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ORIGINAL RESEARCH ARTICLE

“Noise” in climatologically driven ocean models with different grid resolution

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Summary The internally generated variability in the climate system, which is unrelated to any external factors, can be conceptualized as “noise”. This noise is a constitutive element of high-dimensional nonlinear models of such systems. In a three-layer nested simulation, which is forced by climatological (periodic) atmospheric forcing and includes an (almost) global model, a West-Pacific model, and South China Sea (SCS) model, we demonstrate that such “noise” builds also ocean models. They generate variability by themselves without an external forcing. The “noise” generation intensifies with higher resolution, which favors macroturbulence.
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1. Introduction

The climate system is a high-dimensional macroturbulent system, which features many nonlinear processes. Based on the concept of the “stochastic climate model” (Hasselmann, 1976) the trajectory of the climate system can be described as that of an inert system subject to internally generated variations, which may be conceptualized as “noise”. Here, we use the term “noise” to refer to variability which cannot be traced back to external “drivers”. Instead, the variability is generated internally.

The net-effect of very many degrees of freedom interacting through many non-linearities is the creation of variability, which is well described by the mathematical construct of random processes. If this variability is really stochastic, or, in other words: if God is really rolling a dice, is irrelevant, as we cannot disentangle the high-dimensional dynamics, but we find that the description as stochastic noise is doing the job.

Since macro-turbulence is an inherent part of the dynamics of the climate system then such “noise” should be present also in such models. Without such “noise”, the climate system will be incompletely described and may lack

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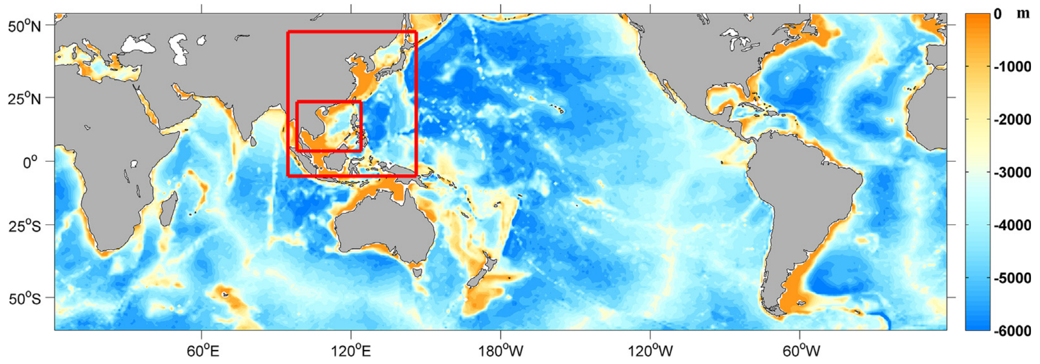

Figure 1 The regions of the three-layer nested simulation, which includes an (almost) global model, a West-Pacific model, and a South China Sea (SCS) model.

Table 1 Spatial averages of the daily BS variances and SSH variances in the SCS simulated by the three models.

	BS variance [Sv^2]			SSH variance [m^2]		
Model	Global	WP	SCS	Global	WP	SCS
Spring	0.5539	0.6141	1.1015	0.0004	0.0004	0.0005
Summer	1.0083	1.3374	2.2178	0.0010	0.0010	0.0012
Autumn	0.4382	0.6262	1.1739	0.0004	0.0004	0.0005
Winter	1.1281	1.3245	1.6055	0.0010	0.0009	0.0011

significant features. Therefore, the recognition of the "noise" is helpful for scientists to explore the climate dynamics and modeling.

"Noise" represents for certain issues a nuisance (hiding real effects, as for instance when deriving eddy statistics from satellite data) but is also constitutive for the dynamical properties of the climate system (von Storch et al., 2001). "Noise", i.e., unprovoked, internal variability, has significant implications for issues like "detection and attribution of climate change" (Hasselmann, 1993) and for numerical experimentation with climate models (Chervin and Schneider, 1976; Weisse et al., 2000).

