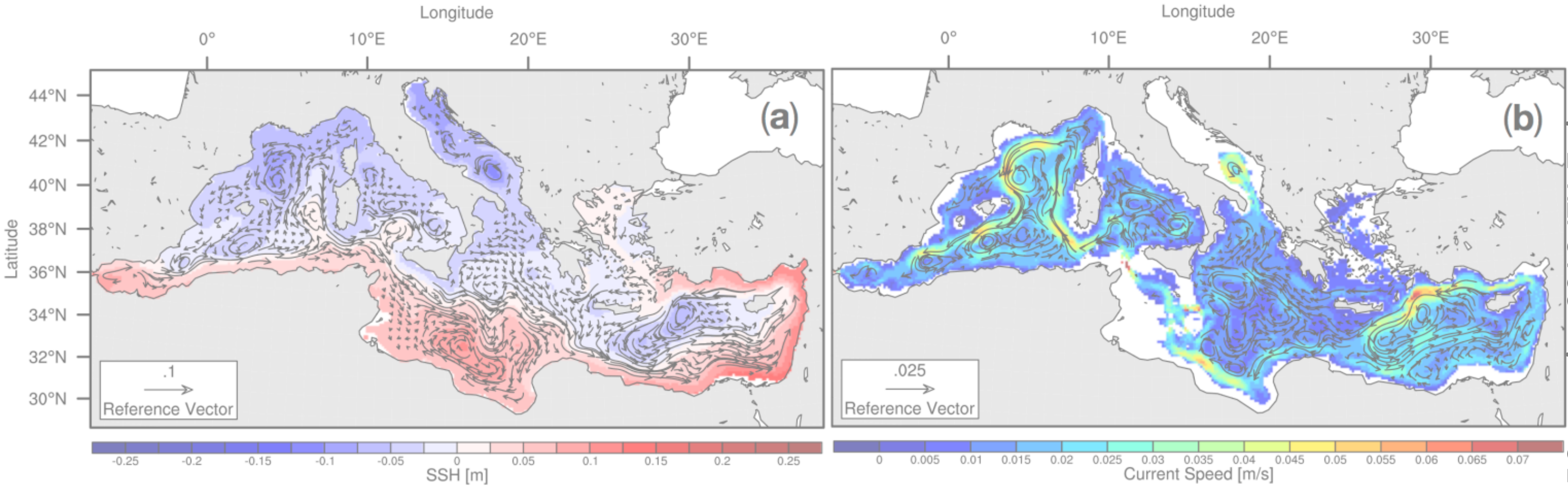


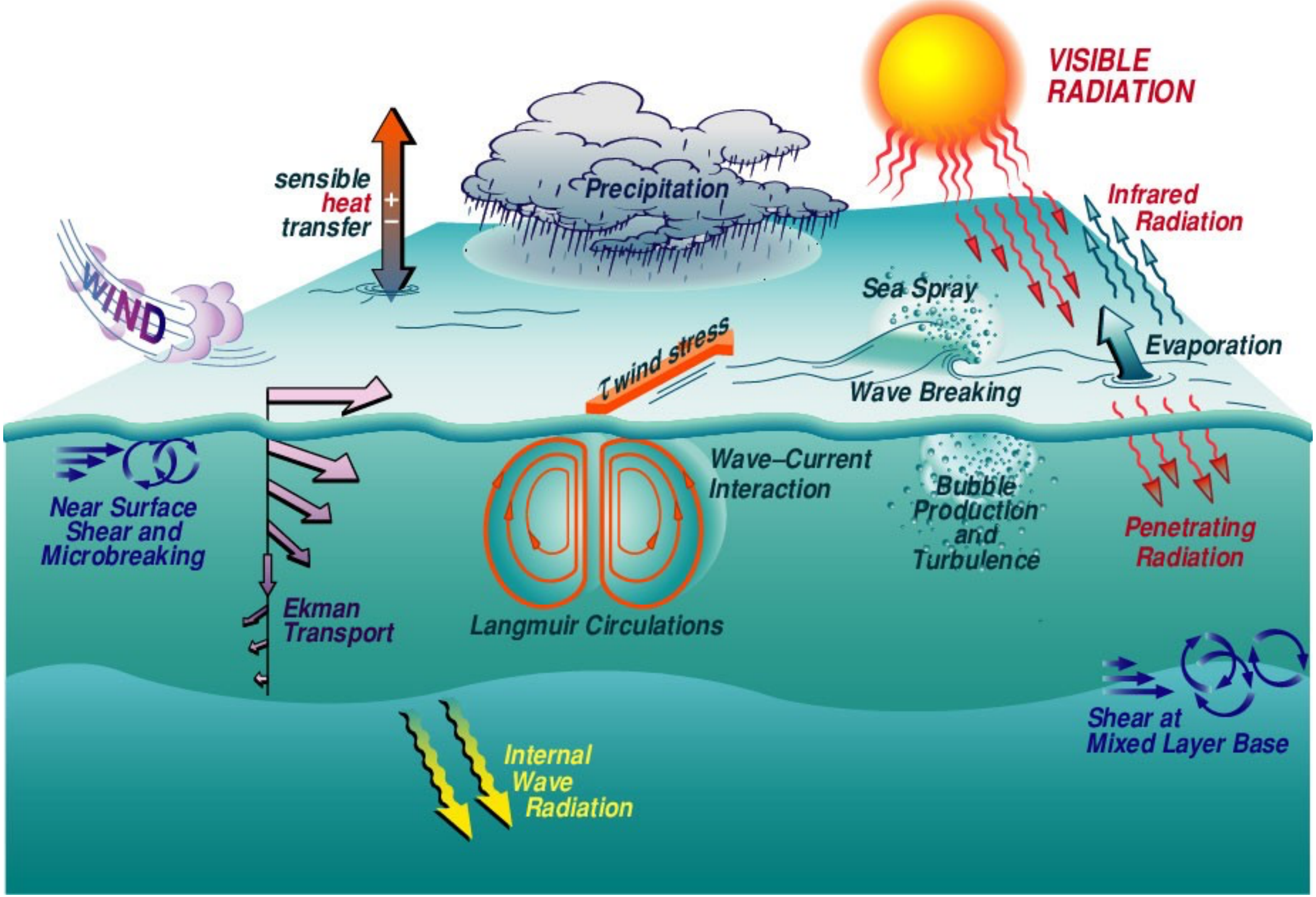
Introduction and ROMS Tutorial

Ufuk Utku Turuncoglu

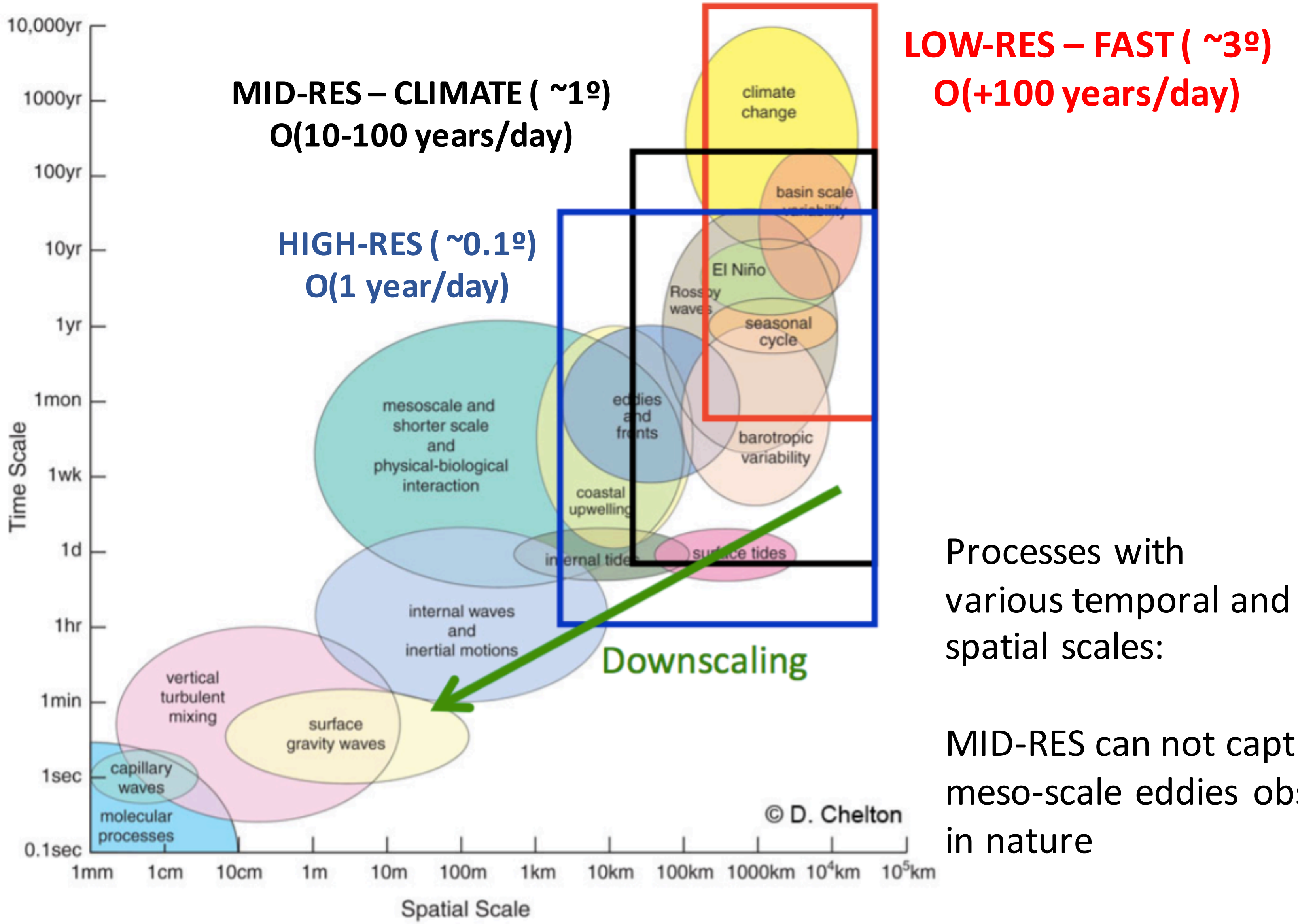
İTÜ, Informatics Institute

1st Regional Earth System Modeling Summer School, 5-7 September 2016, ITU, Turkey

Air-sea Interaction



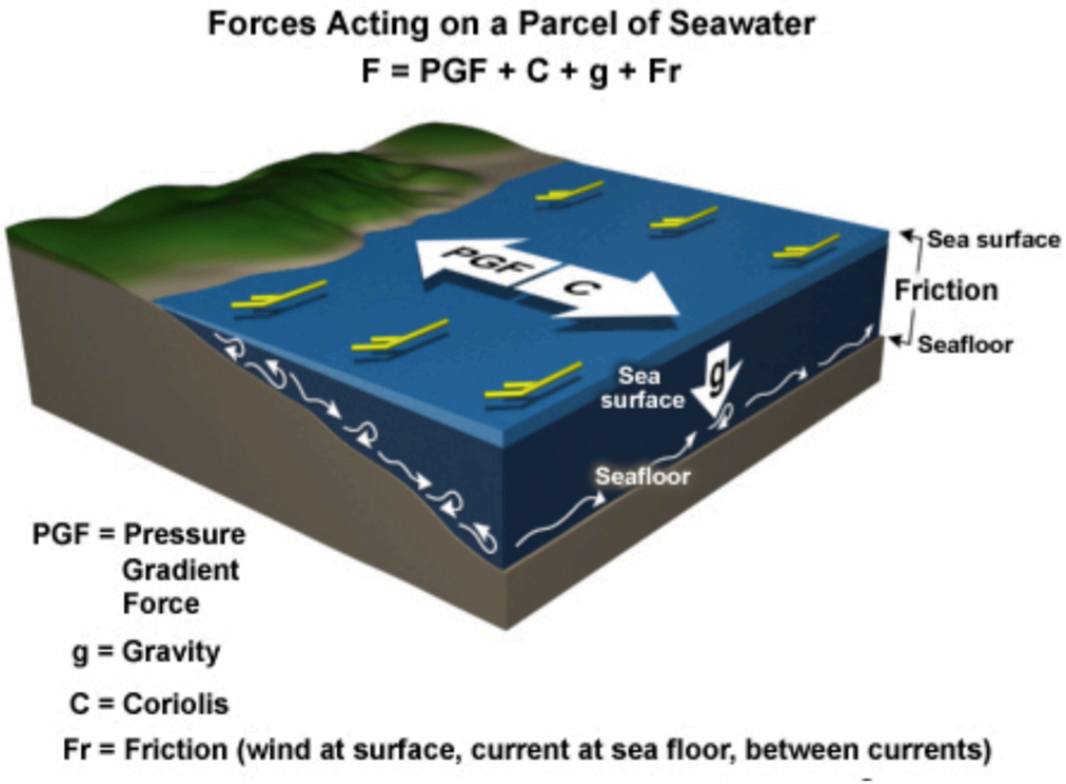
Ocean Modeling Challenges
Space-Time Scales



