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MESOSCALE ACOUSTIC VARIABILITY FROM OCEAN-ACOUSTIC SIMULATIONS

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1. INTRODUCTION

Ocean forecast models that are being developed for Royal Navy operational use will be required to give accurate predictions of the ocean environment for input to sonar performance models. At low frequencies this means that we must be able to account properly for the effects of mesoscale variability due to fronts and eddies. However, how good are ocean models at predicting such features? Are the requirements of the acoustician necessarily met by those of the ocean modeller? While it is true that our understanding of the physics of the upper ocean remains incomplete, other problems occur when we try to represent upper ocean processes in numerical models. In particular the sensitivity of acoustic predictions to changes in forecast model parameters is poorly understood. From a sonar operator's point of view this could be important. Fronts and eddies may account for a 10-20 dB increase in propagation loss. Eddy induced changes in surface duct depth may give rise to significant variations in propagation loss in this region. In this paper we describe work that is being done with ocean models and range dependent acoustic models run together, to study the sensitivity of acoustic predictions to changes in the environment and the forecast model parameters. Of particular interest are the effects of vertical and horizontal resolution, and the representation of subgrid scale processes with eddy diffusion coefficients.

2. MESOSCALE VARIABILITY

Mesoscale features in the ocean will form on the scale of the Rossby radius, R_i, given by

$$R_i = f^{-1}(g'H)^{1/2} \qquad (1)$$

where H is a representative vertical length scale, for example the depth of the warm layer in a two layer model of a front, f is the Coriolis parameter and g' is the reduced gravity given by $g'=g(\rho_2-\rho_1)/\rho_2$. Here g is the acceleration due to gravity and ρ_1 and ρ_2 are the densities of the upper and lower layers. For the example of the polar front east of Iceland (see later), values of H, ρ_1 and ρ_2 are typically 500 m, ρ_1 = 1027.10 kg m^{-3} and ρ_2 = 1027.92 kg m^{-3}, giving $R_i \simeq$ 15 km.

A typical eddy diameter ($2R_1$) would therefore be of order 30 km, which is comparable with the acoustic length scales of interest to naval oceanographers, for example the separation between acoustic convergence zones, which typically is of order 50 km.

Horizontal variability over this scale may have associated with it temperature changes of order 2-3 °C. From the sound speed equation (eg see Apel [1]) we can show that mesoscale temperature perturbations will give rise to sound speed anomalies of approximately 4.8 m s^{-1} for every 1 °C variation in temperature (the salinity effect is about 3% of that due to temperature and therefore ignored). Thus an ocean front may give rise to a 10-15 m s^{-1} variation in sound speed as we pass from one side of it to the other. These differences are comparable with the variations in sound speed over depth that occur as a result of changes in temperature and pressure, so that we would expect mesoscale features to modify sound propagation paths significantly with respect to the horizontal.

Temperature differences are therefore the main source of mesoscale acoustic variability in the ocean and for convenience (see Levers [2]) one can think of the sound velocity (C) being made up of three components, $C = C_1+C_2+C_3$. C_1 is largely deterministic and a function of depth, ie describes changes over the vertical. C_1 is typically about 1500 m s^{-1}. C_2 is of order 10 m s^{-1} and is the mesoscale perturbation in the sound velocity field, while C_3 which is of order 1 m s^{-1} or less, accounts for the smaller scale variability due to internal waves. The latter are not discussed here although they are of importance acoustically and give rise to contact fading in naval sonars.

3. THE SURFACE MIXED LAYER

Naval sonar operators require to know the depth of the surface mixed layer or surface duct. While the characteristics of the surface duct will be influenced primarily by atmospheric forcing, other factors may influence its depth. Figure 1 shows the results of computer simulations of the effects of an underlying field of eddies on the depth of the surface mixed layer.

