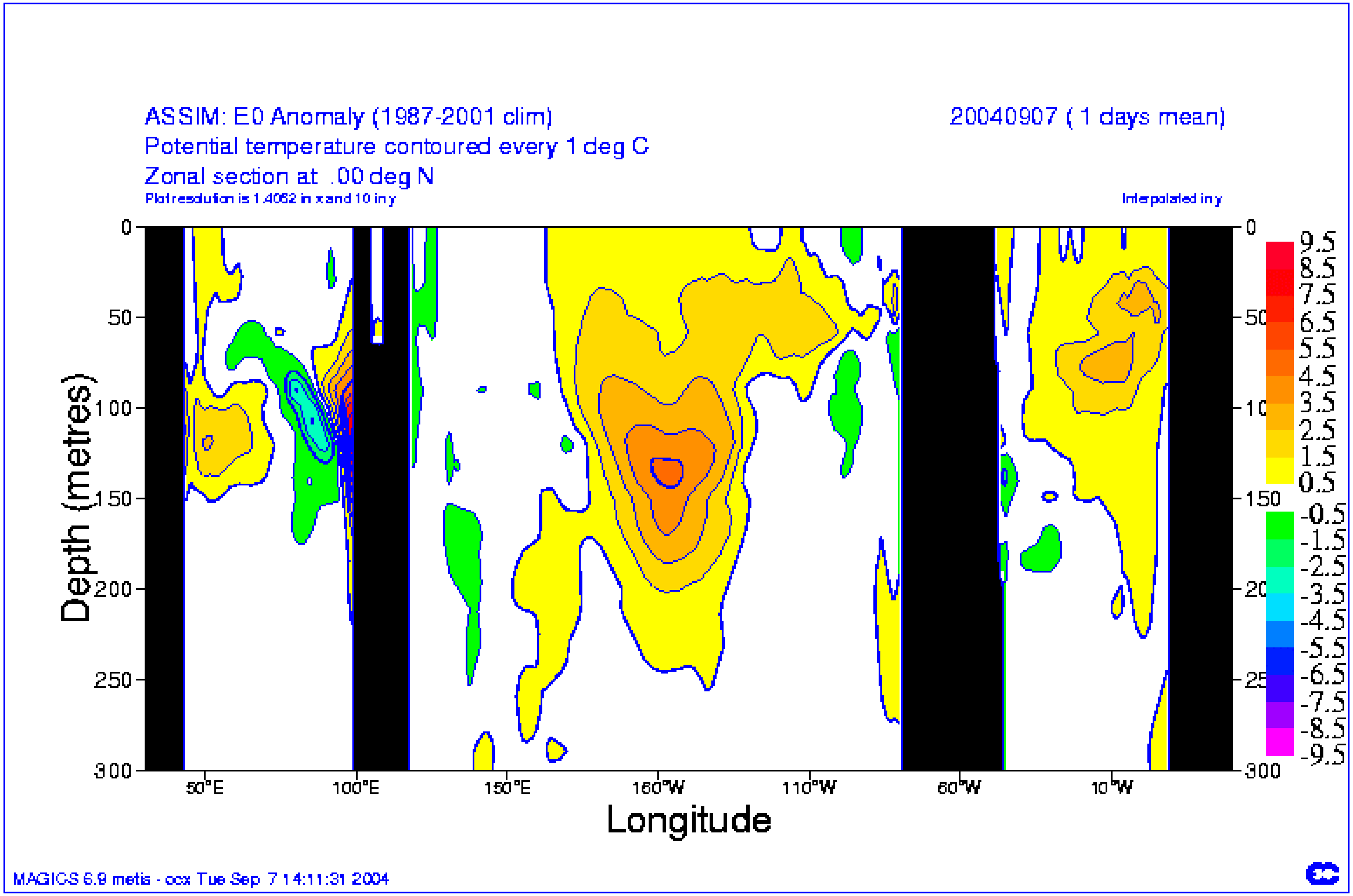
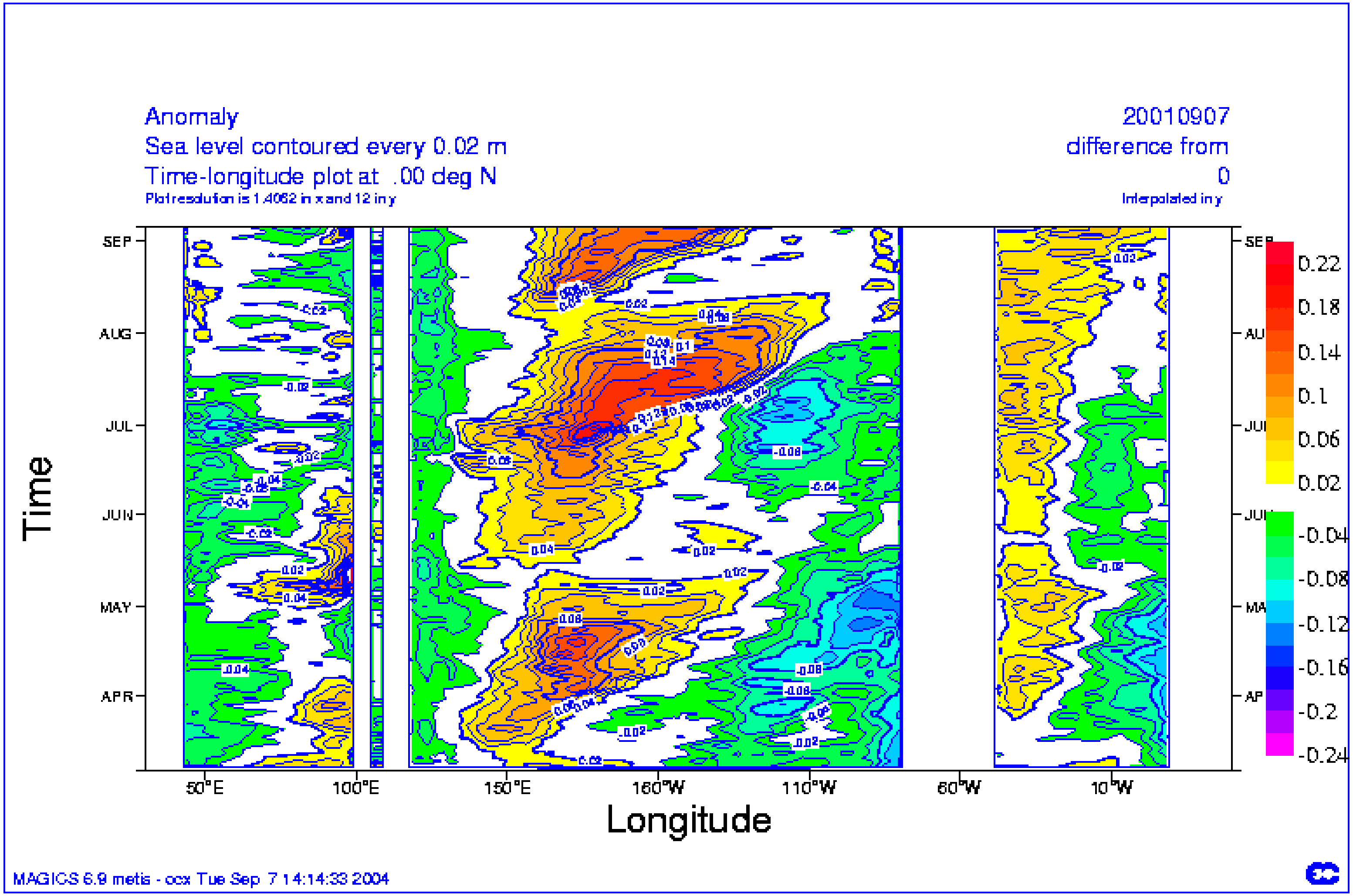
Overview of the ECMWF ocean models

