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EXPERIMENTS OF A REDUCED GRID IN LASG/IAP WORLD OCEAN GENERAL CIRCULATION MODELS (OGCMs)

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ABSTRACT: Due to the decrease in grid size associated with the convergence of meridians toward the poles in spherical coordinates, the time steps in many global climate models with finite-difference method are restricted to be unpleasantly small. To overcome the problem, a reduced grid is introduced to LASG/IAP world ocean general circulation models. The reduced grid is implemented successfully in the coarser resolutions version model L30T63 at first. Then, it is carried out in the improved version model LICOM with finer resolutions. In the experiment with model L30T63, under time step unchanged though, execution time per single model run is shortened significantly owing to the decrease of grid number and filtering execution in high latitudes. Results from additional experiments with L30T63 show that the time step of integration can be quadrupled at most in reduced grid with refinement ratio 3. In the experiment with model LICOM and with the model's original time step unchanged, the model covered area is extended to the whole globe from its original case with the grid point of North Pole considered as an isolated island and the results of experiment are shown to be acceptable.

Key words: spherical coordinates, reduced grid, ocean general circulation model

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1 INTRODUCTION

In global climate models belonging to the finite difference calculation category, the equations are generally solved in normal spherical coordinates. Due to the convergence of meridians towards the poles in spherical coordinates, the combination of this coordinate system and explicit finite-difference methods leads to two problems. First, the pole itself is a point of singularity with direction undefined. Second, due to the dependence of the stability from finite-difference numerics on the size of grid cells, when the minimum cell size decrease, the maximum stable time step will have to decrease accordingly.

For the first problem, the polar point can be treated specially in other ways or use a transformed coordinate system, in which land sits at the pole, instead (this can also eliminate restrictive time step). For the second problem, one method of allowing the use of larger time steps without instability is the filtering of high-frequency components from the model solutions at higher latitudes. Another method to increase time step without causing instability is to take measures to stretch grid cells near the poles by means of equal area grids (Wang et. al.[1]). A third method is to reduce grid numbers toward the polar points, named reduced grids. The most evident difference between equal area grids and reduced grids lies in that the latter elongates grid intervals along equal latitude circle only whereas the former elongate grid intervals both zonally and meridionally compared to normal latitude-longitude grids.

The use of reduced grids in atmospheric models has started dozens of years ago (Kuo and Nordo[2]; Gates and Riegel[3]; Kurihara[4]) and has still been studied and used (Rasch[5]). But the use of reduced grids in ocean models is relatively rare. Wickett, et al.[6]95-96 implemented a reduced grid for a low resolution global ocean general circulation model (its horizontal resolution is 2.5°×2.5°) successfully and their results are very inspiring. In this work, firstly, a similar reduced grid will be introduced to a world ocean general circulation model (Jin et al.[7]). Then it will be

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introduced to a higher resolution model LICOM (Liu[8]), which is an improved version of L30T63. Section 2 will give brief description of the IAP/LASG OGCMs and the reduced grid. Section 3 will present the results of model simulation experiments with the reduced grid introduced into the two models. Section 4 is a brief summary of the work and related short discussion.

2 MODEL DESCRIPTION AND REDUCED GRID

2.1 Model description

The presence of Antarctica allows us to define the OGCM grid southward only to about 80°S, eliminating unnecessary computation. But there is no such convenience for the north, leading to different treatment of model coverage. The first baroclinic OGCM developed at the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics(IAP), covers the scope from 60°S to 60°N (Zhang et al.[9]). The model coverage of the second generation of IAP/LASG OGCM ranges from the Antarctic continent coastline to 70°N in its original version (Chen[10]; Zhang et al.[11]) and to the near North Pole region with the North Pole treated as an island in its revised version (Yu[12]). One of the models used here is the third generation version (L30T63), whose spatial resolutions in both horizontal and vertical are remarkably enhanced and there is an artificial land cell at the North Pole to avoid the singularity of the mesh (Jin et al., 1999). The model has been coupled with a spectral T63 atmosphere general circulation model (AGCM) in open sea (Yu and Zhang[13];Yu and Liu[14]) and further extended to the whole globe under the consideration of sub-grid scale sea ice inhomogenities (Liu[15]). Another model used here is the LASG/IAP Climate Ocean Model(LICOM) which is an improved version of L30T63 and its horizontal resolution is 0.5°× 0.5° with the region near North Pole considered as land as well (Zhang et. al.[16]; Liu et. al.[17]).