How significant are these and other changes in duct depth acoustically? For a sound source in an isothermal duct, propagation loss (PL) is given (see for example Urick [3]) by

$$PL = -5\ \log\left(\frac{8}{R}\left(1-\frac{d}{H}\right)\right) + 5\ \log H + 10\ \log r + (\alpha+\alpha_L)r \qquad (2)$$

Here R is the radius of curvature of sound rays (R = 90,000 m for an isothermal duct), d is the source depth, r is the range in m and α and α_L

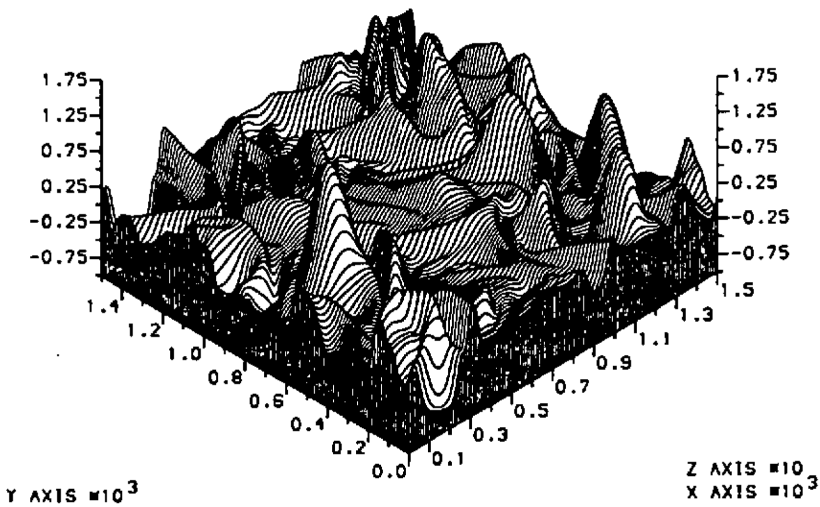

Figure 1 Computer simulation of the effect of ocean eddies on the depth of the surface mixed layer. The figure shows an ocean domain 1500 km x 1500 km. Depth variations of up to ±15 m occur, about a mean depth for the layer of 50 m. These results suggest that layer depth may vary by ±30% due to the eddies. (Results courtesy of Dr W Barkmann, Southampton University).

are the absorption coefficient and the leakage coefficient respectively, in dB m^{-1}. The first three terms on the right hand side of equation (2) represent the effects of geometrical spreading loss, which for d/H constant, varies as some constant plus a term proportional to $H^{1/2}$. However, the last term describes frequency dependent absorption and leakage effects. While α depends on frequency only, α_L is given by (eg Shulkin [4]) as $\alpha_L = 1.1s(F/H)^{1/2}$, where s is sea state and F is frequency. Heathershaw [5] has shown that the $H^{-1/2}$ dependence in α_L can be significant at moderate sea states and high frequencies, exceeding the weak $H^{1/2}$ dependence due to spreading loss and contributing a 2-3 dB variation in propagation loss for a 10% change in duct depth. Such changes may be associated with mesoscale variability.

4. EDDIES AND FRONTS

While mesoscale and meteorologically induced variations in duct depth are clearly important to sonar operators, the occurrence of ocean fronts and eddies is likely to have an even more profound effect on sound propagation. How then can we predict their effect on sonar performance? One solution, of course, is to go to sea and make measurements. While there can be no substitute for observations, and certainly these are required to corroborate the theory, measurements at sea can be costly and time consuming. A further limitation is that they are seldom reproducible and over the length scales of interest to acousticians, may not even be synoptic.

