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COMPARISON OF THREE-DIMENSIONAL OCEAN GENERAL CIRCULATION MODELS ON A BENCHMARK PROBLEM

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ABSTRACT

A french and an american Ocean General Circulation Models are compared on a benchmark test problem. Both models are three-dimensional. They solve the hydrostatic primitive equations of the ocean with two different finite difference techniques. Results show that the dynamics simulated by both models are consistent. Several methods for the running of a model from a known state are tested in the French model : the diagnostic method, the prognostic method, the acceleration of convergence and the robust-diagnostic method.

RESUME

Un modèle français et un modèle américain de Circulation Générale de l'Océan sont comparés sur un problème test. Les deux modèles sont tri-dimensionnels. Ils résolvent les équations primitives hydrostatiques de l'océan avec deux techniques aux différences finies. Les résultats montrent que les dynamiques simulées par les deux modèles sont cohérentes. Plusieurs méthodes pour l'intégration des modèles à partir d'un état connu sont testées dans le modèle français : la méthode diagnostique, la méthode pronostique, l'accélération de convergence, et la méthode diagnostique robuste.

I. INTRODUCTION

The dilution mechanism of the locally concentrated activity by the ocean fluid is the fundamental process with which radiation protection principles for the safety of deep-sea disposal of radioactive wastes are faced. This mechanism should therefore be studied carefully. As most of the consequences of deep sea dumping can only be assumed in a rather remote future, numerical modelling of the highly complex and intricate transfer processes in the environment has become the usual strategy to assess the impact of dumping practice. However there is a large variety of models and the question thus arises of the reliability of their results.

These considerations have motivated a study of the comparative efficiencies of several three-dimensional ocean general circulation models (OGCM) within the framework of the NEA/Subseabed Programme. OGCMs usually describe a very large range of ocean dynamics processes with more or les details and solves fully non-linear equations with elaborated mathematical techniques. Although OGCMs are expected to calculate radionuclide dispersion with a rather high precision, the analysis of the reliability of these models remains difficult. An international consensus has arisen to assess the reliability of such models through careful intercomparisons. The technique of intercomparison may be seen as an "inter-relative validation" of the models. As no absolute validation could be performed so far, intercomparison appears as a powerful tool to assess the individual efficiency of the models.

Only few OGCMs are operational throughout the world. The model developped by BRYAN [1] is generally considered as the archetype three-dimensional OGCM. This model has been recoded by SEMTNER [2], COX [3] and applied to environmental problems by MARIETTA [4]. As this well-known model has been widely used thoughout the World and especially in the USA, we therefore decided to compare it with the French model with it.

The opportunity to compare both models has been given by the NEA/Subseabed and NEA/CRESP programmes. MARIETTA kindly provided the data fields obtained with the US model on the benchmark problem.

Our purpose was therefore restricted to a comparison of the french model with the US model and no conclusion will be drawn concerning the US model.

II. AIMS AND METHODS

Differences in the results provided by the models may be due to a large number of reasons : physical assumptions, mathematical modelling, numerical solving of the equations, programing, processing of the results, etc... A specific benchmark problem has thus been defined to compare the models on an unbiased basis. The benchmark problem is aimed to be typical of sea dumping conditions in the North Atlantic. This benchmark test problem has been fully described in [5]. It mainly consists in a rectangular 3600 m ocean representing the North Atlantic Ocean. The ocean is forced by constant zonally-uniform momentum, heat and salt surface fluxes which are rather schematic but realistic for the long term evolution of that region.

For large scale models of radionuclide transfer, time-average advective and diffusive fluxes are very useful, but radiation protection is often more concerned with stationnary ocean circulation than with seasonal or interannual variabilities. The intercomparison has therefore been performed on the steady or quasi-steady state circulations generated by both models. However it should be emphasized that the computational costs for reaching a steady state with a prognostic three-dimensional OGCM being very high (several tens of CRAY-1 CPU hours) computations with both models have been considered useless. On the contrary, a steady state has been obtained by a prognostic computation with the US model, and the intercomparison has been performed from the fields simulated after 4 000 000 time steps.

Several techniques can be anticipated to reach at low costs the steady state of the French model from the US model fields. The following methods have been tested :

- diagnostic calculations ;
- prognostic calculations ;
- acceleration of convergence in prognostic calculations ;
- robust diagnostic method.

The aim has been to identify a suitable and economical technique for the radiation protection purposes through a careful intercomparison of the results with those obtained with the US model. This technique should simulate at low cost a steady state ocean circulation from given density fields or from given heat, salt and momentum surface fluxes.

In the diagnostic calculations, the density fields (or the salinity and temperature fields) are kept constant : they are supplied by atlases, measurements or simulations carried out with another model (here the US model). The ocean circulation is then due to known density gradients and to the wind stress. The equilibrium of the circulation is reached very rapidly (less than one month of simulation) and this method is quite inexpensive. Practically, the French model has been integrated with the steady state temperature and salinity fields provided by the US model. One should note that this method is very useful for the intercomparison because it allows to compare the dynamical aspect of the models only, the thermodynamical part being steady and similar in both models.

In the prognostic calculations, velocity, temperature and salinity distributions are varying with time. For the intercomparison, the French model has been integrated starting from the initial salinity and temperature steady state fields given by the US models, with the same surface forcings (heat, salt, wind stress). This technique allows to identify the differences between both models when resolving the same stationary problem.

The acceleration of convergence by the method of stretching the times has been proposed by BRYAN [6]. It basically consists in distorting the physics of the ocean by compressing the frequency band of the ocean model. This slows down gravity waves and speeds up abyssal processes. The compressed frequency band is obtained by stretching the times by a factor α :

$$t' = \frac{t}{\alpha}$$

and by introducing a distorted stratification (factor γ) :

$$N'^2 = N^2 \frac{\gamma}{\alpha}$$

where N^2 is the Brunt-Väisälä frequency. The distorted-physics ocean model is expected to converge to the same equilibrium state as the non-distorted model since the distorsion only involves local derivatives versus time. This method seems promising for radiation protection applications, as it allows to simulate a steady-state circulation at reduced costs.

The robust diagnostic method [7] is an extension of the diagnostic method which takes prognostic calculations into account. The robust diagnostic method ioncorporates the conservation of the large-scale fields of heat and salinity as well as momentum. But extra damping-terms are added to the temperature and salinity equations which create artificial sources and sinks to push the predicted fields toward observed values. The rate of this artificial damping is governed by a time constant which is assumed variable with depth. The time constant is chosen rather high in the surface layers, which corresponds to a nearly purely diagnostic model, and rather low in the bottom layers, which allows the mass field to adjust itself to the constraints of the model (this corresponds to a nearly purely prognostic model). The method has been tested with the transfer of data from the US to the French model : the US model fields are then considered as reference data.

