International Workshop on
“Development of Atmosphere-Ocean Coupled Models towards Improvement of Long-Range Forecast”

Tokyo, Japan

8-10 December 2010

Japan Meteorological Agency

The international workshop on development of atmosphere-ocean coupled models towards improvement of long-range forecast was held under the auspices of the Ocean Policy Research Foundation of Japan.

* Ocean Policy Research Foundation (OPRF)

Ship & Ocean Foundation (SOF), alias Ocean Policy Research Foundation, was established in 1975. Under support from the Nippon Foundation, the private non-profit organization is undertaking activities related to a wide range of maritime issues. As the scope of its activities has expanded, SOF has recently adopted a new name, "Ocean Policy Research Foundation," which better illustrates its current concerns and operations — multi-disciplinary researches into ocean-related issues to make practical policy proposals in the areas of marine environment protection, maritime security, marine resources preservation, etc. OPRF is headquartered in Tokyo.

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Summary of the International Workshop on Development of Atmosphere-Ocean Coupled Models towards Improvement of Long-Range Forecast

Climate Prediction Division, Japan Meteorological Agency (JMA)

1. Introduction

The International Workshop on Development of Atmosphere-Ocean Coupled Models towards Improvement of Long-range Forecast was held in Tokyo, Japan from December 8 to 10, 2010. The objectives of the workshop were to review current capabilities, recent progress and future prospects for ocean-atmosphere coupled modeling in operational and research communities, and to address requirements to improve the quality of long-range forecasts. In particular, the workshop highlighted key issues related to improvements of the seasonal forecast focusing on the Asian region. The following themes were discussed:

- The climate variability in the Asian region and its predictability on a seasonal time-scale.
- The current capability of seasonal forecasts in the global and Asian regions.
- The on-going developments and future prospects of coupled models with additional components such as dynamical sea ice models and stratospheric processes.
- The requirement of observations to improve seasonal forecasts.

The workshop was attended by eight invited speakers including overseas scientists from Australia, China, the UK, the USA and more than 40 scientists in Japan. The 3-day workshop was organized into four sessions: “Public symposium,” “Air-sea interactions in the Pacific-Indian region,” “Current status of development of CGCM (Coupled General Circulation Model)” and “Future developments of CGCM for better seasonal prediction.” Presentations in each session were followed by discussions. Discussions, recommendations and conclusions are summarized in this document.

The JMA would like to thank all participants for their excellent contributions. The outcome of the workshop will contribute to the future strategy and plans for the development of seasonal forecast systems at the JMA and other operational weather services.

All presentation files are available from the JMA website (http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html).

2. Climate Variability in the Pacific-Indian region

The climate in the Asian region is influenced by the variability of the Asian monsoon, Indian Ocean and El Niño-Southern Oscillation (ENSO). It is well known that the Asian monsoon variability is related to ENSO. To better represent the monsoon variability and the interaction between the monsoon and ENSO, it is necessary to use the atmosphere-ocean coupled models for seasonal predictions. It was reported that most coupled models can represent ENSO and the related interannual variability of major circulation patterns over the tropics such as the western Pacific[1], Africa and South America.

Recent studies have found that El Niño induces the oceanic warming in the tropical Indian Ocean, which influences atmospheric conditions in East Asia during the next summer[2]. This “Indian Ocean capacitor effect” is recognized as one of the primary sources of predictability of atmospheric circulation in East Asia during boreal summer, since a relatively strong connection between the tropics and extratropics exists in the western North Pacific[3]. The JMA new coupled model reproduces the Indian Ocean warming associated with El Niño, and shows clear improvements in boreal summer forecasts in the western North Pacific[4, 5]. The next step would be further improvement in representing the circulation patterns (teleconnections) from the tropical Pacific and Indian Oceans into the extratropics including East Asia, Australia, North America and even Europe.

Typhoon activity is also associated with ENSO and Indian Ocean conditions. The aforementioned mechanism serves the feasibility of the seasonal typhoon forecast[6]. Skillful forecasts were demonstrated by operational seasonal forecast systems[7, 8]. It was also shown that seasonal forecasts of tropical cyclones in the western North Pacific and tropical cyclones in other regions are issued at several operational/research centers[9].