Since the nonlinear high-dimensional ocean system is part of the climate system, we suggest that the ocean system should also generate significant "noise", which is unrelated to any external factors (atmospheric forcing, lateral boundary conditions, and so on). Moreover, since "noise" takes place in climate models describing macro-turbulence, we suggest that the formation of "noise" in the ocean model may intensify with ocean model resolution increasing.

Some may find our suggestion about noise in ocean models almost trivial; indeed, in the framework of the stochastic climate model, it is mostly so. However, most climate modelers hardly know about the stochastic climate model, and it seems that many climate scientists are not aware of this unprovoked variability. There seem to be quarter in the climate science community, where efforts are made to find "explanations" for whatever what appears as not normal, but which may be simply the effect of this internal variability.

In the present study, we use a three-layer nested numerical simulation, which is subject to climatological atmospheric forcing, to test our hypothesis. The concerned region in this study is the South China Sea (SCS). The existing and intensity of "noise" in the SCS will be discussed in the framework of this three-layer nested simulation. The model resolutions change from coarse to fine, so the "noise" generation is conditioned by different model resolution.

The present paper is organized as follows. A brief introduction the simulation setup is given in Section 2. The results of the simulation and "noise" in the simulation are presented in Section 3. Conclusions are summarized in Section 4.

The subject of this paper is not finding out how well the simulations of the dynamics of the SCS are reproducing observed features. Such studies have been plentiful (e.g., Wang et al., 2006; Zhang and von Storch, 2016), but the issue dealt with here is merely the conceptual issue of "noise" generation.

2. Simulation setup

The ocean model used in this study is the Hybrid Coordinate Ocean Model (HYCOM). The HYCOM used in this study is a primitive equation ocean general circulation model. Its vertical coordinates are isopycnic in the open, stratified ocean, but smoothly change to z coordinates in the weakly stratified upper-ocean mixed layer, and change to terrain-following sigma coordinate in shallow water regions, and back to z-level coordinates in very shallow water (Bleck, 2002). The vertical mixing schemes chosen in this paper is the K-Profile Parameterization (KPP) scheme (Large et al., 1994). The KPP scheme provides mixing throughout the water column with an abrupt but smooth transition between the vigorous mixing in the surface boundary and the relatively weak diapycnal mixing in the ocean interior.

A three-layer nested numerical simulation in HYCOM is performed, with an almost global model (60°S—54°N, 180°W—180°E) with 1° grid resolution, an embedded West-Pacific (WP) model (6°S—48°N, 95°E—146°E) with 0.2° grid resolution, an embedded South China Sea (SCS) model (4°N—24°N, 98.4°E—124.4°E) with 0.04° grid resolution. The different integration regions are shown in Fig. 1.

The global model starts from the state of zero velocity and is run 50 model years. After 25 model years, the global model reaches a (cyclo) stationary state. The fields of last 25 model years in the global model are taken as the boundary forcing fields for the WP model. The fields in the 26th year of the global model are taken as the initial state of the WP model, which is run for 25 years. After 2 model years, the WP model trajectory becomes stationary. The fields of last 23 model years in the WP model are taken as the boundary forcing fields for the SCS model. The fields in the 3rd year of the WP model are taken as the initial state of the SCS model, and the SCS model is run 23 model years. After 2 model years, the SCS model reaches stationary.

The nested simulation is exposed to periodic climatological atmospheric forcing, with a fixed annual cycle, and without weather variability. The atmospheric forcing, including the net shortwave longwave radiation, precipitation, air relative humidity, air temperature, sea surface temperature, and wind speed, are all from the monthly Comprehensive Ocean-Atmosphere Data Set (COADS) climatology with 1 grid resolution.

