Overview of the ocean models at ECMWF

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1. Introduction

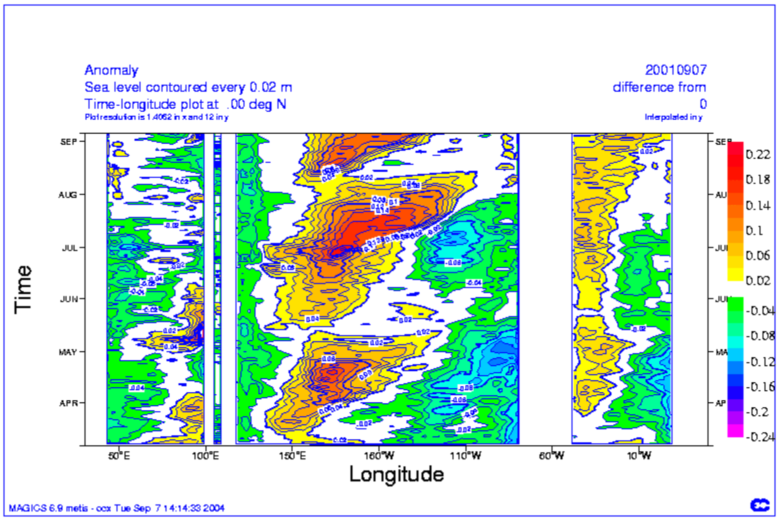
ECMWF uses two ocean models. Although it has no ocean model development programme of its own, considerable effort goes into configuring and adapting the ocean models for specific applications. The ocean models in use are those developed within Europe. They are the HOPE model developed by MPI, Hamburg and the OPA model developed by CNRM/LODYC/CERFACS. These models have been described in large part by others. Before recapping, it is useful to define the purposes for which we use ocean models.

The ocean model is used to provide a daily analysis of the world's oceans, using all available in situ ocean thermal data. These analyses are global and some of the products are available on the web. The analyses are used as initial conditions for forecasts made with the coupled atmosphere ocean model. Two different forecast products are made operationally: monthly forecasts are made every week and forecasts out to 6 months are made every month. In both cases ensembles of forecasts are made, 51 members in the case of monthly forecasts and 40 in the case of seasonal forecasts.

As explained in Stockdale et al 1998, it is necessary not just to perform the forecasts but to create an ensemble of past events too. The coupled model drifts and does not represent the full spectrum of variability. Anomalies are calculated with respect to the model climatology rather than with respect to nature. This means that an extensive set of calculations is needed to create the model climatology and to validate the model as well as an extensive ensemble of forecasts. Some 1000 years of coupled model integrations are needed to calibrate the model and 240 years are used each year in making the real-time forecasts. This is far more than is often used for climate change scenarios though in the case of climate simulations the need for ensembles of runs is now recognised. These numbers show that seasonal forecasting needs so many years of coupled integration that only modest resolution for the ocean (and atmosphere) can be used.

The current ocean resolution of HOPE is 1/3rd of a degree in the meridional direction near the equator, and 1 degree in the extratropics. The zonal resolution is 1 degree throughout. Examples of the ocean analysis and of the seasonal forecasts are given in fig 1. These are of interest because of the possibility of El Nino conditions strengthening in the following months. The sea level analysis clearly shows the presence of ocean Kelvin waves propagating eastwards, triggered by MJO/westerly wind events in the west Pacific. These have led to a progressive warming in the east. For more details of the various analysis products and forecasts see the seasonal and monthly web pages at www.ecmwf.int.

The ocean model which is used operationally is HOPE-E. It has been in 'operational or quasi-operational' use since 1996 and used in research for some time before that. The model is described in Wolff, et al 1997 from which much of the following material is taken. We also use the OPA ocean model: there is an active programme in ocean data assimilation in collaboration with CERFACS. In addition there is a collaboration with NERSC on the Ensemble Kalman filter, which has OPA as its ocean model kernel. The OPA model, version 8.1, is described in Madec et al 1998. We currently use OPA8.2 but the dynamical core is largely the same as OPA8.1 though some differences will be noted later.