From an observational standpoint, in-situ observations with mooring buoys, XBTs (eXpendable BathyThermograph), Argo floats, surface drifters and other measurements have been deployed in the tropical

Indian Ocean by the Indian Ocean Observation System (IndOOS)[10]. The pioneering observational research activity through international collaboration makes it possible to study in depth Indian Ocean variability such as the Indian Ocean dipole (IOD) mode[11], which affects climate in the Asia-Pacific region. The expanded and intense observations in the Indian Ocean would improve the quality of seasonal forecasts and support model development through advanced verification in the Indian Ocean. Assessment of the benefit/impact on the practical seasonal forecast skill and formulation of future optimal and sustainable observational plans would have to be done among research and operational communities.

Recommendations

- Understand key climate processes and atmosphere-ocean interactions in the tropical Pacific-Indian regions as well as associated teleconnections toward the extratropics.
- Diagnose and assess how well the above processes are simulated and predicted on a year-to-year basis in CGCMs.
- Review the optimal and sustainable observation network in the Indian Ocean.

3. Current status and future developments of CGCMs

The SST variability in the equatorial Pacific dominated by ENSO is well predicted a few seasons and sometimes even two years in advance[12, 13]. ENSO-related precipitation anomalies in the tropics and subtropics, and tropical cyclone activity are successfully predicted by CGCMs[7, 14, 15]. Although the current coupled models successfully reproduce ENSO variability in the central-eastern Pacific, the models more or less suffer from the mean bias errors or spatial patterns (cold tongue and double ITCZ: InterTropical Convergence Zone) of ENSO variability[16, 17]. Atmospheric physical parameterization such as cumulus parameterization is a control factor for ENSO characteristics. It was reported that the newly developed cumulus parameterization gives better representation of mean states and ENSO behaviors in the MIROC5 (Model for Interdisciplinary Research on Climate version 5) model[18]. The improvement in reproducing ENSO behaviors is still a challenging topic and should be investigated with more sophisticated diagnostic techniques[19]. ENSO-related teleconnections in the extratropics are reproduced in most models, but detailed patterns are not necessarily to be satisfactorily predicted[16, 17]. Assessment of simulations for teleconnection patterns is essential in order to improve their model behavior[16].

The Madden-Julian Oscillation (MJO) is a source of predictability, especially on a monthly time scale. MJO prediction is improved by modifications of physical parameterizations and better initial conditions[20, 21]. The cloud resolving global model (NICAM: Nonhydrostatic ICosahedral Atmospheric Model) successfully simulates organized MJO special structures and propagation. At the moment, although it is impossible to run the cloud resolving global model for the operational forecast due to its computational cost, the cloud resolving model demonstrates promising results for future operational forecasts[22].

Better representation of extratropical variability is an important aspect as well. The representation of atmospheric blocking frequency may be improved by a better climate mean state[23] and better representation of the horizontal gradient of potential vorticity by increasing model resolution[22]. The North Atlantic Oscillation and/or Arctic Oscillation are dominant variabilities for seasonal predictability over Europe and are closely related to stratosphere-troposphere coupling and the extratropical ocean SSTs.

The upgrade of the horizontal and vertical resolution with higher model top is beneficial for better stratosphere-troposphere coupling[24, 25] and resolved high frequency disturbance. The upgrade of the ocean model resolution also provides better representation of the tropical instability wave, midlatitude SST fronts and western boundary currents[23]. These benefits for the forecast skill and costs required should be reviewed and assessed in operational configurations.

An ocean data assimilation system is an essential part of a seasonal forecast system. Every operational center has been improving ocean data assimilation techniques. New techniques including coupled assimilation[20], quasi-coupled data assimilation[26] or pseudo EnKF (Ensemble Kalman Filter) assimilation[27] have been developed. These improved ocean data assimilation techniques contribute to seasonal forecast skills.

Land surface processes are known to be a source of predictability on a monthly time scale[28]. Better surface land models and their initialization will give higher forecast quality at an extended-range time scale. New land models and initialization techniques have been developed at operational centers[20 27]. Further development including assimilation with satellite observation will be desired to give better initial conditions.

A dynamical sea ice model is a component that can improve predictability in the foreseeable future. Dynamical sea ice coupled models and initialization methods are under development at major operational centers. The international intercomparison project (IceHFP: sea Ice Historical Forecast Project) has been underway as a sub-project of WCRP/CHFP (World Climate Research Programme/Climate-system Histrical Forecast Project)[29]. The activity will provide an opportunity to understand the capability and potential use of sea ice coupling for seasonal forecasts.