2.2 Reduced grid

A reduced grid is one in which grid numbers along the zonal circle is reduced as the pole is approached to provide a more isotropic grid than the normal latitude-longitude grid. Just as mentioned above, the introduction of reduced grids can promote computation efficiency greatly. By modifying the grid such that the number of grid cells in zonal direction decreases as the pole is approached, the cells remain much more uniform in size. The use of this 'reduced grid' not only increases the allowable time step given by numerical stability condition, but also decreases the number of grid cells used by the model. Because the modifications of grid only occur at a small number of latitudes, the numerics on the majority of the grids needn't change. The smaller number of grid cells and the reduction of filter executions require less computation and thus lead to considerable saving of the model's overall amount of computation time.

In implementation of reduced grid in LASG/IAP OGCMs, the resolution reduction ratio or refinement ratios are mostly taken to be 3. As an example, the case of a ratio of 3 in the model is illustrated by Fig.1. This is based on the following considerations. At first, for the OGCMs' Arakawa B type grid, by using only the odd-integer refinement ratio, the north-south cell walls of coarse cells align with north-south cell walls of fine cells for both the tracer and velocity cells. This means that each fine cell at an interface is adjacent to one and only one coarse cell, simplifying the calculation of fluxes across interfaces and allowing a consistent set of operations for both the tracer and velocity grid variables. Second, the smaller the refinement ratio used in the reduced grid, the lesser the disparity there will be between the sizes of the smallest and the largest cells. In addition, since the minimum resolvable wavelengths as well as phase speed change less between grids when lower ratios are used, ratios as low as possible will be expected to decrease numerical errors due to interface arrangements. Thus a ratio of 3 should be the best choice to achieve uniformity of algorithms (Wickett, et al.[6]91-92).

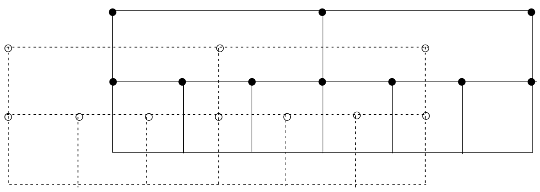

Fig.1 Tracer (solid) and velocity (dashed) grids for an interface with a refinement ratio of 3. Solid circles are tracer points and open circles are velocity points.

In implementation of the reduced grid, the original numerical methods of the ocean model needn't to be modified except for those cells adjacent to an interface between different resolutions. For these cells, the finite-difference numerics are modified and interpolation and average calculations are needed. Since Wickett et al.[6]93-94's work shows that local errors in the vicinity of the interfaces, especially for the zonal velocities, are minimized by using linear interpolation of coarse grid values in the zonal direction, the linear interpolation method is also used in this work.

Implementation of the reduced grid in L30T63 is only a tentative experiment to accumulate experiences and make preparations for the ultimate aim, that is, to extend model coverage to the whole world in the finer resolution model LICOM without limitation of unpleasantly small time step. In Implementation of reduced grids in L30T63, there is only one interface at nearly 65°N. In Implementation of reduced grid in LICOM, there are 3 interfaces altogether, lying at 86.5°N, 81.5°N and 65.5°N respectively, with resolution 0.5°×0.5° in model domain left for tracer variables.