This robust-diagnostic method seems promising for radiation protection applications to the marine environment as it is able to take into account field measurements as well as theoretical dynamics aspects of the ocean in the simulations of the ocean three-dimensional general circulation. The obtained results are expected to be self-consistent with the measurements (at least to some extent), i.e. "self validated". The main drawback of the method is that uncertainty on field measurements are not completely removed by the model and may lead to inaccuracies of the simulated circulation.

III. RESULTS

The comparison of the velocity fields obtained pronostically with the US model and diagnostically with the French model (with the same temperature and salinity constant fields) shows a good global agreement (fig. 1). The flow patterns are very similar and the maximum speeds nearly equal in both models at all depth except at 1150 m where circulation is cyclonic in the US model but rather slow and anticyclonic in the French model. This might indicate differences in the calculation of the integrated hydrostatic pressure in both models, leading to differences in the depth of the no-motion level (this level seems deeper in the French model). These differences could also explain the lower value of the barotropic streamfunction maximum in the French model (fig. 2). However, the streamfunction exhibits rather the same pattern in both models. In order to verify the correct programming of the algorithm that calculates the barotropic mass transport streamfunction in the French model, several mathematical methods have been tested on a two-dimensional test problem [8]. A new method, based on a

Preconditionned Conjugate Gradient has been shown to be more efficient and will be definitely implemented in the French model code.

Computational noise clearly appears in the results of the French model at high latitude. This noise exhibits a band geometry which indicates that it is due to the C-grid [9]. It is known [10] that the B-grid (used in the US model) is better than the C-grid when the space resolution is low, but less precise when the resolution is high. The resolution is defined here as the grid-spacing divided by the Rossby radius of deformation. At high latitudes in the test problem, the 2° grid spacing leads to a rather poor resolution that generates stationary noise in the results of the French model (because of the C-grid). To verify this conclusion, we performed a diagnostic simulation with the French model using a 1° grid spacing (twice higher resolution) : the noise at high latitudes was then completely removed. One should note that this computational noise occurs with poor space resolution even with the diagnostic method using rather smooth density fields. This result thus call for rather high resolution simulation with the C-grid models when diagnostic or semi-diagnostic methods are used with field measurements. Field measurements are inherently not smooth and the C-grid models need a high resolution to take such data into account without generating computational noise.

Consistency between US (prognostic) and French (diagnostic) results demonstrates that both models involve the same dynamical features (the thermodynamical aspects are constant and imposed in the diagnostic calculation performed with the French model and can not be compared so far). This partly validates the French model relatively to the US model and strengthens the confidence in the US model.

Prognostic simulations have been performed with the French model starting from the initial density fields of the US model, and forced by the same wind stress and surface heat and salt fluxes. Figures 3 show the results after 24000 time steps (i.e. 500 days). The flow circulation and the temperature and salinity fields have rather the same pattern in the US and French models. Some differences are nevertheless clearly noticeable : the barotropic mass transport streamfunction is larger in the US model ; the maximum velocity is larger in the US model for the upper layers, but larger in the French model for the lower layers ; at depth 1150 m, the circulation is cyclonic in the US model and anticyclonic in the French model. These dynamical differences in the circulation entail slight differences in the resulting tracer fields. Moreover one should note that a stationary computational noise is generated in the Northern part of the domain in the French model. As for the diagnostic calculations, this noise is due to the poor grid resolution.

The prognostic calculations show that transients are not simulated in an exactly similar manner by both models. But the differences do not lead to an unacceptable divergence of the results. The main difference concerns the barotropic velocities (larger in the US model). The results also confirm that the French model should not be run prognostically with a poor space resolution.

The method of acceleration of convergence to steady state has been tested through simulations of 24 000 time steps of 12 hours (i.e. about 33 years). The initial state comes from the US model fields and the same forcings are applied. The French model does not reach an exact steady state after the 33 year period, but the variations of kinetic energy are rather low after this period, which indicates that the model hardly evolves any longer (at least in the upper layers). One should first note that no specific computational instability is generated due to the method of convergence acceleration (but computational instabilities due to the poor resolution still remain in these runs). The results moreover look satisfying (fig. 4). The barotropic mass transport streamfunction is exactly similar to the one obtained with the purely prognostic calculations : the convergence method does not alter the computation of the streamfunction at all. The quasi-steady state obtained in the upper layers after a 33 years period has a pattern fairly similar to the state obtained with the US model. The velocity calculated by the French model is nevertheless significantly slower in the upper layers, and much slower in the lower layers. This leads to a rather different tracer fields pattern in the deepest layer (fig. 5). In conclusion, the surface forcing leads to a quasi-similar response of both models ; but the lower layers are more or less free to adjust to the model dynamics which are computed somewhat differently in the US and French models.

The robust-diagnostic method results in a simulated circulation that crudely exhibits the thermodynamical features of the diagnostic simulation and the dynamical features of the prognostic simulation (fig. 6). The maximum velocity is a little larger in the upper and lower layers of the US model, and in the central layers of the French model respectively. A computational noise is also generated in the velocity fields with the robust diagnostic method in the French model, due to the poor space resolution of the grid. But the magnitude of the spurious noise remains rather low, except in the vertical velocity field. At depth 1150 m, the circulation in the French model is clearly anticyclonic. The temperature and salinity fields remain nearly unchanged. That the tracer fields do not exhibit any computational noise. We thus conclude that the robust diagnostic method combines convenient aspects of both the diagnostic and the prognostic methods. However, the tracer fields provided by the US model are free from noise, so that this conclusion does not necessarily hold when the robust-diagnostic method is used with tracer fields obtained by field measurements which are far from smooth.

IV. CONCLUSION

This study yields to the following conclusions :

i - As far as the US model can be considered validated (through a long and wide use in a large number of studies), the French model can now be regarded as validated relatively to the US model.

ii - As both models have been developed independently, the consistency between the results of both models on the same benchmark problem strengthens the confidence in the validity of both codes.

iii - Different numerical schemes used in the models yield different results. These differences are dynamically significant but should not entail large inconsistencies from a radiological point of view. It is nevertheless advisable not to underestimate the numerical features in the development of futur models as they have been shown here to affect the simulations to some extent.

iv - Several methods can be anticipated to run these models. The results show that the method of convergence acceleration and the robust diagnostic method are well suited to radiation protection purposes as they allow less expensive simulations with no significant deformation of the ocean circulation (as far as tracer transport is concerned).

v - The most significant differences between the US and French models is the amplitude of the barotropic mass transport streamfunction. New algorithms have been developed for the French model and tested in other studies and this point of the French code should then be considered as validated.

vi - The French model should be used with rather fine space horizontal resolution in order to avoid spurious numerical noise.