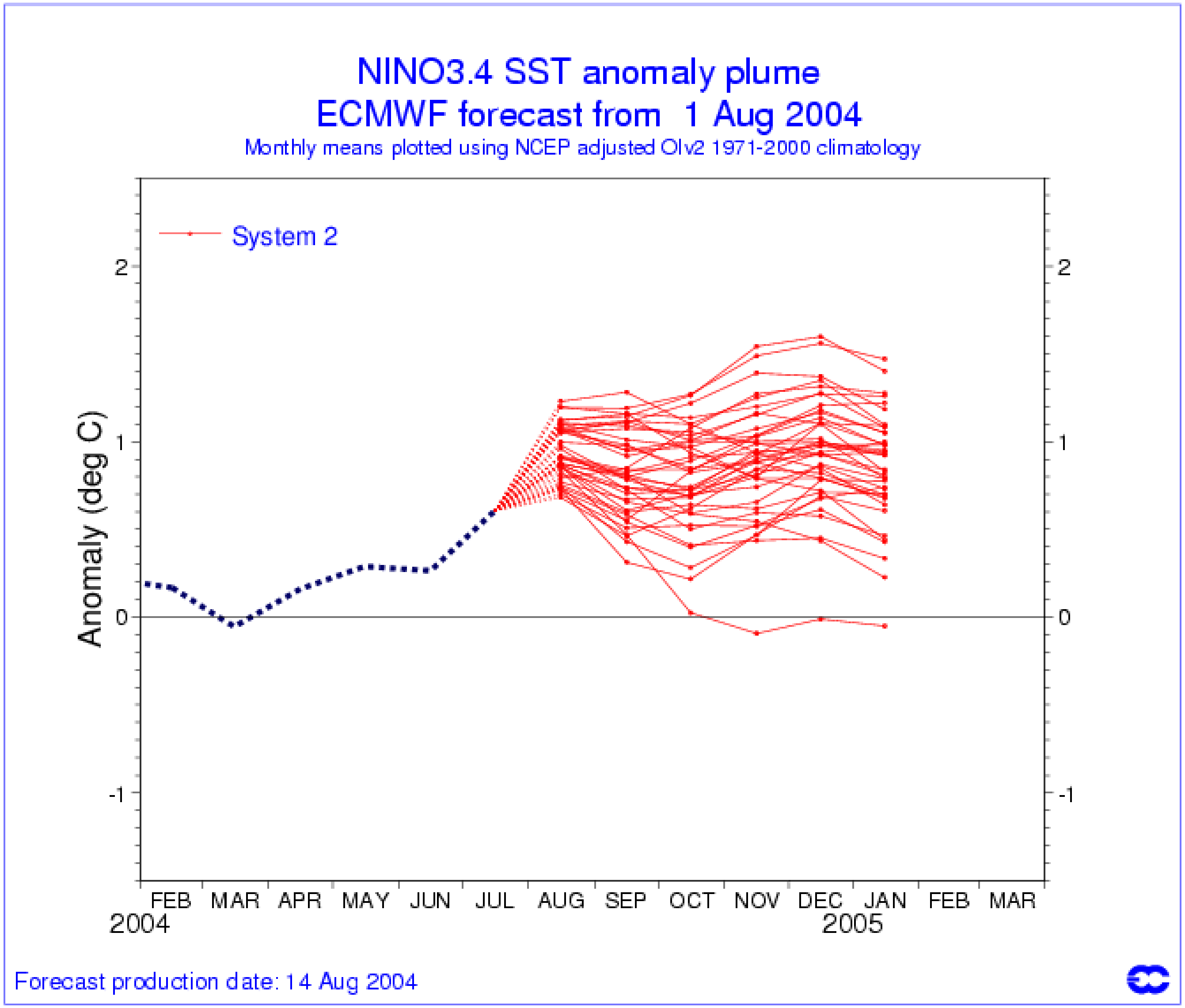
David Anderson

USES of ocean models at ECMWF

- Real-time ocean analysis is performed daily. Delayed products (11 days) are on the web.
- The analysis is global. It includes equatorial sections, sea level maps, north-south transects.
- Monthly forecasts are made weekly using a coupled ocean-atmosphere model (T159) and the real-time ocean analyses.
- Seasonal forecasts are made monthly using the same ocean model but T95 atmosphere and delayed ocean analysis.


ASSIM: E0 Anomaly (1987-2001 clim)
Potential temperature contoured every 1 deg C
Zonal section at .00 deg N
Plot resolution is 1.4062 in x and 10 in y
20040907 (1 days mean)
Interpolated in y
Depth (metres)
Longitude
50°E
100°E
150°E
160°W
110°W
60°W
10°W
0
50
100
150
200
250
300
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5
-5.5
-6.5
-7.5
-8.5
-9.5
MAGICS 6.9 metis - ocx Tue Sep 7 14:11:31 2004


Anomaly
Sea level contoured every 0.02 m
Time-longitude plot at .00 deg N
Plot resolution is 1.4062 in x and 12 in y
20010907
difference from
0
Interpolated in y
SEP
AUG
JUL
JUN
MAY
APR
Time
50°E
100°E
150°E
160°W
110°W
60°W
10°W
Longitude
0.22
0.18
0.14
0.1
0.06
0.02
-0.04
-0.08
-0.12
-0.16
-0.2
-0.24
MAGICS 6.9 metis - ocx Tue Sep 7 14:14:33 2004


NINO3.4 SST anomaly plume
ECMWF forecast from 1 Aug 2004
Monthly means plotted using NCEP adjusted OIv2 1971-2000 climatology
System 2
Anomaly (deg C)
2
1
0
-1
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
2004
2005
Forecast production date: 14 Aug 2004

- The ocean model is HOPE-E. It has been in ‘operational’ use since 1996, and even earlier. See Wolff, Maier-Reimer and Legutke , Duetsches KlimaRechenZentrum 1997. This manual gives full coverage of the model. Much of this talk comes from this source.
- We also use the OPA ocean model for data assimilation development and in EU projects ENACT, ENSEMBLES and MERSEA. OPA is described in part in OPA 8.1 Ocean General Circulation model reference manual by Madec, Delecluse, Imbard and Levy 1998.
- See www.lodyc.jussieu.fr/opa
- The version we use is OPA8.2 /OPA9 ORCA configuration.

- The ocean differs from the atmosphere in several respects:
- Lateral boundaries
- Stiff upper surface.
- Almost incompressible
- Small radius of deformation (30km)
- => Large range of space and time scales.
- For our purposes we need to make hundreds of years of coupled integrations each year so can not resolve the radius of deformation scale.
- Each run is typically 6 months long, sometimes 50 years of ocean-only runs as part of the data assimilation or extended multi-annual coupled integrations. We do not make runs of hundreds or thousands of years. We have less interest in the deep ocean.

HOPE

- Equations are:
- Momentum (u,v),
- Sea surface height,
- Temperature and salinity (T,S),
- Continuity for an incompressible fluid (w),
- Hydrostatic and Boussinesq

- It uses an E grid (rotated B grid).
- Merits of B,C grid
- B considered good for low resolution (eg Bryan and Cox model, the pioneering ocean model for decades)
- C more natural for e.g. reduced gravity equations, isopycnic models…

See Haidvodel and Beckmann Numerical Ocean Circulation Modelling Imperial College Press 1999 Update soon?