Processes with various temporal and spatial scales:

MID-RES can not capture meso-scale eddies observed in nature

Ocean Modeling: Physics



- Forces
  - Gravity (g)
  - Pressure Gradient Force (PGF) due to horizontal height and density differences
  - Coriolis force (f) due to rotating earth
  - Friction – between wind and sea surface, between current and sea floor, and between between water masses having different velocities

$$Newton's\ Second\ Law \rightarrow F = ma$$

$$\sum F = PGF + g + f + Friction \rightarrow Navier\ Stokes$$

Physics in ROMS

Glenn et al., 2016

$$\underbrace{\frac{\partial u}{\partial t}}_{\text{Acceleration}} = \underbrace{-\frac{\partial (uu)}{\partial x} - \frac{\partial (vu)}{\partial y}}_{\text{Horizonal advection}} \underbrace{- \frac{1}{\rho_0}\frac{\partial P}{\partial x}}_{\text{Pressure gradient}} + \underbrace{\left(\underbrace{\frac{\tau_s^x}{h\rho_0}}_{\text{Surface}} - \underbrace{\frac{\tau_b^x}{h\rho_0}}_{\text{Bottom}} \right)}_{\text{Stress}} + \underbrace{fv}_{\text{Coriolis}} \quad (3)$$

momentum balance

$$\underbrace{\frac{\partial v}{\partial t}}_{\text{Acceleration}} = \underbrace{-\frac{\partial (uv)}{\partial x} - \frac{\partial (vv)}{\partial y}}_{\text{Horizonal advection}} \underbrace{- \frac{1}{\rho_0}\frac{\partial P}{\partial y}}_{\text{Pressure gradient}} + \underbrace{\left(\underbrace{\frac{\tau_s^y}{h\rho_0}}_{\text{Surface}} - \underbrace{\frac{\tau_b^y}{h\rho_0}}_{\text{Bottom}} \right)}_{\text{Stress}} - \underbrace{fu}_{\text{Coriolis}} \quad (4)$$

$$\left(A_{kt} \frac{\partial T}{\partial z} \right)_{z=0} = \frac{Q_{net}}{\rho_0 C_p} \quad (6)$$

$$\frac{\partial T}{\partial t} = -\frac{\partial (uT)}{\partial x} - \frac{\partial (vT)}{\partial y} - \frac{\partial (wT)}{\partial z} + \frac{\partial A_{kt}\frac{\partial T}{\partial z}}{\partial z} + \mathcal{D}_T + \mathcal{F}_T \quad (5)$$

heat balance

$$\left(A_{kt} \frac{\partial T}{\partial z} \right)_{z=0} = \frac{Q_{net}}{\rho_0 C_p} \quad (6) \qquad \left(A_{kt} \frac{\partial T}{\partial z} \right)_{z=-h} = 0 \quad (7)$$

surface boundary cond. bottom boundary cond.

Ocean Modeling Challenges
Rossby Radius of Deformation

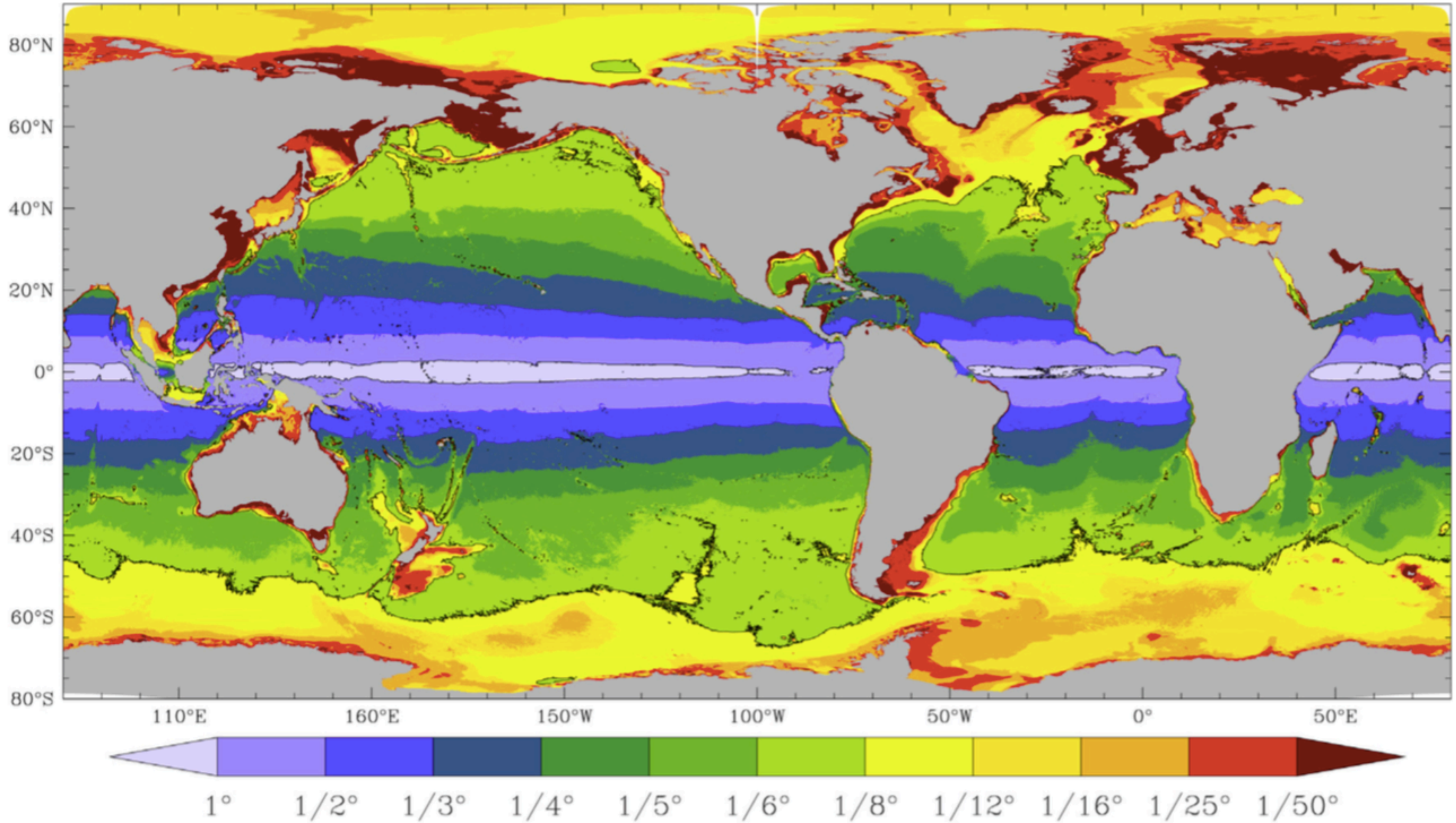
First mode of Internal gravity wave speed

$$R = \sqrt{\frac{c_g^2}{(f^2 + 2\beta c_g)}}$$

Coriolis parameter

meridional gradient of f

R. Hallberg / Ocean Modelling 72 (2013) 92–103 93



The horizontal resolution needed to resolve the first baroclinic deformation radius with two grid points
Solid black line represent the regions that can be solved by 1° – 1/8° horizontal resolution

Parameterizations

- It is used to include physical effects of unresolved sub-grid scale processes such as turbulence
  - Lateral mixing of momentum and tracers by mesoscale and sub-mesoscale eddies
  - Vertical mixing of momentum and tracers (surface and bottom boundary layers, interior)
  - Tidal mixing
  - Convection
  - Diurnal cycle for shortwave heat flux and penetration through water column (Jerlow Water Type, …)
  - ...
- Physically based
- As simple as possible (computational overhead!)
- As few parameters as possible

Parameterizations in ROMS

- Vertical mixing (momentum and tracers)
  - K-profile (LMD; Large et al., 1994)
    - Surface Boundary Layer
    - Interior
  - Mellor-Yamada 2.5 (Mellor and Yamada, 1982)
  - Generic Length Scale (GLS; Umlauf and Burchard, 2001; Warner et al., 2005)
    - k-kl
    - k-epsilon
    - k-omega
    - k-generic
- Horizontal mixing of momentum and tracers
  - Geopotential (const. depth) / isopycnic (const. density)

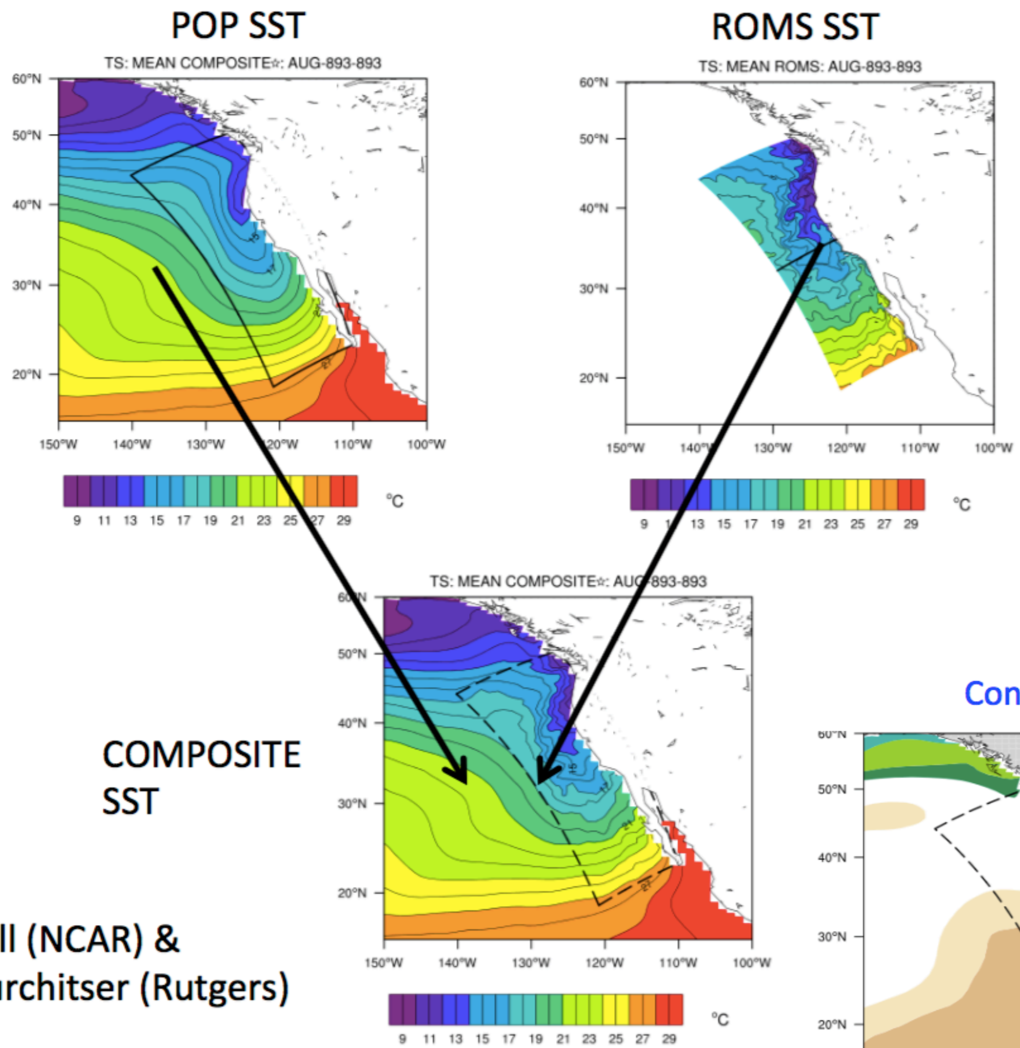
Why do we need regional models?