These positive conclusions have led us to develop a World Ocean Circulation Model based on the the French model code. This World Ocean Model will be used to assess the dispersion of radionuclides with a rather fine resolution at a global scale, and to provide water mass flux data for low-resolution box models.

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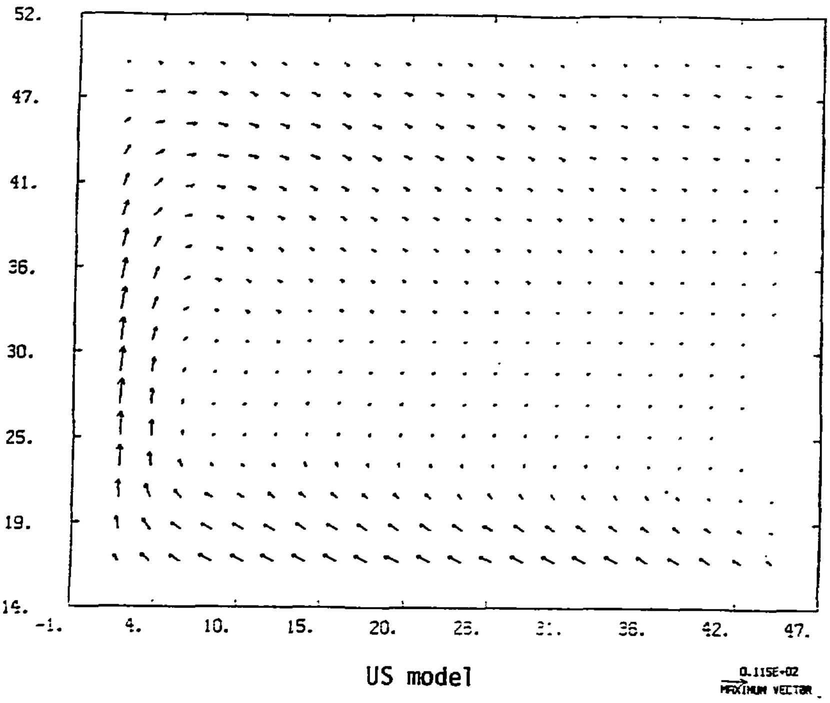
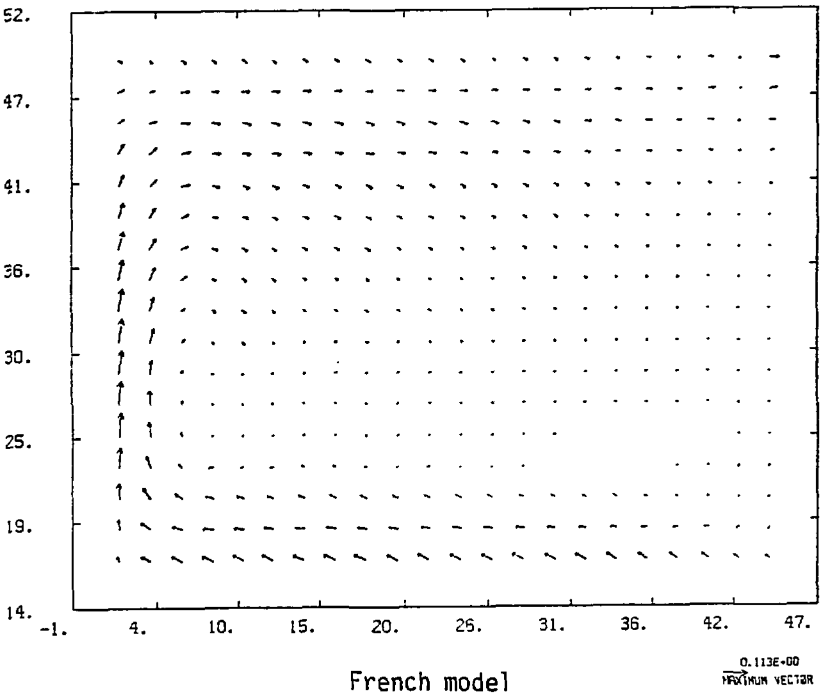
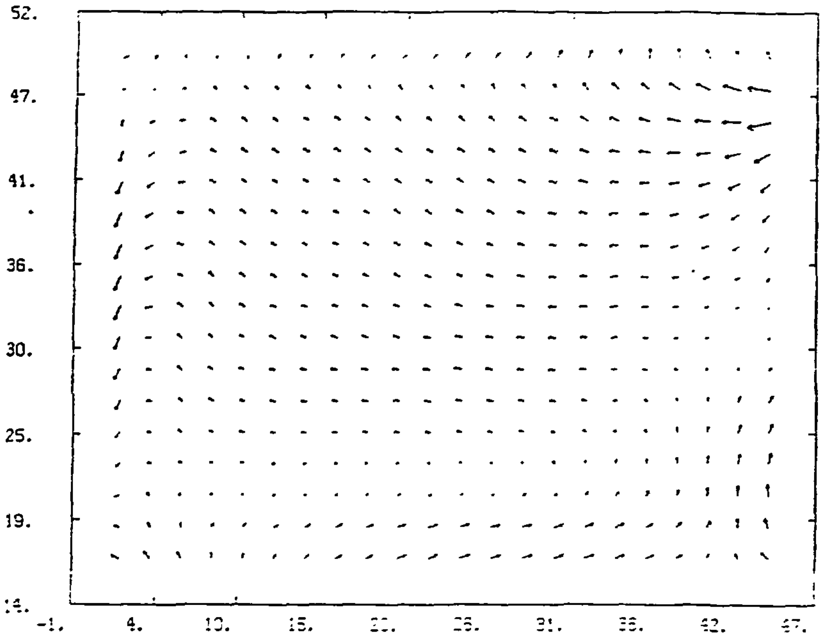