3 RESULTS OF SIMULATION EXPERIMENTS

3.1 Experiment results in L30T63

The model is integrated for nearly 900 years from an intermediate restart dataset. The global mean annual kinetic energy and global mean annual temperature are chosen as indicators to trace the model's conservative characteristics. At the first 40 years, the global annual kinetic energy decreases sharply (as illustrated by Fig.2a). After that, it increases with growth rate decreasing gradually and at about 600th year it begins reaching nearly the quasi-equilibrium state. The global mean annual temperature experiences sharp increase in the first 100 years (See Fig.2b). After that, the increasing rate decreases gradually and after about 600 years the global mean annual temperature also begins reaching nearly the quasi-equilibrium state. It can be drawn from the curves of the two indicators that the model can reach the quasi-equilibrium state after sufficiently long integration and will not blow up after the implementation of reduced grids. The diagnostics presented above provide some measure of the overall stability of the OGCM. The relative stability of long integration is a necessary condition for the use of the model in studies of climate variability and change.

Results of four oceanic fields-sea surface temperature, barotropic stream function, meridional overturning stream function and sea surface height are inspected and they show no apparent problem in the reduced grid model (figures omitted). Emphasis of analysis will be put on the differences between the reduced grid model and the original one.

From the differences of sea surface temperature from two models (figures omitted), It is clear that, as is expected, the apparent difference zone is confined to high northern latitudes. In March, the biggest differences occur near the Norway Sea and Laborador Sea. In September, the biggest differences occur near the Nansen Sea. These results are related to the situations that there are three passages of grids in the Greenland Sea and Norway Sea in the reduced grid model whereas the passage of Bering Strait has been closed. But the differences of barotropic stream function (figure omitted) don't show apparent local confinement features, this may partly be due to the fact that barotropic stream function itself is small in high northern latitudes.

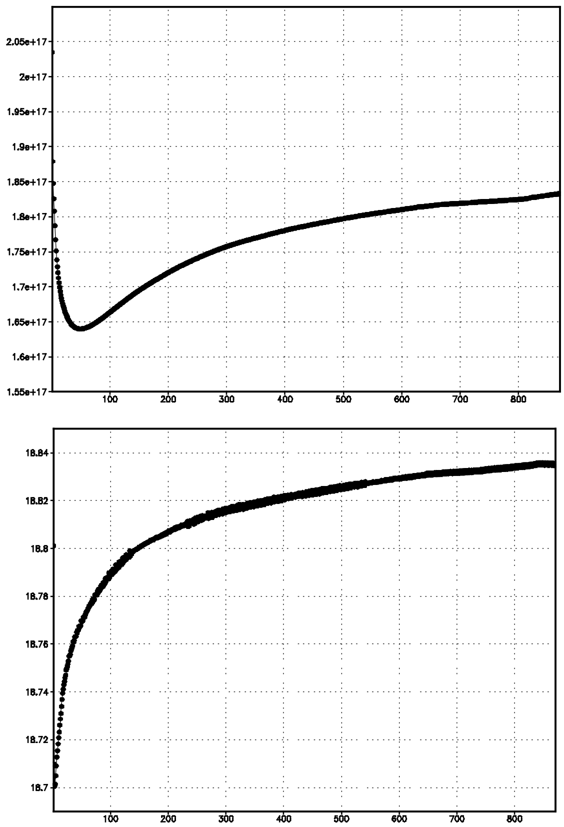

Fig.2 Curves of variation of global total annual kinetic energy and global mean annual sea surface temperature. Unit of horizontal axis is year. (a) Kinetic energy. Unit of vertical axis is J. (b) Temperature. Unit of vertical axis is degree in Celsius.