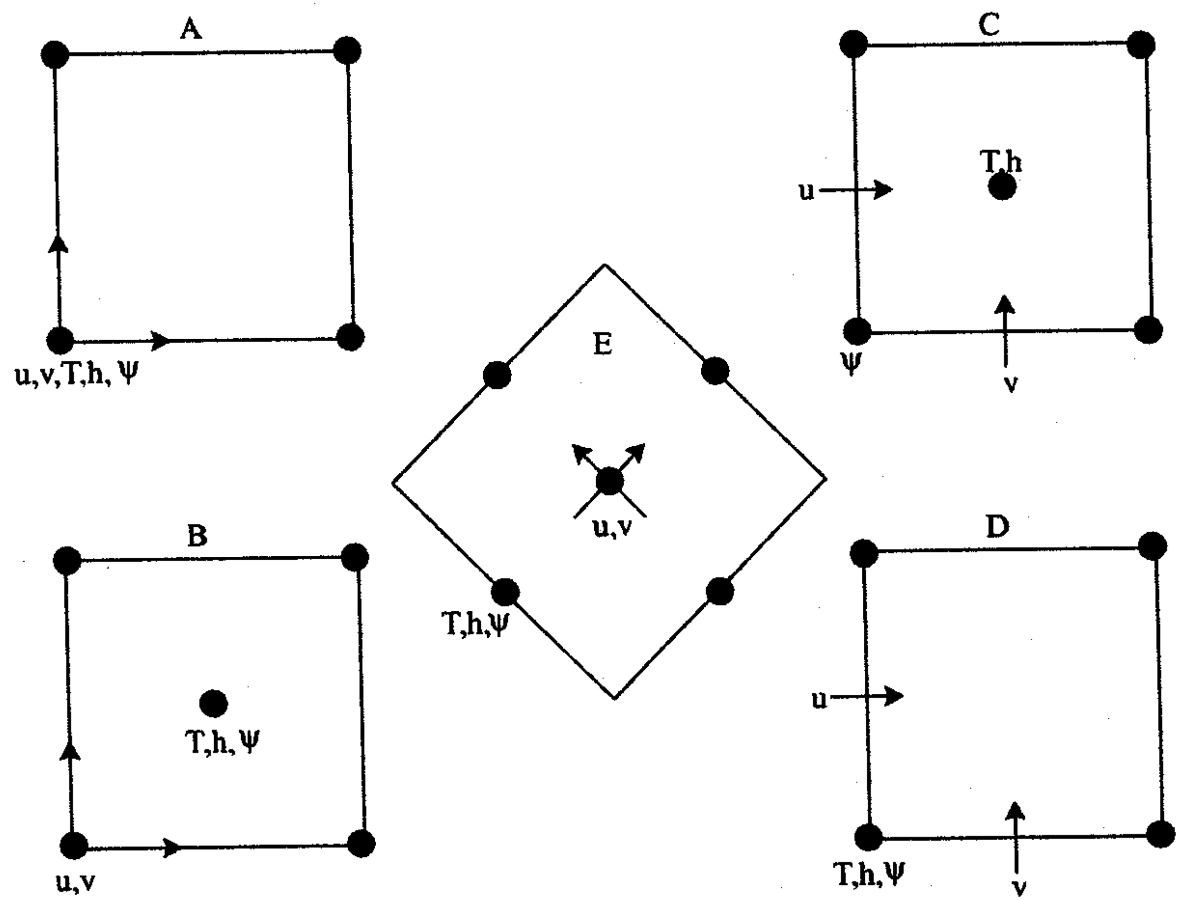
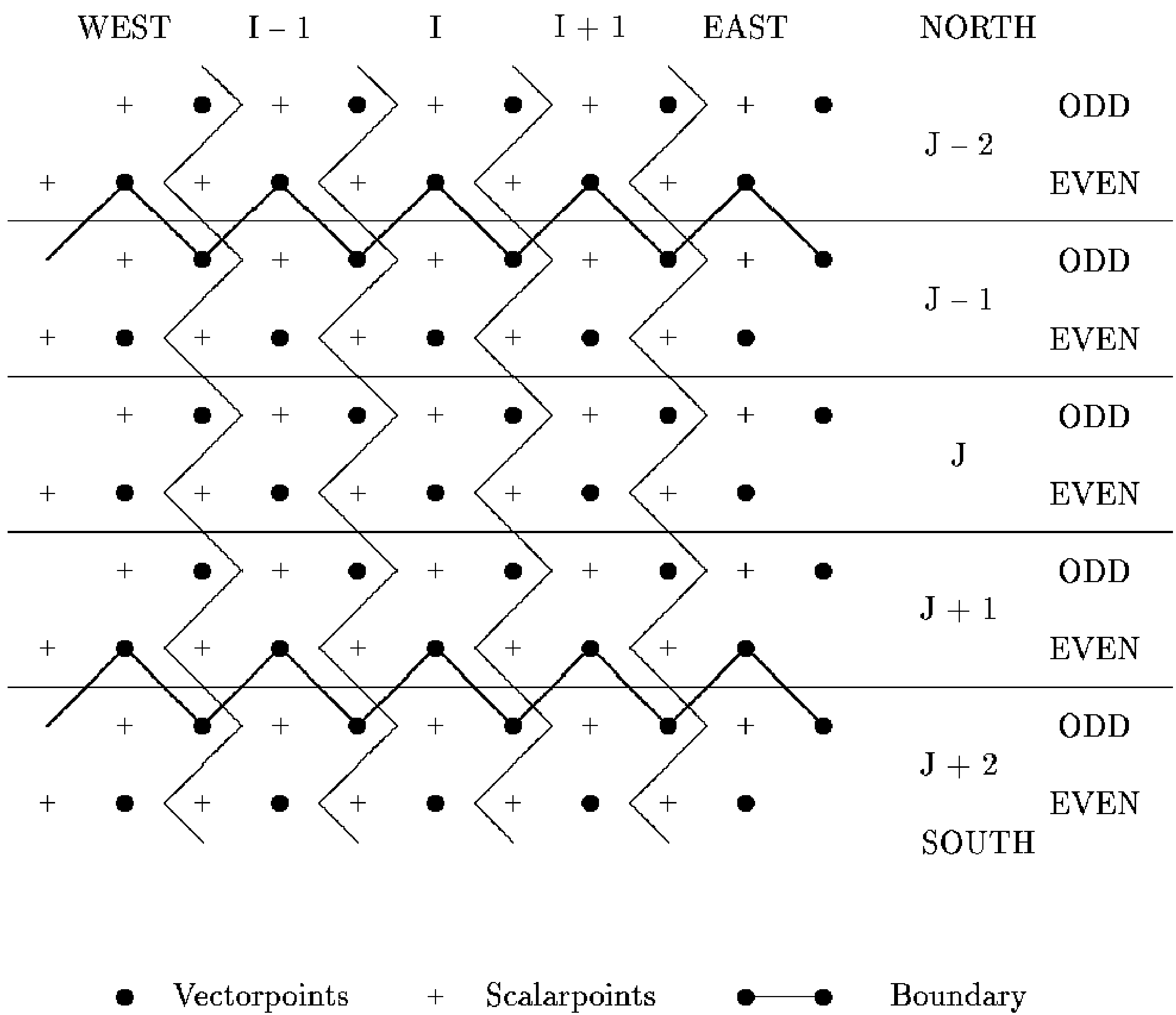
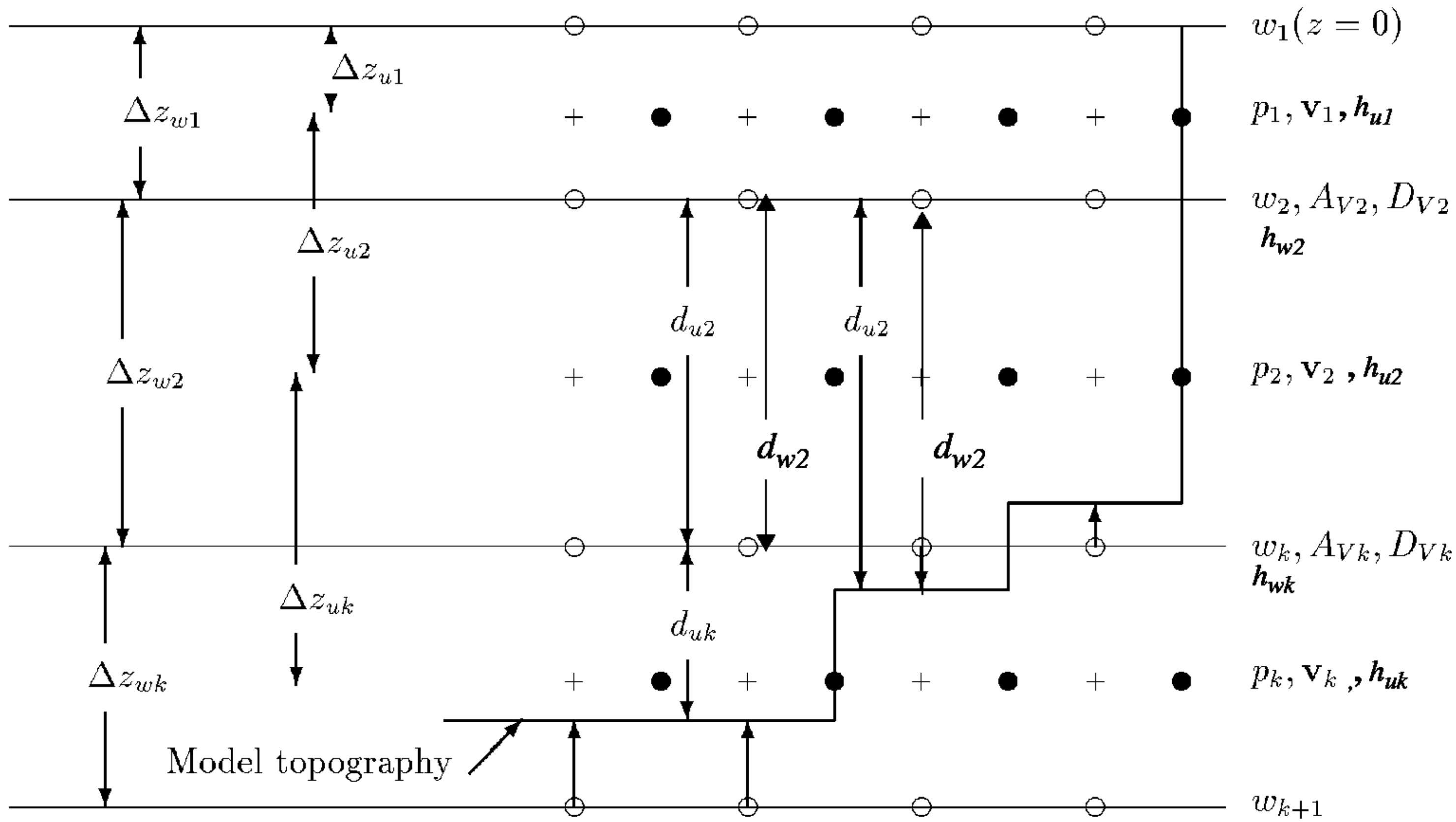