- We need higher spatial resolution to solve science problems such as
  - Climate variability and prediction (i.e. sea level change, extreme events)
  - Coastal processes and ecosystems (i.e. upwelling)
  - Estuaries, interconnected basins (i.e. TSS)
  - Marginal seas (Mediterranean / Black / Marmara Seas)
  - …
- Information for impacts and adaptation purposes
- Investigating processes that are better represented in higher spatial and temporal scales

Regional Modelling Approaches

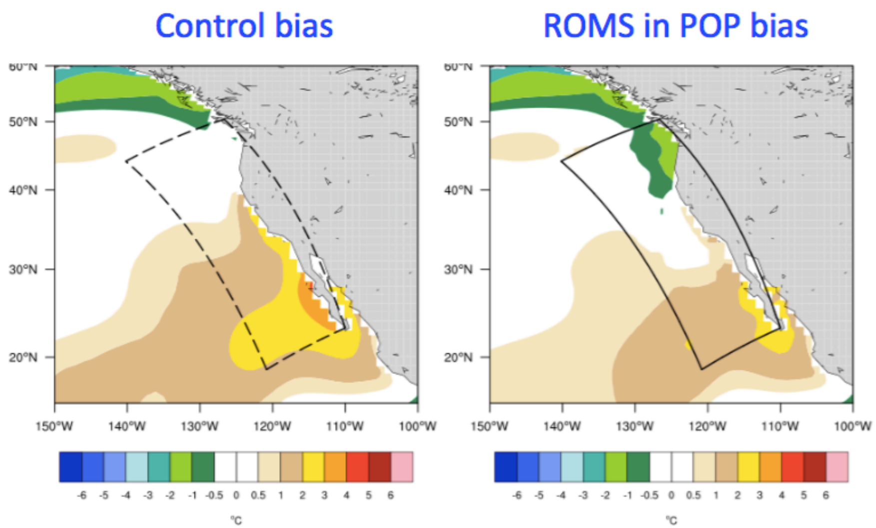
- High resolution global models (not practical due to requirement of extensive computational resources and data management issues – post-processing)
- Dynamic and static grid refinement in global models (it might help to reduce biases)
- Imbedded high resolution model with in a coarser model (two-way interaction among models can be tricky)
- Regional ocean models with/without open boundary conditions (coming from observations or global models)

ROMS imbedded in POP



In this case, regional ocean model (ROMS) is used together with global ocean model (POP) to improve global model's SST

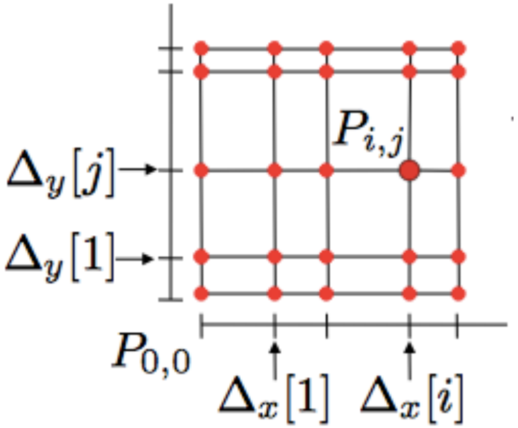
The coupling tools such as ESMF and MCT help to integrate different models



Justin Small (NCAR) &
Enrique Curchitser (Rutgers)

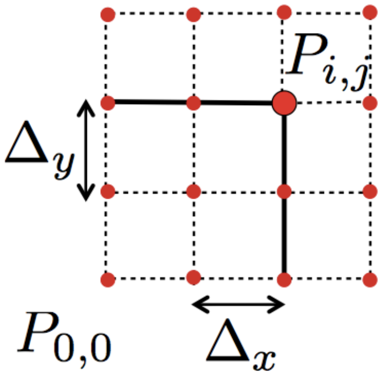
Ocean Model – Horizontal Grids

- Structured grid
  - Generic representation of rectangular and curvilinear type of grids
  - Grid positions can be computed (procedural)
  - It can be uniform (dx=dy) and non-uniform (dx≠dy)



non-uniform

$$P_{i,j,k} = \underbrace{\boxed{P_{0,0}}}_{\text{origin}} + \underbrace{\boxed{\Delta_x}}_{\text{spacing}}\boxed{[i]}\vec{e}_x + \boxed{\Delta_y}\overbrace{\boxed{[j]}}^{\text{dimension}}\vec{e}_y + \boxed{\Delta_z}\boxed{[k]}\vec{e}_z$$



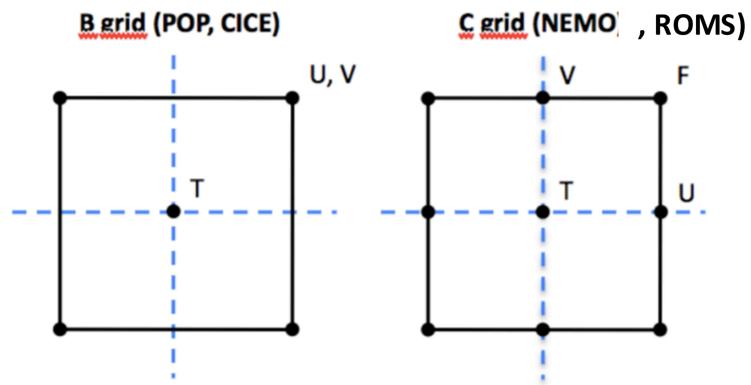
uniform

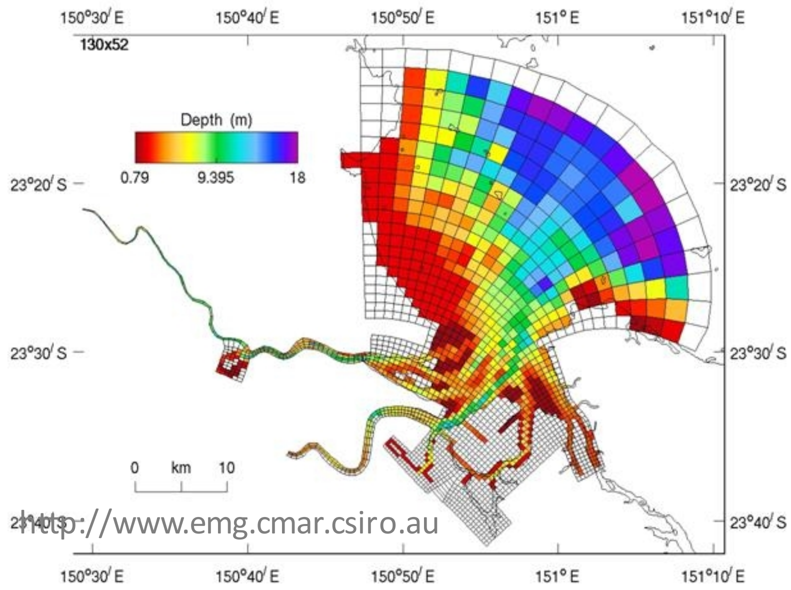
$$P_{i,j,k} = P_{0,0} + i\Delta_x\vec{e}_x + j\Delta_y\vec{e}_y + k\Delta_z\vec{e}_z$$

Represented by the combination of origin, dimension and spacing

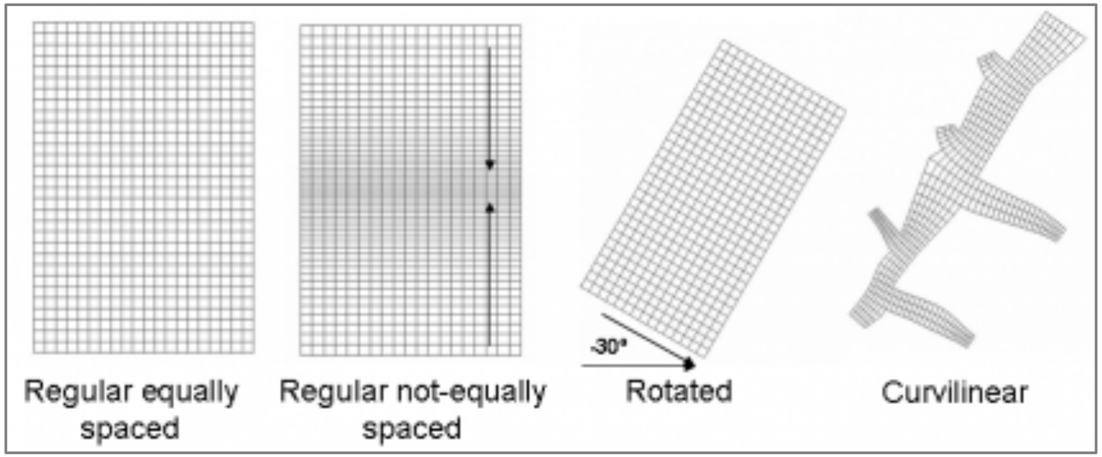
Ocean Model – Horizontal Grids

- Curvilinear grid
    - When the solution domain is not rectangular Cartesian grids cannot be used.
    - Structured curvilinear grids are based on mapping of the flow domain onto a computational domain

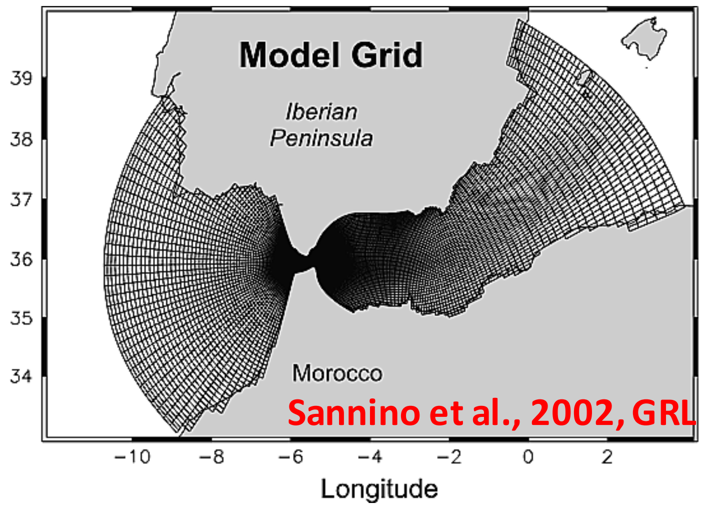




http://www.emg.cmar.csiro.au



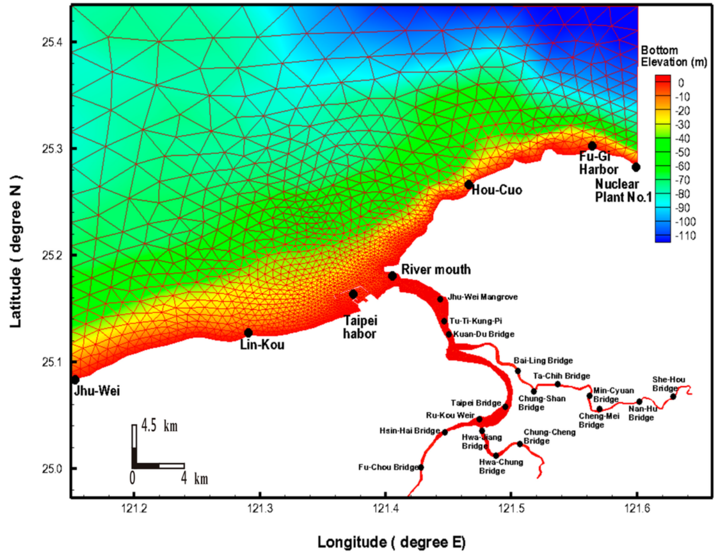
http://www.mohid.com/wiki/index.php?title=Grid