An ocean wave model is another key component that should be implemented in ocean-atmosphere coupled models to improve the simulation of sea-air interactions. ECMWF (European Centre for Medium Range Weather Forecast) has been running an ocean wave coupled model for many years[14]. It was reported that ocean wave coupling is beneficial for atmospheric forecasts. Though JMA models don't have an ocean wave component at the moment, it is necessary to develop the ocean wave coupled model.

In the current development of numerical climate modeling, a unified modeling approach between earth system models (ESMs) and weather/climate prediction models is a possible strategy to narrow the prediction gap in model development between days and longer time-scales by introducing new physical schemes developed for ESMs into seasonal forecast models[30].

The simulation of model uncertainty has been shown to improve the reliability of probabilistic forecasting systems. Different approaches including multi-model ensembles like EUROSIP (EUROpean Seasonal to Inter-annual Prediction), stochastic parameterizations, or multi-scheme ensembles are utilized in operational seasonal forecast systems.

Recommendations

- Reduce systematic errors and promote climatorological diagnostics and process-based development of physical parameterizations.
- Improve representation of climate variability (ENSO, IOD, teleconnection, etc.) in seasonal forecast models.
- Include sea ice and land surface models and their initialization.
- Develop an ocean wave coupled model and initialization/assimilation system.
- Assess the impact of increasing the vertical and horizontal resolution of the seasonal forecast system.
- Understand stratosphere-troposphere interaction and assess the impact of high-top models to further improve seasonal forecast models.
- Better represent model uncertainty and stochasticity in forecast systems by introducing multi-model ensembles, stochastic parameterizations, or multi-scheme ensembles.

References

1. Chowdary et al. (2010) *J. Geophys. Res.* **115**, D22121, doi:10.1029/2010JD014595
2. Xie et al. (2009) J. *Clim.* **22**, 730–747.
3. Kosaka & Nakamura (2010) J. *Clim*. **23**, 5085–5108.
4. Yasuda et al. (2007) *CLIVAR Exchange*, **12**, 4, 18–24.
5. Yasuda (2010) Air-sea interaction over the Indian Ocean after El Niño in JMA/MRI-CGCM seasonal forecast experiment, http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html.
6. Du et al. (2011) *J. Clim.* **24**, 315–322.
7. Vitart et al. (2007) *Geophys. Res. Lett.* **34**, L16815, doi:10.1029/2007GL030740.
8. Takaya et al. (2010) *J. Meteorol. Soc. Jap.* **88**:5, 799–812.
9. Camargo et al. (2007) *World Meteorological Organization Bulletin* **56**, 297–309.
10. Information is available at the Indian Ocean Observing System (IndOOS) website: http://www.clivar.org/organization/indian/IndOOS/obs.php.
11. Saji et al. (1999) *Nature* **401**, 360–363.
12. Jin et al. (2008) *Clim. Dyn*. DOI 10.1007/s00382-008-0397-3.
13. Luo et al. (2008) *J. Clim.* **21**, 84–93.
14. Buizza et al. (2010) Future perspective of seasonal prediction system developments at ECMWF. http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html.
15. Scaife 2010: Introduction to Seasonal Prediction and Numerical Models. http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html.

16. Stoner et al. (2009) *J. Clim.* **22**, 4348–4372.
17. Takaya 2010: Background of Symposium/Workshop, Proc. Int. Workshop on Development of Atmosphere-Ocean Coupled Models towards Improvement of Long-range Forecast. http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html.
18. Watanabe et al. (2010) *J. Clim.* **23**, 6312–6335.
19. Guilyardi et al. (2009) *Bull. Amer. Meteor. Soc.*, **90**, 325–340.
20. Pan (2010): The NCEP Climate Forecast System Version 2. http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html
21. Buizza et al. (2010): Strategy for seasonal prediction developments at ECMWF. http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html
22. Kimoto (2010) Expanding the horizon of seasonal prediction using state-of-the-art climate models. http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html
23. Scaife et al. (2010) *J. Clim.*, **23**, 6143–6152.
24. Ineson and Scaife (2009) *Nature Geoscience* **2**, 32–36.
25. Imada and Kimoto (2009) Geophys*. Res. Lett.*, **36**, L03706, doi:10.1029/2008GL036421.
26. Fujii et al. (2009) *J. Clim.* **22**, 5541–5557.
27. Alves et al. (2010) Current status and strategy of CGCM and ocean analysis system developments in Australia. http://www.jma.go.jp/jma/en/Activities/cgcm_2010/cgcm_ws_2010.html
28. Koster et al. (2010) *Geophys. Res. Lett*., **37**, L02402, doi:10.1029/2009GL041677.
29. Information is available at CLIVAR website: http://www.clivar.org/organization/wgsip/chfp/iceHFP/iceHFP.php
30. Hurrell et al. (2009) *Bull. Amer. Meteor. Soc.*, **90**, 1819–1832.