US model



French model

Figures 1 : horizontal velocity at depth 25 m



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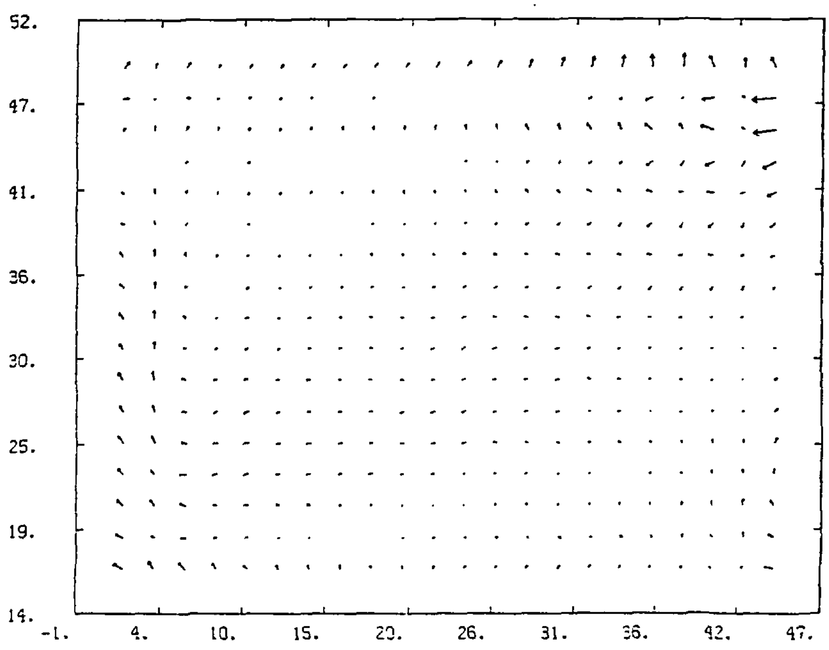
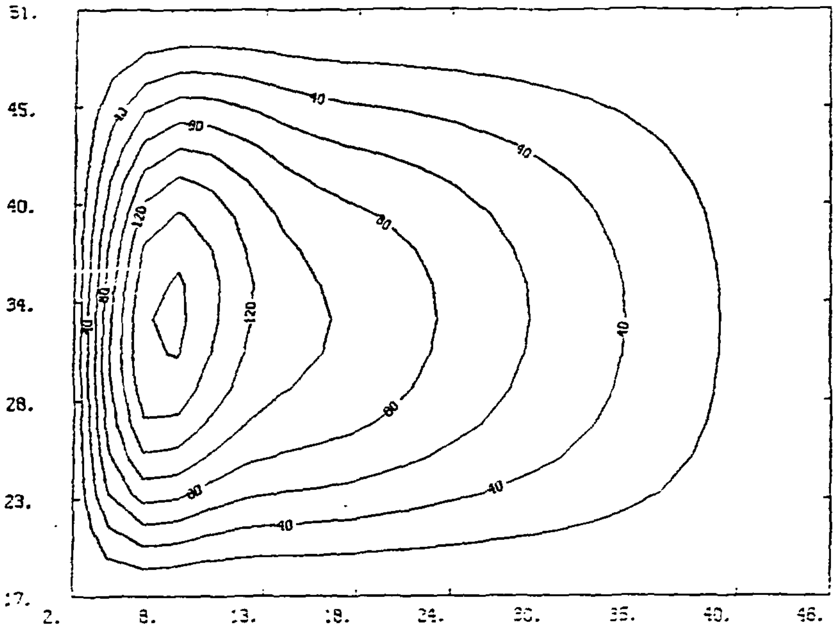


French model

Figures 1 : horizontal velocity at depth 1150 m



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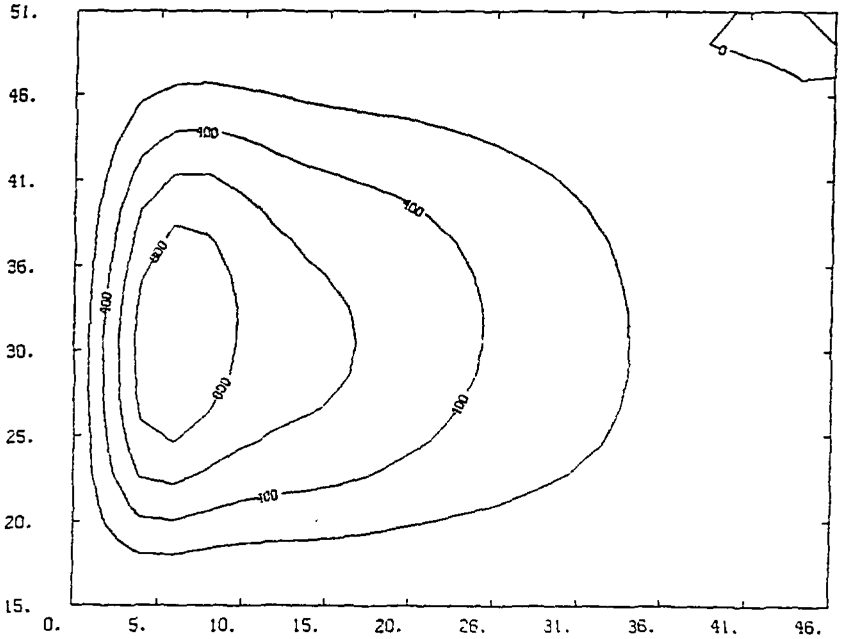
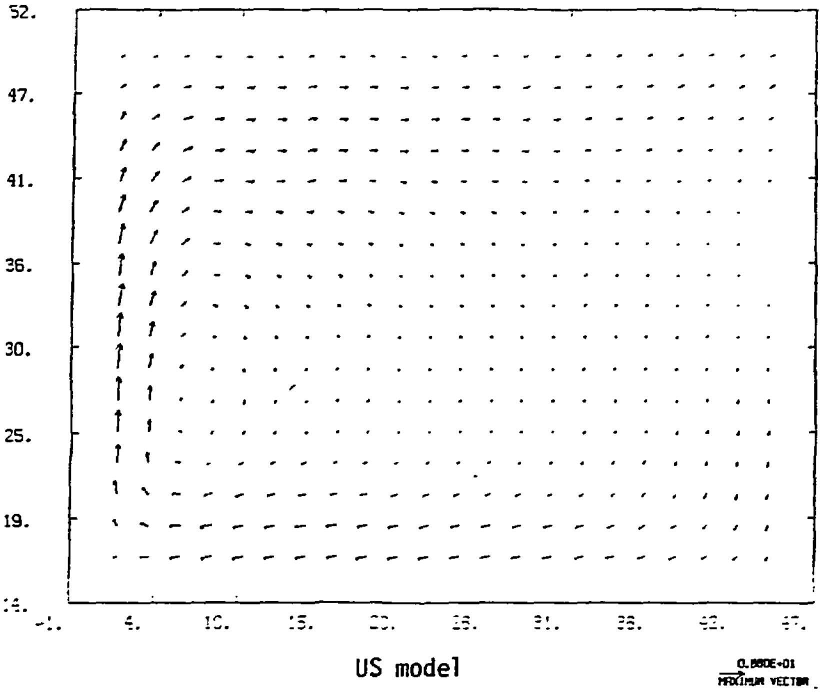


French model

Figures 2 : barotropic mass transport streamfunction (contour interval of 2 Sv)