The daily average data of the last 21 year in these three models are used to study the "noise". The barotropic stream-

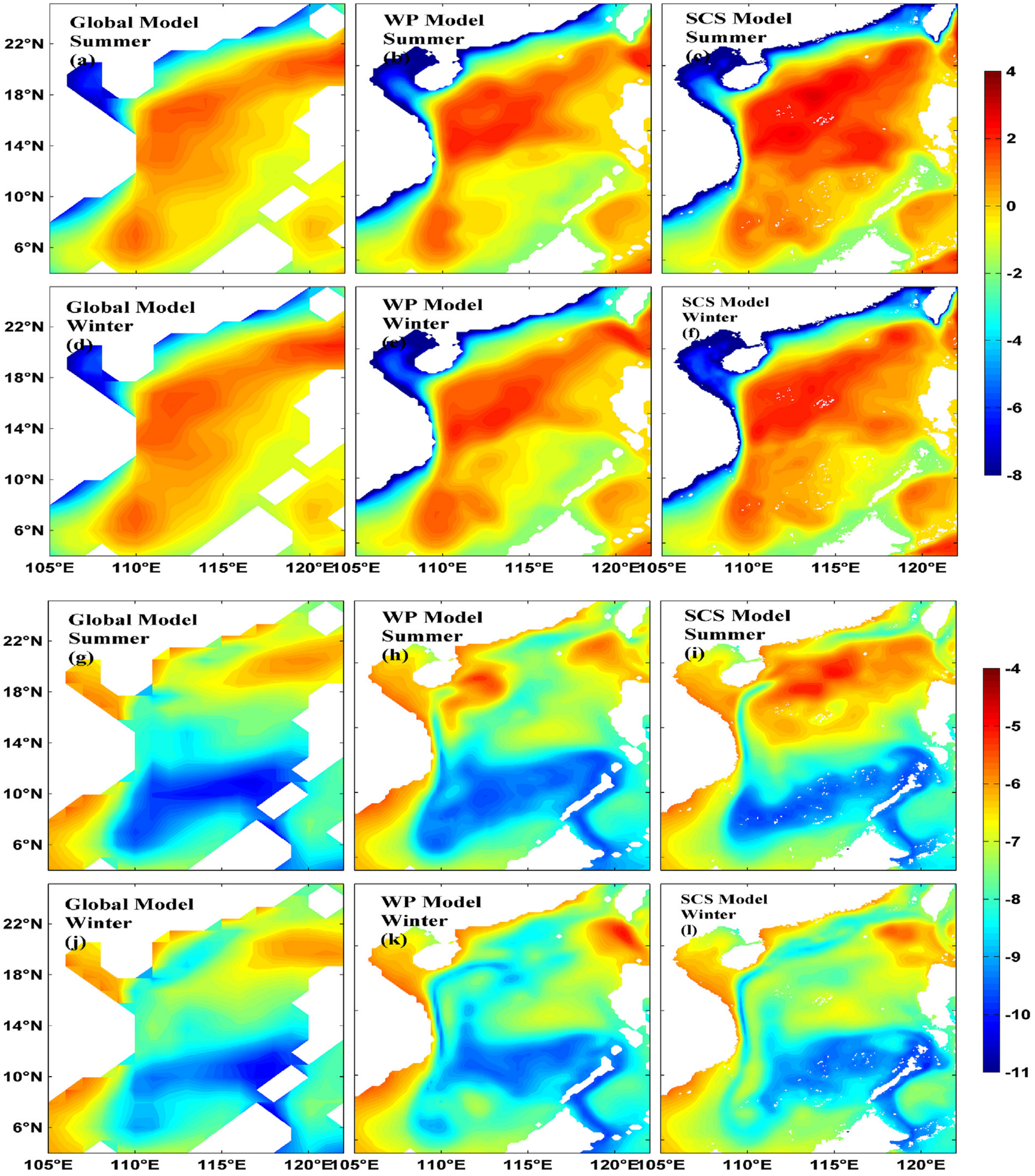

Figure 2 The spatial distributions of logarithm of daily variances of BS (top) and SSH (bottom) in the SCS simulated for summer and winter by the global model (a, d; g, j), the WP model (b, e; h, k) and the SCS model (c, f; i, l).