Agenda of Workshop

WEDNESDAY, 8 DECEMBER 2010:
OPENING : Opening and Introduction to Meeting (Kiyotoshi Takahashi (JMA))

1030-1040 Welcome address (Akihide Segami (Director-General of the Global Environment and Marine Department, JMA))

Group photo

1045-1050 Announcement about the workshop schedule (K. Takahashi (JMA))
1050-1130 Yuhei Takaya (JMA)
Introduction of the background of the symposium/workshop

SESSION 1 : Public Symposium (K. Takahashi (JMA))

1330-1400 Registration
1400-1410 Opening address (Kunio Sakurai (Director-General, JMA))
1410-1420 Introduction to the symposium (K. Takahashi (JMA))
1420-1500 Adam Scaife (UKMO)
Seasonal prediction and Climate models
1500-1540 Shuhei Maeda (JMA)
Improvements of seasonal prediction by introducing CGCM

Break

1600-1640 Roberto Buizza (ECMWF)
Future perspective of coupled monthly-to seasonal prediction system developments at ECMWF
1640-1720 Masahide Kimoto (U. Tokyo)
Better climate information for society

THURSDAY, 9 DECEMBER 2010:
SESSION 2: Air-sea interactions in the Pacific-Indian region (S.-P. Xie (IPRC))

0930-1010 Shang-Ping Xie (IPRC/UH) [Keynote presentation]
Modes of Indo-Pacific variability and predictability of East Asian climate
1010-1040 Yukio Masumoto (JAMSTEC)
IndOOS (Indian Ocean Observing System): Present status and recent highlights on air-sea interactions in the Indian Ocean

Break

1100-1130 Tamaki Yasuda (MRI/JMA)
Air-sea interaction over the Indian Ocean after El Nino in JMA/MRI-CGCM seasonal forecast experiment

SESSION 3: Current status of development of CGCM

Review of CGCM development (H.-L. Pan (NCEP))

1330-1410 Hua-Lu Pan (NCEP) [Keynote presentation]
The NCEP Climate Forecast System (CFS) : Status and Plan

1410-1440 Jing-Jia Luo (JAMSTEC)
Seasonal prediction and coupled model development activities at JAMSTEC

1440-1510 Yongqiang Yu (IAP)
The basic performance of IAP coupled GCM FGOALS2.0

Ocean Analysis for Seasonal Predictions (O. Alves (CAWCR))

1530-1610 Oscar Alves (CAWCR) [Keynote presentation]
Current status and strategy of CGCM and ocean analysis system developments in Australia

1610-1640 Yousuke Fujii (MRI/JMA)
Coupled model Simulation by Constraining Ocean Fields with Ocean Data thorough the JMA operational ocean data assimilation system

1640-1710 Masafumi Kamachi (MRI/JMA)
Strategy and issues to be addressed in the sea-ice assimilation

FRIDAY, 10 DECEMBER 2010:

SESSION 4: Future developments of CGCM for better seasonal prediction (T. Ose (MRI))

0930-1000 Adam Scaife (UKMO)
Strategy for development of seasonal prediction system at UKMO

1000-1020 Roberto Buizza (ECMWF)
Strategy for development of seasonal prediction system at ECMWF

1020-1040 Nobumasa Komori (Earth Simulator Center)
CFES: Coupled GCM for the Earth Simulator---Current status and future directions

Break

1055-1125 Masahide Kimoto (U. Tokyo)
Expanding the horizon of seasonal prediction using state-of-the-art climate models

