High-resolution effort

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Abstract

Recent pioneering development of high-resolution climate models provides promising and compelling evidence that increases in the resolution of both the atmosphere and ocean contribute to better representation in simulating the mean state and various space-and-time scale variability. The use of higher resolutions improves the reproducibility of small scale variability such as oceanic eddies and currents. The more realistic representation of these phenomena would ameliorate some common deficiencies in present operational seasonal prediction models. In this manuscript, a review of high-resolution modeling is given, and future effort needed for operational application is discussed focusing on the seasonal prediction.

1 Introduction

The resolutions of atmospheric and oceanic general circulation models draw a primary attention at modeling centers since the higher resolutions are expected to give ability to represent smaller scale phenomena with less help of sub-grid scale parameterizations and potentials to improve prediction skills. The sensitivity of the performance on the model resolutions has been extensively studied with atmospheric models and coupled models in the past (e.g., Tibaldi et al., 1990; Boyle 1993; Brankovic and Gregory, 2001; Guilyardi et al., 2004; Navarra et al., 2008; Pope and Stratton, 2002; Roberts et al., 2004). Effects of further increase of model resolutions have been explored as more computational power became available in recent years. The highest resolution climate models at present possess ability to resolve fine scale weather and oceanic features (i.e., eddies and currents). These model simulations give us an opportunity to explore potentials and prospects of the seasonal prediction with high resolution models.

This paper is intended to give a broad review of high resolution modeling and to discuss evidences of the superiority in high resolution models, prospects and effort needed for operational use. In the following, Section 2 shortly reviews the past and current capability of seasonal and climate models. Section 3 shows comprehensive examples of the advantage in high resolution models. Section 4 discusses some on-going efforts and possible approaches for high-resolution opearational seasonal forecasting. A summary and conclusions are given in Section 5.

2 Past and present capability of seasonal prediction

In the last few decades, the computational power of high performance computers (HPCs) has been increased by at a factor of roughly 1000 during the last decade on average according to Top500 statistics[1]. In the operational seasonal prediction, the increase of computational resources has been partly used for increasing the number of ensemble members, extending periods of retrospective forecasts (hindcasts), or having additional components such as the ocean, etc. Besides these upgrades the resolution of operational seasonal prediction models has been increased in terms of horizontal and vertical resolutions both in atmospheric and oceanic components. The progress of resolutions in the ECMWF seasonal prediction system is shown in Table 1 as an example. Steady upgrades of resolutions have been done together with upgrades of HPCs. Other modeling centers also had more or less similar upgrades in accordance with their forecast system design and affordable computer resources. The current resolutions of operational seasonal prediction systems are summarized in Appendix B of Molteni et al. (2011).

3 Advantage in high-resolution models

The advantage in high-resolution coupled models has been studied at several modeling centres. These resource-intensive simulations can be feasible thanks to the massive computational resources available in recent years. In these simulations, the resolution of ocean models is much higher than that of any operational seasonal prediction models. The simulations revealed that the resolution of ocean models has substantial effects on the results. Table 2 summarizes configurations of high-resolution coupled models at several centers. In this section, some results from these pioneering studies are reviewed to foresee the prospects of future seasonal predictions with high-resolution models.

System	Year	Atmospheric model	Oceanic model
System 1	1997	IFS Cy15r8, T63 (~210 km), L31	HOPE, 2.8x2.8-0.5 deg. (10N-10S), L20
System 2	2001	IFS Cy23r4 TL95 (~210 km) L40	HOPE 1.4x1.4-0.3 deg.(30N-30S), L29
System 3	2003	IFS Cy31r1, TL159 (~125km) , L62	HOPE, 1.4x1.4-0.3 deg.(30N-30S), L29
System 4	2011	IFS Cy36r4, TL255 (~80km), L91	NEMO, 1x1-0.3 deg., L42

Table 1. Configurations of ECMWF seasonal prediction systems

[1] http://top500.org/

Model	Modeling Centre	Atmos. Model Resolution	Ocean Model Resolution	Reference
CM2.4/CM2.5/CM2.6	GFDL	1/0.5/0.5° 100/50/50km	0.25/0.25/0.1° 25/25/10km	Delworth et al. (2012)
CCSM4	NCAR	CAM3.5 0.23°x0.31°	POP2 0.1°	McClean et al. (2011)
MIROC4h	CCSR/NIES/FRCGC	CCSR/NIES/FRCGC AGCM v5.7 T213 ~0.5°	COCO v3.4 0.28125x0.1875	Sakamoto et al. (2012)
HiGEM	UKMO HC/ NERC	HadGEM1 N144 1° ~90 km	NEMO 1/3	Shaffrey et al. (2009)
CFES	ESC JAMSTEC	AFES 50km T239	OFES 0.25°	Komori et al. (2008)