Sannino et al., 2002, GRL

Ocean Model – Horizontal Grids

- Unstructured grid
  - It is more suitable to use in complex coastlines such as interconnected basins
  - Formulation in unstructured meshes more difficult and expensive (2-4 times slower)



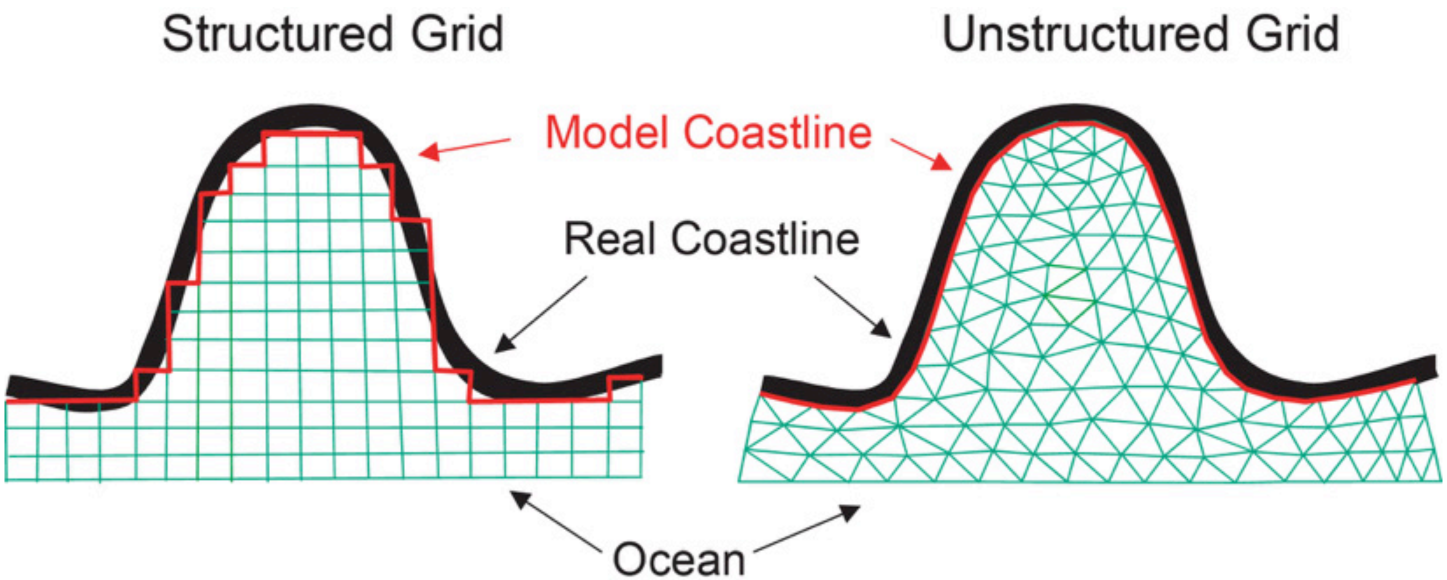
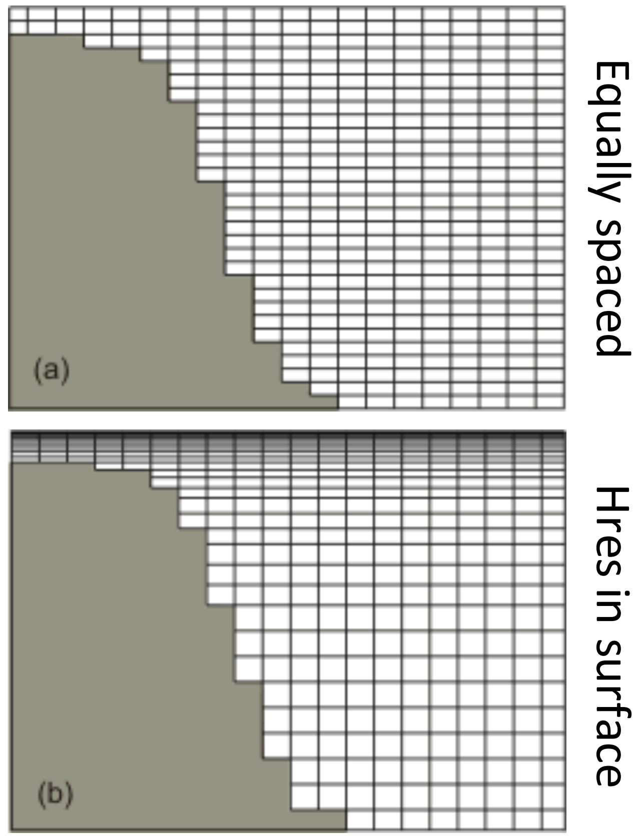


Figure 1. An example of fitting a structured grid (left) and an unstructured grid (right) to a simple coastal embayment. The true coastline is shown in black, the model coastline in red. Note how the unstructured triangular grid can be adjusted so that the model coastline follows the true coastline, while the unstructured grid coastline is jagged -- which can result in unrealistic flow disturbance close to the coast. Credit: Chen, C., R.C. Beardsley, and G. Cowles. An unstructured grid, finite-volume coastal ocean model (FVCOM) System. Oceanography 19(1):78-89 (2006). http://dx.doi.org/10.5670/oceanog.2006.92

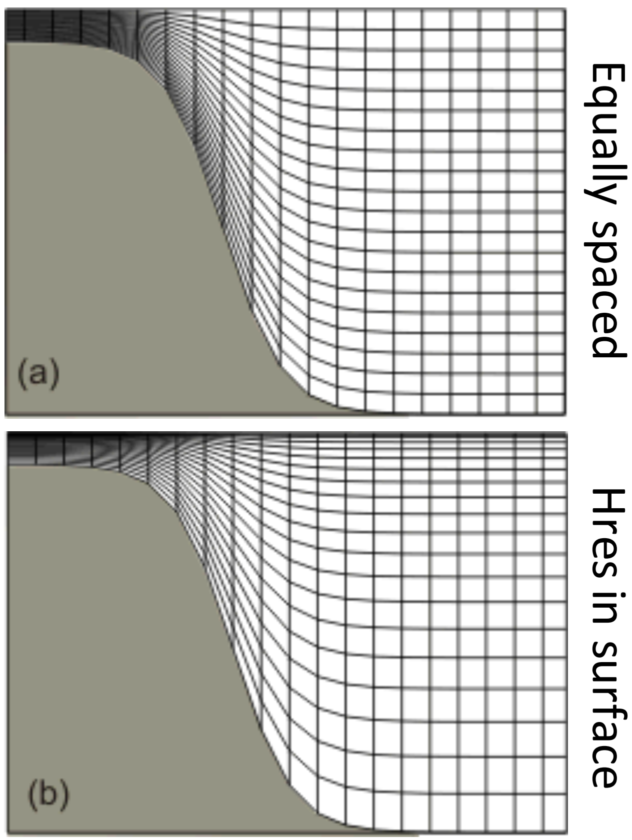
Ocean Model – Vertical Grids

- The choice of a vertical coordinate system is one of the most important aspects of a model design and strongly depend on application
- Z-coordinate (i.e. MITgcm, MOM):
    - It is the simplest system and used by various ocean models
    - Z-coordinate model has problem with the regions of sloping topography such as coastal regions. In here, the levels intersect the bathymetry and unrealistic vertical velocities near the bottom can result.
    - Increasing the number of vertical levels will improve the representation of the near-bottom flow, but at a high computational cost.



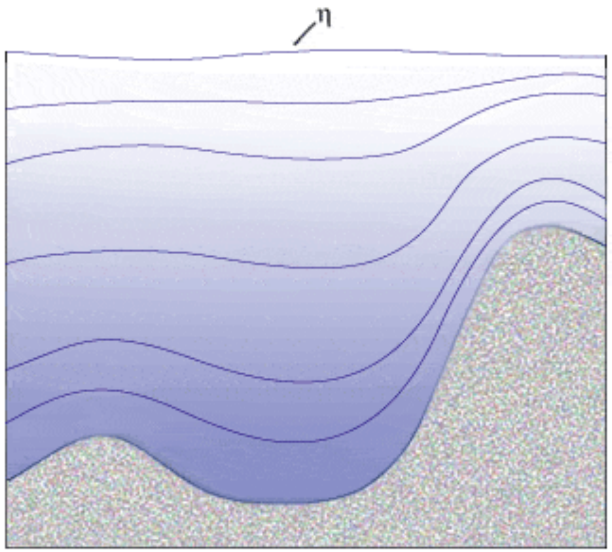
Ocean Model – Vertical Grids

- Sigma or S-coordinate (i.e. ROMS, POM):
  - Help to keep same number of vertical layer in everywhere independent from the depth of the water column. The layer thickness vary with the depth
  - The layers are more closely spaced near the surface and/or bottom than in the interior, thus allowing the boundary layers to be better resolved.
  - This type of coordinate is most appropriate for continental shelf and coastal regions, where the bottom and surface boundary layers may merge.
  - They have difficulty handling sharp topographic changes from one grid point to another. Pressure-gradient errors can give rise to unrealistic flows.
  - Smoothing might help !



Ocean Model – Vertical Grids

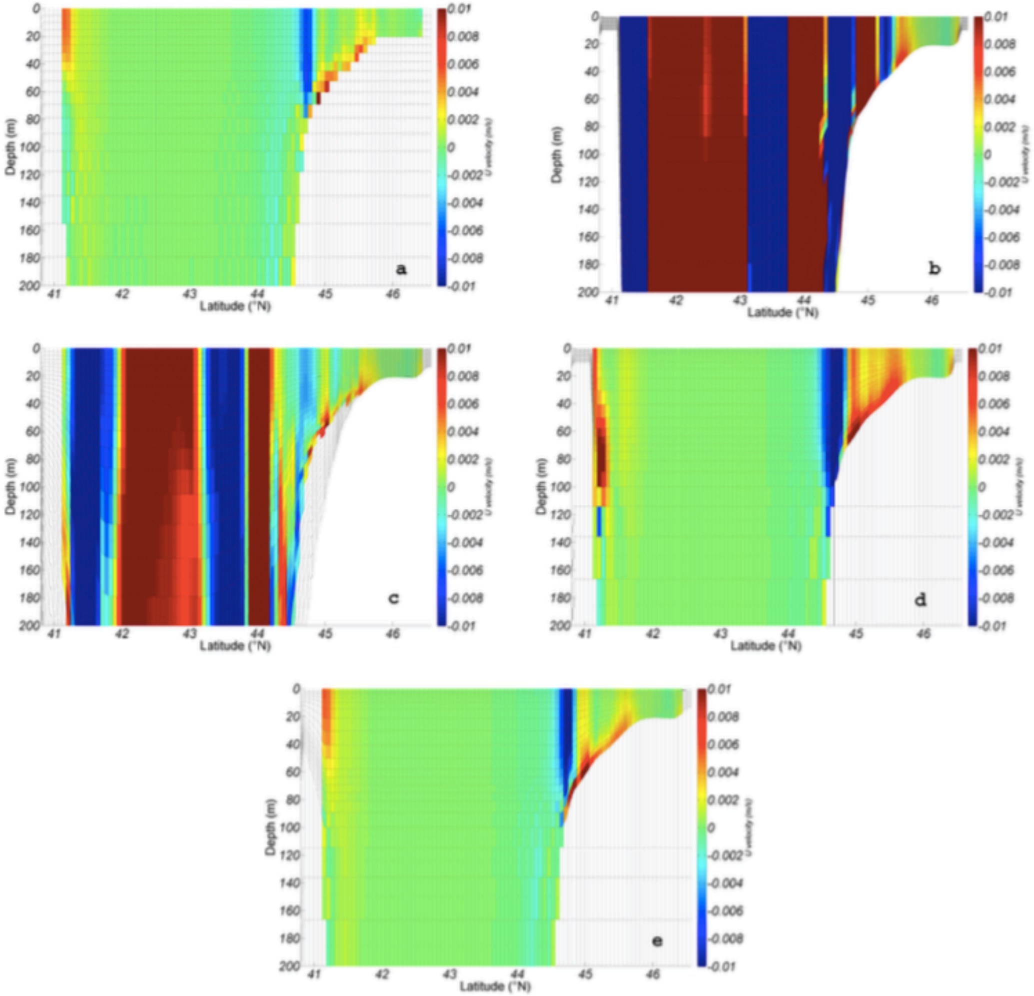
- Isopycnal coordinates:
  - These models use the potential density referenced to a given pressure as the vertical coordinate.
  - This system basically divides the water column into distinct homogeneous layers, whose thicknesses can vary from place to place and from one time step to the next.