1125-1200 Discussion and summary of the workshop (on a proposal)

1200-1205 Closing address (Kiyoharu Takano (Director of Climate Prediction Division, JMA))

SESSION 5: Technical Tour

1330-1700 Visiting Earth Simulator Center

Background of Symposium and Workshop

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1. Introduction

The climate system in the Asia-Pacific region is a complex system dominated by the variability of the Asian monsoon, the ENSO and the Indian Ocean. The seasonal forecast in the Asian region still remains one of the most challenging tasks. There is increasing evidence that explains seasonal variability and supports the feasibility of the seasonal forecast in this region. Recent research has elucidated some mechanisms of the atmosphere-ocean coupled system in the Asia-Pacific region.

The JMA started to issue 3-month forecasts and warm/cold season forecasts based on dynamical models in 2003. In February 2010, the JMA has introduced the atmosphere-ocean coupled model (JMA/MRI-CGCM; Yasuda et al. 2007) to its operational seasonal forecast. The new system shows substantial improvement over the sub-tropics, tropics, and in the Asian monsoon variability. These results suggest improvement of seasonal forecasts in the Asian region. The workshop highlights great advances made in recent decades and prospects of seasonal forecasts using atmosphere-ocean coupled models in the future.

2. JMA Seasonal Ensemble Forecast System

The JMA seasonal ensemble forecast system consists of an atmosphere-ocean coupled model and an ocean data assimilation system. The coupled model uses the low-resolution version (T_L95L40) of the JMA operational global atmospheric model and the Meteorological Research Institute (MRI) Community Ocean Model (MRI.COM-G; Tsujino et al. 2010). The ocean data assimilation system called MOVE/MRI.COM has been developed at the MRI of the JMA (Usui et al. 2006). This system employs a 3D-Var analysis method using vertical coupled temperature-salinity EOF modes (Fujii and Kamachi 2003). Nine ensemble member integrations are carried out every five days with accelerated ocean analysis. Perturbed atmospheric initial conditions are produced by a breeding method in the northern hemisphere and the tropics (Chikamoto et al. 2005). These atmospheric perturbations are used to produce oceanic initial perturbations.

3. Skill of JMA Seasonal Ensemble Forecast System

Here, some results are highlighted among the verifications of the new JMA Seasonal Ensemble Forecast System. This system has been better able to predict the NINO3.4 SST and western North Pacific SST than the old JMA coupled model for ENSO prediction. The SST forecast skills (anomaly correlation coefficients; ACC) for the Indian Ocean and the western North Pacific and equatorial eastern Pacific (NINO3) are summarized in Figure 1. As expected, ACCs are good for boreal winter and relatively poor for boreal summer because of the so-called “spring barrier.” The JMA/MRI-CGCM shows relatively good skill during January to April in the western North Pacific, and moderate skill during January to June in the Indian Ocean. These delayed good skill peaks for the ENSO seasonal phase result from the delayed influence of ENSO variability thorough the “atmospheric bridge mechanism” in the tropics (e.g., Klein et al. 1999).

The new coupled model shows clear improvement for the boreal winter forecast (Fig. 2). In addition, the boreal summer forecasts for the Asian region benefit from the improvement of the SST forecasts in the tropical basins such as the Indian Ocean and the western North Pacific (not shown). In fact, the Asian monsoon variabilities are significantly improved with the coupled model (Fig. 3; Yasuda et al. 2007). The good skill of the East Asian monsoon presumably stems from the “Indian Ocean capacitor effect” proposed by Xie et al. (2009). The 2010 summer is an example of the “Indian Ocean capacitor effect.” JMA operational forecasts showed above-normal SST over the Indian Ocean basin and above-normal (active) rainfall over the Indian Ocean. Corresponding to these conditions, the V-shaped response in the sea-level pressure was seen above the Indian Ocean and the maritime continent. In East Asia, the anti-cyclonic circulation anomaly in the lower troposphere and suppressed rainfall east of the Philippines were seen during the summer of 2010. These conditions caused the westward extension of the subtropical high and hot summer in the south and west part of Japan. Recently, Chowdary et al. (2010) investigated the skill of 11 coupled models in predicting the East Asian summer monsoon and showed the coupled models successfully predicted the East Asian summer monsoon variability. Their results are consistent with our improvements using the new JMA seasonal forecast system.