Fig. 2. Schematic of the placement of model variables on the staggered horizontal Arakawa grids used in ocean models. T refers to tracer and density, u, v refer to horizontal velocity components, h refers to layer thickness, and ψ refers to horizontal streamfunction or surface height. This figure is taken from Fig. 3.1 of Haidvogel and Beckmann (1999).


WEST
I – 1
I
I + 1
EAST
NORTH
ODD
J – 2
EVEN
ODD
J – 1
EVEN
ODD
J
EVEN
ODD
J + 1
EVEN
ODD
J + 2
EVEN
SOUTH
Vectorpoints
Scalarpoints
Boundary

- Vector points:
- u, v, forcing stress.
- Scalar points:
- T, S, η, p, ρ, w
- The grid is lat lon, with treatment for the pole.
- The equatorial region has higher resolution.
- Topography uses partial steps.



W offset horizontally and vertically relative to u,v

$$\frac{\partial u}{\partial t} = \Im u$$

$$\Im u = (\Im_1 + \Im_2 + \ldots \Im_m)u$$

$$(\Re_m(\Re_{m-1}(\Re_{m-2}(\ldots\Re_1)))\ldots)u^n \approx \left(\sum_{i=1}^{m} \Im_i\right)u^n$$

$$\frac{u^n - u^{n-1}}{\Delta t} = (\Re_m(\Re_{m-1}(\Re_{m-2}(\ldots\Re_1)))\ldots)u^n$$

- Time scales:
- Fast barotropic
- Intermediate baroclinic
- Slower tracer (T, S)
- Very slow equilibrium solutions (hundreds to thousands of years)

- Ocean models have three (at least) distinctive time-scales: barotropic, baroclinic and tracer fields. Typical timescales are : hours to days, weeks, centuries. Here we discuss the first two. Sometimes the tracer (T,S) fields have a timestep an order of magnitude larger than the baroclinic (velocity) timestep. But we don’t do that.

- Strategies
- Accelerate T,S to equilibrium with infrequent updates and long time-steps (old fashioned , problematic, not done here).
- Slow-down barotropic. (See later)
- (Barotropic probably isn't that important though my attempts to remove it completely did make ~1K difference at equator as I recall. If you keep the barotropic then it is costly.)

- For a flat bottomed ocean with uniform stratification and for linear dynamics, it is possible to represent the solution as an infinite number of vertical modes.
- These are usually called:
- The barotropic mode in which u, v are almost independent of depth.
- An infinity of baroclinic modes of which the first few are the most important (usually).
- Even when the stratification is not uniform, the ocean bottom is not flat and the flow not linear, the concept is still useful.

- The speed of the barotropic mode is typically (gH)^1/2 where H is the depth of the ocean. If H is ~5000m and g~10 ms-2, the speed of the waves is typically 225 m/s.
- The speed of the fastest baroclinic wave (the 1st) is typically <3m/s. So, there is nearly two orders of magnitude difference between these. Further for climate purposes the barotropic mode is not so important. Almost all models handle the barotropic mode separately to the baroclinic.

- In HOPE, this is done by calculating the depth-integrated flow and saying that is the barotropic mode and then solving for that directly. A number of assumptions have gone into this.
- For the moment we concentrate on the solution of the barotropic mode. At high resolution, direct solvers are too costly in terms of memory needed. Likewise, iterative solutions are not efficient, especially for massively parallel machines.

- Split the velocity into a depth-averaged part (‘barotropic’) and a depth-dependent part (‘baroclinic’). (These are no longer non-interactive as in the linear mode case but the split basically works).
- u=U+u’

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \zeta}{\partial x} + \int_{-H}^{0} \frac{\partial}{\partial x} p' dz = G_U ,$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \zeta}{\partial y} + \int_{-H}^{0} \frac{\partial}{\partial y} p' dz = G_V ,$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = Q_\zeta .$$

- The standard approach in HOPE was to make these implicit and derive an (elliptic) equation for ζ, which was then solved by Gauss elimination and back substitution.

- This is efficient but needs a lot of memory. It works fine for the low resolution model (2deg X 2 deg 'B' grid) but not for the higher resolution model (1X1 'B' with 1/3 X 1 near the equator).

$$u_t - fv = -g\eta_x$$

$$v_t + fu = -g\eta_y$$

$$\eta_t + H\left(u_x + v_y\right) = 0$$

- Consider the free surface equations

$$u_{tt} + f^2 u = -fg\eta_y - g\eta_{xt}$$

$$v_{tt} + f^2 v = +fg\eta_x - g\eta_{yt}$$

$$u = -\frac{g}{f}\eta_y - \frac{g\eta_{xt}}{f^2}$$

$$v = +\frac{g}{f}\eta_x - \frac{g\eta_{yt}}{f^2}$$

$$\eta_t - \frac{gH}{f^2}\left(\eta_{xxt} + \eta_{yyt} + \beta\eta_x\right) = 0$$

$$\left(\frac{f^2}{gH}\eta_t - \eta_{xxt} - \eta_{yyt}\right) = -\beta\eta_x$$

$$\eta_t - \frac{gH}{f^2}\left[\eta_{xxt} + \eta_{yyt} + \beta\eta_x\right] = 0$$