  - This choice of coordinate works well for modeling tracer (T, S) transport, which tends to be along surfaces of constant density.
  - The main advantage of these models is the computational cost. They could run in higher horizontal resolution rather than vertical one.
  - Their applications are limited with the costal regions and boundary layers (surface and bottom).

Black Sea Example

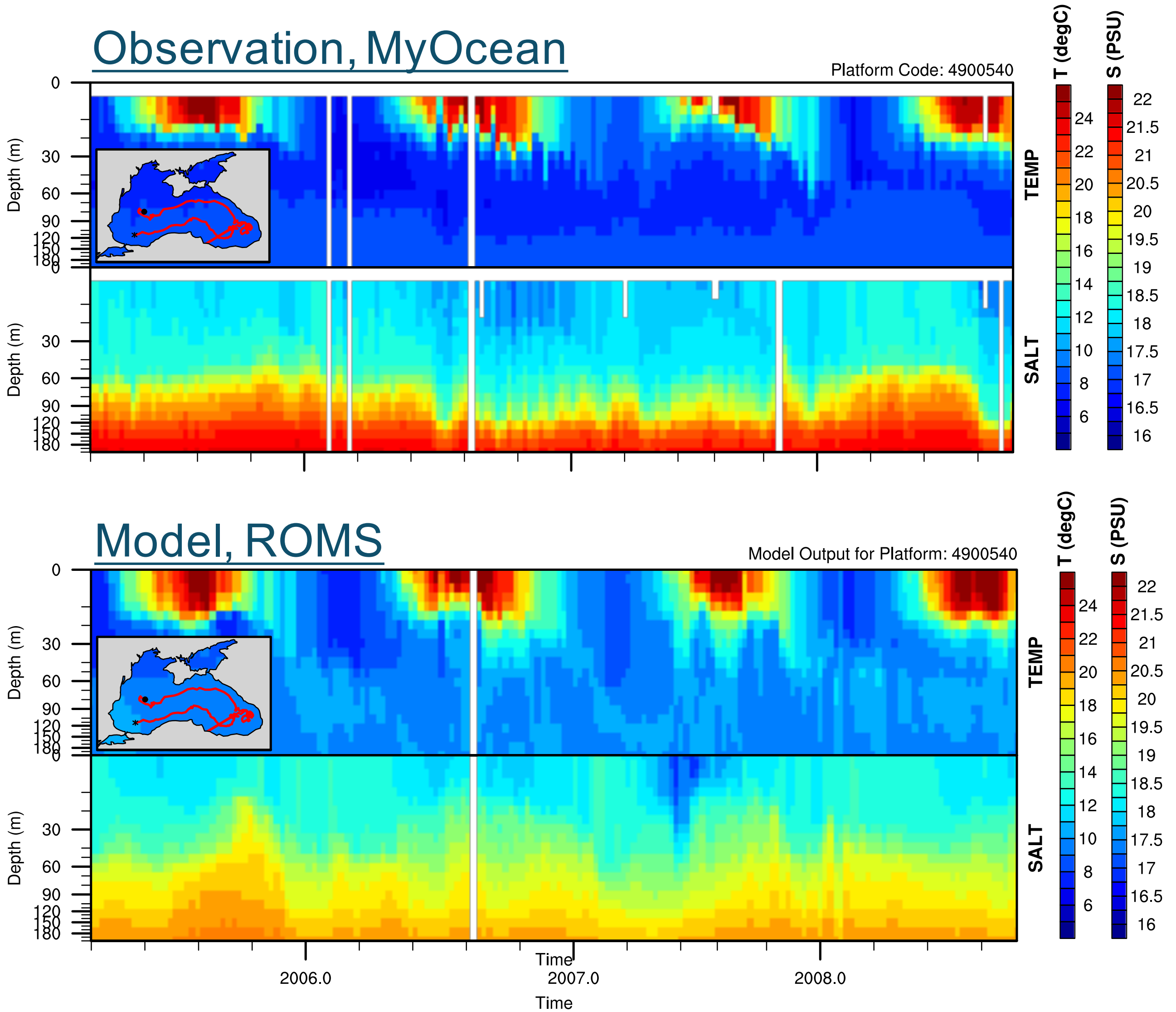
- A sensitivity study of NEMO ocean model with different vertical grid configurations

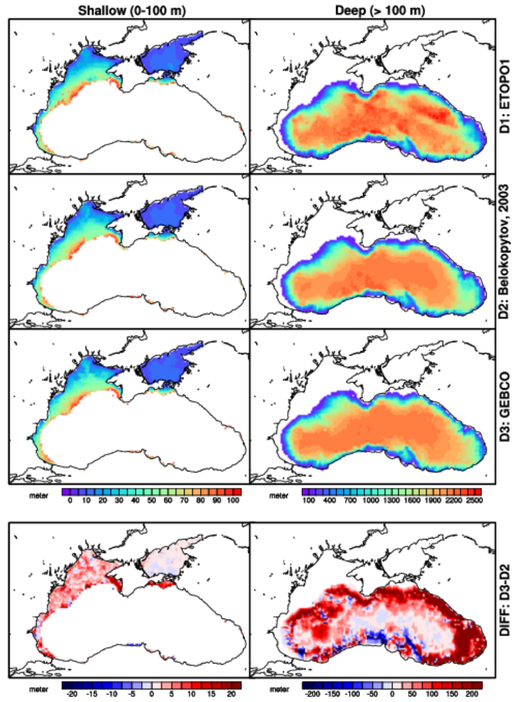


Spurious zonal velocities along 31º E after 3.5 months of simulation: **(a)** z-coordinate; **(b)** s-coordinate; **(c)** s-coordinate with enveloping topography; **(d)** s-on-top-of-z; **(e)** s-enveloped-top-of-z.

Shapiro et al., 2013

Black Sea Example





ROMS ocean model configured for Black Sea

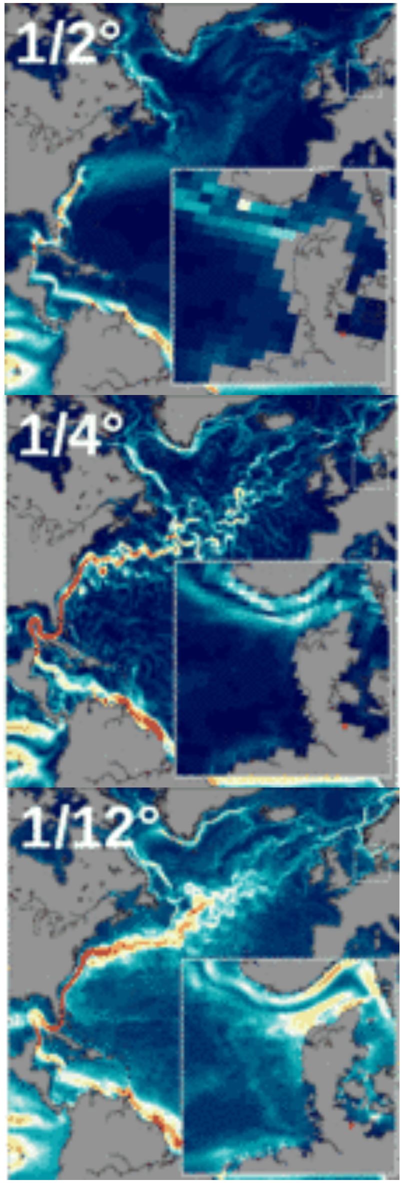
Due to sharp bathymetry gradient, the model produces unrealistic vertical mixing of tracers

Sensitivity to horizontal resolution

ORCA05

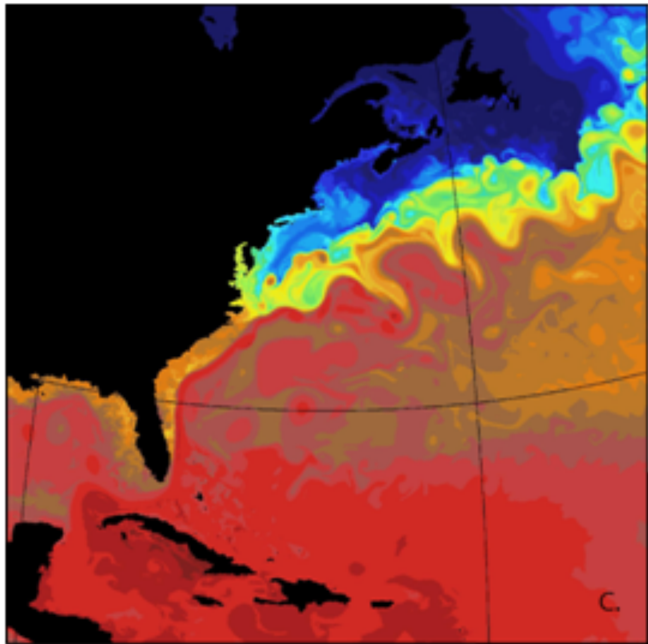
ORCA025

ORCA12



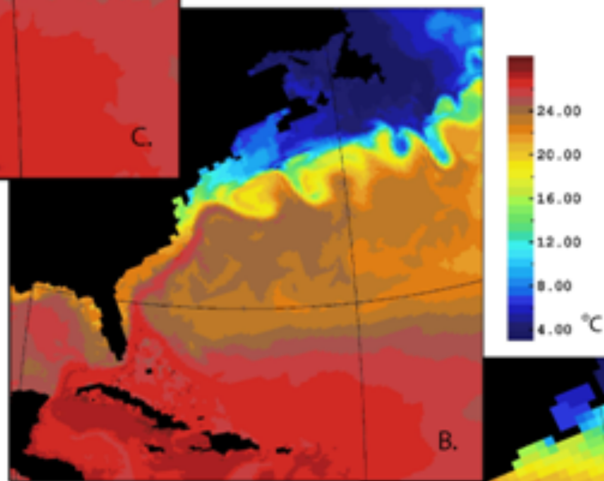
http://www.geomar.de/en/research/fb1/fb1-tm/ocean-models/

1/12°



http://noc.ac.uk/science-technology/climate-sea-level/changing-circulation/high-resolution-global-modelling