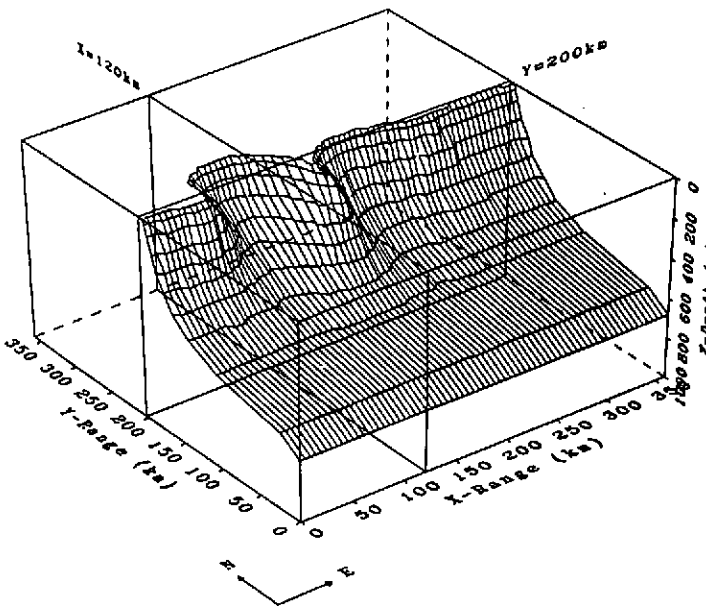

Figure 2 Computer simulation of eddies on an ocean front. The diagram shows a three-dimensional view of the 6° isothermal surface 16 days after initialisation. Acoustic calculations have been carried out on the sections at X=120 km and Y=200 km.

An alternative approach is to run 3-D ocean models and acoustic models together. Increases in computer power over the last decade mean that it is now possible to generate quite realistic simulations of ocean fronts and eddies. Figure 2 shows a simulation of eddies on an ocean front. These results are from a high resolution primitive equation model. The model is set up with 15 levels in the vertical, with $\Delta z = 25$ m in the top two levels and $\Delta z = 75$ m in the remaining 13 levels giving a total depth of 1025 m. The horizontal range increments are $\Delta x = \Delta y = 5$ km with 72 increments in the x and y directions giving overall dimensions of 360 km x 360 km. Further details of the model are given in Heathershaw et al [6] and Heathershaw and Maskell [7].

The model was set up with a temperature front running from west to east. Temperature values were chosen to correspond to the polar front east of Iceland, although in this case, as we have not incorporated realistic bottom topography, the comparison should be taken no further. However, the model is able to produce eddies and frontal features with realistic space and time scales. For the situation studied here, theory [8] would predict a maximum growth rate for features having a wavelength of $2\pi R_1 = 96$ km corresponding to a Rossby radius of $R_1 = 15$ km. In the examples shown here, eddies have been generated by applying a baroclinic step perturbation at the front. Other forms of perturbation are possible, including barotropic. The model may also be initialised with discrete eddy features.

It is also possible to simulate ocean currents. Although these give only a small perturbation in the sound velocity field, ie less than .1%, they may be important in lateral spreading of sound energy through ocean features. Operationally they may contribute to bearing angle errors in towed arrays (see Baer [9]). Coupled ocean-acoustic modelling techniques could be used to study such effects.

To study the effect of the eddies that form at the front on sound propagation, sections have been taken through and along the front (see Figure 2) at X = 120 km and Y = 200 km, respectively. Temperature and salinity values at model grid points on these sections were then used to calculate sound speed profiles for input to an acoustic ray theory model. The model chosen for this particular study was GRASS (see Harrison [10] for a useful description of this model).

Figure 3 illustrates the results of acoustic ray tracing along the front and shows how the ray paths are modified in the presence of eddies. Of particular interest to sonar operators will be the increase in propagation loss that is associated with these features. Figure 4 shows a propagation loss curve corresponding to the section along the front shown in Figure 2. This has been calculated with a fully absorbing ocean bottom. (Note that it is possible to perform ocean-acoustic simulations with variable bottom loss conditions - see Heathershaw and Gething [11]). Rays striking the sea surface were specularly reflected without loss. Phase independent intensity calculations were made with 1440 rays in a range of angles ± 15° about the horizontal. Ray amplitudes were attenuated by a factor $e^{-\alpha r}$