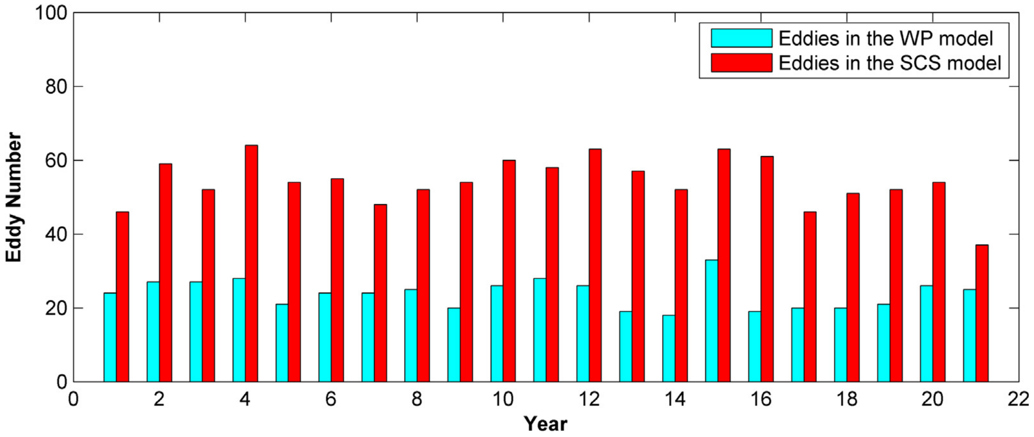

Figure 3 The annual number of eddy tracks in the WP simulation (blue bar) and in the SCS simulation (red bar).

function (BS) and sea surface height (SSH) simulated by these three models are discussed in this study.

3. Results

3.1. The amount of variability of BS and SSH in these three models

We measure the amount of variability by the variances of daily values at each grid point. The variance is calculated by subtracting the annual and semi-annual cycle. The annual and semi-annual cycle are fitted from the full-time series by harmonic analysis.

Table 1 lists variances of daily BS and SSH averaged across the SCS. The BS variances in the WP model are increased compared to the global model, and even larger variances can be found in the SCS model. The SSH variances in the WP model are approximately equal to that in the global model, and slightly larger variances are found in the SCS model.

The maps in Fig. 2 show the spatial distributions of the logarithm of BS variances and SSH variances in the SCS in two seasons (summer and winter monsoon) simulated by these three models (global, WP, and SCS). From the global model to the SCS model, with the model resolution increasing, the BS variances in the whole SCS strongly increase. In terms of SSH the changes are regionally different: While in the northern SCS, an increase from the global model to the SCS model is emerging, in the southern SCS, the differences are small. We suggest that the higher resolution model generates more or more intense eddies, which leads to intensified variability on all time scales (Hasselmann, 1976).

For comparing the eddies in the WP model and SCS model, we employed an eddy detection and tracking algorithm to search all eddies in the SCS. In order to compare, the SSH of the SCS model is interpolated from 0.04° resolution to 0.2° resolution. This algorithm only relies on the discrete SSHA (Zhang and von Storch, 2018). The potential eddy points are determined by the SSHA extrema in a moving 5 × 5 grid box according to the suggestion of Faghmous et al. (2015), with a relative intensity ≥ 5 mm. The relative intensity (RI) is defined by the absolute SSHA difference of the extrema and the mean SSHA of the other 24 neighbors in the box. The eddy centers at the consecutive time steps that are