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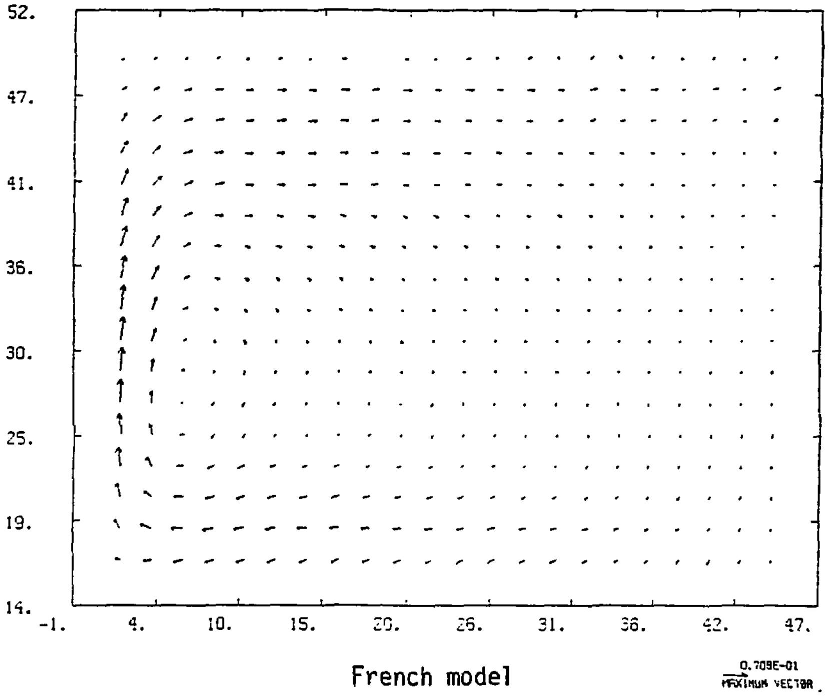
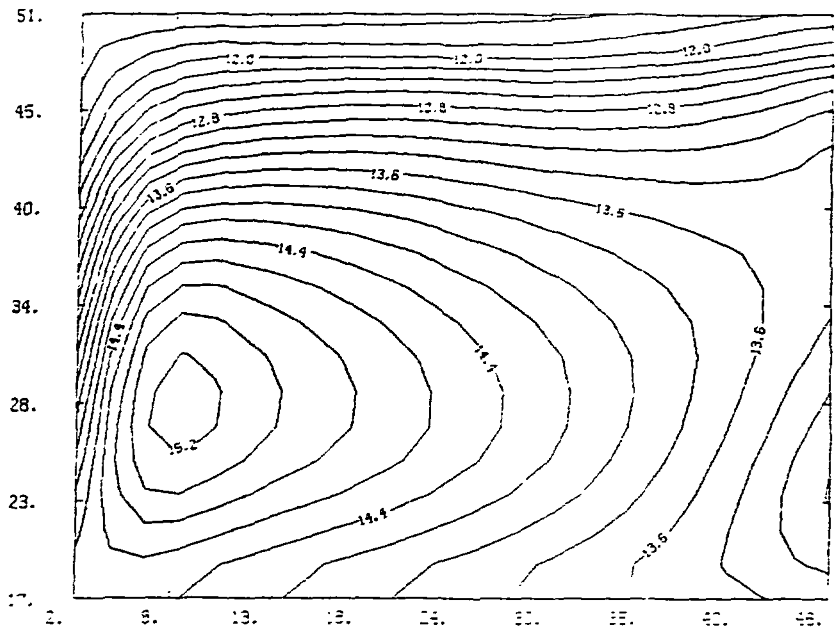


French model

Figures 3 : horizontal velocity at depth 150 m



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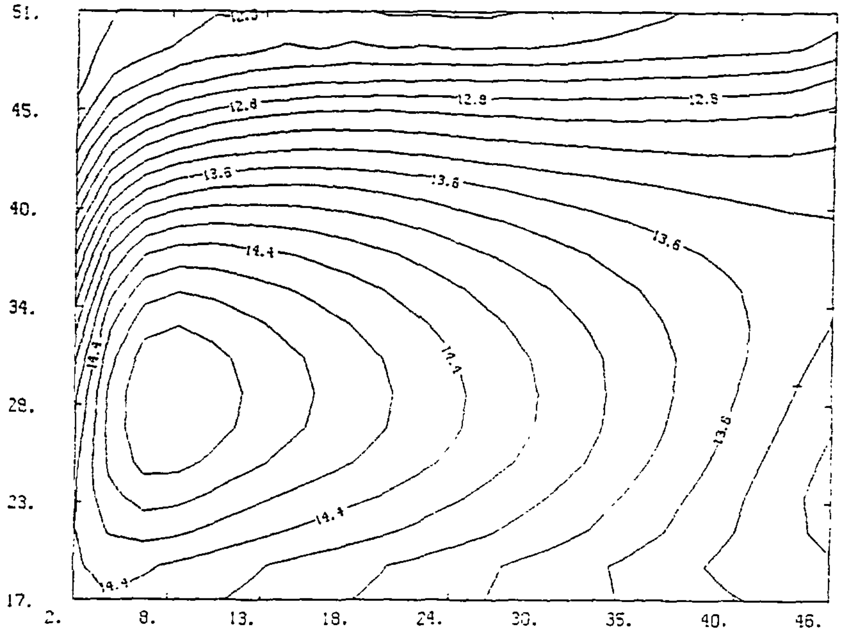
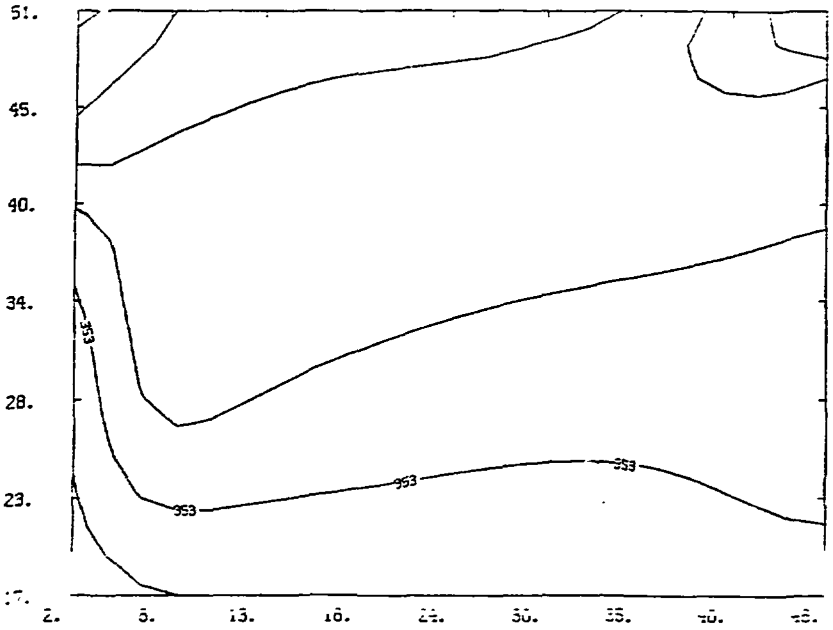