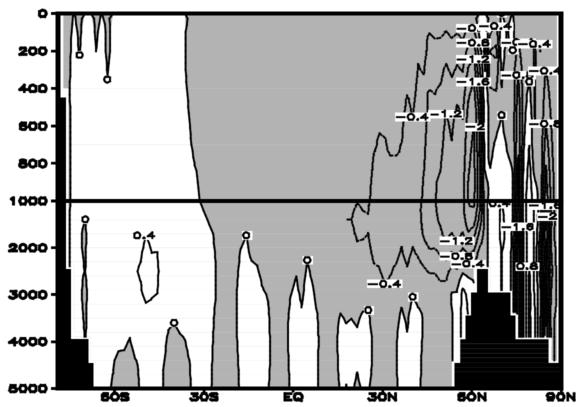

Fig.3 Differences of meridional overturning stream function between results from the reduced grid model and those from the original one. Contour interval is 0.4 Sv and areas of minus values have been shaded.

Differences of meridional overturning stream function (as illustrated in Fig. 3) show that the influence of reduced grids on meridional currents can extend as south as 30°N and the maximum difference occurs below 800 m. The main effect of reduced grid introduction is weakening the meridional overturning stream function with the exception of an about 10 latitude degree belt near 70°N below 800 m. The differences of the two version models are acceptable compared to their original amplitudes.

The introduction of reduced grids contributes to the increasing of sea surface level with its effect extending as far as 30°N in the Atlantic Ocean. The maximum difference can reach 8 cm in the Arctic Ocean (figures omitted).

The differences of zonal mean ocean temperature and salinity (as illustrated in Fig.4) are mainly confined to nearly north of 60°N. Above 1000 m, the introduction of reduced grids mainly gives rise to increased ocean temperature and its effect is on the contrary below 1000 m. However, the introduction of reduced grids is responsible for the decreasing of salinity from ocean surface to ocean bottom.

Results of statistical significance test (student t test) show that, with a confidence level of 90%, differences of almost all variables analyzed above are insignificant (the exception is for the sea surface level in the Arctic Ocean).

One major advantage of the reduced grid is to increase numerical stability and to save computation time. Although the time steps are the same in the simulations, with the introduction of reduced grid in L30T63, a single model run can save about 20% of total computation time. Four additional experiments with enlarged time step of integration (varying from 2 to 5 times of the original time step respectively) are performed. Three integrations (with 2 to 4 times of the original time step respectively) were conducted for 100 years with no obvious phenomenon of instability appearing in the results. The left one cannot be finished due to growth of instability.

3.2 Experiment results in LICOM

In section 3.1, it is shown that the reduced grid can be introduced into the framework of L30T63 successfully. Since LICOM is an improved version of L30T63, it is expected that the reduced grid can also work well in LICOM. The experiment results in LICOM with implementation of reduced grid are given

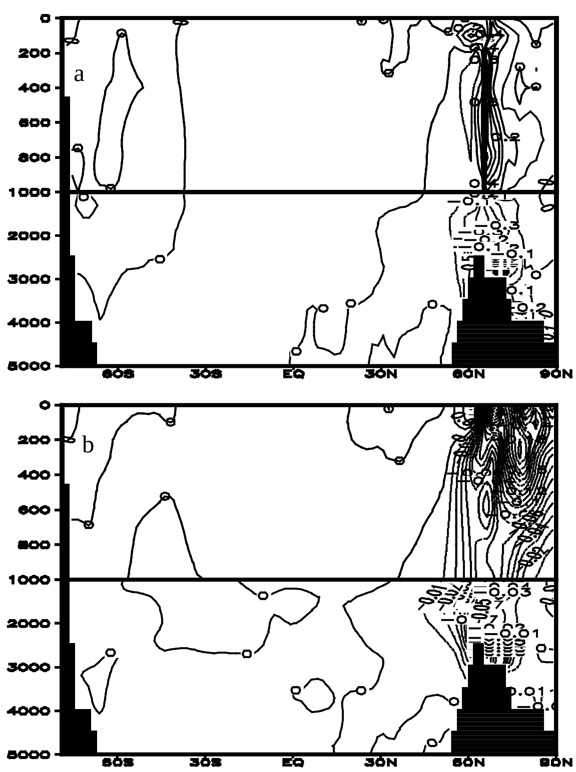

Fig.4 Differences of zonal mean ocean temperature and salinity between results from the reduced grid model and those from the original one. (a) Temperature. Contour interval is 0.1 Celsius. (b) Salinity. Contour interval is 0.01psu.