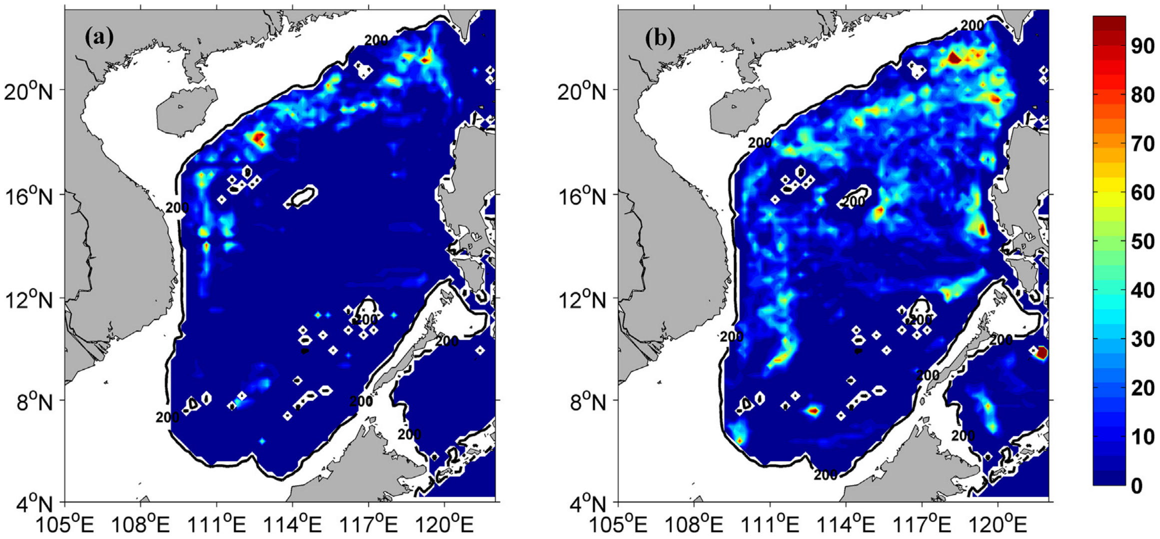

Figure 4 The total number of eddy occurrence for the 21 model years in the WP model (a) and SCS model (b). The units are the numbers of the eddy. The black lines indicate the 200 m isobaths.