1/4°



1°

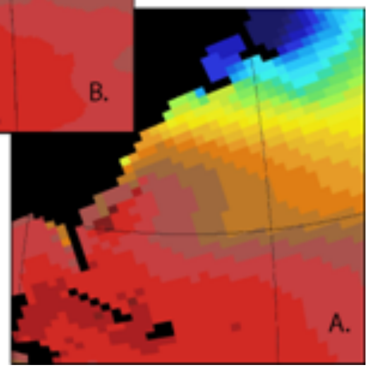
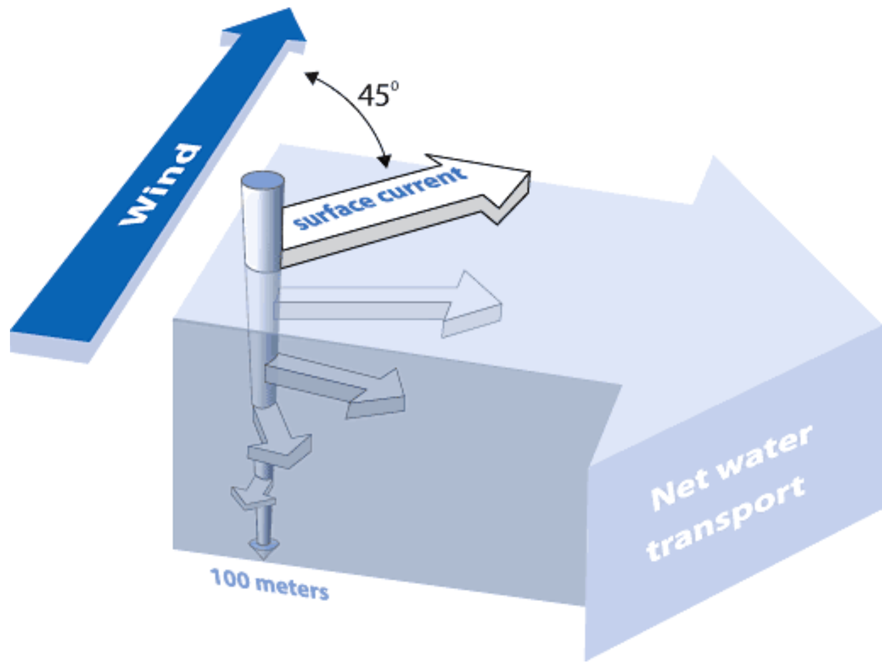


Figure 1. The predicted Sea Surface Temperature (SST) for the Gulf Stream region after one model year of integration in three different versions of the global ocean model. The models differ only in their horizontal resolution.
Panel A. shows the results from a 1° resolution model which fails to resolve a recognisable Gulf Stream.

At 1/4° (**panel B.**), a narrow Gulf Stream is formed but it fails to leave the American coast at the correct latitude and penetrates too far north before beginning its eastward journey.
Our latest model with a 1/12° resolution (**panel C.**), shows a much more realistic Gulf Stream which carries more and warmer water towards Northern Europe.

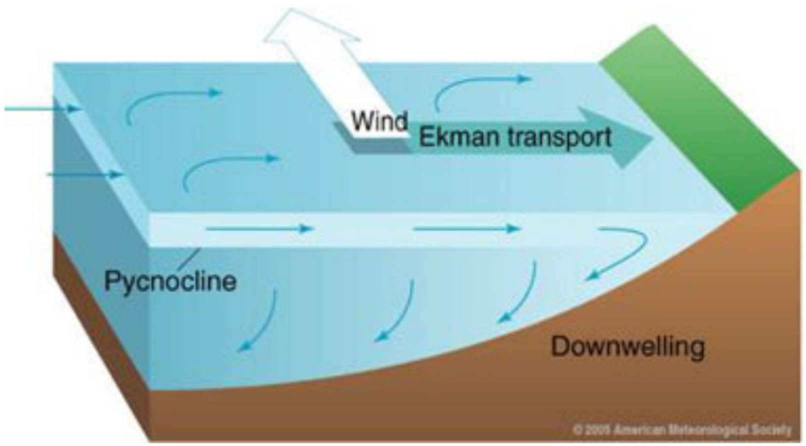
Ocean Motion – Ekman Transport

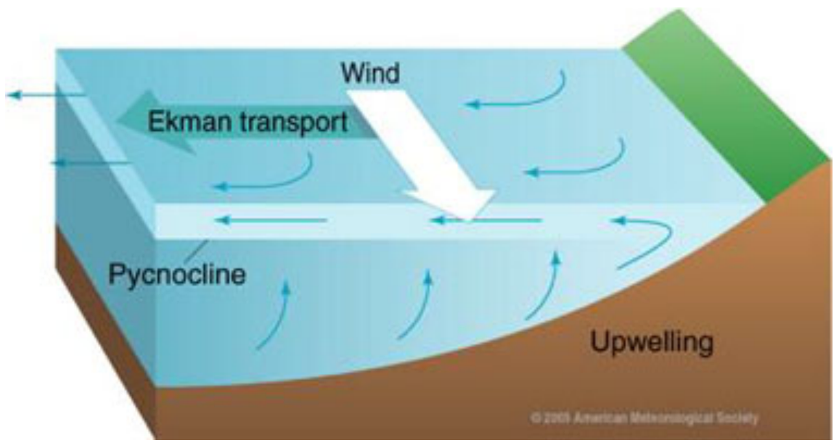


- The Ekman spiral, named after Swedish scientist Vagn Walfrid Ekman (1874-1954) who first theorized it in 1902, is a consequence of the Coriolis effect.
- As a result, each successively deeper layer of water moves more slowly to the right or left, creating a spiral effect.
- Because the deeper layers of water move more slowly than the shallower layers, they tend to "twist around" and flow opposite to the surface current.

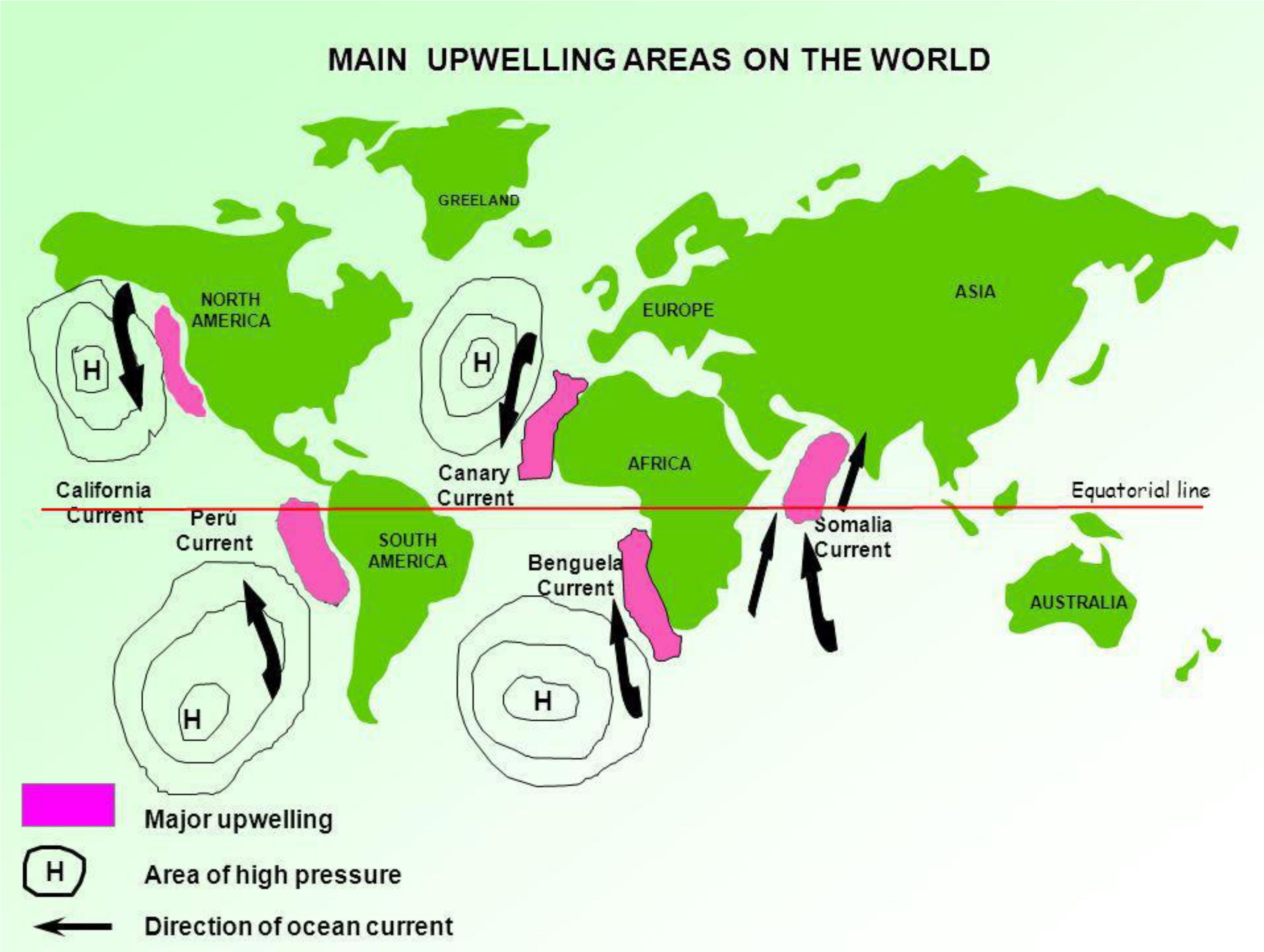
Ocean Motion – Upwelling

- Where Ekman transport moves surface waters away from the coast, surface waters are replaced by water that wells up from below in the process known as upwelling. This example is from the Northern Hemisphere.
- Where Ekman transport moves surface waters toward the coast, the water piles up and sinks in the process known as downwelling. This example is from the Northern Hemisphere.