Table 2. High-resolution models at modeling centers

3.1 Oceanic component

The resolutions of an oceanic component are often categorized into three categories depending on resolved scales, namely non-eddy-permitting resolution, eddy-permitting resolution and eddy-resolving resolution (e.g., Bryan 2007). The non-eddy-permitting resolution refers to the resolution of more than about one degree, in which models could not resolve ocean meso-scale eddies. In these resolutions, the eddy mixing (harmonic horizontal diffusion of the isopycnal layer thickness) is often parameterized by Gent and McWilliams (1990) scheme or its derived versions (Gent 2011). The eddy-permitting resolution is within the middle of non-eddy-permitting resolution and eddy-resolving resolution. The typical resolution would be 0.25 degrees or quarter degrees. With the eddy-permitting resolution, models can resolve meso-scale eddies to some extent, but cannot fully resolve the eddies in high latitudes where the eddy scale is finer than in low latitudes. Therefore the thickness diffusion parameterization is sometimes applied in order to compensate eddy mixing (e.g., Sakamoto et al., 2012). Lastly the eddy-resolving resolution refers to the resolution of less than about 0.1 degree. Models with this fine horizontal spacing fully resolve ocean eddies, and currents satisfactorily without thickness diffusion parameterizations.

Both eddy-permitting and eddy-resolving models improve representations of ocean eddies and currents (i.e., the Gulf Stream, the Kuroshio Current, the variability of meso-scale eddies) compared with non-eddy-permitting-resolution models. We discuss below some prominent aspects in the ocean, readers who would like to learn more details may be referred to some studies listed in Table 2 and studies of their high resolution simulations.

The meso-scale eddy activity in the mid- and high-latitudes is certainly better represented with eddy-permitting resolution models (Sakamoto et al., 2012; Shaffrey et al., 2009). The eddy-resolving models has a superiority in reproducing observed eddy activity in the high latitudes and representing the eddy mixing effect even without any thickness diffusion parameterizations (McClean et al., 2011).

The western boundary currents (WBCs) are visibly improved with finer resolution ocean models (e.g., Delworth et al., 2012; Kirtman et al., 2012), for instance, more intense and narrower WBCs represented in finer resolution models are in better agreement with observations. This improvement is also beneficial for representing observed sharp sea surface temperature (SST) gradients (Kirtman et al., 2012). It was found that sharp SST gradients have a significant influence on simulating the storm track activity (e.g., Minobe et al., 2008; Taguchi et al., 2009; Woollings et al., 2010) over the SST fronts and their downstream. The impacts are clearly seen in surface heat fluxes and precipitation (e.g., Kirtman et al., 2012; Minobe et al., 2008). In addition, it is reported that the deficit of the Atlantic blocking is improved by alleviated SST with a finer resolution ocean model (Scaife et al., 2011).

Observational and modeling studies have elucidated that small-scale oceanic eddies have influence on the variability of atmospheric boundary layer (e.g., Chelton et al., 2004; Small et al., 2008). The studies with high resolution satellite observations and model simulations found that small-scale SST, surface wind, surface momentum flux, sensible and latent heat fluxes show coherent patterns. Furthermore, small-scale air-sea interaction can be properly captured only when the ocean component is eddy resolving (Bryan et al., 2010). Kirtman et al. (2012) has investigated the air-sea interaction using simultaneous pointwise correlations between turbulent heat flux (sensible +latent, positive upward) and SST. They found that the ocean forcing to the atmosphere is considerably stronger in an eddy-resolving ocean coupled model than a non-eddy-permitting ocean coupled model. This enhanced ocean forcing in mid- and high- latitudes is attributed to the enhanced SST variance in high resolution ocean models.

Many climate models with a relatively low resolution ocean component often share common equatorial Pacific SST biases, namely a cold tongue being confined in too narrow equatorial band or extending too far west. These equatorial SST errors affect the convection and forced teleconnection patterns. For seasonal forecasting, replicating a realistic teleconnection is a key to improve the response to the tropical forcing (JMA, 2010). The better representation of cold tongue with high-resolution ocean models (e.g., Shaffrey et al., 2009; Sakamoto et al., 2012) offers better mean states of circulation, and providing realistic teleconnections (Dawson et al., 2012).

