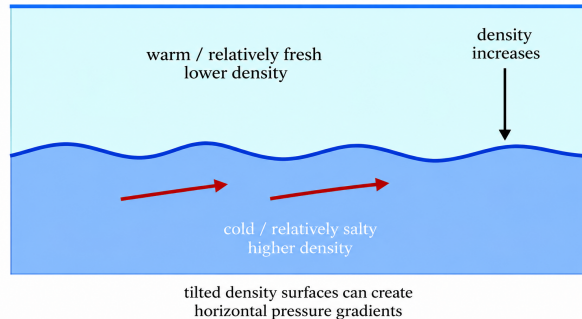
$$\rho = \rho(T, S, p).$$

In general,

- warmer water tends to be less dense;
- saltier water tends to be denser;
- pressure increases density with depth.

Density differences produce pressure gradients and buoyancy forces.

$$T, S \rightarrow \rho \rightarrow p \rightarrow \text{circulation}$$



The Primitive Equations

Putting the main approximations together gives the **primitive equations** used by many ocean circulation models.

A schematic set is

$$\frac{Du}{Dt} - fv = -\frac{1}{\rho_0}p_x + F_u,$$

$$\frac{Dv}{Dt} + fu = -\frac{1}{\rho_0}p_y + F_v,$$

$$p_z = -\rho g,$$

$$u_x + v_y + w_z = 0,$$

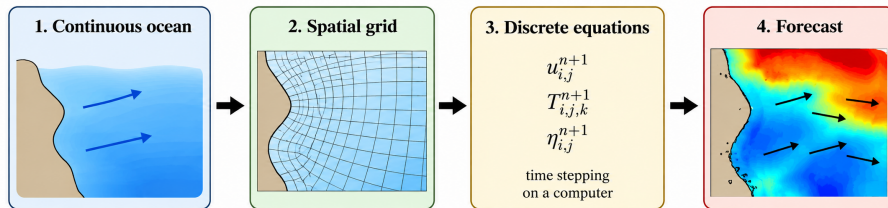
together with tracer equations for T , S , and an equation of state: $\rho = \rho(T, S, p)$.

What Has Been Simplified?

We have equations.

But a computer cannot solve these continuous equations directly.

From Equations to a Numerical Ocean Model



From Physics to Prediction

Numerical methods transform the continuous governing equations into calculations that can be performed on a computer.

This is where models such as ROMS/CROCO enter the forecasting system.

From Ocean State to Ocean Prediction

- Grp1: Why did operational ocean prediction develop several decades later than operational weather prediction?
- Grp2: What roles do **observations**, **dynamical models**, and **data assimilation** play in a modern ocean prediction system?
- Grp3: Why can an ocean forecast never be completely independent of observations, even though the model equations predict the future state?

Predictability, Uncertainty, and Applications

- Grp4: What factors limit how far into the future the ocean can be predicted accurately?
- Grp5: If two ocean models initialized from the same analysis produce different forecasts, what could explain the differences?
- Grp6: How might **ensemble forecasting** help us distinguish between a confident prediction and a highly uncertain one?

From Governing Equations to Numerical Ocean Models.

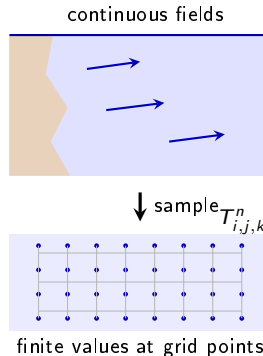
From Continuous Equations to Numbers

The primitive equations describe a continuous ocean:

$$u(x, y, z, t), \quad v(x, y, z, t), \quad T(x, y, z, t), \quad S(x, y, z, t).$$

A computer cannot calculate these quantities at every point in continuous space and time. Instead, we approximate the ocean at a finite number of locations:

$$(x_i, y_j, z_k, t^n), \quad T(x, y, z, t) \longrightarrow T_{i,j,k}^n.$$



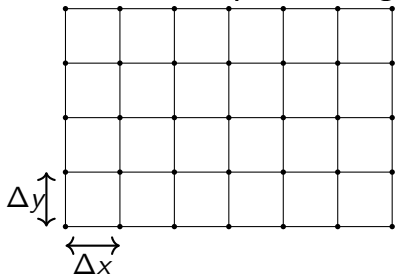
Discretization

Discretization converts continuous governing equations into a finite system of algebraic equations.