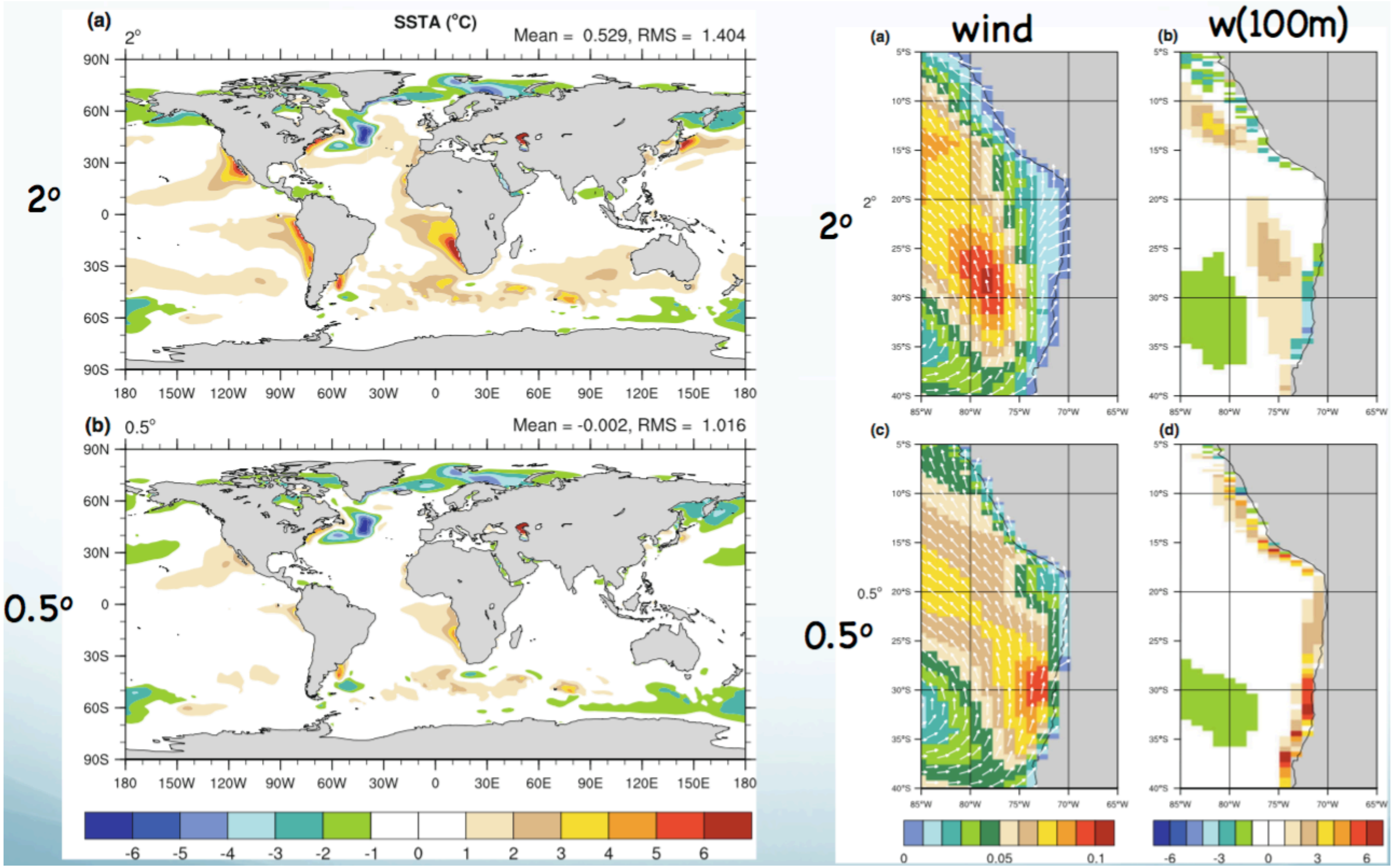




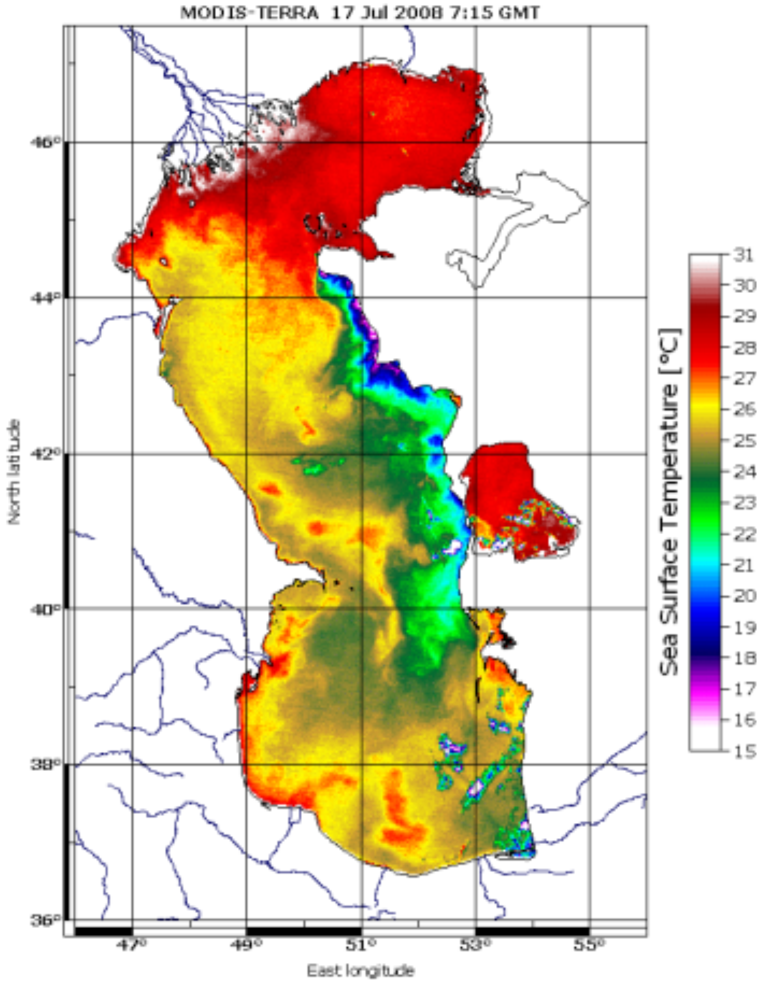
Ocean Motion – Upwelling …



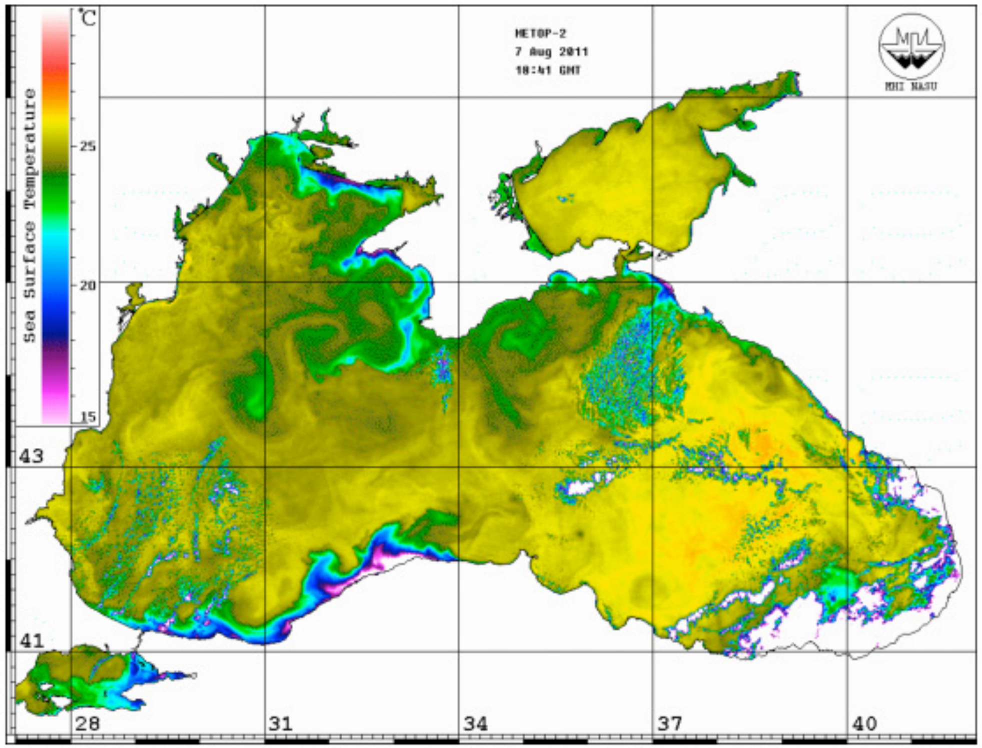
Ocean Motion – Upwelling …



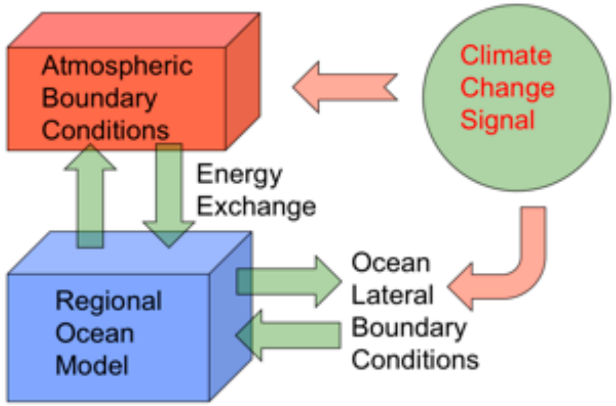
Ocean Motion – Upwelling …

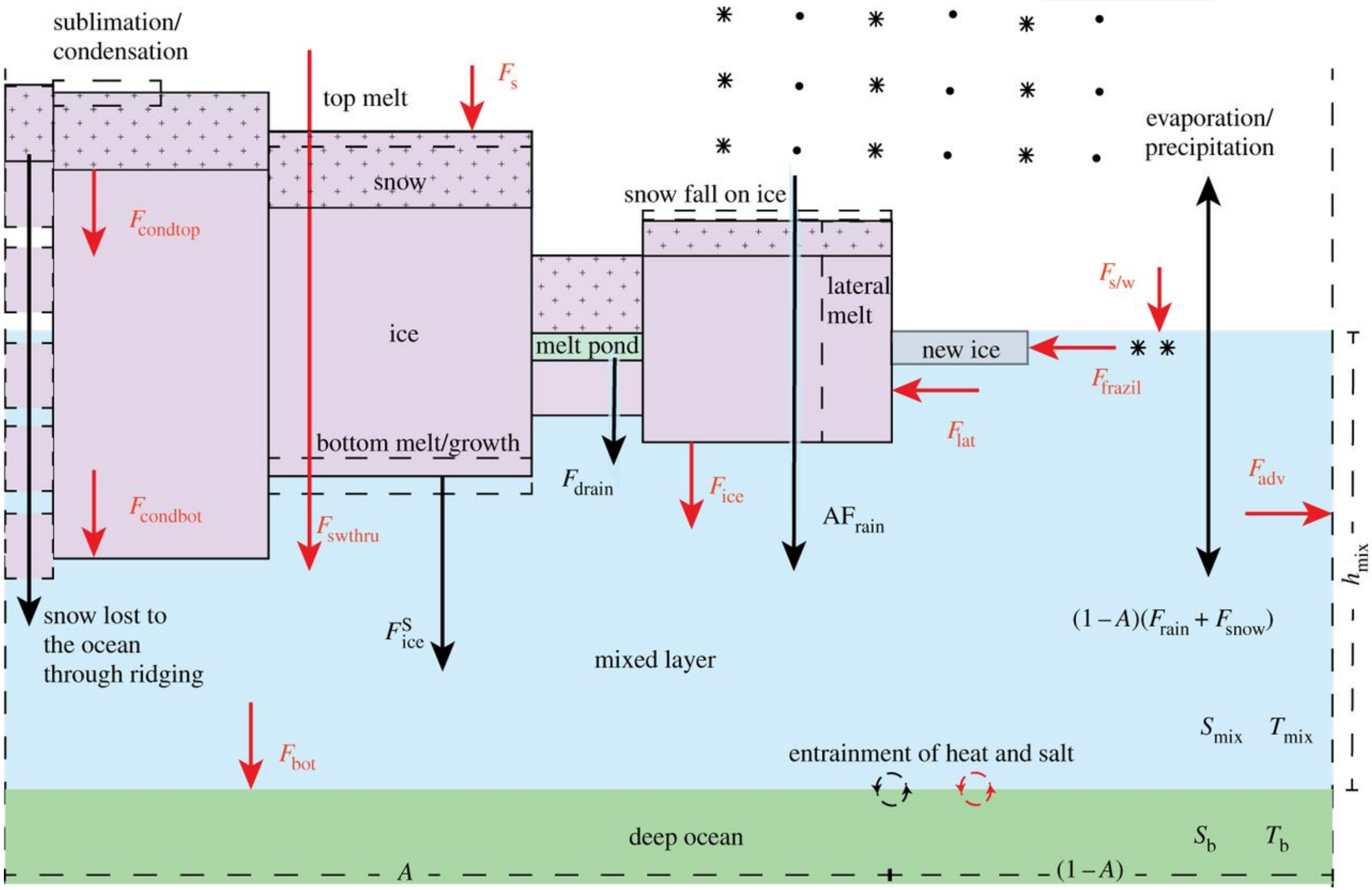


Regional examples: Caspian Sea, Black Sea



Input for Ocean Models

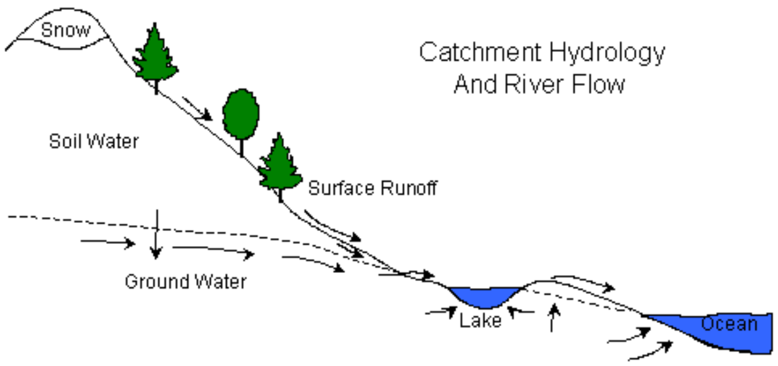




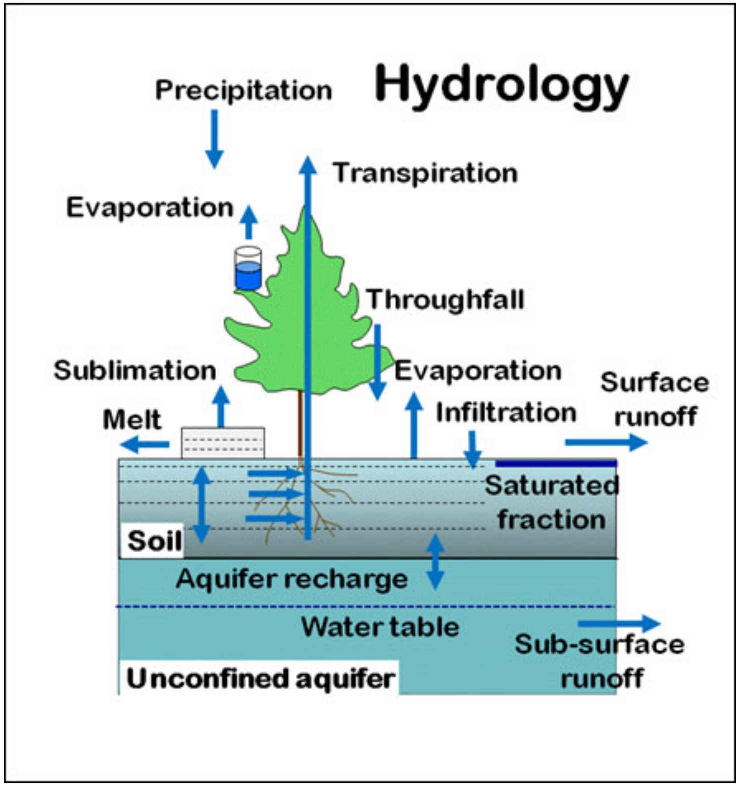
Input for Ocean Models …

- Definition of horizontal and vertical grid
- Interpolation of bathymetry (ETOPO, GEBCO etc.)
- Initial conditions (WOA, SODA, global ocean models). MEDAR/MEDATLAS can be used for Mediterranean and Black Seas.
- Atmospheric forcing (Reanalysis datasets such as ERA-Interim, NCEP/NCAR, COARE, global and/or regional atmosphere model)
- Open boundary conditions (T, S, SSH, U, V …; SODA, Global ocean circulation model such as MOM)
- River input (freshwater) from GRDC, RivDis etc. It could be also calculated using river routing or hydrological model.

Input for Ocean Models …



Copyright Bonan, G.B. (2002) Ecological Climatology: Concepts and Applications. Cambridge University Press, Cambridge



Rivers contributes to the net freshwater budget of the ocean / inland seas / lakes

It also affects the dynamics by changing the salinity and stratification around coastlines

The river plumes might have big impact in ocean.

Input for Ocean Models …

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- Interpolation of bathymetry (ETOPO, GEBCO etc.)
- Initial conditions (WOA, SODA, global ocean models). MEDAR/MEDATLAS can be used for Mediterranean and Black Seas.
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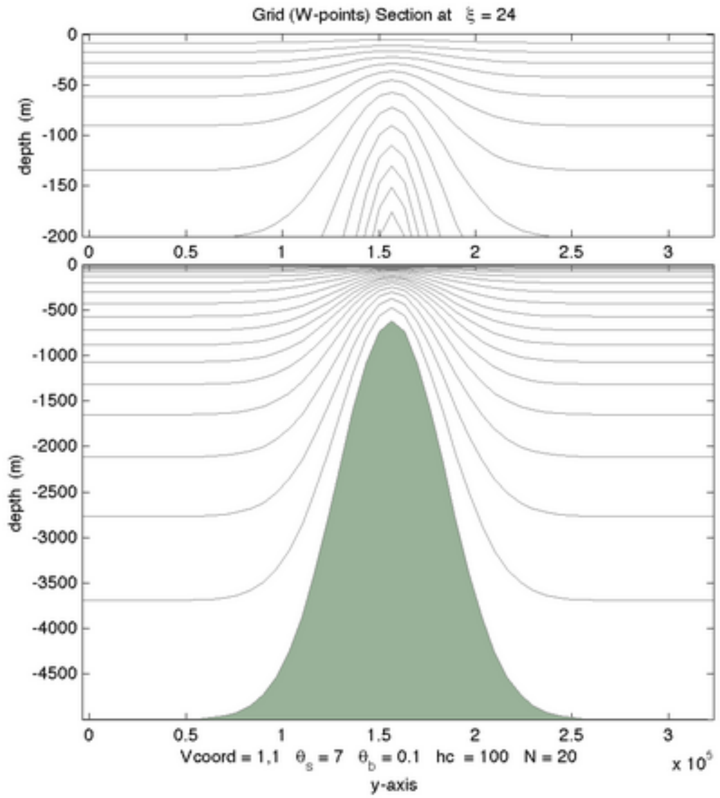
Grid Generation



- **Realistic and/or analytic**
- **ROMS uses s-coordinate in vertical and it follows bathymetry**
- **The distribution of vertical layers can be controlled using set of parameters**
- **In horizontal, curvilinear grid is supported**
- **Grid Generation Tools:**
  - **MATLAB: SeaGrid, Gridgen, EasyGrid …**
  - **Python: octant, pyroms, …**
  - **Analytic grid can be also defined using Fortran**
- **The grid generation plays crucial role in the stability**

Grid Generation

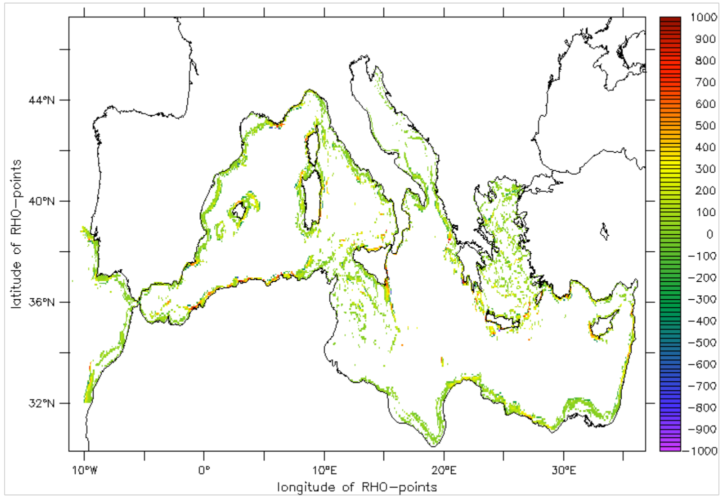
- **Bathymetry smoothing:**

```
GET_2DFLD   - surface air relative humidity,             t =      0 00:00:00
                (Rec=0001, Index=1, File: CAS_forcing_Qair_1996-2008.nc)
                (Tmin=          0.0000 Tmax=         4748.8750)
                (Min =  2.00517376E-03 Max =  7.59032093E-03)
GET_2DFLD   - rain fall rate,                            t =      0 00:00:00
                (Rec=0001, Index=1, File: CAS_forcing_rain_1996-2008.nc)
                (Tmin=          0.0000 Tmax=         4748.8750)
                (Min =  0.00000000E+00 Max =  1.07682618E-05)

Maximum grid stiffness ratios:  rx0 =    2.500000E-01 (Beckmann and Haidvogel)
                                rx1 =    3.998703E+00 (Haney)

Initial basin volumes: TotVolume =   7.2973633985E+13 m3
                       MinVolume =   7.9395051795E+06 m3
                       MaxVolume =   1.8480204838E+10 m3
                         Max/Min =   2.3276267753E+03
```

H_{smooth}-H_{raw}



- **Grid stiffness ratios:**

$$r_{xo} = \max\left(\frac{\Delta h}{2\bar{h}}\right) = \max\left(\frac{|h_i - h_{i-1}|}{h_i + h_{i-1})}\right)$$