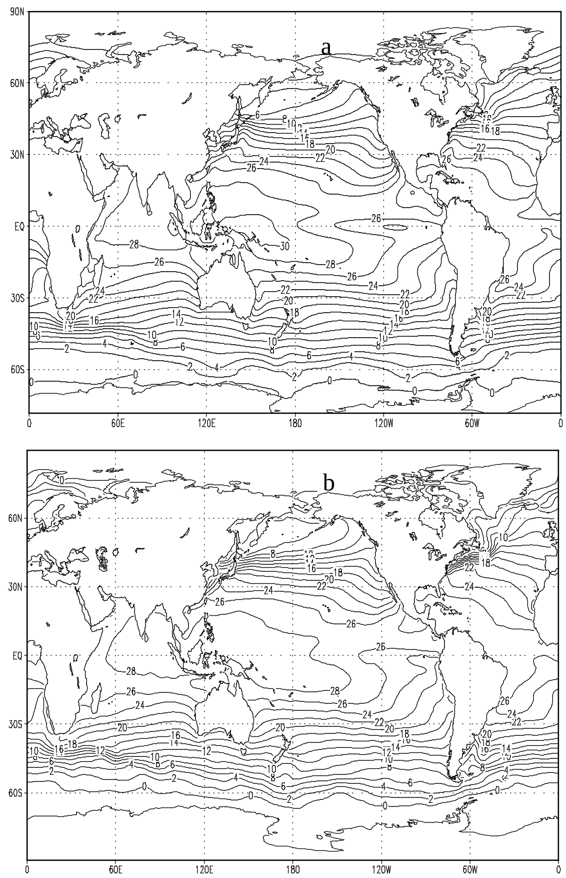

Fig.5 Distribution of sea surface temperature from model result (a) and observation result (b). Contour intervals are all 2K.

below.

The pattern of sea surface temperature distribution is similar to that of the original model with the region near North Pole considered as land (figure not shown). Because most part of sea surface temperature in high northern latitudes is close to freezing point, its pattern of distribution cannot be discerned well with contour interval of 2K. Compared to global ocean hydrography(equivalent to Levitus) with a high quality Arctic Ocean dataset(Steele, et. al.[18]) result (Fig.5b), simulated sea surface temperature is warmer in the west Pacific warm pool and cooler in places near Antarctica coast obviously. Both patterns of sea surface temperature distribution in high northern latitudes where the reduced grid is employed share similar characteristics.

The barotropic stream function shown in Fig.6 is

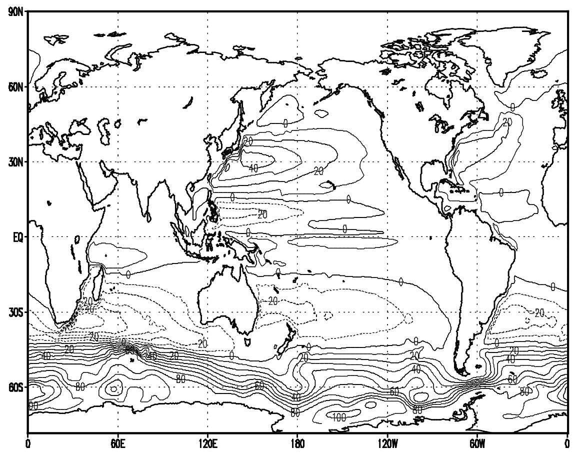

Fig.6 Distribution of barotropic stream function. Contour interval is 10 Sv.