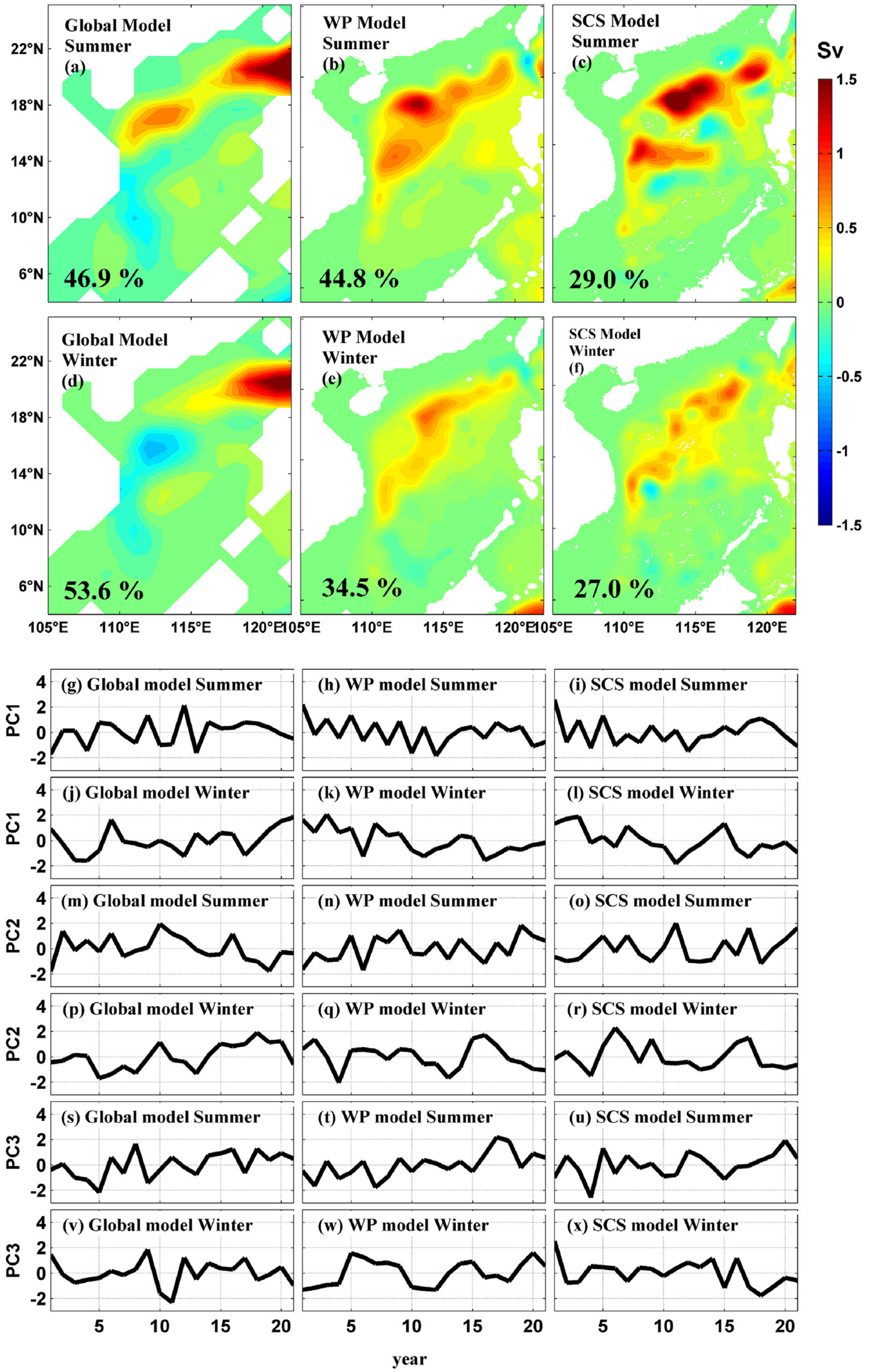

Figure 5 The first leading EOF patterns (in Sv) (a—f) and associated standardized principal component (PC1) (g—l) of the summer and of winter mean BS in the SCS. The PC2 (m—r) and PC3 (s—x) of BS in the SCS in summer and winter are from the three-layer nested simulation. The numbers in the bottom left corner of (a—f) indicate the percentages of variance described by the first leading EOF.