$$\omega/k = \frac{-\beta}{(k^2 + l^2 + f^2/c^2}$$

$$f \sim 10^{-4} s^{-1}$$

$$c \sim 220 m/s$$

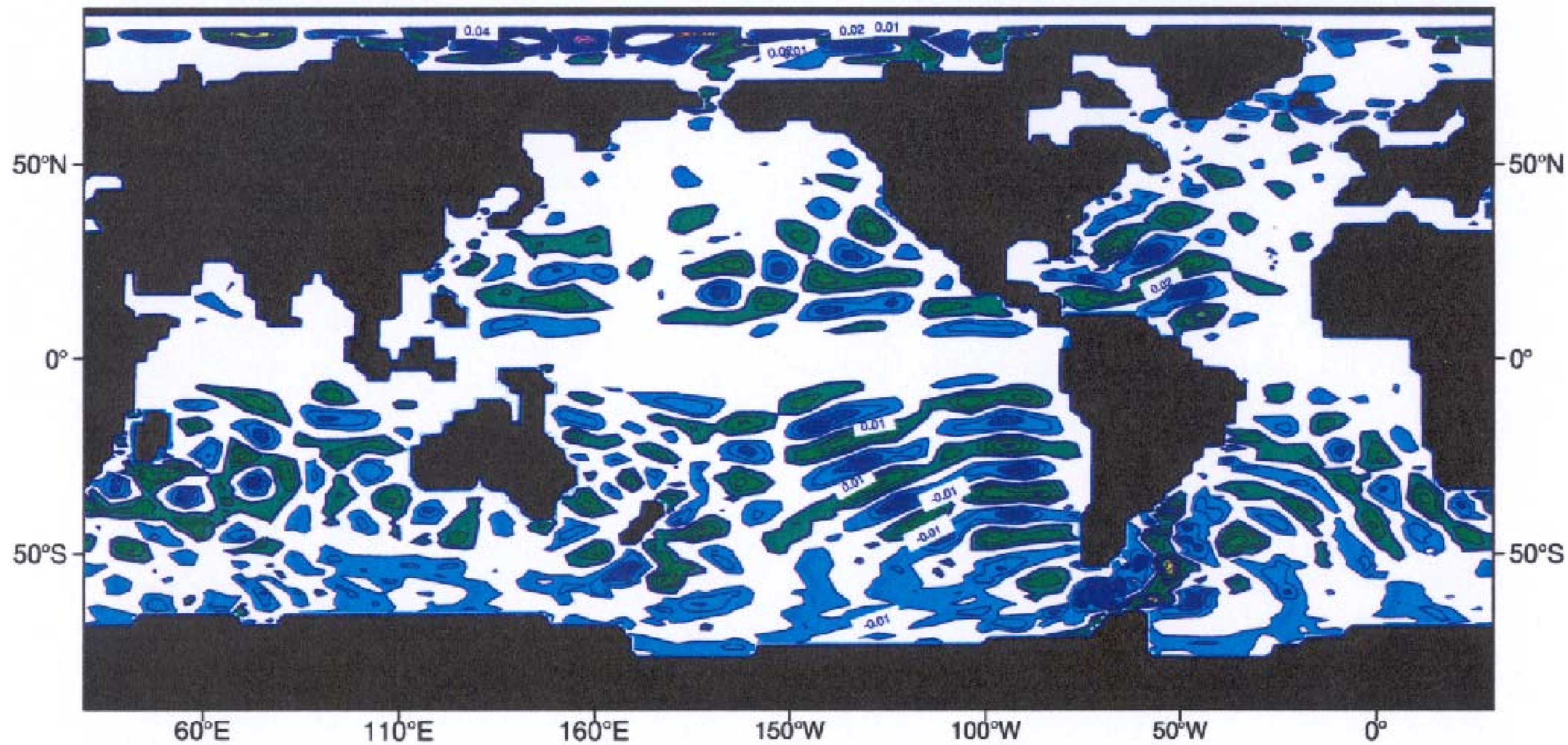
$$f^2/c^2 \sim 0.25x10^{-12}$$

Rigid lid approximation drops the divergence term (the f/c term). This is not acceptable for l,k,<10-6. i.e. wavelengths longer than 60 degrees.

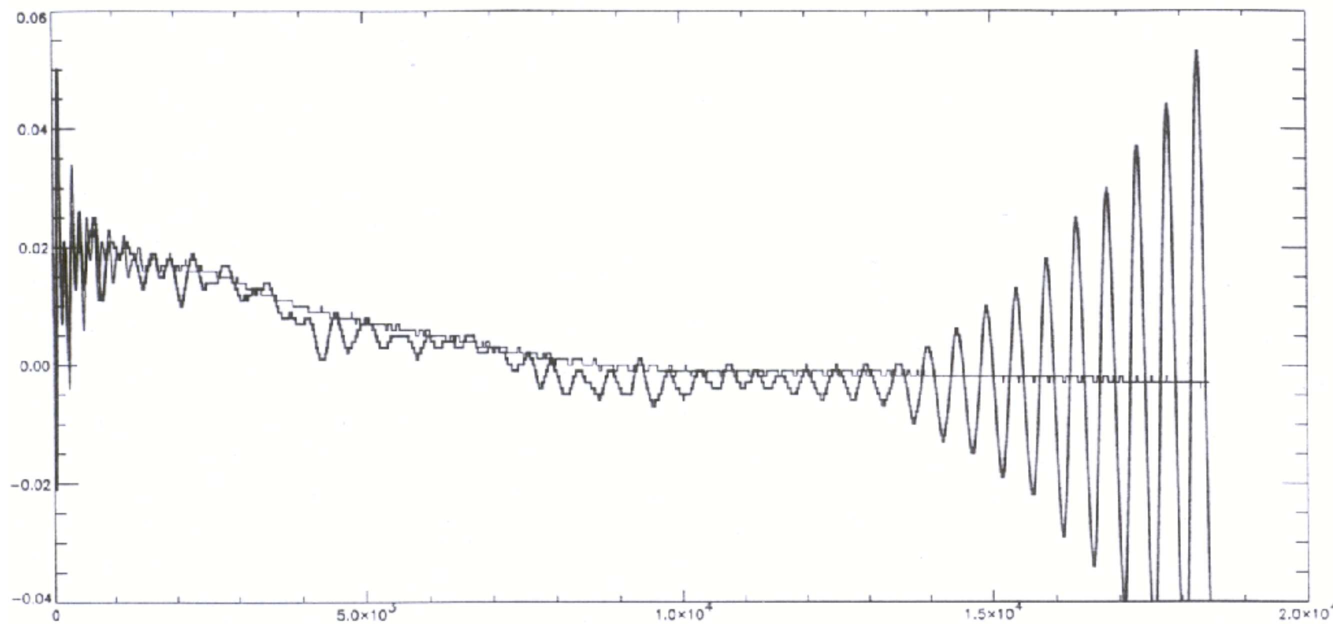
Magdalena Balmaseda

- One strategy is to multi-step the barotropic mode: i.e. use lots of little steps for the barotropic and then a big step for the baroclinic.
- The grid is 1deg X 1deg (rotated) (1.41 unrotated), except near the equator where it is 1/3 degree in the meridional direction to allow better resolution of the equatorial Kelvin wave (later).

- Multi-step barotropic largely follows Killworth et al 1991 JPO 1991 but has some new features. (Balmaseda)
- Time average barotropic solution over two baroclinic time steps.
- Apply + and X operators which conserve mass (only done every 4th timestep).
- Timestepping uses Euler Backward (predictor-corrector).
- Δt= 15 secs barotropic, 3600 secs baroclinic in the Ocean analysis
- Δt= 36 secs barotropic, 3600 secs baroclinic in the Ocean forecasts, (g=g/4) Tim Stockdale.



Balmaseda



Eta v time. Note the splitting. This can be removed by averaging the barotropic over two baroclinic timesteps. See Griffies et al MWR 2001, and Ocean Modelling 2, 2000. The barotropic and baroclinic are not totally separated by vertical averaging.

Time flow

- 1 vertical advection and viscosity (upstream, implicit, tridiag)
- Horizontal viscosity (shear dependent)
- 2 Biharmonic to avoid grid splitting
- 3Horizontal momentum advection (half split)
- 4 Baroclinic, implicit, iterative

  (Linear density eqn,

  a*new+(1-a)*old, a for u,v,and b for pressure

  a=0.5,b=0.5 is neutral but gives a computational mode. Use a=1, b=0.5)

5 Barotropic

6 T,S predictor corrector.

ORCA/OPA8.2, 9.0

- Written in generalised orthogonal curvilinear coordinates.