The Numerical Grid

The first step is to divide the ocean into computational cells.

Horizontal computational grid



The grid determines

- where model variables are calculated;
- the smallest spatial scales that can be represented;
- much of the computational cost of the forecast.

Spatial Resolution

For a horizontal grid,

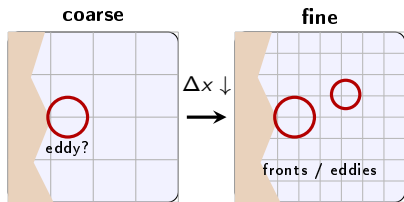
$$\Delta x, \quad \Delta y$$

represent the grid spacing.

A smaller grid spacing gives higher resolution:

$$\Delta x \downarrow \implies \text{more spatial detail.}$$

But it also means more grid cells and greater computational cost.

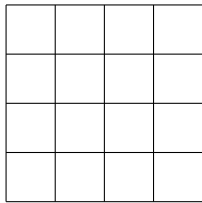


Operational Trade-Off

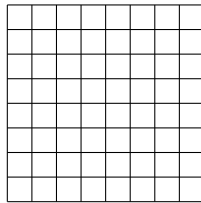
The highest-resolution model is not automatically the best operational model. The forecast must finish early enough to be useful.

What Does Resolution Mean Physically?

Suppose two models cover the same region.



Coarse grid



Fine grid

Higher resolution can better represent

- coastlines and bathymetry;
- narrow currents;
- fronts;
- eddies; and
- coastal circulation.

Finite-Difference Idea

Consider the spatial derivative

$$\frac{\partial T}{\partial x}.$$

On a numerical grid, it can be approximated by

$$\left. \frac{\partial T}{\partial x} \right|_i \approx \frac{T_{i+1} - T_{i-1}}{2\Delta x}$$

for a centred finite difference.

Thus,

derivatives $\longrightarrow$ differences between neighbouring grid values.

This is one of the fundamental ideas behind numerical ocean models.

Where Are the Variables Stored?

Ocean-model variables do not necessarily occupy the same location within a computational cell.

Many ocean models use a **staggered grid**.

One widely used arrangement is the

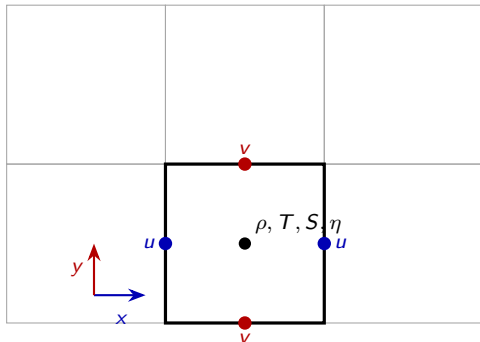
Arakawa C-grid.

In a C-grid,

- sea level and tracers are stored near cell centres;
- u is stored on the east–west cell faces;
- v is stored on the north–south cell faces.

CROCO uses an Arakawa C-grid.

The Arakawa C-Grid



In a C-grid,

- sea level and tracers are stored near cell centres;
- u is stored on east–west cell faces;
- v is stored on north–south cell faces.

Why Stagger the Variables?

This improves the numerical representation of velocity, pressure gradients, divergence, and other important dynamical quantities.

The Ocean Is Three-Dimensional

A horizontal grid is not enough.

The water column must also be divided vertically.

Two common approaches are:

Fixed Depth Levels

Levels occur at prescribed depths:

$$z = z_1, z_2, \dots, z_N.$$

Often called z coordinates.