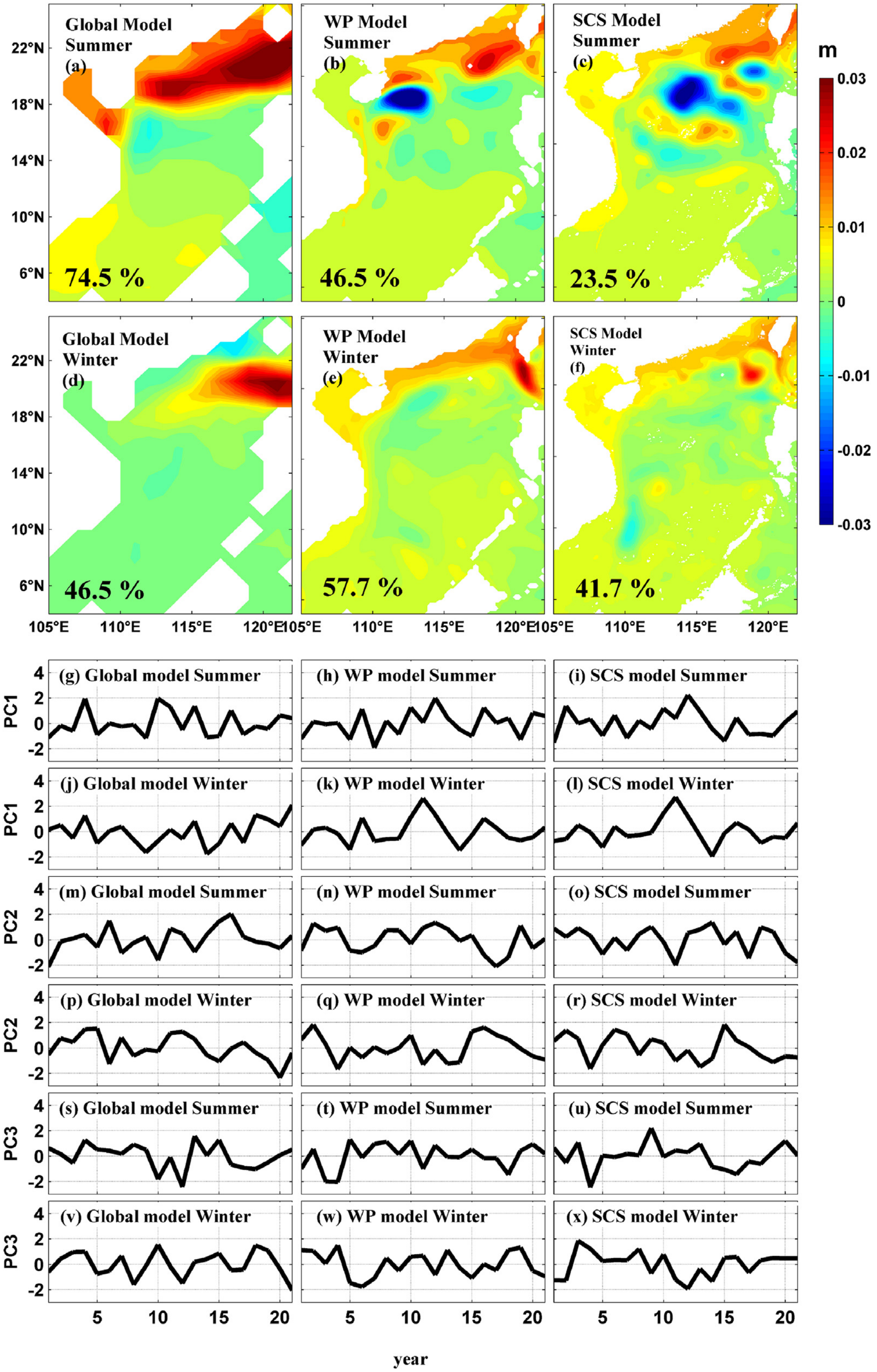

Figure 6 The first leading EOF patterns of SSH (in m) (a—f) and associated standardized principal component (PC1) (g—l) of SSH in the SCS in summer and winter from the three-layer nested simulation. The PC2 (m—r) and PC3 (s—x) of SSH in the SCS in summer and winter are from the three-layer nested simulation. The numbers in the bottom left corner of (a—f) indicate the percentages of variance described by the first leading EOF.

Table 2 Cumulative percentages of variance described by the first three EOFs of BS (left) and SSH (right) in the SCS.

	BS			SSH		
	Global model	WP model	SCS model	Global model	WP model	SCS model
Spring	84.5	81.3	56.6	85.7	80.9	57.8
Summer	74.3	75.3	53.3	90.5	67.7	52.8
Autumn	82.2	64.7	54.1	90.8	68.2	67.0
Winter	76.5	72.1	48.9	80.8	77.8	63.2

connected if their distance is ≤ 25 km (considering the eddy traveling speed ≤ 25 km per day) and the RI difference is ≤ 1.5 times of the RI in the previous time step. For the eddy tracks, the eddy should be tracked over at least 30 days.

Fig. 3 shows that the annual eddy track numbers generated by the WP model are in all years smaller than those found in the SCS model. The eddy tracks numbers are comparable to those found by Chen et al. (2011) in satellite data.

Fig. 4 shows the distribution of eddy occurrence for the 21 model years in the WP model and the SCS model, according to which the SCS model generates more eddies in the SCS, especially in the northern SCS.

We conclude that, since the atmosphere forcing of these three models is the same without any weather or interannual-variability, this increased variability in higher resolution models is internally generated by models.