Some deficiencies remain in the new system. For example, the representation of spatial patterns of ENSO variability and its teleconnections is a typical example. Figure 4 illustrates regression patterns of SST and 500-hPa height on NINO3 SST. The common errors in coupled models are also seen in the new coupled model. For instance, the cold tongue overshoot westward and the teleconnection pattern is displaced and distorted. Better representation of teleconnection patterns is a key for improving tropical influence on extratropical circulation.

4. Summary

The atmosphere-ocean coupled model was introduced to the JMA seasonal ensemble forecast system in February 2010. The new system shows better skill in predicting ENSO variability and Asian monsoon variability. The new system shows overall improvement in extratropical circulation as well. These are promising results toward seasonal prediction in the Asian region with coupled models. Improvements in the representation of ENSO variability and its teleconnection patterns will be expected to improve extratropic skills in the Asian region.

Reference

Chikamoto, Y., H. Mukougawa, T. Kubota, H. Sato, A. Ito, and S. Maeda, 2007: Evidence of growing bred vector associated with the tropical intraseasonal oscillation. Geophys. Res. Lett., 34, L04806, doi:10.1029/2006GL028450.

Chowdary, J. S., S.-P. Xie, J.-Y. Lee, Y. Kosaka, and B. Wang (2010), Predictability of summer northwest Pacific climate in 11 coupled model hindcasts: Local and remote forcing, J. Geophys. Res., 115, D22121, doi:10.1029/2010JD014595.

Fujii, Y., and M. Kamachi 2003: Three-dimensional analysis of temperature and salinity in the equatorial Pacific using a variational method with vertical coupled temperature-salinity empirical orthogonal function modes. J. Geophys. Res., 108, 3297, doi:10.1029/2002JC001745.

Ishii, M., A. Shouji, S. Sugimoto, and T. Matsumoto, 2005: Objective Analyses of Sea-Surface Temperature and Marine Meteorological Variables for the 20th Century using ICOADS and the Kobe Collection. Int. J. Climatol., 25, 865–879.

Klein, S. A., B. J. Soden, N.-C. Lau, 1999: Remote Sea Surface Temperature Variations during ENSO: Evidence for a Tropical Atmospheric Bridge. J. Climate, 12, 917–932.

Tsujino, H. T. Motoi, I. Ishikawa, M. Hirabara, H. Nakano, G. Yamanaka, T. Yasuda, and H, Ishizaki 2010: Reference manual for the Meteorological Research Institute Community Ocean Model (MRI.COM) version 3. Tech. Rep. MRI., 59. ISSN 0386-4049. Available online at http://www.mri-jma.go.jp/Publish/Technical/index_en.html.

Usui, N., S. Ishizaki, Y. Fujii, H. Tsujino, T. Yasuda, and M. Kamachi, 2006: Meteorological Research Institute Multivariate Ocean Variational Estimation (MOVE) System: Some early results. Adv. Space Res., 37, 806-822.

Wang, B., and Z. Fan, 1999: Choice of South Asian summer monsoon indices. Bull. Amer. Meteor. Soc., 80, 629–638.

Webster, P. J., and S. Yang, 1992: Monsoon and ENSO: Selectively interactive systems. Quart. J. Roy. Meteor. Soc., 118, 877–926.

Xie, P. and P. A. Arkin, 1996: Analysis of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions, J. Climate, 9, 840–858.

Xie, S.-P., K. Hu, J. Hafner, H. Tokinaga, Y. Du, G. Huang, and T. Sampe, 2009: Indian Ocean Capacitor Effect on Indo–Western Pacific Climate during the Summer following El Niño. J. Climate, 22, 730–747.

Yasuda, T., Y. Takaya, C. Kobayashi, M. Kamachi, H. Kamahori and T. Ose, 2007: Asian Monsoon Predictability in JMA/MRI Seasonal Forecast System. CLIVAR Exchange, 12, 4, 18–24. Available online at http://www.clivar.org/.