Above mentioned evidences suggests the advantage of high-resolution ocean components for seasonal and climate predictions.

3.2 Atmospheric component

The increase of horizontal and vertical resolutions of atmospheric models has impacts on a wide range of atmospheric representations in models. Many studies have examined the topics to assess the advantage of higher resolution models (Tibaldi et al., 1990; Boyle, 1993; Brankovic and Gregory, 2001; Jung et al., 2012). Some results are summarized in this section.

Jung et al. (2012) have recently investigated high-resolution simulations with ECMWF atmospheric models at several resolutions. They found that increasing horizontal resolution improves the mean climate of tropical precipitation, the tropical atmospheric circulation, the frequency of occurrence of Euro-Atlantic blocking, and the representation of extratropical cyclones in large parts of the Northern Hemisphere extratropics.

The improvement of the Euro-Atlantic blocking is consistent with Jung et al. (2006) and Matsueda et al. (2009). Jung et al. (2012) found that the improvement of blocking is attributed to a better representation of topography by their sensitivity test. However the reason of the consistent improvement in some models is still an open question. By any reasons, the improvement of climatological states would decrease the frequency error of the atmospheric blocking (Scaife et al., 2010; Scaife et al., 2011; Berner et al.,, 2012).

It is expected that the seasonal forecasts benefit from the better teleconnection with improved mean climate of atmospheric circulations. Jung et al. (2012) reported that increasing resolutions lead to moderate seasonal skill improvement during boreal winter in the tropics and Northern Hemisphere, but no discernible improvement was found during summer with the ECMWF atmospheric model. On the other hand, several studies pointed out that the ocean model resolution is more crucial to represent better teleconnection (Section 3.1).

Representations of the severe weather such as tropical cyclones or torrential rain is most likely improved with a higher resolution atmospheric component. For example, the intensity and structure of tropical cyclones in day-to-day operational forecasts are quite different depending on models' resolutions (i.e., high-resolution deterministic forecasts, moderate-resolution medium-range forecasts, low-resolution seasonal forecasts). Manganello et al. (2012) systematically investigated simulated tropical cyclones with various resolutions, and found that higher resolution models show more accurate intensity and structures of simulated tropical cyclones.

So far we discussed the horizontal resolution, but increasing the vertical resolution also potentially brings better behaviour in the atmospheric boundary layer to the stratosphere. The high vertical resolution has a great benefit for the boundary layer simulations, leading to better behaviours of vertical mixing and cloud processes. Stratosphere-troposphere processes also get a lot of attentions in a community of the seasonal prediction. Currently the intercomparison aimed to assess the stratosphere impacts on the seasonal prediction (Stratosphere-resolving Historical Forecast Project: Strat-HFP) is undergone in the WGSIP. The impacts of high-top stratosphere was investigated using CMIP5 simulations by Charlton-Perez et al. (2012), demonstrating the merit of having the high-top stratosphere to better represent the stratosphere-troposphere interaction.

4 Some efforts and approaches

The high-resolution simulations with massive computational resources have demonstrated the fidelity of long integrations with the current model framework. On the other hand, operating higher resolution seasonal prediction models requires a lot of future efforts for efficient use of the limited computational resources and development of systems suited to corresponding resolutions.

Therefore operational models need to be highly scalable on parallel computers. And each component (sub-model) as well as communication software 'coupler' (Redler et al., 2010; Yoshimura and Yukimoto, 2008) and the model structure (Mogensen et al., 2012) should be efficient enough.

One option for saving computational time would be use of nested ocean coupled model (Hiroyuki Tsujino, MRI/JMA, personal communication). He makes attempt to develop nested ocean models for coupled simulations. Another option would be the adaptive mesh refinement (AMR, Slingo et al., 2009; Weller et al., 2010), however, a great effort will be necessary in developing AMR techniques as well as sub-grid parameterization, data assimilation in variable resolution grids (Weller et al. 2010).