Terrain-Following Levels

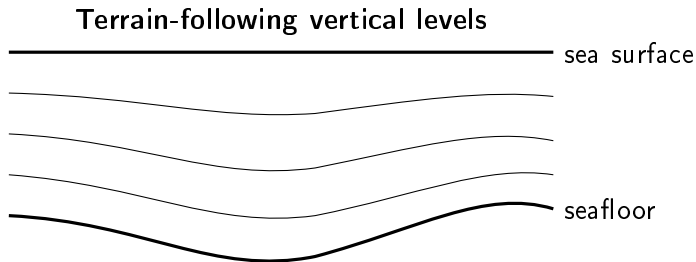
Vertical levels follow the shape of the ocean bottom.

Often called σ or terrain-following coordinates.

CROCO uses **terrain-following vertical coordinates**.

Terrain-Following Coordinates

In a terrain-following system, the vertical coordinate adjusts to the local water depth.



These coordinates provide good representation of

- coastal regions;
- continental shelves; and
- bottom boundary processes.

Discretizing Time

Space is discretized using a grid.
Time must also be discretized:

$$t^0, \quad t^1, \quad t^2, \quad \dots$$

with

$$t^{n+1} = t^n + \Delta t.$$

For a simple equation

$$\frac{\partial \phi}{\partial t} = F(\phi),$$

a basic time-stepping approximation is

$$\phi^{n+1} = \phi^n + \Delta t F(\phi^n).$$

The model repeatedly advances the ocean state from one time level to the next.

A Forecast Is Thousands of Small Time Steps

Suppose we want a three-day forecast:

$$T_{\text{forecast}} = 72 \text{ h.}$$

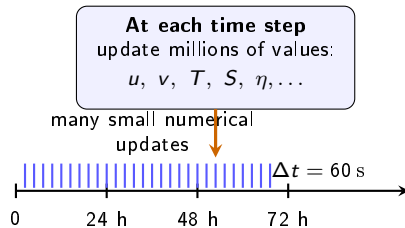
If the model time step is

$$\Delta t = 60 \text{ s,}$$

then the model must perform approximately

$$N = \frac{72 \times 3600}{60} = 4320$$

time steps.



Operational forecasting is therefore computationally intensive.

Can We Choose Any Time Step?

No.

Information cannot propagate arbitrarily far across the computational grid during one time step.

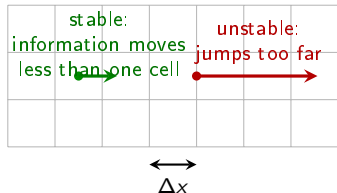
A simple form of the Courant–Friedrichs–Lewy condition is

$$C = \frac{U\Delta t}{\Delta x} \lesssim C_{\max}.$$

This is known as the **CFL stability condition**.

- U is a characteristic propagation speed;
- Δt is the time step;
- Δx is the grid spacing.

distance travelled in one step $\sim U\Delta t$



Resolution Has a Computational Price

Increasing horizontal resolution means

$$\Delta x \downarrow .$$

But the CFL constraint generally requires

$$\Delta t \downarrow .$$

At the same time, the number of grid cells increases.

Thus,

higher resolution $\Rightarrow$ more grid cells + more time steps

and therefore

higher resolution $\Rightarrow$ greater computational cost.

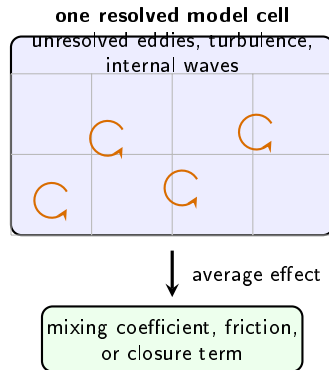
Parameterization

A parameterization represents the average effect of unresolved processes on the resolved model variables.

Examples include

- vertical turbulent mixing;
- subgrid-scale mixing;
- bottom friction;
- unresolved internal-wave effects;
- surface flux processes.

Parameterizations are therefore an important source of **model uncertainty**.



Global and Regional Ocean Models

Operational ocean forecasting systems commonly use both.

Global Model

- covers the global ocean;
- no lateral open boundaries;
- provides large-scale circulation;
- typically more computationally expensive for a given resolution.