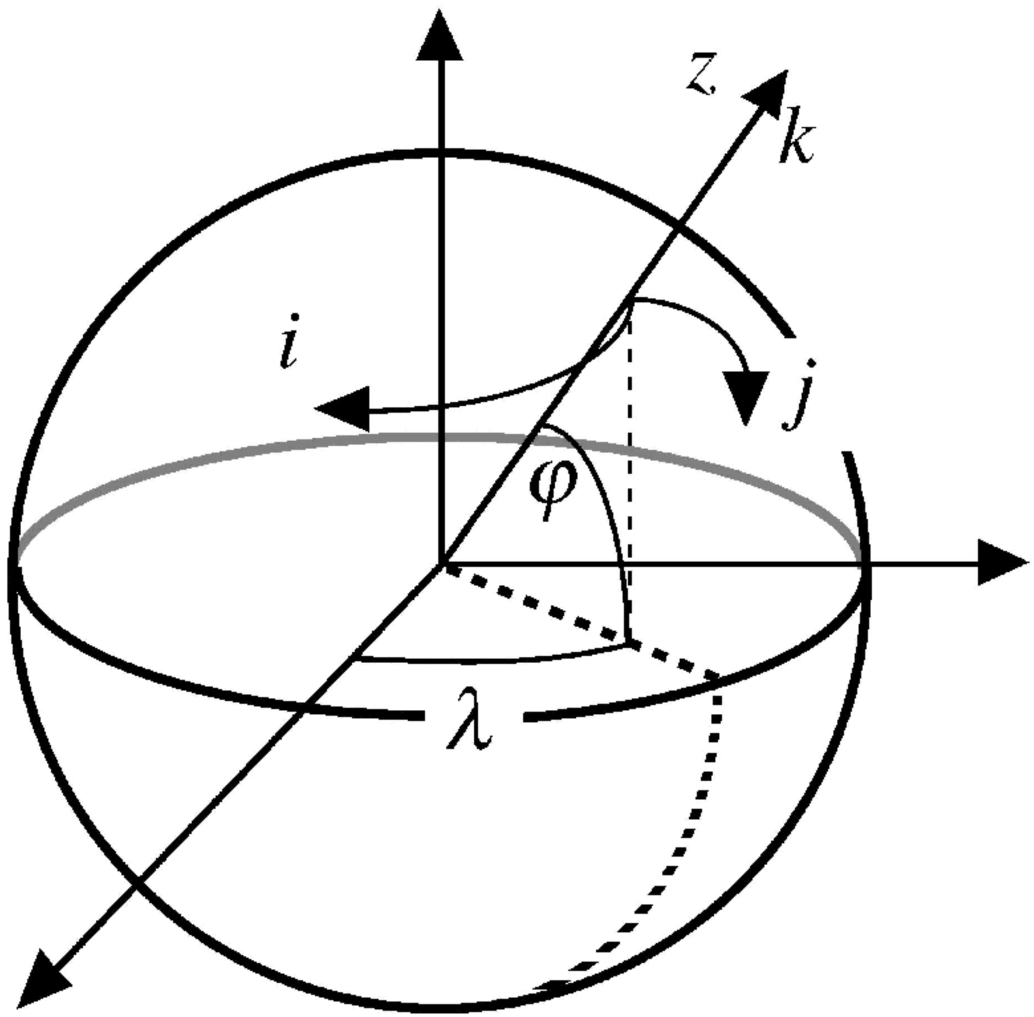


Figure I.2: the geographical coordinate system (λ, φ, z) and the curvilinear coordinate system (i, j, k).

$$\frac{\partial \mathbf{U}_h}{\partial t} = -\left[(\nabla \times \mathbf{U}) \times \mathbf{U} + \frac{1}{2} \nabla \left(\mathbf{U}^2 \right) \right]_h - f\, \mathbf{k} \times \mathbf{U}_h - \frac{1}{\rho_o} \nabla_h p + \mathbf{D}^{\mathbf{U}} \tag{I.1.1}$$

$$\frac{\partial p}{\partial z} = -\rho\, g \tag{I.1.2}$$

$$\nabla \cdot \mathbf{U} = 0 \tag{I.1.3}$$

$$\frac{\partial T}{\partial t} = -\nabla . \left(T\, \mathbf{U} \right) + D^T \tag{I.1.4}$$

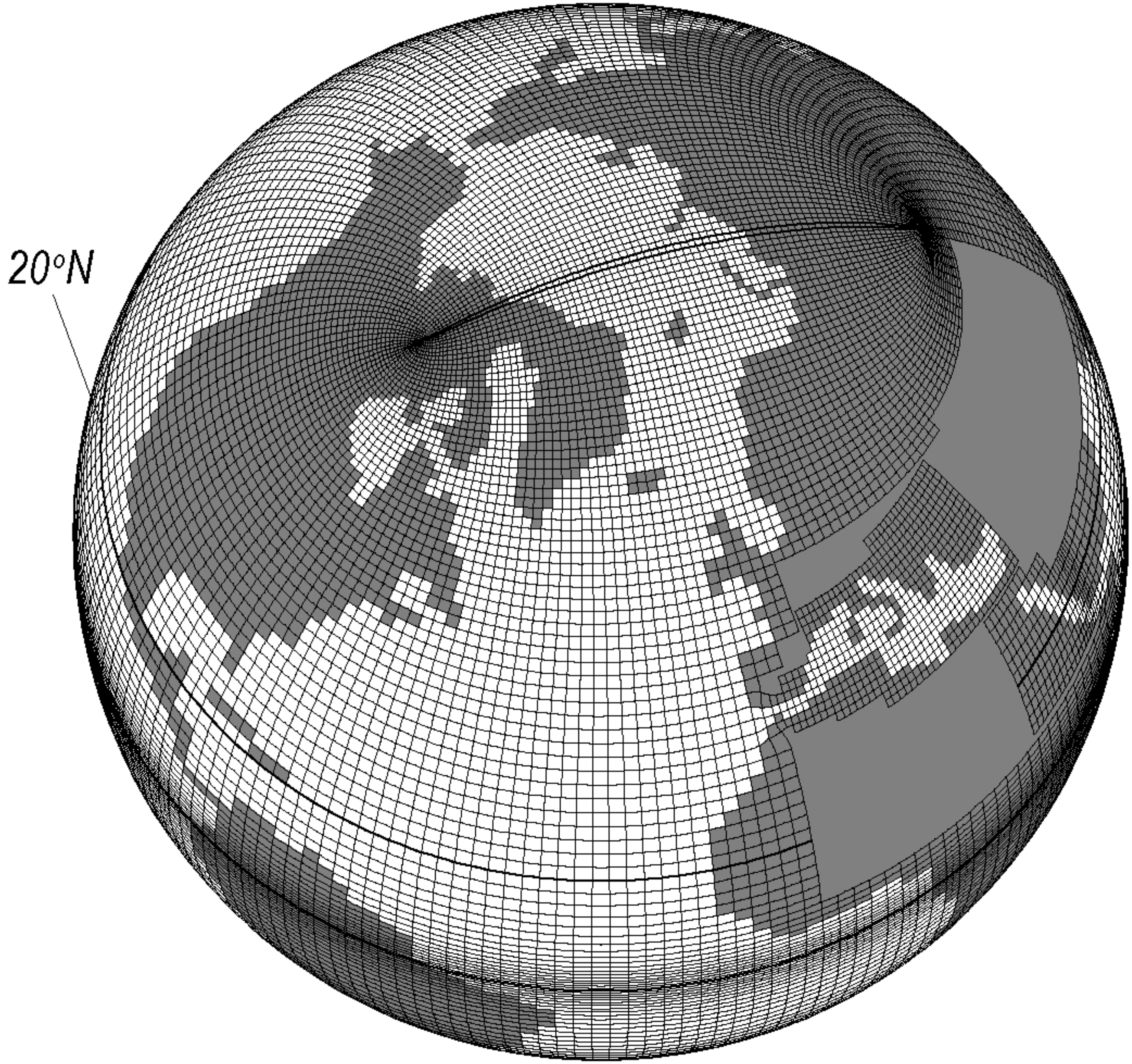
$$\frac{\partial S}{\partial t} = -\nabla . \left(S\, \mathbf{U} \right) + D^S \tag{I.1.5}$$