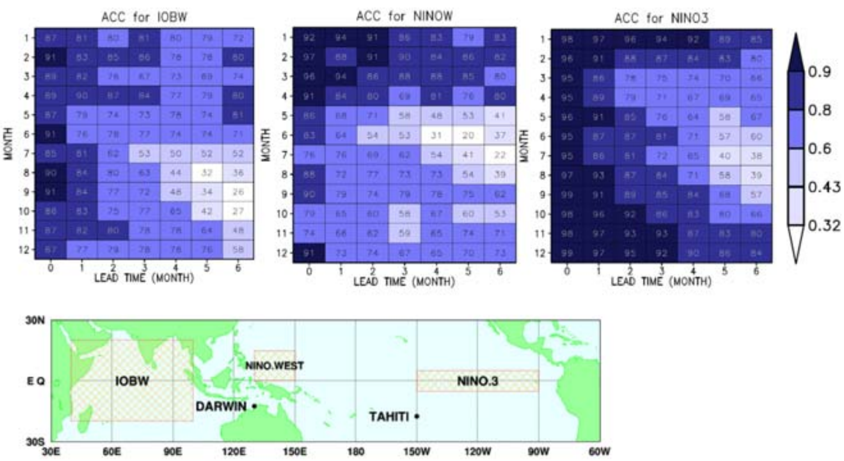

Figure 1. Anomaly correlation coefficients for the Indian Ocean, the western North Pacific and the equatorial eastern Pacific with respect to the lead time and initial months.

Regions verified are shown in the lower figure.

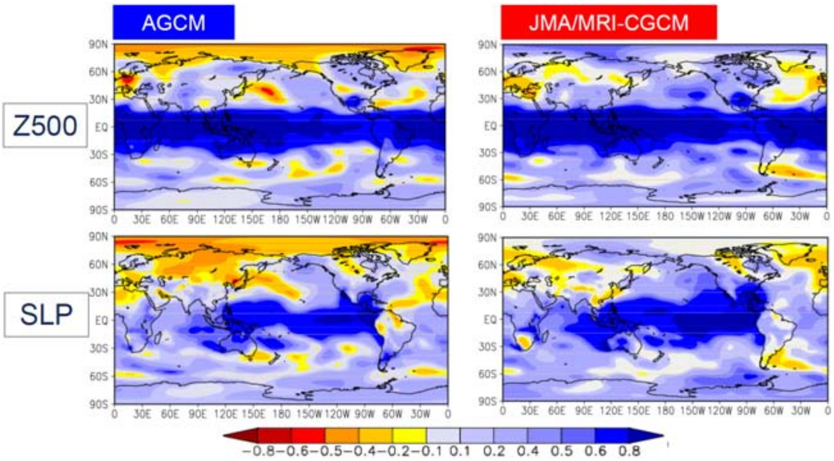

Figure 2. Anomaly correlation coefficients for the boreal winter (December–February).

The scores of (upper) 500-hPa height and (lower) sea-level pressure starting from August during 1984–2005 for (left) the old JMA seasonal forecast system with an AGCM and (right) the new system with a CGCM are verified with the JRA-25 reanalysis.

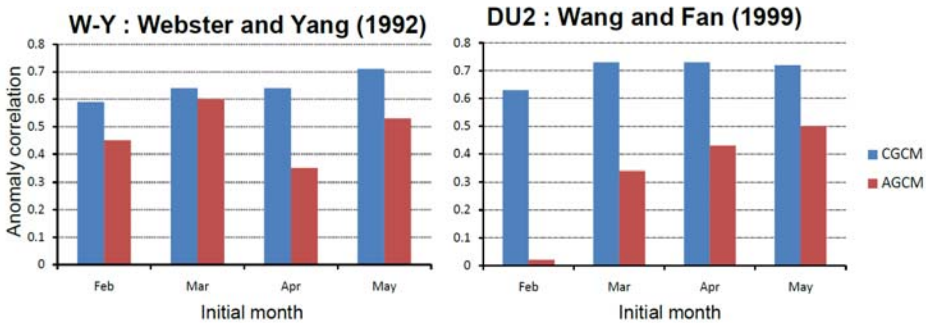

Figure 3. Anomaly correlation coefficients of monsoon indices for the boreal summer (June-August).

The scores of (left) the Webster-Yang index (Webster and Yang 1992) and (right) the Wang and Fan index (Wang and Fang 1999) starting from initial months of February to May during 1984–2005 with the old JMA seasonal forecast system (AGCM) and the new system with a CGCM are verified with the JRA-25 reanalysis.