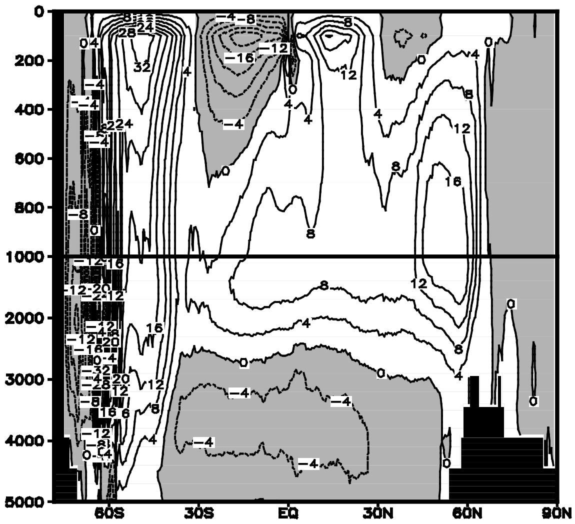

Fig.7. Distribution of global meridional overturning stream functions. Contour interval is 4 Sv.

the vertical integral of the ocean mass transport and is mainly associated to the distribution of the wind stress curl. North of 60°N, barotropic stream function is very week (less than 10 Sv). In other parts, the pattern is similar to that of the original model with the region near North Pole considered as land.

Fig.7 shows the zonal mean meridional overturning stream functions for the World Ocean and Atlantic Ocean. North of 60°N, global meridional overturning is very week (less than 4 Sv). Likewise, in other parts, the pattern is similar to that of the original model with the area near North Pole considered as land. For Atlantic meridional overturning, it is difficult to distinguish the differences between results of the two models (figure omitted).

The distribution of sea surface height, which has been one of the prognostic variables of the LASG/IAP ocean models free from the rigid-lid approximation. With the introduction of reduced grid, the model is able to simulate characteristics of the sea surface height distribution within Arctic Ocean. It is seen that the minus sea surface height in Barents Sea and Kara Sea is reproduced well but the sea surface height characteristics corresponding to the Beaufort Gyre cannot be reproduced (figure omitted).

Fig.8a and Fig.8b show the zonal mean temperature and salinity respectively. In high northern latitudes, the features of low temperature from sea surface to sea bottom and relatively high salinity below 1000 m are reproduced quite well. In other parts, both patterns are similar to those of the original model in which the region near North Pole is considered as land.

Close checks are made for temperature and meridional current in the region near the 3 interfaces (86.5°N, 81.5°N and 65.5°N). Results of four zonal-vertical cross sections (along 88ºN, 83ºN, 67ºN and 64ºN zonal circles respectively) and locally enlarged horizontal distributions from 60ºN to 89°N at three levels (50 m, 500 m and 1000 m) in the vertical show that no signals of severe oscillations appear.

With time steps being reduced to one tenth of the original size and the model domain extended to 89°N with normal grids (i.e. no reduced grids are employed), an additional experiment is carried out with LICOM. Unfortunately, the integration can proceed to no more than one year at most. This is predicable since the length of one degree along the zonal circle at 65°N is about 24 times of that at 89ºN.

4 SUMMARY AND DISCUSSIONS

Reduced grid is implemented in two LASG/IAP world ocean general circulation models-- L30T63 and its improved version LICOM. In the experiment with L30T63, with time step unchanged though, execution

