Multi-Scale Weather/Climate Simulations with Coupled Non-hydrostatic Atmosphere-Ocean GCM on the Earth Simulator

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The coupled non-hydrostatic atmosphere-ocean-land model has been developed in the Earth Simulator Center. Outline of the coupled model is introduced and its characteristics are presented. Results from preliminary validations including forecasting experiments are described. Progresses in model development from view points of numerical schemes and physical rain process are presented. After optimizing computational performance, performance analysis has been performed on the Earth Simulator. As the results of optimization, ultra high performance with the coupled non-hydrostatic atmosphere-ocean has been achieved. Computational performance of the coupled non-hydrostatic atmosphere-ocean model has attained about 52–55% of theoretical peak performance.

Keywords: Coupled atmosphere-ocean general circulation model, weather, climate, forecasting, high performance computing, the Earth Simulator

1. Introduction

Intense research effort has been focused on understanding weather/climate system using coupled atmosphere-ocean general circulation models. It is widely accepted that the most powerful tools available for assessing future weather/climate are fully coupled atmosphere-ocean models. Earth Simulator Center (ESC) has been developed coupled non-hydrostatic atmosphere-ocean general circulation model to be run on the Earth Simulator with both ultra high resolution and high performance computing. Qualified information from results of those simulations might provide significant impacts for forecasting/projecting of weather and climate.

In this report, we show a draft configuration of the coupled non-hydrostatic atmosphere-ocean model which has developed in ESC in section 2. Simulation results and computational performance of the coupled non-hydrostatic atmosphere-ocean model are presented in section 3 and 4, respectively. Furthermore, progress in developing the coupled non-hydrostatic atmosphere-ocean model have been introduced in section 5.

2. The coupled Non-hydrostatic Atmosphere-Ocean model and Non-hydrostatic/ hydrostatic OGCM

The atmosphere component is mainly compromised of the non-hydrostatic dynamical core with fully compressive flux form and Smagorinsky-Lilly type parameterizations for sub-grid scale mixing, Reisner type cloud microphysics with mixed phases, cumulus convective processes and simple radiation scheme. We can not describe the detail configuration in this report, however, further information can be found in [1, 2, 3, 4]. In the ocean component, the in-compressive hydrostatic configuration with the Boussinesq approximation can be utilized based on [5, 6]. Outline of configuration of the non-hydrostati/hydrostatic ocean model is described in [3].

Regional version for both the atmosphere and ocean components is introduced to any target regions on the sphere, because Coriolis and metric terms are introduced in the formulations of the regional version. Several boundary conditions are available with one way or two way nesting schemes.

Not only the global models but also the regional models, coupled non-hydrostatic atmosphere-ocean model has been introduced. In the regional coupled model, a regional atmosphere component is coupled to a regional ocean component with the same horizontal resolution. Lateral boundary condition for each regional component is given from a wider regional or global model with one way or two way nesting schemes.

Interface between atmosphere and ocean components is coupled without any correction through transferring momentum, heat, fresh water fluxes and sea surface temperature. Since in general, time step in an ocean component is set longer than it of an atmosphere component, momentum, heat fluxes and fresh water fluxes are time-averaged during defined time. The averaged fluxes are transferred to the ocean component as upper boundary condition. Sea surface temperature, which is defined by a temperature at the most upper layer, is given to the atmospheric component as constant heat source during the same time interval.

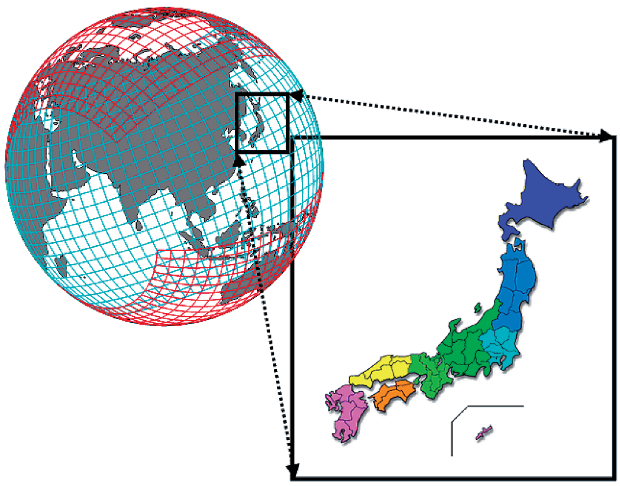


Fig. 1 A schematic figure of global and regional models with nesting schemes.