The GPU parallel computing is a potential technical approach in weather and climate modeling. GPU computing is the use of a GPU (graphics processing unit) together with a CPU (central processing unit) to perform computations of scientific and engineering applications. This technology offers unprecedented computational speed-up with thousands of efficient small cores on GPUs designed for parallel computation. Even though extensive optimization of model codes including restructure and rewriting of the source codes is required to make better use of the GPUs for weather and climate models, the achieved efficiency would outweigh costs and efforts. For example, a global model based on a Non-hydrostatic Icosahedral Model (NIM) is under development for a possible next generation model in order to run with the GPU parallelization . The Tokyo Institute of Technology and Japan Meteorological Agency have collaboratively demonstrated a cloud resolving model simulation on GPU based HPC 'TSUBAME 2.0' (Shimokawabe et al., 2010).

Besides technical efforts, it should be noted that physical parameterization schemes in both atmosphere and ocean components, and data assimilation techniques especially for ocean analysis need to be prepared for forthcoming high-resolution operational seasonal forecast systems. . For example, the convection scheme is to be improved to reproduce better MJOs, which may not be improved by only increasing the horizontal resolution (Jung et al. 2012). Regarding the ocean assimilation, a four-dimensional variational analysis gave a better analysis in a high resolution western north pacific analysis (Yosuke Fujii, MRI/JMA, personal communication).

5 Summary and Concluding Remarks

The paper overviewed the advantage of high-resolution seasonal prediction models, and discussed the prospects and efforts needed for the future progress. Recent studies have proved well-established advantageous evidences of high-resolution atmosphere and ocean components for climate simulations. In particular, it is recognized that finer resolution (eddy-resolving- and eddy-permitting-resolution) ocean models drastically improve their performance in simulating realistic climate states. The same would hold true for seasonal predictions with the coupled models, and the results would justify to utilizing higher resolution models for seasonal forecasting.

The paper also discussed on-going developments and future challenges. Although demonstrations of high-resolution simulation with existing climate models showed the fidelity and capability of high-resolution operational seasonal predictions with current HPCs and model source codes, these simulations are too expensive for available computational resources at present and in the near future. The some technical and engineering approaches such as ocean model nesting, AMR or GPU parallelization are to be developed for more efficient simulations. Given the rapidly changing HPC technology, these attempts and challenges should not be excluded and be considered as possible options for the future seasonal prediction. These efforts would make a short path to implementation of weather and oceanic eddy resolved models to the operational seasonal prediction.

Acknowledgements

The author would like to thank the organizers for their invitation to this excellent seminar. The author would also thank Dr. H. Tsujino, Dr. Y. Fujii and other colleagues for fruitful discussions and comments.

References

Berner et al. (2012), Systematic Model Error: The Impact of Increased Horizontal Resolution versus Improved Stochastic and Deterministic Parameterizations. J. Clim., 25, 4946–4962.

Boyle (1993), Sensitivity of dynamical quantities to horizontal resolution for a climate simulation using the ECMWF (cycle 33) model. J. Clim., 6, 796–815.

Brankovic and Gregory (2001), Impact of horizontal resolution on seasonal integrations. Clim. Dyn., 18, 123–143.

Bryan et al. (2007), Resolution convergence and sensitivity studies with North Atlantic circulation models. Part I: The western boundary current system. Ocean Modelling, 16(3-4), 141–159.

Charlton-Perez et al. (2012), Mean Climate and Variability of the Stratosphere in the CMIP5 models. J. Geophys. Res. submitted.

Cheltonet al. (2004), Satellite measurements reveal persistent small-scale features in ocean winds. Science 303, 978–983.

Dawson et al. (2012), Importance of oceanic resolution and mean state on the extra-tropical response to El Niño in a matrix of coupled models. Clim. Dyn.

Delworth et al. (2012), Simulated Climate and Climate Change in the GFDL CM2.5 High-Resolution Coupled Climate Model. J. Clim., 25, 2755–2781.

Gent and McWilliams (1990), Isopycnal mixing in ocean circulation models. J. Phys. Oceanogr., 20, 150–155.

Gent (2011), The Gent-McWilliams parameterization: 20/20 hindsight. Ocean Modelling. 39, 1-2, 2-9.

Guilyardi et al. (2004), Representing El Nino in coupled ocean–atmosphere GCMs: The dominant role of the atmospheric component. J. Clim., 17, 4623–4629.

Imada, and Kimoto (2012), Parameterization of Tropical Instability Waves and Examination of Their Impact on ENSO Characteristics. J. Clim., 25, 4568–4581.

JMA (2010), Workshop report of an international workshop on“Development of Atmosphere-Ocean Coupled Models towards Improvement of Long-Range Forecast”, available online at http://ds.data.jma.go.jp/tcc/tcc/library/JMA2010WS_Summary.pdf.