French model

Figures 3 : temperature at depth 500 m (contour interval of 0.2°C)



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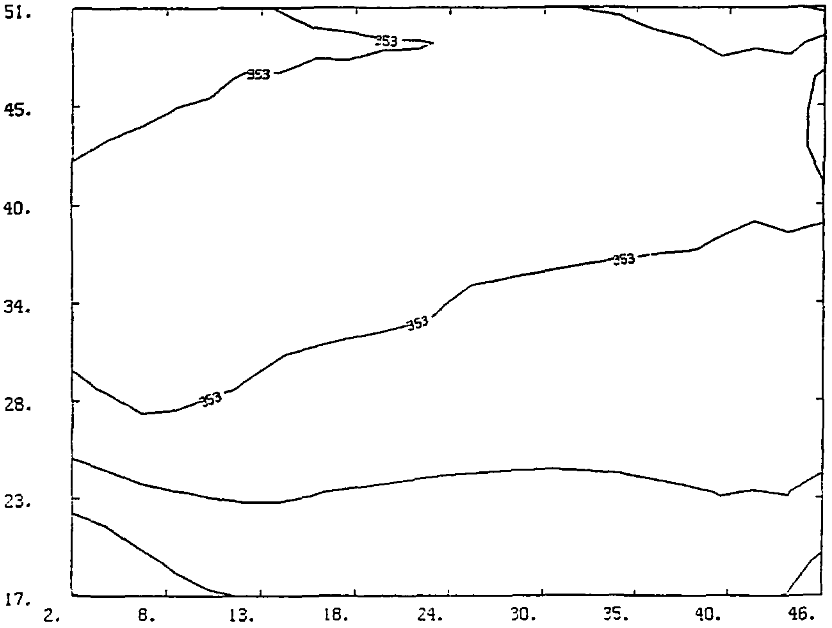
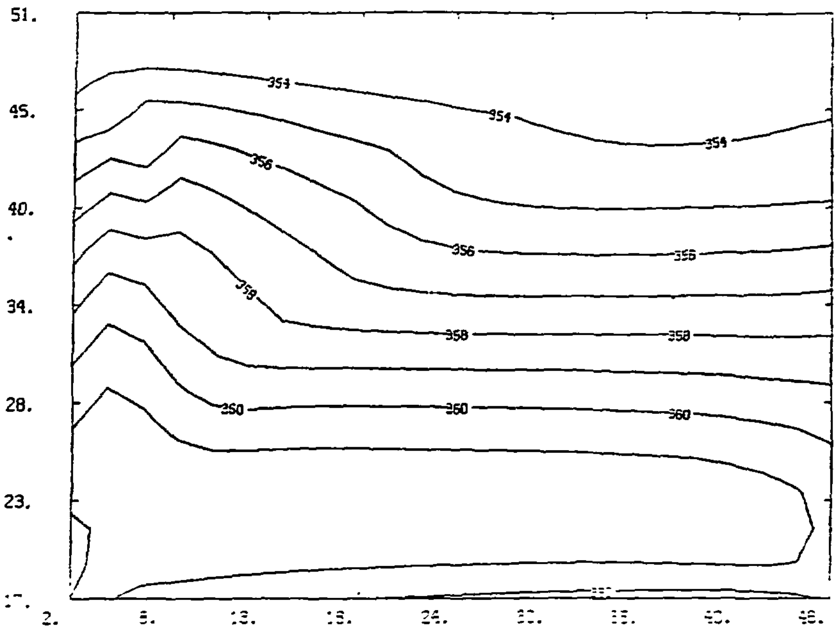


French model

Figures 3 : salinity at depth 2050 m (contour interval of 0.000002)



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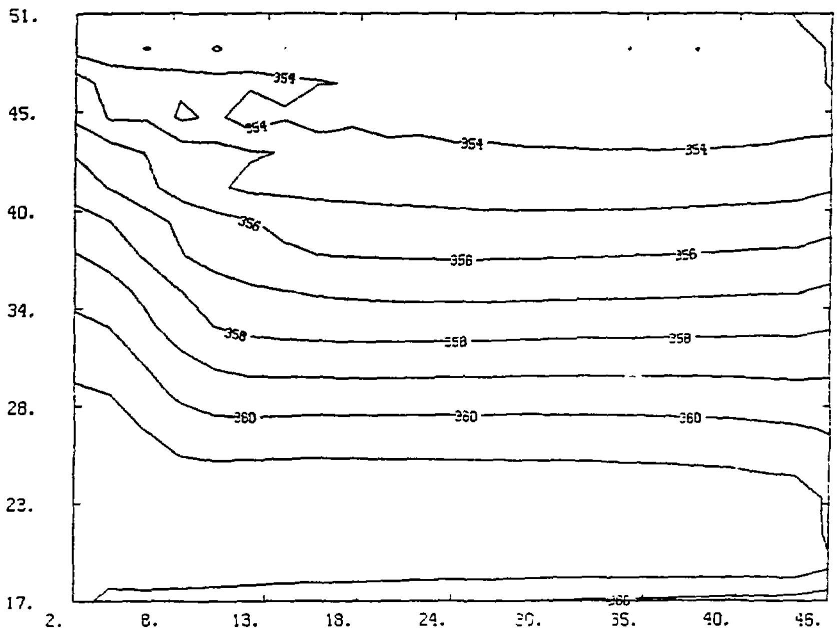
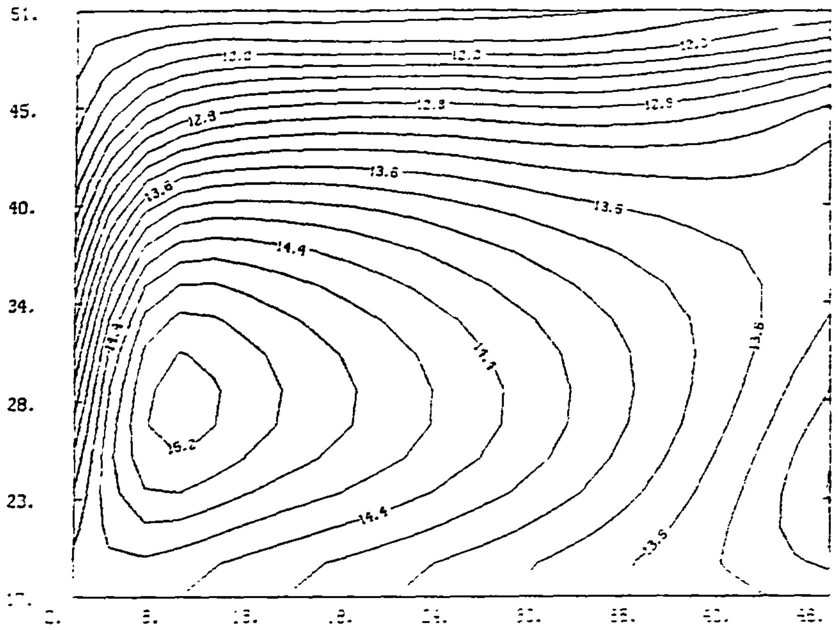
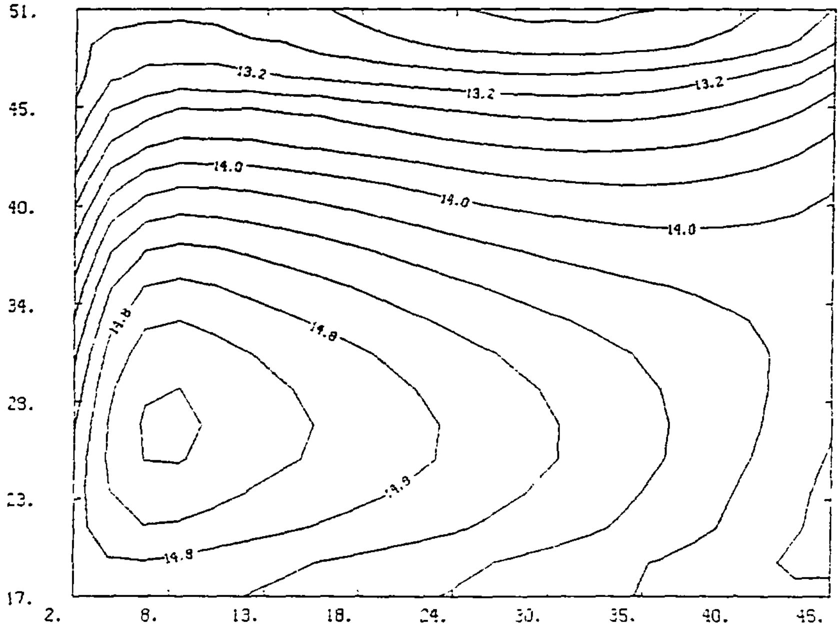