3. Validation Experiments: Forecasting of Typhoon Tracking and Intensity with the Fully Coupled Model

The coupled non-hydrostatic atmosphere-ocean model was validated by performing 120 hours forecasting experiments of tracking and intensity of typhoon ETAU in 2003. An initial condition was defined at 15UTC on 06th Aug 2003 and experiments were integrated until 15UTC on 11th Aug 2003. In Japan region sorrounded by 19.582N – 49.443N and 123.082E – 152.943E, the non-hydrostatic atmosphere and ocean components were coupled with 2.78 km resolution for horizontal. 32 and 44 vertical layers were used for the atmosphere and ocean components, respectively. In the atmosphere component, only cloud micro-physics was used in spite of any cumulus parameterization.

Initial data of atmosphere in the Japan region was made by interpolation from Grid Point Value (GPV) data, which was provided with 100 km horizontal resolution by Japan Meteorological Business Support Center. For global atmos-

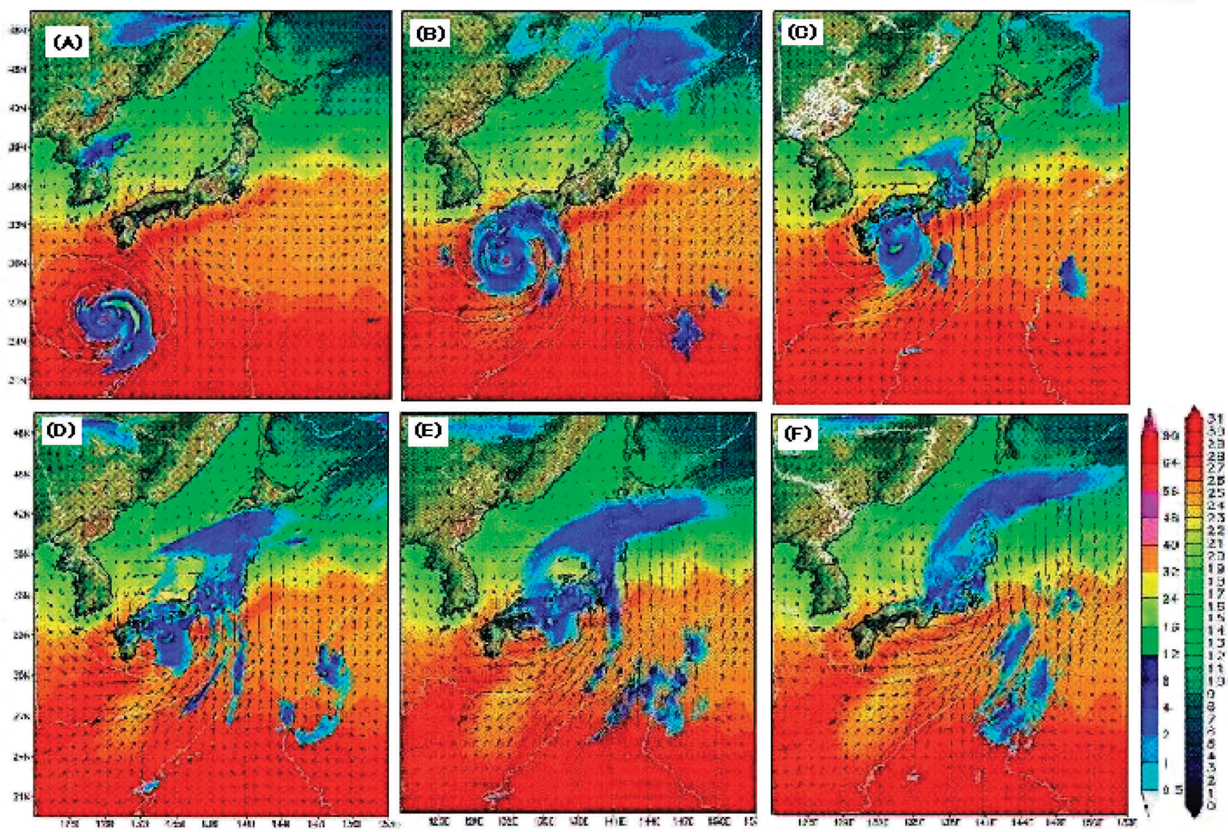


Fig. 2 Precipitation distribution (mm/h), wind velocity with black allow and SST distribution during typhoon ETAU attacked Japan region. Left-hand side color bar shows volume of precipitation and right-hand side color bar presents SST temperature.