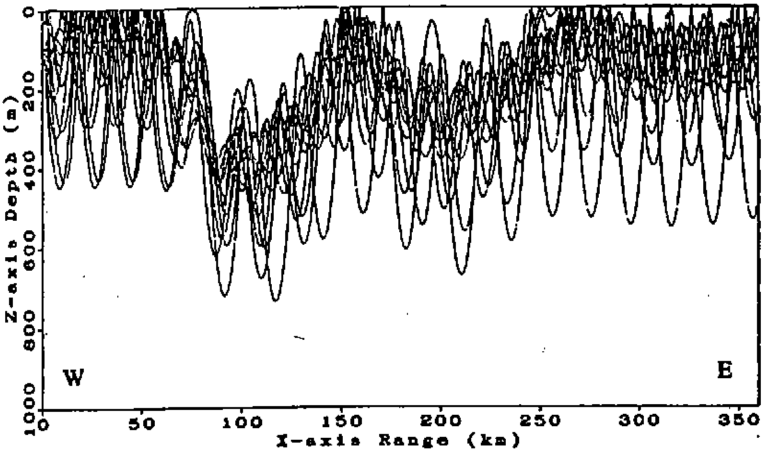

Figure 3 Ray trace for sound propagating along the front, from west to east, on the section at Y=200 km shown in Figure 2. The sound source has been placed at a depth of 100 m on the western boundary of this section. Sound energy is deflected below the warm core 'eddies' that form at the front.

where α is the volume attenuation coefficient. A value of $\alpha = 1.41 \times 10^{-\text{[illegible]}}$ dB km^{-1} was chosen for these studies.

Figure 4 confirms previous findings that propagation loss increases associated with mesoscale features in the ocean, may be of order 10-20 dB or greater. In particular, along front propagation characteristics will show a great deal of variability with range. Perhaps of more interest in the results shown in Figure 4 is the comparison with range independent predictions, ie what you would predict if you did not know that the front was there.

While these results indicate that we are able to realistically simulate the effect of eddies and fronts on sound propagation, using ocean models, important limitations may occur due to limited spatial resolution in numerical model grids. Ocean models require the governing equations of motion to be solved on finite difference grids. The choice of grid size and time step in a numerical model is governed by the phase speed of the fastest disturbance that it is required to model. Other constraints on grid size will be computer memory size and the overall dimensions of the area to be modelled. Prototype ocean forecast models are being developed with a resolution of 1° (~100 km). However, as computer power increases

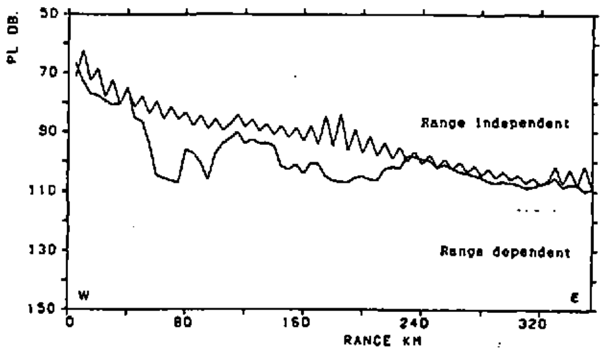

Figure 4 Variation in propagation loss (PL) for sound propagating along the front from west to east. This diagram illustrates the difference between range dependent and range independent conditions. Variations in propagation loss of up to 25 dB, compared to the range independent case, occur in the vicinity of the eddies.

this is expected to improve to .1° (~10 km), at which resolution the models become 'eddy resolving'.

Further complications arise in numerical schemes with eddy diffusion coefficients that are used to describe subgrid scale transfers of heat and momentum. Consider the horizontal momentum equations (written in Cartesian co-ordinates for simplicity).

$$\frac{\partial u}{\partial t} + (\underline{q}.\nabla)u - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + A_H\nabla^2 u + A_V\frac{\partial^2 u}{\partial z^2} \qquad (3)$$

$$\frac{\partial v}{\partial t} + (\underline{q}.\nabla)v + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + A_H\nabla^2 v + A_V\frac{\partial^2 v}{\partial z^2} \qquad (4)$$

Here $\underline{q}$ = (u,v,w) are the velocity components in directions (x,y,z), f is the Coriolis parameter and A_H and A_V are horizontal and vertical eddy diffusion coefficients. ρ_0 is a reference density and ∇ is the operator $(\partial/\partial x\ ,\ \partial/\partial y)$. Similarly in the equations for conservation of heat and salt, eddy diffusion coefficients are used to describe subgrid scale transfers of these quantities.