French model

Figures 4 : salinity at depth 25 m (contour interval of 0.0001)

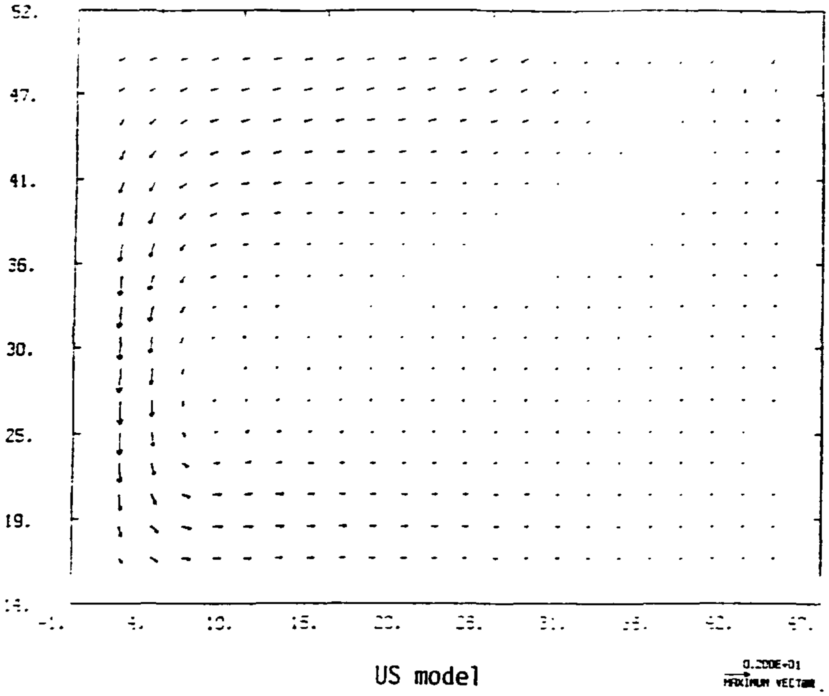


US model

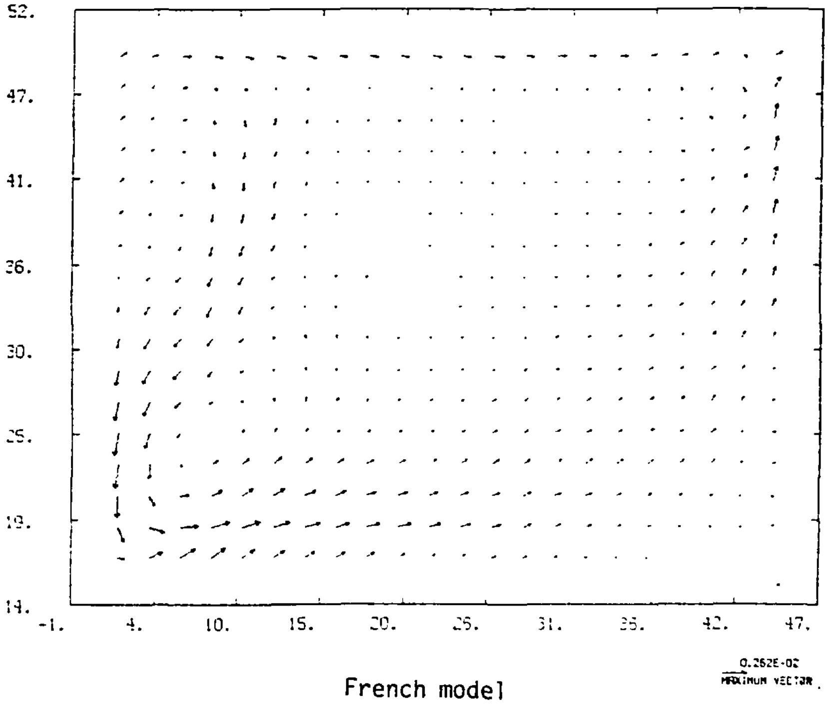


French model

Figures 4 : temperature at depth 500 m (contour interval of 0.2°C)