phere forecasting simulation, the GPV data was used to an initial data with 5.5 km horizontal resolution and 32 vertical layers by linear interpolation. Global atmosphere simulation with 5.5 km horizontal resolution had been performed and its results was used as lateral boundary condition of the atmosphere component in Japan region. Boundary data in the above Japan region was input from results of the global forecasting simulation with 5.5 km horizontal resolution every large time step of the 3rd order Runge-Kutta method.

In the ocean component, an initial data was prepared after spinning an ocean state up from a state of without motion. Spin up has been performed by 15 years integration by using climatological surface boundary data of World Ocean Atlas (WOA). After 15 years integration, 10 days integration from 27th July in 2003, which was earlier than the initial state of forecasting, had been executed with 6 hourly data provided by NCAR. Although 10 days integration might be considered too short to represent surface structure of the ocean, especially mixed layer, its condition was adopted in these experiments as the first step. After spinning the ocean state, initialized atmosphere and ocean components were coupled in above Japan region without any flux correction.

Figure 2 (A)–(F) shows time series results of 120 hours forecasting with the coupled model in Japan region. Distribution of blue gradation shows precipitation distribution whose unit is mm/h. Fine structure such a rain band has been represented in (A). Those distribution structure showed drastic change as a typhoon attacked and went through Japan. Arrows direction and length show direction and intensity of wind on the lowest grid point whose height was 32 m over ground. In the ocean, SST response to a typhoon was showed in (B)–(F). Oscillation due to a typhoon disturbance was recognized not only in SST but also in vertical velocity or temperature distribution (data now shown). These experiments were considered as the first case with such a ultra high resolution with fully coupled models.

4. Ultra High Performance Computation on the Earth Simulator

In this project, we have been intense to development of the coupled model with ultra high performance computation on the Earth Simulator. In order to considerable parallel, not only each component of the coupled model but also coupling architecture should be considered to perform with high efficiency.

The following cases were selected up in order to measure computational performance on the Earth Simulator.

CASE 1: The coupled non-hydrostatic atmosphere-ocean model with 1.5 km resolution in horizontal direction and 72 vertical layers for Japan region.

CASE 2: The stand-alone global atmosphere component with 2.26 km horizontal resolution and 32 vertical layers.

CASE 3: The developed stand-alone ocean component with 1.4 km resolution in horizontal direction and 40 vertical layers for the North Pacific basin and region between the equator and 30°S.

In both cases of CASEs 1 and 2, only cloud microphysics was used in the atmospheric component. Therefore, the atmospheric component has performed as a cloud resolving/permitted model. Through processes of development of the coupled mode, memory in atmosphere, ocean and the coupled model was designed to be optimized without redundant (details of the optimization technique are not shown in this report due to limited pages). The number of grid points in each CASEs of the above was constrained by the maximum memory used in the each model on 512 nodes, which are usually available nodes on the Earth Simulator.

Earth Simulator users can use the performance analysis tool FTRACE (Flow TRACE) which is a built-in counter in the Earth Simulator. By using FTRACE, we can obtain the data such that the number of floating-point operations and vector instructions, clock counts, averaged vector loop length and delay time due to out-of-cache operations. We use this tool to measure the computational performance of each CASEs. Especially, the flops values of the all CASEs are determined on the basis of the performance information output for each MPI process. Each flop value can be derived as the total number of floating point operations for all the processors divided by the maximum elapsed time. Computational performances for all CASEs are shown in Table 1.

In Table 1, the coupled non-hydrostatic atmosphere-ocean model has achieved very excellent sustained performance of 17.07 Tflops, which is 52.1% of the theoretical peak performance on 512 nodes of the Earth Simulator. For both of stand alone non-hydrostatic atmosphere and ocean components have attained well performance on the Earth Simulator. Especially, in global simulation with stand alone non-hydrostatic atmosphere component shows that sustained performance presents 18.74 Tflops, which is 57.2% of the theoretical peak performance on 512 nodes. This result shows that the well sustained performance is obtained not only for the coupled model but also both stand alone atmosphere and ocean components on wide range of system configurations of the Earth Simulator.