Regional Model

- covers a selected region;
- requires lateral boundary conditions;
- permits finer local resolution;
- can focus resources on the area of interest.

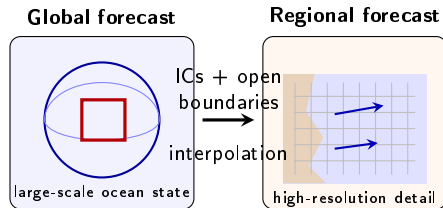
Why Use a Regional Model?

Suppose our region of interest is relatively small.

Running an extremely high-resolution global model may be unnecessary.

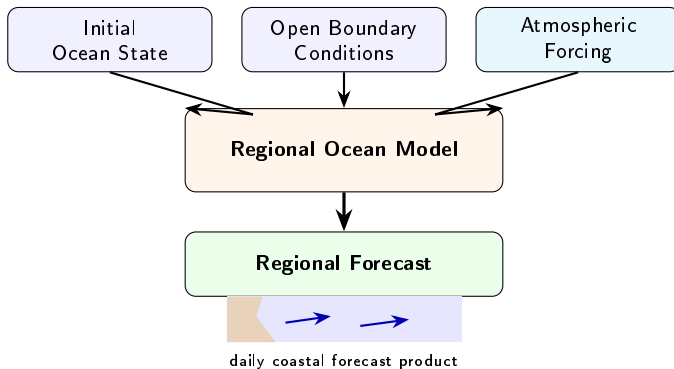
Instead, a regional model focuses computational resources where detail is most needed.

This approach allows greater detail where it is most needed.



The Regional Forecasting Problem

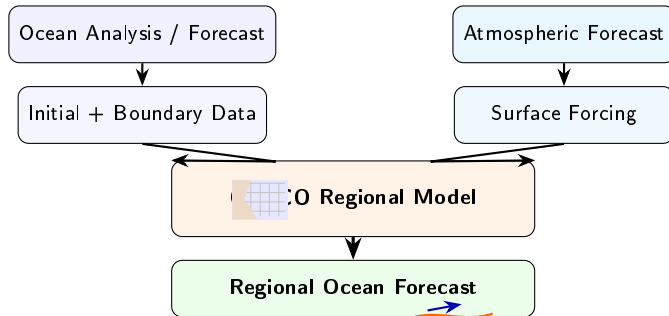
A regional ocean forecast requires several ingredients:



This architecture will become central in the practical session.

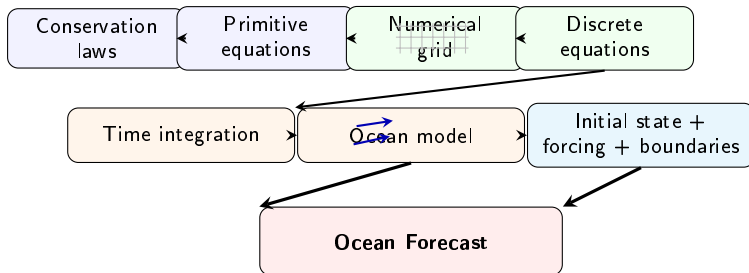
Where Does CROCO Fit?

CROCO is a regional ocean circulation modelling system based on the primitive equations.



In the afternoon, we will follow this workflow in practice.

From Physics to an Operational Forecast



The forecast is the result of physics, numerics, data, and operations working together.

But an Ocean Model Is Still Not a Forecast System

At this point we have

$$\boxed{\text{Ocean Model}} + \boxed{\text{Initial Conditions}} + \boxed{\text{Forcing}} + \boxed{\text{Boundary Conditions}}.$$

That is enough to perform a numerical forecast experiment.

But an **operational** system must also answer:

- Where do the latest observations come from?
- How is the initial state generated?
- How are new atmospheric forecasts acquired?
- What happens when data arrive late?
- How is the forecast checked?
- How quickly must the forecast finish?
- How are products delivered to users?