$$\rho = \rho(T, S, p) \tag{I.1.6}$$

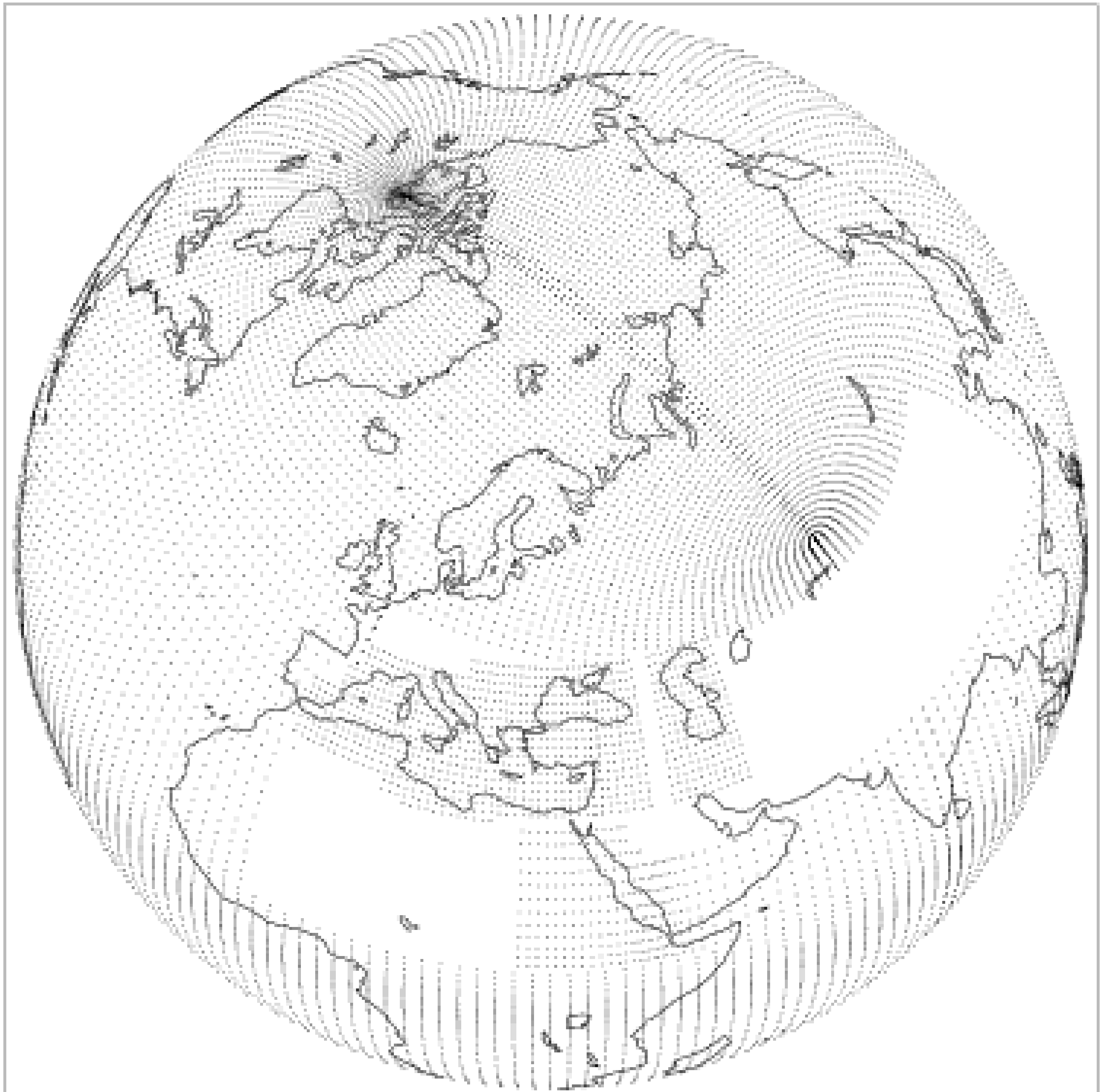
* momentum equation:

$$\frac{\partial u}{\partial t} = +\left(\zeta + f\right)v - \frac{1}{e_3} w \frac{\partial u}{\partial k} - \frac{1}{e_1}\frac{\partial}{\partial i}\left(\frac{1}{2}\left(u^2 + v^2\right) + \frac{p_h}{\rho_o}\right) - \frac{1}{\rho_o e_1}\frac{\partial p_s}{\partial i} + D_u^{\mathbf{U}} \qquad (1.3.10)$$

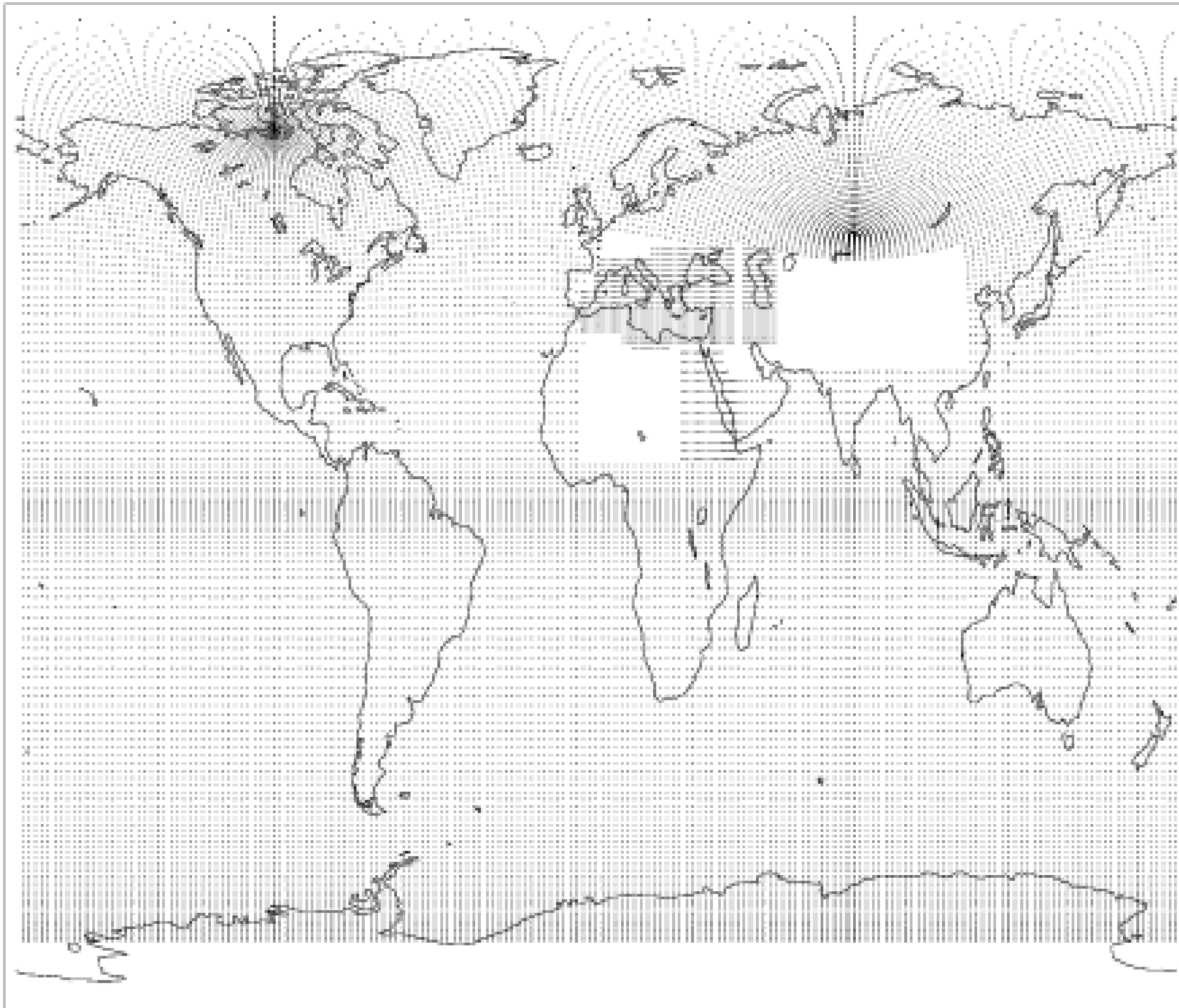
$$\frac{\partial v}{\partial t} = -\left(\zeta + f\right)u - \frac{1}{e_3} w \frac{\partial v}{\partial k} - \frac{1}{e_2}\frac{\partial}{\partial j}\left(\frac{1}{2}\left(u^2 + v^2\right) + \frac{p_h}{\rho_o}\right) - \frac{1}{\rho_o e_2}\frac{\partial p_s}{\partial j} + D_v^{\mathbf{U}} \qquad (1.3.11)$$