When horizontal resolution of the atmospheric component is same as it of the oceanic component, it is the easiest way to conserve total amount of fluxes throughout whole integration. In simulations with the coupled model such as in CASE 1, the shared memory architecture within each node was used for communication of fluxes between atmosphere and ocean components. Table 2 shows that cost of communication between atmosphere and ocean has been achieved.

Table 1 Computational performance on the Earth Simulator.

CASE identifies a name of experiments; TPN is the total number of nodes; TAP is the total number of arithmetic processors; grid pts is the number of grid points in the each CASE; Mflops/AP is the corresponding megaflops per an arithmetic processor; Vector length is averaged length of vector processing; V. OP ratio is the vector operation ratio; Tflops is the total telaflops sustained over the duration, exclusive of I/O; Peak ratio is the percentage of total tela flops to the theoretical peak performance; Parallel ratio are estimated by comparing with elapse time on 256 or 207 nodes, and Parallelization efficiency and Speedup are measured by degradation in elapse time relative to single arithmetic processor.

CASE	TPN	TAP	grid pts	Mflops/AP	Vector Length	V.OP ratio	Tflops	Peak ratio	Parallel ratio	Parallelization efficiency	Speedup
CASE1	512	4096	3,662,807,040	4166.7	229	99.30%	17.07	52.10%	99.9973	90.00%	461
	384	3072		4273.8	229	99.30%	13.13	53.40%	99.9968	92.30%	354.6
	256	2048		4401.9	229	99.30%	9.02	55.00%	—	94.80%	242.6
CASE2	512	4096	2,713,190,400	4575.2	228	99.50%	18.74	57.20%	99.9983	93.60%	479.1
	384	3072		4606.1	228	99.50%	14.15	57.60%	99.9969	95.10%	365.2
	256	2048		4692.4	228	99.50%	9.61	58.70%	—	96.70%	247.5
CASE3	498	3984	4,718,592,000	3629.3	240	99.30%	14.46	45.40%	99.9940	80.60%	401.3
	398	3184		3568.5	240	99.30%	11.36	44.60%	99.9890	83.80%	333.7
	207	1656		4234.3	240	99.30%	7.01	52.90%	—	90.90%	188.2

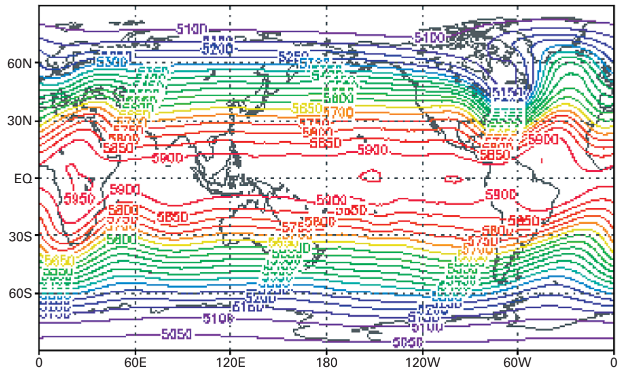
Table 2 Computational cost balance on 512 nodes of the Earth Simulator in the coupled non-hydrostatic atmosphere-ocean model.

Component	Elapsed time (sec)	Ratio to total elapsed time
Atmosphere component	460.641	97.09%
Ocean component	13.548	2.86%
Data exchanging for copling	0.256	0.05%
Total elapsed time	474.445	—

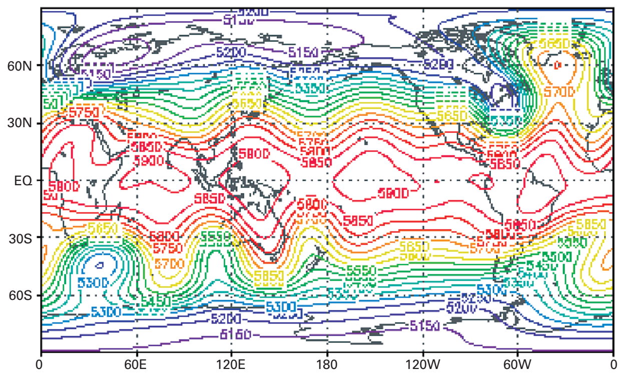
Table 2 suggests that optimization of an atmospheric is dominant in order to realize high performance computation under the same lateral resolution