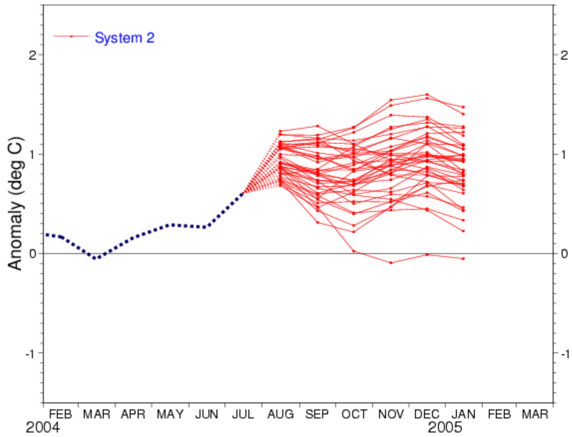


Figure 1 Upper *panel shows a Hovmoller plot of Sea level along the equator as a function of time. The Indian ocean is on the left, the Pacific in the middle and the Atlantic on the right. Red colours indicate the ocean surface is a few cm higher than normal, blue that it is lower than usual. Higher levels indicate warmer temperatures, usually at a depth of ~100m. The analyses are particularly interesting at this time because of the considerable MJO activity and the possibility of a substantial El Nino developing. An ocean analysis is available every day though the web is updated only once per week.*

Lower panel shows some forecasts for the Nino 3.4 region. There are 40 lines, one for each ensemble member. These forecasts are made routinely by the operational coupled ocean atmosphere model. The ocean initial conditions come from the ocean analysis system.

2. Ocean models

The ocean differs from the atmosphere in several respects. It has lateral boundaries, is almost incompressible, has a ‘stiff’ upper surface and a small radius of deformation, which can be as small as 10km in polar regions. This means that the range of scales which one would like to resolve is large- all the way from global down to a few kilometres. As mentioned earlier, the number and length of the integrations needed mean that practically the scales that can be resolved are considerably larger than those needed to resolve the radius of deformation. For monthly or seasonal forecasts only the upper ocean is important and primarily the equatorial regions. For this reason there has been less interest in the deep ocean and less effort has been devoted to the high latitudes.

The equations used in HOPE are two momentum equations, an equation for T and one for S where T is potential temperature and S is salinity, the continuity equation for an incompressible fluid, and an equation for the surface height. The hydrostatic and Boussinesq approximations have been made. The grid is an E grid. A more recent version of HOPE uses a C grid. See Haidvogel and Beckmann 1999, and Griffies 2004 for further discussion of grids, including a more extensive discussion of the relative merits of various ocean formulations. The E-grid was originally used for a very course resolution model, and then adopted for the HOPE model. The C-grid is in more common use as model resolutions have improved. Fig 2 shows the layout adopted in the HOPE-E model. The grid is lat-long with treatment for the north pole; near the north pole, a mini island is introduced. The south pole causes no difficulty because of the Antarctic land mass.

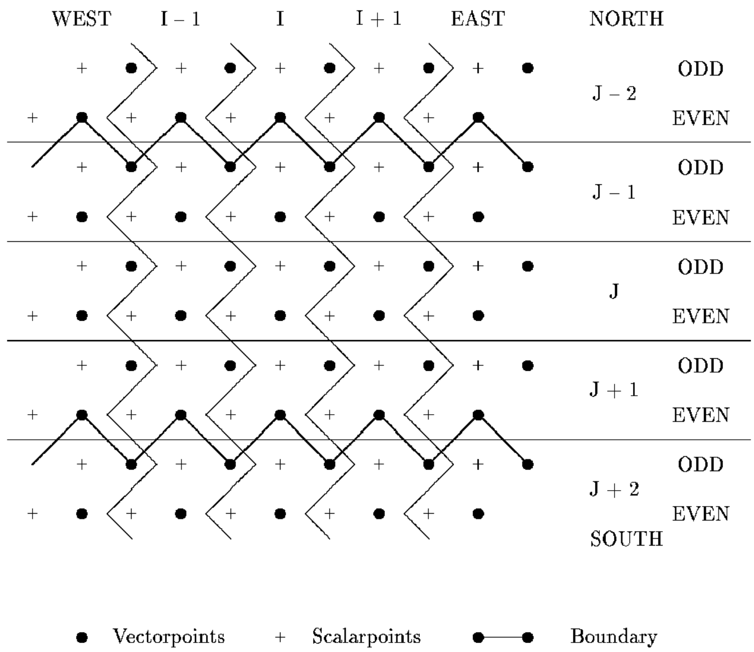


Figure 2. The layout of the E-grid in the HOPE ocean model. 'Vector' points indicate where the u and v components of the horizontal velocity are located. 'Scalar' points indicate the location of temperature and salinity. From Wolff et al., 1997.