Jung et al. (2012), High-Resolution Global Climate Simulations with the ECMWF Model in Project Athena: Experimental Design, Model Climate, and Seasonal Forecast Skill. J. Clim., 25, 3155–3172.

Jung et al. (2006), Sensitivity of extratropical cyclone characteristics to horizontal resolution in the ECMWF model. Quart. J. Roy. Meteor. Soc., 132, 1839–1857.

Komori et al. (2008), Deep ocean inertia-gravity waves simulated in a high-resolution global coupled atmosphere–ocean GCM, Geophys. Res. Lett., 35, L04610.

Kirtman et al. (2012), Impact of Ocean Model Resolution on CCSM Climate Simulations, Clim. Dyn., in press.

Manganello, et al. (2012), Tropical Cyclone Climatology in a 10-km Global Atmospheric GCM: Toward Weather-Resolving Climate Modeling. J. Clim., 25, 3867–3893.

Matsueda et al. (2009), Future change in wintertime atmospheric blocking simulated using a 20-km-mesh atmospheric global circulation model. J. Geophys. Res., 114, D12114.

Minobe et al. (2008), Influence of the Gulf Stream on the troposphere, Nature, 452, 206–209.

McClean et al. (2011), A prototype two-decade fully-coupled fine-resolution CCSM simulation, Ocean Modelling, 39, 1–2, 10–30.

Molteni et al. (2011), The new ECMWF seasonal forecast system (System 4), ECMWF Tech. Memo. 656, pp. 51.

Mogensen, et a. (2012), Coupling of the NEMO and IFS models in a single executable, ECMWF Tech. Memo. 673, pp. 23.

Navarra et al. (2008), Atmospheric horizontal resolution affects tropical climate variability in coupled models. J. Clim., 21, 730–750.

Pope and Straton (2002), The processes governing horizontal resolution sensitivity in a climate model. Clim. Dyn., 19,3, 211–236.

Roberts et al. (2004), Impact of an eddy-permitting ocean resolution on control and climate change simulations with a global coupled GCM. J. Clim. 17(1),3-20.

Redler et al. (2010), OASIS4 – a coupling software for next generation earth system modelling. Geosci. Model Dev., 3, 87–104.

Sakamoto et al. (2012), MIROC4h–a new high-resolution atmosphere-ocean coupled general circulation model. J. Meteor. Soc. Japan, in press.

Scaife et al. (2011), Improved Atlantic winter blocking in a climate model, Geophys. Res. Lett., 38, L23703.

Scaife et al. (2010), Atmospheric Blocking and Mean Biases in Climate Models. J. Clim., 23, 6143–6152.

Scaife et al. (2011), Improved Atlantic winter blocking in a climate model, Geophys. Res. Lett., 38, L23703.

Shaffrey et al. (2009), U.K. HiGEM: The New U.K. High-Resolution Global Environment Model—Model Description and Basic Evaluation. J. Clim., 22, 1861–1896.

Shimokawabeet al. (2011), 145 TFlops Performance on 3990 GPUs of TSUBAME 2.0 Supercomputer for an Operational Weather Prediction, Procedia Computer Science, 4, Proceedings of the International Conference on Computational Science, ICCS 2011, 1535–1544.

Slingo et al. (2009), Developing the next-generation climate system models: challenges and achievements, Phil. Trans. R. Soc. A, 367, 815–831.

Small et al. (2008), Air–Sea interaction over oceanic fronts and eddies. Dynamics of Atmosphere and Oceans, 45, 274–285.

Taguchi et al. (2009), Influences of the Kuroshio/Oyashio Extensions on air–sea heat exchanges and storm-track activity as revealed in regional atmospheric model simulations for the 2003/4 cold season. J. Clim., 22 (24), 6536–6560.

Tibaldi et al. (1990), Extended-range predictions with ECMWF models: Influence of horizontal resolution on systematic error and forecast skill. Q. J. R. Meteorol. Soc., 116, 835–866.

Weller et al. (2010), Challenges Facing Adaptive Mesh Modeling of the Atmosphere and Ocean. Bull. Amer. Meteor. Soc., 91, 105–108.

Woollings et al. (2010), Storm track sensitivity to sea surface temperature resolution in a regional atmosphere model, Clim. Dyn., 35, 341–353.

Yoshimura and Yukimoto (2008), Development of a Simple Coupler (Scup) for Earth System Modeling. Papers in Meteorology and Geophysics, 59, 19–29.