20°N

ORCA GRID



ORCA GRID



- ORCA 2 has a ‘2 degree’ grid, refined near the equator to 0.5 degrees.

- Time step = 96 mins.
- The barotropic free surface is filtered of external gravity waves.
- A leap-frog scheme is used in time.
- There is an Asselin filter to remove the parasitic mode.

- Basic references:
- Ross Murray 1996, Explicit generation of orthogonal grids for ocean models. J Comp Phys 126, 251..

- G Madec M Imbard 1996. A global ocean mesh to overcome the north pole singularity. Climate Dynamics 12, 381..
- Embedded circles in polar stereographic plane.
- Embedded ellipses (Did not follow Murray as Murray not quasi –isotropic and is discontinuity in derivative grid spacing across stretched/lat-lon grid).

- The free surface is handled implicitly with the same time step as the baroclinic. A term B grad (d(eta)/dt) is added to the barotropic momentum eqn. This has a damping effect for waves faster than B. Chose B=2dt.

- Roullet and Madec JGR 105, 23,927.. (2000)

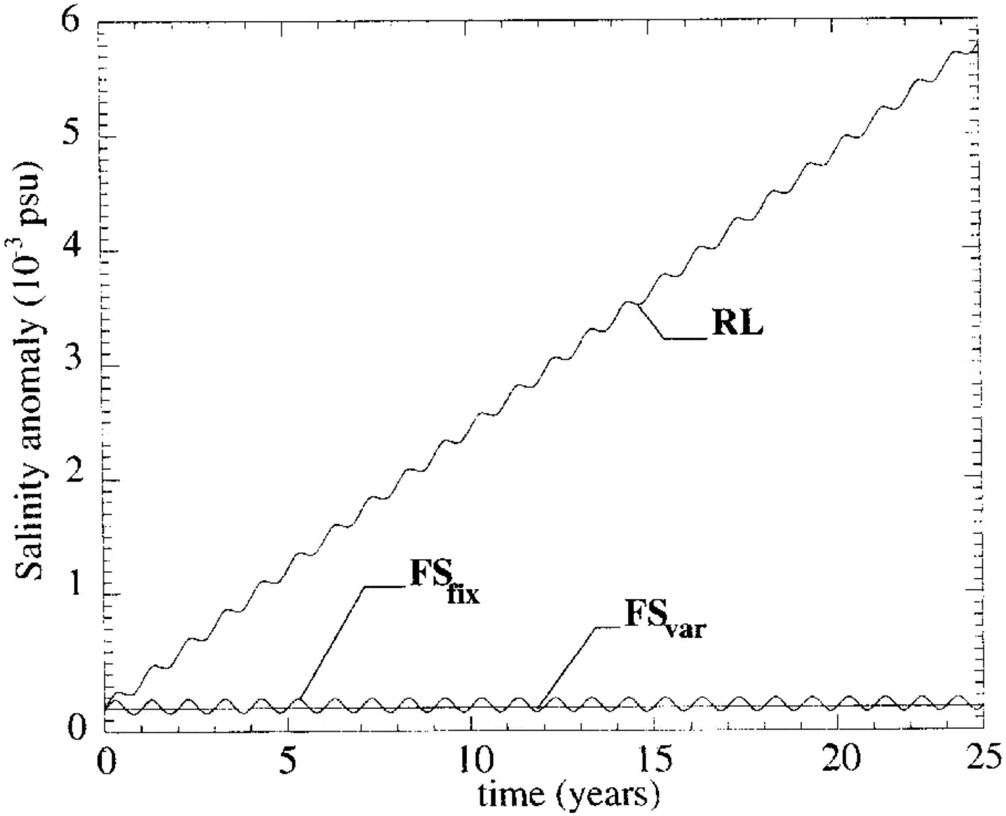


Figure 5. Time evolution of the global mean salinity for the rigid lid (RL), free surface volume (FS_{fix}) and variable volume (FS_{var}) simulations. RL is drifting because of the correl evaporation (precipitation) regions and high (low) sea surface salinity. FS_{fix} is oscillating while FS_{var} strictly conserves the salt content.

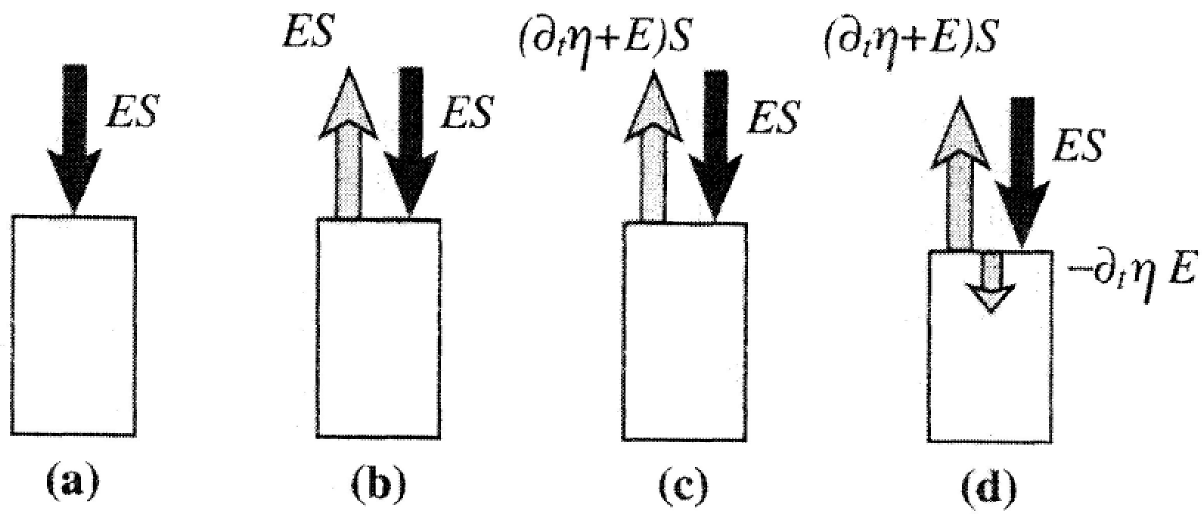


Figure 1. Schematic balance at the air-sea interface for the different fresh water flux formulations: (a) rigid lid and virtual salt flux; (b) natural; (c) linear free surface; and (d) nonlinear free surface with varying level thickness. For Figure 1c a residual advective salt flux through the air-sea interface still remains ($\partial_t \eta S$) so that salt content is not conserved.

- 31 levels, (10m near surface)
- Richardson number mixing
- Large and McWilliams
- TKE (Bougeault and Lacarrere MWR, 1989, Gaspar JGR 1990, Blanke and Delecluse1993)