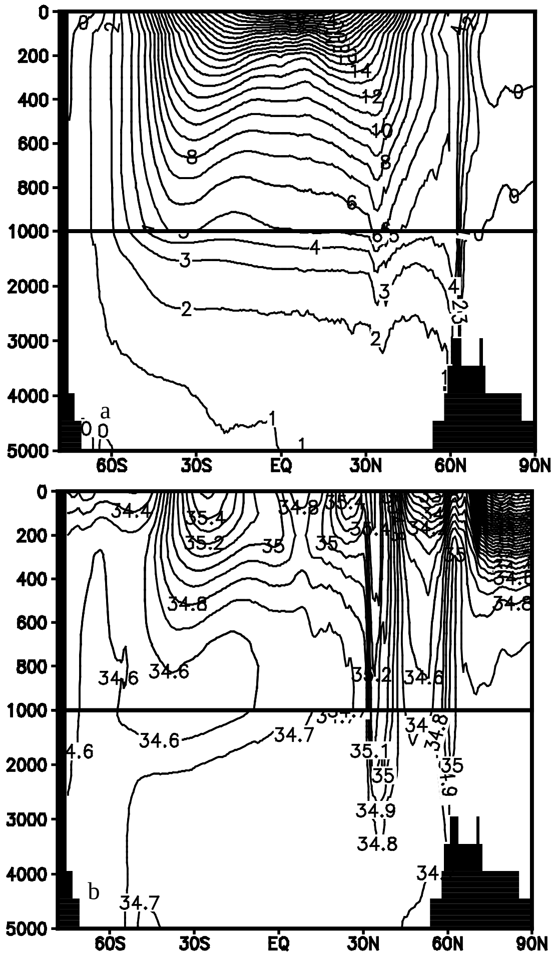

Fig.8. Distribution of zonal mean ocean temperature and salinity. (a) Temperature. Contour interval is 1 Celsius. (b) Salinity. Contour interval is 0.1psu.

time per single model run is shortened significantly owing to the decrease of grid number and filtering execution in high latitudes. In the experiments of reduced grid, execution time of filtering is reduced greatly but it cannot be removed completely still. The main effect of introduction of reduced grid is weakening the meridional overturning stream function. The differences of zonal mean ocean temperature and salinity are mainly confined to around north of 60ºN. Above 1000 m, the introduction of reduced grids mainly contributes to the increasing of ocean temperature and its effect is just reversed below 1000 m. However, the introduction of reduced grids contributes to decreased salinity from ocean surface to ocean bottom. In the experiment with model LICOM, with the model's original time step unchanged, the model covered area is extended to the whole globe from its original version with the region near North Pole considered as land. Compared to global ocean hydrography (equivalent to Levitus) with a high quality Arctic Ocean dataset result, both patterns of sea surface temperature distribution in high northern latitudes where the reduced grid is employed share similar characteristics. With the introduction of the reduced grid, the model is able to simulate characteristics of the sea surface level distribution within the Arctic Ocean. The negative sea surface level in the Barents Sea and Kara Sea is reproduced well but the sea surface level characteristics corresponding to the Beaufort Gyre cannot be reproduced. In addition, in high northern latitudes, the features of low temperature from sea surface to sea bottom and relatively high salinity below 1000 m are reproduced quite well.

The experiment results of both model show that the reduced grid can work well in the models' framework. With the introduction of reduced grids, the integration time steps can be enlarged and calculation efficiency can be promoted greatly. In the experiments with L30T63, the time step of integration can be quadrupled at most in reduced grids with a refinement ratio of 3. This is of great value especially for finer resolution models. For example, in LICOM, 1 degree interval along the equator zonal circle is about 111 km whereas the same 1 degree interval along the 89.5°N zonal circle is only about 1 km. If special measures are not taken, it is difficult to extend the model horizontal area to the whole globe even if strict filtering and smoothing is employed. With the enhancement of computing capacity, the model resolution of LICOM will be improved further in the near future and the problem of converging meridians towards the poles will be more urgent to deal with. From the experiment results in section 3, it seems that the reduced grid might be one of the practical choices to deal with that problem in frameworks based on LASG/IAP world ocean general circulation models.

In the original model, isopycnal mixing parameterizations, which simulate the natural mixing of model quantities along surfaces of constant density rather than just horizontally, are included. But, at present, isopycnal mixing parameterizations haven't been adapted to work with the reduced grid and are not used here. This also gives rise to the differences of simulation result between the model L30T63 and its version of reduced grid. In addition, simulation experiments of longer integration for reduced grid LICOM are also needed.

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