The vertical distribution of points is shown in fig 3. The vertical velocity is located in between velocity points. A feature that was innovative at the time of the development of HOPE is the method of partial steps for orography: the topography does not need to fill the full depth of the bottom layer. Several ocean models now have this capability.

T, S, ζ, p, ρ are all evaluated at the same point, with ω evaluated at the same latitude, longitude but offset in the vertical. ζ represents displacements of the top surface and ω represents vertical velocity.

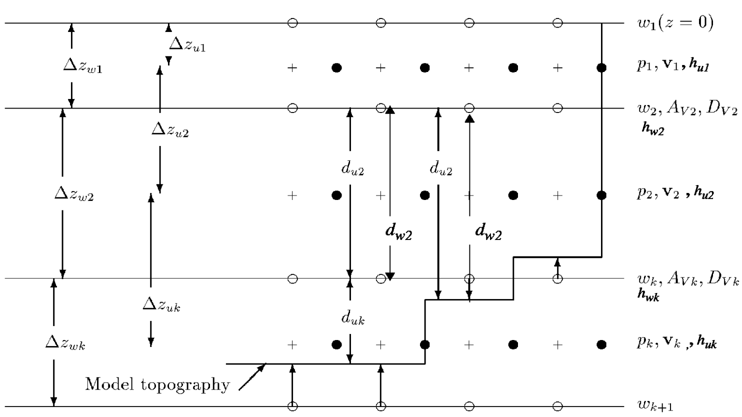


Figure 3 Plot showing the layout of the vertical grid. Note that the bottom layer topography does not need to fill the layer. From Wolff et al., 1997.

The time integration uses the method of fractional steps as described in Press et al. 1989. The ocean differs from the atmosphere in that there are markedly different time scales possible: there are the slower and more important baroclinic processes and the fast barotropic processes. Tracers, such as T and S change on a slower advective timescale. The speed of barotropic gravity waves is ~200m/s. Although the barotropic Rossby waves also travel much faster than their baroclinic counterparts they are much slower than the gravity waves. The restriction of having to deal with external gravity waves is such that they were usually filtered or slowed down.

3. The barotropic mode

In the case of a flat-bottomed ocean with uniform stratification and linear dynamics, it is possible to represent the solution in terms of normal modes. The lowest order mode is called the barotropic and then baroclinic modes follow with increasing vertical structure and slower wave speeds (Gill 1982). Typical speeds for the barotropic mode are √(gH) where g is gravity and H is the depth of the ocean. This gives values over 200m/s in mid ocean where the depth is ~5000m. For the first baroclinic mode the speed is ~3m/s: there is a huge separation in propagation speeds between the barotropic and baroclinic wave speeds. If nothing is done about it, the timestep of the model will be set by the CFL limit on the barotropic external gravity wave mode, even though this mode is not very important for climate purposes.

An early approximation (Bryan 1969) is the so-called rigid lid approximation. This increases the effective speed of external gravity waves to infinity and effectively removes them from the CFL limit. Unfortunately this approximation damages the propagation of external Rossby waves, which although not of the greatest importance in climate studies are signals that can be seen clearly by instruments such as the altimeter and are related to transport in currents such as the Gulf Stream. One does not want to damage these waves too much. The following analysis shows the properties of some waves and the effect of the rigid lid approximation. We start with the linear free surface equations for fluid in an ocean of uniform depth H.

$$
\begin{aligned}
u_t - fv &= -g\varsigma_x \\
v_t + fu &= -g\varsigma_y \\
\varsigma_t + H(u_x + v_y) &= 0
\end{aligned}
$$

By differentiating the first two equations by t and substituting for the time derivative of v and u one obtains:

$$
\begin{aligned}
u_{tt} + f^2 u &= -fg\varsigma_y - g\varsigma_{xt} \\
v_{tt} + f^2 v &= +fg\varsigma_x - g\varsigma_{yt}
\end{aligned}
$$

Applying an inertial filter (dropping second derivatives in t) eliminates inertial gravity waves yielding:

$$
\begin{aligned}
u &= -\tfrac{g}{f}\varsigma_y - \tfrac{g}{f^2}\varsigma_{xt} \\
v &= +\tfrac{g}{f}\varsigma_x - \tfrac{g}{f^2}\varsigma_{yt}
\end{aligned}
$$

Substituting for u and v in the ς equation, and dropping second order terms, gives

$$
\frac{f^2}{gH}\varsigma_t - \varsigma_{xxt} - \varsigma_{yyt} = -\beta\varsigma_x
$$

For a plane wave with frequency ω and wave number k in the x direction and l in the y direction, this equation gives rise to the following dispersion relation, where c=√gH.