However, eddy coefficient values (particularly A_H) are usually chosen to given numerically stable solutions to the governing hydrodynamic and thermodynamic equations, often solved in finite difference form. Does this affect the acoustics? The answer is, yes it may do. Figure 5 shows simulations of the eddy field, from the model described previously, with different values of A_H but at the same time following the initial disturbance to the front. This shows quite clearly that larger values of A_H (ie a 'stickier' ocean) will suppress the growth of features and give less detail in the modelled fields. The values of A_H typically chosen in ocean modelling are those which give a stable numerical calculation and growth rates and scales appropriate to the oceanographic phenomenon being modelled. The question is, is the value of A_H chosen significant acoustically, and can we quantify its effect?

To answer this question we consider the x momentum equation only (equation 3). By neglecting the non-linear advective terms $(\underline{q}.\nabla)u$ and vertical diffusion (A_V) (the latter will be of order 10^{-7} smaller than A_H), and further by 'turning off' the background vorticity field and neglecting the Coriolis and pressure gradient terms, fv and $\frac{1}{\rho_0}\frac{\partial p}{\partial x}$, we can write a simplified equation

$$\frac{\partial u}{\partial t} = A_H \frac{\partial^2 u}{\partial x^2}$$

Figure 5 Isotherms at 12.5 m depth 8 days after initialisation with eddy diffusion coefficient values of $A_H = 2 \times 10^7$ cm^2 s^{-1} (left) and $A_H = .1 \times 10^7$ cm^2 s^{-1} (right). Temperatures in the bulk of the water either side of the front are given. The contour interval is 0.5 °C. This figure illustrates the diffences in detail that can be simulated with different eddy diffusion coefficient values.

By inspection this gives a relation between length (L) and time (T) scales of the form $L = (A_H T)^{1/2}$ where L is now a length scale associated with the size of a feature and T a time scale for it to decay (as a result of diffusion). Table 1 gives values of L corresponding to different values of T and A_H.

Table 1

Values of the length scale L corresponding to different times, T, and the eddy diffusion coefficient A_H.

T (days)	A_H ($\times 10^7$ cm² s⁻¹) 2	1	.5	.1
	L(km)			
2	18.6	13.1	9.3	4.2
4	26.3	18.6	13.2	5.9
8	37.2	26.3	18.6	8.3
16	52.6	37.2	26.3	11.8
32	74.4	52.6	37.2	16.6

30 km

The results in Table 1 show, for example, that if the background vorticity field is turned off, information on a length scale L = 30 km (ie roughly an eddy diameter from equation (1)), will be lost after about 8 days with $A_H = 1 \times 10^7$ cm² s^{-1}, and after about 16 days with $A_H = .5 \times 10^7$ cm² s^{-1} (note that time doubles as A_H halves). This suggests that ocean forecast models with these values of A_H, would need to be updated or reinitialised at intervals of 8-16 days to retain this level of detail in the forecast fields.

5. SUMMARY

Further work is in progress with the models described here to examine the sensitivity of acoustic predictions to changes in the environment and in forecast model parameters. In addition to studying the effects of eddy diffusion, as described above, we are examining the effects of spatial resolution and looking at different methods of perturbing the ocean model. In particular, work is in progress to study the interaction between eddies and fronts. This has relevance to the forecasting problem, where the technique of 'bogussing' a forecast field with details of frontal features taken from generic models, is used to improve the quality of the forecast. Other work is in progress using 1-D mixed layer models to study the effects of vertical resolution. For the frontal simulations described above, Δz values of 25 or 75 m were chosen. This represents insufficient resolution for the acoustics. It is also necessary to understand the way in which mixed layer models treat near-surface temperature gradients.

In summary, coupled ocean-acoustic models provide a very powerful tool for studying sound propagation in the ocean and in particular in improving our understanding of the sensitivity of acoustic predictions to fundamental processes (eg the mesoscale variability of the oceans) and the parameters that are used to represent them in ocean forecast models.

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