Beckman & Haidvogel Number (1993)
Reduced by smoothing < 0.25

$$r_{x1} = \max\left(\frac{z_{i,j,k} - z_{i-1,j,k} + z_{i,j,k-1} - z_{i-1,j,k-1}}{z_{i,j,k} + z_{i-1,j,k} - z_{i,j,k-1} - z_{i-1,j,k-1}}\right)$$

Haney Number (1991)
Reduced by smoothing and vert. coordinate modification < 6.0

- **Tool: Matlab smoothing toolbox (LP_Bathymetry)**
  http://drobilica.irb.hr/~mathieu/Bathymetry/

Initial and Lateral Boundary Conditions

- Realistic and/or analytic
- Requires (3d for IC and 2d for Lateral BC)
  - salinity,
  - temperature
  - current (u and v)
  - sea surface height fields.
- The input files are defined in netCDF format
- The input files should be recreated when the horizontal and vertical grid changed!
  - There is no need to change files for atmospheric forcing if horizontal grid is same
- Atmospheric forcing
  - Momentum, heat and freshwater fluxes or atmospheric conditions

Installation

- The code is distributed using SVN repository
- Users need to register to access the codehttps://www.myroms.org/index.php?page=RomsCode
- Get code
  svn checkout https://www.myroms.org/svn/src/trunk MyDir
- Directories

```
.
|-- Atmosphere
|-- Compilers                OS/Architecture/compiler specific files
|-- Data
|-- Lib
|-- Master
|-- ROMS                     ROMS source code, files related with test cases
|-- User
|-- Waves
`-- makefile
```

Installation

- **Directories under ROMS/**

```
.
|-- Adjoint
|-- Bin                  ROMS build script, build.sh
|-- Drivers
|-- External             Input parameter files for tests, *.in and varinfo.dat
|-- Functionals          Files to create analytic initial and boundary conditions
|-- Include              Option files for test cases, CPP options
|-- License_ROMS.txt
|-- Modules
|-- Nonlinear            Source files for non-linear model
|-- Obsolete
|-- Programs
|-- Representer
|-- SeaIce
|-- Tangent
|-- Utility              Source files for utility modules
`-- Version
```

Installation

- Main steps:
  - Modify build environment (i.e. Compilers/Linux-ifort.mk)
    - External libraries (netCDF, HDF etc.)
    - MPI compiler (OpenMPI, IntelMPI, …)
    - OpenMP ?
  - Copy build script from ROMS/Bin/build.sh to installation directory
  - Create or copy application specific header file
    - CPP options for model customization
  - Edit build.sh
    - Case identifier (i.e. UPWELLING)
    - Specify source directory
    - MPI, compiler definitions
  - Run build script to install model, ./build.sh

Installation

- Application specific options are defined by CPP definitions
- CPP definitions act as a filter to create customized model source code
- CPP options include:
    - Momentum equations (mixing, advection, bottom friction, …)
    - Tracer equations (mixing, advection, relaxation, rivers …)
    - Pressure gradient algorithm
    - Atmospheric boundary conditions (i.e. bulk flux alg.)
    - Analytical field definitions (grid, initial conditions etc.)
    - Vertical mixing parameterizations (GLS, MY, LMD, …)
    - Open boundary conditions
    - Biological (i.e. NPZD, EcoSim) + Sediment Transport models
    - Sea-ice …

Referances

- http://www.oc.nps.edu/nom/modeling/vertical_grids.html
- http://imos.org.au/fileadmin/user_upload/shared/IMOS%20General/ACOMO/ACOMO_2014/presentations/wednesday/Robin_Robertson__Recovered_.pdf