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

In the deep ocean H is ~4000m so the last term in the denominator has magnitude ~.25x10^{-12}. This term arises from the movement of the top surface. If we make the rigid-lid approximation, then we drop this term. If k or l are ~10^{-6} or larger (wavelengths smaller than 60 degrees), then dropping this term isn't so important, but for smaller k or l i.e. large-scale Rossby (planetary) waves, the dispersion relationship is seriously distorted. Waves may even travel in totally the wrong direction. The rigid lid approximation was common 10 to 20 years ago but is less frequently made now.

If the rigid lid approximation is made, then, for the barotropic mode, the horizontal velocities are independent of depth. (This is not quite true in the free surface formulation since the top surface can move up or down slightly). Even when the stratification is not uniform, the ocean bottom is not flat and the flow not linear, as in a realistic simulation of the ocean, the concept of a barotropic and baroclinic split is still useful. The depth integrated flow is taken to represent the barotropic flow and the depth dependent part is called the baroclinic flow. There is no need to further split the baroclinic part into baroclinic modes. i.e. u=U+u' where U is the barotropic velocity and u' is the baroclinic. Equations for U,V and u',v' can then be derived. The barotropic and baroclinic modes are not separable in the presence of topography, nonlinearity and non uniform stratification and so there will be cross terms.

In HOPE, the barotropic mode was originally solved by making the equation set (fig 4) implicit, deriving an (elliptic) equation for ζ and solving for that by Gaussian elimination and back substitution. This approach works well for our low resolution version of the ocean model (0.5X2 in the equatorial region and 2X2 at higher latitudes) but needs too much memory at higher resolution. Although an iterative solver is possible we chose to go for an explicit representation of the barotropic mode. Therefore we developed a multi-step approach whereby the barotropic mode was stepped forward with a Δt of 15 secs while the timestep for the rest of the model was 3600 secs. The multi-stepping strategy follows closely that of Killworth et al 1991. A number of features are needed: + and X operators are as found by Killworth et al. 1991, and the barotropic solution has to be integrated over two baroclinic timesteps and then averaged. The barotropic mode is integrated using an Euler-backward time differencing scheme. Since baroclinic processes are slow compared to the barotropic they can be taken as constant over a timestep in the barotropic equation. Fig 5 shows the oscillations that can develop if averaging over two baroclinic timesteps is not applied. See also Griffies et al 2001. During forecasts made with the coupled model, the barotropic mode is speeded up using a value of gravity one quarter of its normal value. This allows the timestep for the barotropic mode to be increased to 36 secs. (Stockdale, private communication). No such acceleration is used in the ocean analysis phase, however as a close match to data such as observed sea-level is required there.

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

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

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

Figure 4Shows the equations for the barotropic mode in the notation of HOPE. The p', G and Q terms are terms that involve 'baroclinic' processes.