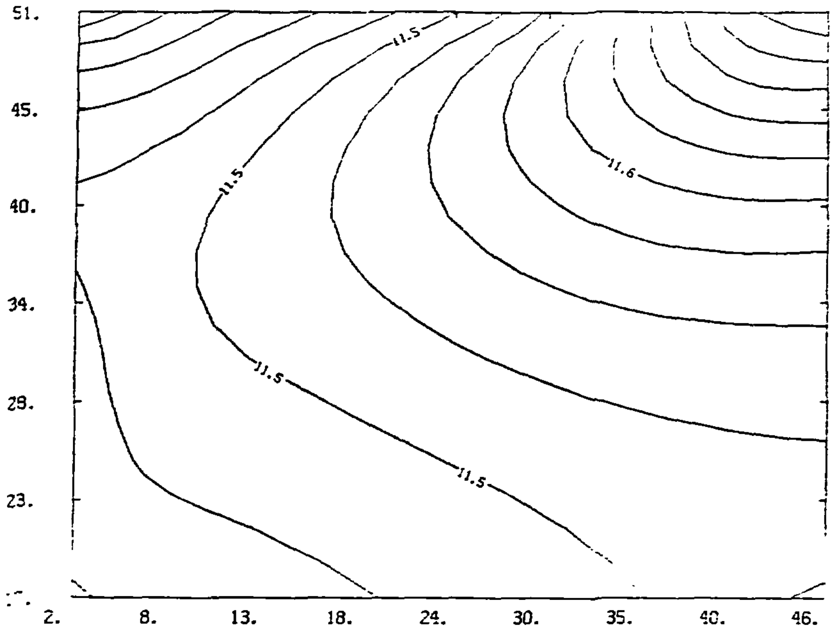


US model



French model

Figures 4 : horizontal velocity at depth 3150 m



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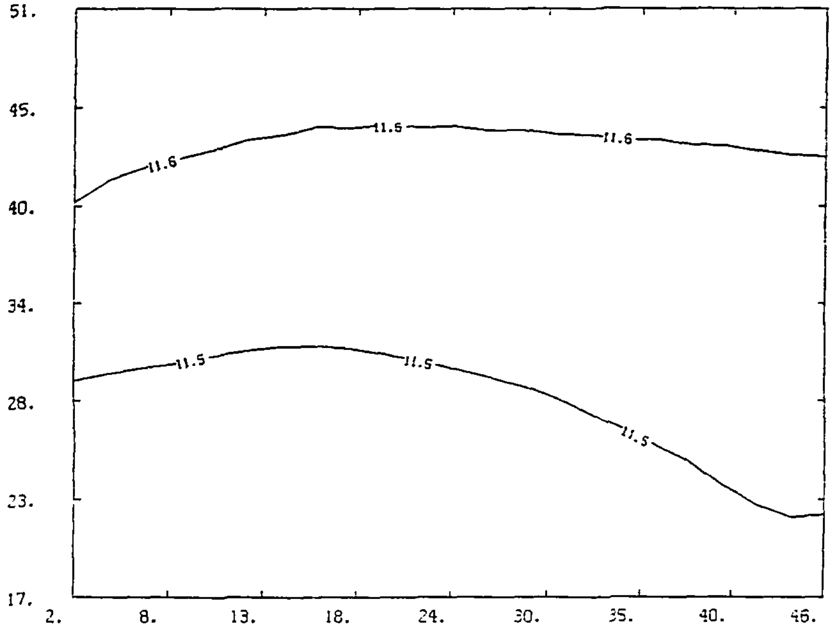
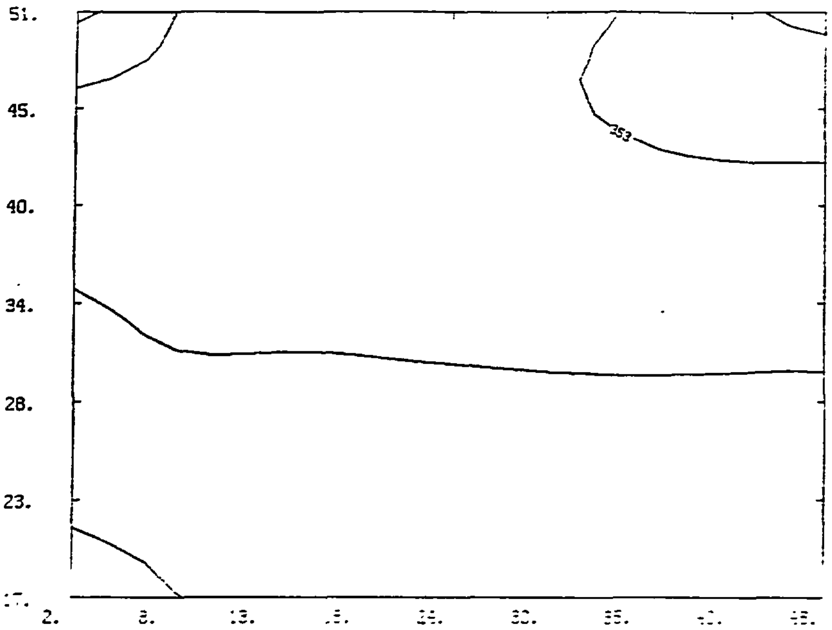


French model

Figures 5 : temperature at depth 3150 m (contour interval of 0.02°C)



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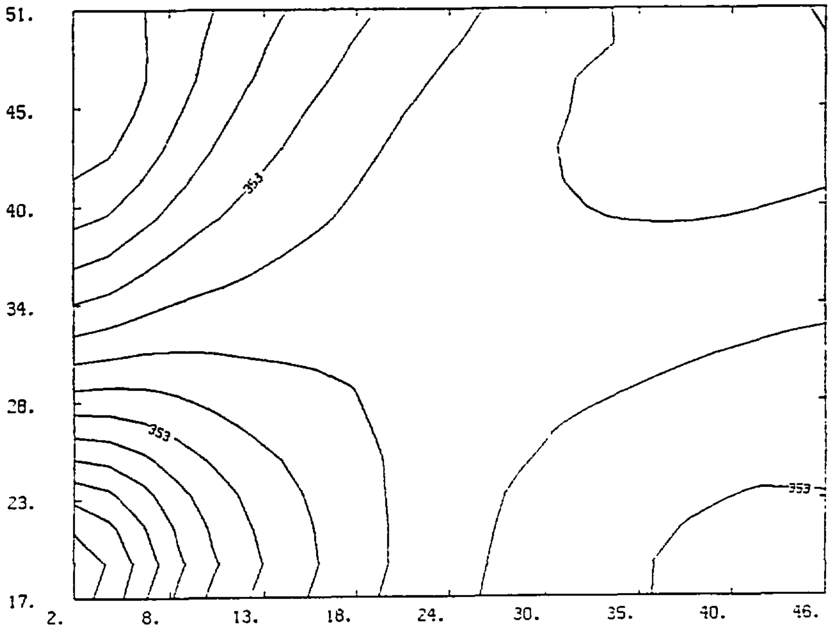

French model

Figures 5 : salinity at depth 3150 m (contour interval of 0.000002)