3.2. Dominant modes of BS and SSH in these three models

Empirical Orthogonal Functions (EOF) decompose the time series of fields. A few orthogonal modes capture the main variability (Lorenz, 1956; von Storch and Zwiers, 1999). We apply the EOF decomposition to the BS and SSH fields in the South China Sea. The EOFs have been normalized so that the standard deviation of the time coefficients (principal component, PC) is 1 — so that the different intensity of the EOFs is given by the patterns.

Figs. 5 and 6 show the first leading EOF patterns and associated standardized principal component (PC) for BS and SSH, respectively. All the PCs of BS and SSH in these three models appear stationary. The variability is not due to trends, which may be indicative for equilibrating from an initial state. Since the forcing in these three models is periodic and "without weather", these variations must be caused by internal dynamics, likely in the spirit of the "stochastic climate model".

Table 2 lists the sum of percentages of variance described by the first three EOFs for BS and SSH, respectively. We find that the leading EOFs of BS in the global model represent a higher percentage of cumulative variance than that in the WP model, and the leading EOFs of BS in the WP model explain the higher percentage of cumulative variance than that in the SCS model. From the global model to the SCS model, with model resolution increasing, the percentages of the sum of variances represented by the first three EOFs for BS decrease (except for summer).

The situations with of SSH are similar to that of BS, except for winter: The first leading EOF of SSH in the global model explains a lower percentage of variance than that in the WP model (Fig. 6). We speculate that, because the resolution in the global model is too coarse, the Kuroshio invasion path in the global model is farther west and much broader than that in reality and in the WP and SCS simulations — which is reflected by a very strong first leading EOF (Fig. 6). Therefore, the variability in the northern SCS in the global model is exaggerated compared to both the WP and SCS model.

We conclude that higher resolution models generate more "noise" so that a smaller percentage of the overall variability is represented by the dominant EOFs in the higher resolution models.

4. Conclusion

Basing on a three-layer nested simulation, which is forced by periodic climatological atmospheric forcing, featuring a global model, a West-Pacific model and South China Sea model, we find that high-dimensional nonlinear-systems like ocean dynamics generate variability by itself without an external forcing, and that "noise" generations are stronger in models with higher resolution, which favors the building of macro-turbulence. Here "noise" is meant as variability which emerges in an "unprovoked" manner, i.e., which is unrelated to external drivers, and is not deterministically related to initial conditions.

It is important to note that we are not referring to low-dimensional non-linear systems which may generate beautiful attractors and other phenomena, but high-dimensional systems, whose variability maybe described by stochastic processes.

Ocean models can generate "noise" by internal nonlinear or stochastic dynamics, in the spirit of the "stochastic climate model". From the global model to the SCS model, with model resolution increasing, the "noise" generation increase. The higher resolution models can internally generate variability, which is absent in the lower resolution models. Because that higher resolution models generate more "noise", a smaller percentage of the overall variability is represented by dominant EOFs in the higher resolution models. The higher resolution models generate more "noise", which can motivate the generation of eddies in the ocean. This is important for scientists who study eddies in ocean models.

"Noise" may in some cases be a nuisance, but in dynamical simulations, it is a constitutive element of the dynamics of the system, which makes the dynamics richer, but creates the need of statistical efforts for determining if a change is beyond the range of internal variations. This becomes a significant issue when studying the effects of climate change or numerical experiments on the effect of formulating processes in models.

So far, this practice is not widely recognized in ocean sciences (but, see for instance Leroux et al., 2018), even if this mechanism is an almost trivial consequence of the concept of the stochastic climate model. In atmospheric sciences this is well-known, which may be related to the fact that atmospheric eddies have been part of the dynamics in most quasi-realistic atmospheric models, while global ocean models have for long operated with coarse resolution, without eddies but strong numerical viscosity and diffusion so that the late Ernst Maier—Reimer joked that older ocean models would be filled with mustard and not with water.

Another factor, which may limit the role of such internal variability in coastal seas, is the presence of tides, which acts as a kind of viscosity, erasing quickly and efficiently the emergence of non-forced long-living anomalies.

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