5. Progress in Model Development

In model development progress, two subjects of main results are described in this report. The first progress is the introduction of the advanced numerical scheme: Cubic Interpolated Propagation-Conservative Semi-Lagrangian scheme with Rational function which is called CIP method. The CIP method of characteristics has been used to solve the hyperbolic equation for long. It describes the rapid waves, such as the acoustic wave and gravity wave, in the viewpoint of their direct relationship to the nonlinear dynamics. In the field of geophysical fluid dynamics, we use the characteristic method to deal with the gravity wave in a spherical shallow water model with topography, and solve the advection-type equation with the CIP method. After applied to the Williamson test case 2, 5 and 6, it shows robust results even if for the large Courant number situation. The appearance of topography term in the characteristic equation makes the computation some inefficient, because the topography is out of the restriction of the characteristic condition. The following Figure 3 shows the horizontal fluid height of Williamson test 5 on the sphere after day 7 and day 15 with a CFL number of 1.5. The spatial resolution is 0.35294 degree, and a time step of 159.03 s is adopted. These results suggest that further long time step might be available without high accuracy for numerical computation.



(a) after 7days integration with CFL = 1.5



(b) after 15 days integration with CFL = 1.5

Fig. 3 Results of Williamson test 5 with horizontal resolution 40 km.

The next progress showed the impact of turbulence effect on the particle collision in cloud. Rain process is the most important and difficult physical process in weather/climate models. In the current status, we use cloud microphysics of bin-type models. However, in ultra high resolution model, we should reconsider rain processes whether the model is suitable or available. We focused on turbulence effects on collisions of cloud droplets and studied whether the inclusion of the turbulence effect improves the timing and distribution of precipitation. We referred simulations named as RUN-T using our new developed collision kernel model with the turbulence effects. Simulations named RUN-NoT have performed using the hydrodynamic kernel of equation without the turbulence effects. Figure 4 shows the estimated rainfall rates on the mountain surface. In RUN-T, the rainfall rates are larger than those in RUN-NoT at the upstream slope (-2 km $\leq X - x_m \leq 0$ km) and behind the ridge (2 km $\leq X - x_m \leq$ 4 km). The spatial-averaged rainfall rate over the mountain is 1.25 mm/h in RUN-T, which is 20% larger than 1.05 mm/h in RUN-NoT.

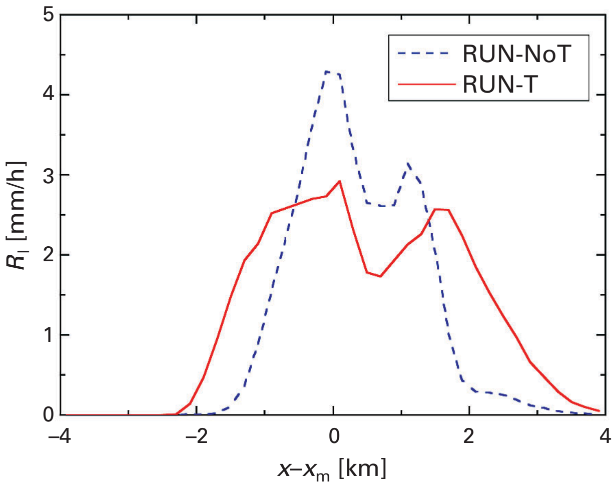


Fig. 4 Spanwise-averaged rainfall rates over the mountain.

Results suggest that the turbulence promotes the particle collision growth and produces larger amount of rain in orographic precipitation process.

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地球シミュレータ用・非静力学・大気海洋結合モデルの開発

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キーワード：Coupled atmosphere-ocean general circulation model, weather, climate, forecasting, high performance computing, Earth Simulator

地球シミュレータの性能を最大限に活用可能な非静力学・大気海洋結合モデルを開発した。大気、海洋大循環モデルは、それぞれ地球シミュレータセンターでスクラッチから開発したシミュレーションコードであり、大気、海洋ともに全球10km以下の水平解像度でのシミュレーションを前提として開発を進めて来た。平成17年度は、積雲パラメタリゼーションを用いず、雲微物理過程を用いた大気モデルと海洋モデルを結合して、非静力学・大気・海洋結合モデルのプロトタイプを完成した。