But an Ocean Model Is Still Not a Forecast System

At this point we have

$$\boxed{\text{Ocean Model}} + \boxed{\text{Initial Conditions}} + \boxed{\text{Forcing}} + \boxed{\text{Boundary Conditions}}.$$

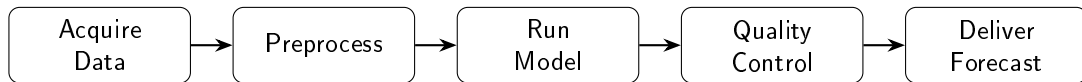
That is enough to perform a numerical forecast experiment.

But an **operational** system must also answer:

- Where do the latest observations come from?
- How is the initial state generated?
- How are new atmospheric forecasts acquired?
- What happens when data arrive late?
- How is the forecast checked?
- How quickly must the forecast finish?
- How are products delivered to users?

The Operational Constraint

Consider a forecast valid for tomorrow.

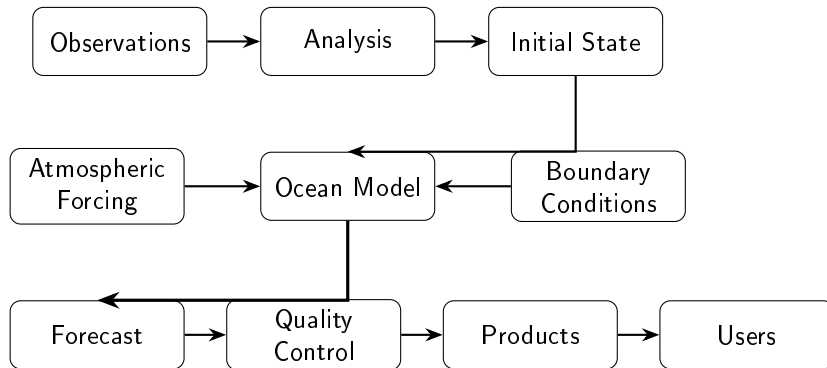


Every stage must finish within a limited operational window.

A Critical Difference

A scientifically accurate forecast that arrives after the decision has already been made may have little operational value.

The Complete Forecast Chain



Operational ocean forecasting is the management of this entire chain.

We now have a numerical ocean model.

But suppose we want to run it every day.

Think About This

At 06:00 tomorrow morning, what must happen automatically for us to produce a reliable three-day ocean forecast?

Think about:

data • initialization • forcing • computation • quality control • delivery

This is where an ocean model becomes an operational forecasting system.

Equation Exercises – I

- ① A regional ocean model has a horizontal grid spacing of

$$\Delta x = 5 \text{ km.}$$

Approximately how many grid cells are required in the x-direction to represent an ocean domain that is 1500 km wide?

- ② Temperature values at three consecutive grid points are

$$T_{i-1} = 24.0^\circ\text{C}, \quad T_i = 25.0^\circ\text{C}, \quad T_{i+1} = 26.0^\circ\text{C}.$$

If $\Delta x = 10 \text{ km}$, estimate $\left. \frac{\partial T}{\partial x} \right|_i$ using the centred finite-difference approximation:

$$\left. \frac{\partial T}{\partial x} \right|_i \approx \frac{T_{i+1} - T_{i-1}}{2\Delta x}.$$

- ③ A model uses a time step

$$\Delta t = 120 \text{ s.}$$

How many time steps are required for a 3-day forecast?

Equation Exercises – II

- ① Consider the CFL number $C = \frac{U\Delta t}{\Delta x}$.

For $U = 2 \text{ m s}^{-1}$, $\Delta x = 5 \text{ km}$, $\Delta t = 600 \text{ s}$, calculate C .

If stability requires

$$C \leq 1,$$

is this time step acceptable?

- ② Suppose the horizontal grid spacing is reduced from $\Delta x = 10 \text{ km}$ to $\Delta x = 5 \text{ km}$.

For the same characteristic velocity U , how must Δt change if the CFL number is to remain unchanged?

- ③ A model domain initially contains

$$N_x \times N_y = 300 \times 200$$

horizontal grid cells. If both Δx and Δy are reduced by a factor of two, approximately how many horizontal grid cells will the new model have? What does this imply for computational cost?