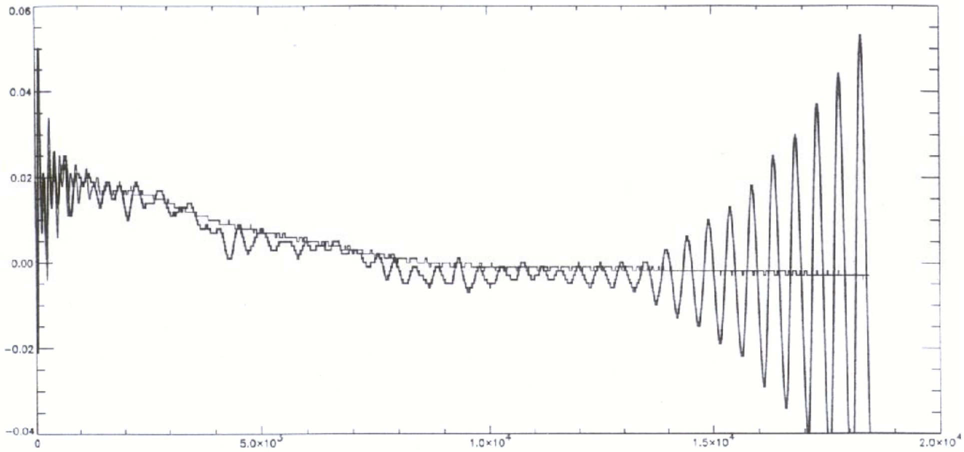


Figure 5 Plot of sea level against time showing the oscillations that arise if improper account is taken of baroclinic - barotropic interaction. The oscillation period is two baroclinic timesteps. The smooth curve is when the averaging is applied.

4. The OPA model

This model is written in generalised curvilinear coordinates as defined in fig 6. The momentum equations are written in vorticity form and the equations for T and S are in flux form. Equations for hydrostatic balance, incompressibility and an equation of state are also used as shown in fig 7. The u and v components in generalised coordinates are shown in fig 8.

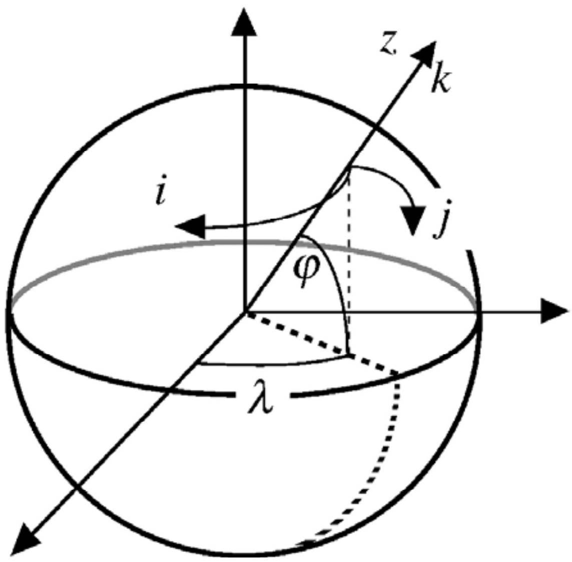


Figure 6 The geographic coordinate system and the curvilinear system (i,j,k). From Madec et al., 1998.

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

$$\frac{\partial p}{\partial z} = -\rho\, g$$

$$\nabla \cdot \mathbf{U} = 0$$

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

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

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

Figure 7 shows the vector form of the equations used in OPA.

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

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

Figure 8 The form of the momentum equations in generalised coordinates. From Madec et al., 1998.

The grid that is used for OPA is that defined for ORCA2. It is shown graphically in fig 9. At mid latitudes the grid is 2X2 degrees. There is an enhanced meridional resolution in the equatorial region. South of 20N the grid is lat-lon, but north of 20N the grid is defined by a series of ellipses. This strategy is based on Madec and Imbard 1996 but uses displaced ellipses rather than circles (Madec private communication). The two poles in the northern hemisphere are located over land. A polar view is also shown in fig 9.

The timestepping used in OPA is different to that used in HOPE. A leap frog is used for non-diffusive processes. Time-splitting is suppressed by using a time smoothing (Asselin) filter.

The strategy for handling the barotropic mode is somewhat different to those outlined above. The handling of the free surface in the presence of a fresh water flux is discussed in Roullet and Madec 2000. Various approximations are considered but the one used in the version of OPA being tested at ECMWF is the free surface with constant volume approximation. This does not conserve the total ocean salt content though it nearly does, at least in the configuration tested by Roullet and Madec. In more realistic tests the ocean salt content can vary by more than fig 5 of Roullet and Madec would suggest.