本結合モデルの物理的性能を検証するために、日本領域において大気、海洋とも水平2.78km、鉛直76層の設定において、2003年台風10号の進路と強度の予測を、8月6日から120時間(5日間)行い、妥当な結果が得られることを確認した(図1)。

本結合コードは、大気、海洋の各コンポーネントが非常に高い計算性能を実現しており、大気海洋結合コードとしても、実用上の限界値に近い理論ピーク性能比である52～55％の非常に高い計算性能を達成した(表1)。

モデル開発においては、さらに精度の高い数値計算手法である特性線CIP法の球面上への拡張開発を世界に先駆けて推進し、また、降雨過程の雨粒の生成過程に乱流の効果を導入した新しい雲物理過程の開発、加えて、都市気象の特性を考慮したモデルの導入とそのインパクト解析など、新しい成果が得られている(結果は省略)。

今後は、さらなる計算、物理スキームの高精度化とともに、スケールの異なる現象をどのように総合的に扱うべきかを念頭に入れた大気海洋結合シミュレーションコードの開発を推進する予定である。

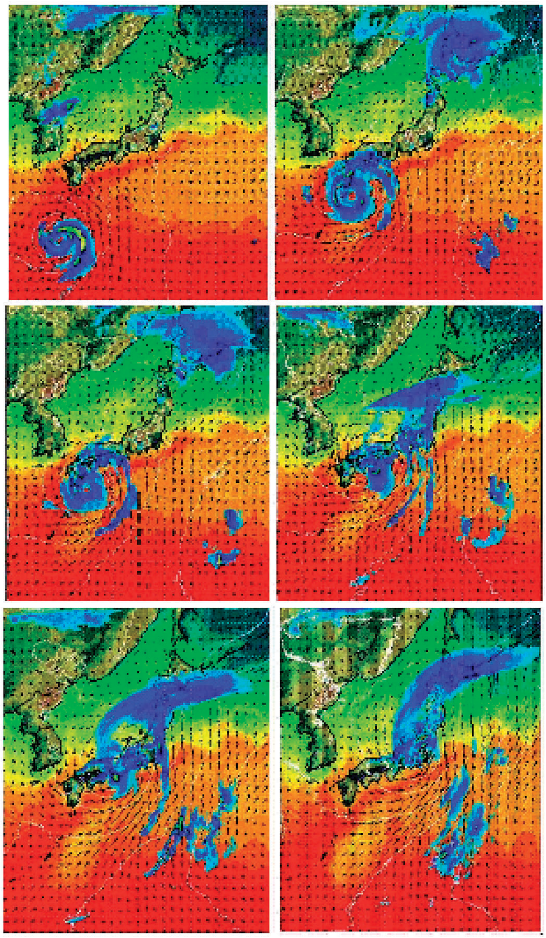

図1　本結合モデルを用いた、水平解像度2.78km、鉛直76層の解像度における2003年台風10号の進路と強度の120時間シミュレーション予測結果。

表1　地球シミュレータ上における本結合コード、大気、海洋コードの計算性能。(表中の記号は、本文を参照いただきたい。)

CASE	TPN	TAP	grid pts	Mflops/AP	Vector Length	V.OP ratio	Tflops	Peak ratio	Parallel ratio	Parallelization efficiency	Speedup
結合コード	512	4096	3,662,807,040	4166.7	229	99.30%	17.07	52.10%	99.9973	90.00%	461
	384	3072		4273.8	229	99.30%	13.13	53.40%	99.9968	92.30%	354.6
	256	2048		4401.9	229	99.30%	9.02	55.00%	—	94.80%	242.6
大気コード	512	4096	2,713,190,400	4575.2	228	99.50%	18.74	57.20%	99.9983	93.60%	479.1
	384	3072		4606.1	228	99.50%	14.15	57.60%	99.9969	95.10%	365.2
	256	2048		4692.4	228	99.50%	9.61	58.70%	—	96.70%	247.5
海洋コード	498	3984	4,718,592,000	3629.3	240	99.30%	14.46	45.40%	99.9940	80.60%	401.3
	398	3184		3568.5	240	99.30%	11.36	44.60%	99.9890	83.80%	333.7
	207	1656		4234.3	240	99.30%	7.01	52.90%	—	90.90%	188.2