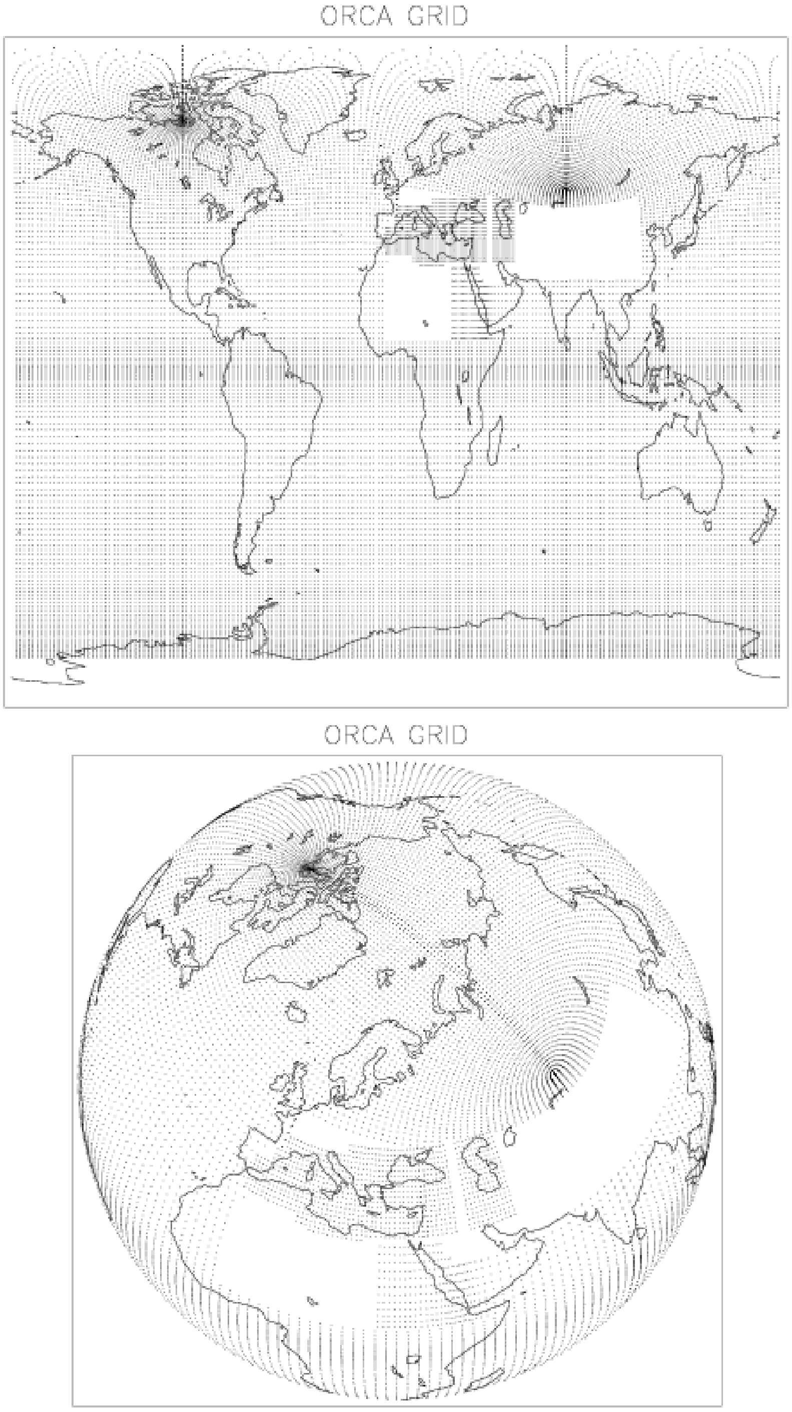


Figure 9 Two different views of the grid used in the ORCA2 model. The upper panel shows more clearly the higher resolution near the equator and the lat-long grid used south of 20N. The lower panel shows more clearly the grid used in the northern hemisphere.

The barotropic equation is not multi-stepped; neither is it made implicit. The approach adopted is to add a damping term in the momentum equation. It transforms the surface into a rigid lid for the fastest gravity waves while letting the slower waves evolve freely. It is claimed it has no effect on the Rossby and planetary waves. The numerics and cost of the scheme are comparable to those of an implicit scheme.

5. Summary

Two different ocean models are in use at ECMWF; these are HOPE-E developed at Max Planck Institute fur Meteorologie, Hamburg and OPA 8.2 in the ORCA2 configuration, developed at LODYC in Paris. Both models have been well described elsewhere so the reader is best to consult these references. Some features that are more recent than the model descriptions are discussed. The models use different grids (E and C) and different strategies for handling the time discretisations. The barotropic mode can be solved either by Gaussian elimination or multi-stepping in the case of HOPE or by adding a forcing term to make the model rigid-lid as far as external gravity waves are concerned in OPA. The polar problem in the northern hemisphere is also handled differently, by inserting an artificial pole in HOPE, by displacing the pole(s) in OPA.

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