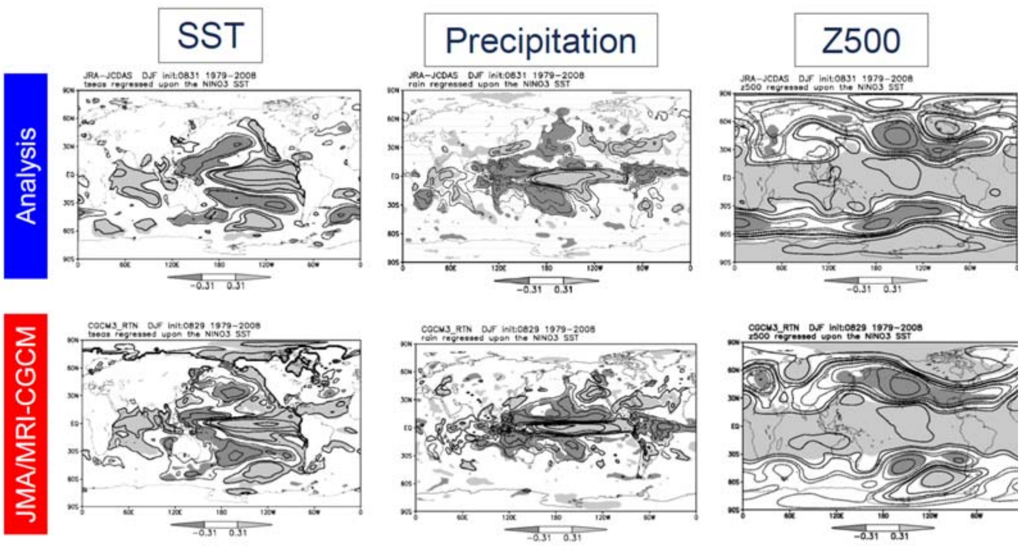

Figure 4. Teleconnection patterns regressed on NINO3 SST for boreal winter (December-February)

The regression patterns on NINO3 SST during 1979–2008 with (upper) analyses and (lower) the JMA/MRI-CGCM. Shades indicate that anomaly correlations are exceeding 95 % confidence levels. The regressions in (upper) analyses are computed with the COBE-SST analysis (Ishii et al. 2005), the CPC Merged Analysis of Precipitation (Xie and Arkin 1996) and the JRA-25 500-hPa hight analysis. The regressions in (lower) the forecast are computed with single member integration with the JMA/MRI-CGCM.

Seasonal Forecasting Activities at CLIVAR WGSIP and the UKMO Hadley Centre

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Summary

We present a summary of the current scientific foci and related coordinated international experiments being used to guide improvements in seasonal forecast capability through the CLIVAR Working Group on Seasonal to Interannual Prediction (WGSIP). We also discuss plans and activities specific to the UKMO Hadley Centre's long range forecasting activities. The UKMO recently introduced its Global Seasonal Forecast System 4 (GloSea4) into operational use. This new system has double the horizontal resolution of the previous operational seasonal forecast system and the hindcast is run in real time to allow rapid updating of the climate model at its core. We therefore discuss some of the very recent changes already made to GloSea4 and planned future upgrades.

We also discuss ongoing model development at the UKMO Hadley Centre. We have developed a new, high resolution coupled model which removes the classic problem of a westward extension of ENSO anomalies in the tropical Pacific. Our new model also corrects the Westerly bias in the Atlantic Ocean and removes much of the deficit in Atlantic Blocking frequency. Blocking is a key process for generating extreme seasonal anomalies and we aim to eventually introduce this model into seasonal forecast operations, although its computational cost currently prohibits this.

1. Scientific foci of the CLIVAR-WGSIP

The CLIVAR Working Group on Seasonal to Interannual Prediction is composed of 13 international members from major seasonal forecast centres around the globe. It aims to **"develop a programme of numerical experimentation for seasonal-to-interannual variability and predictability, paying special attention to assessing and improving predictions."** WGSIP is already running the Climate Historical Forecast Project. Forecast groups participating in this project are running sets of ensemble hindcast (reforecast) experiments for past seasons and providing an agreed set of data which is being hosted at the Centro de Investigaciones del Mar y la Atmosfera (CIMA). The data are currently being uploaded and will be made available to researchers worldwide.

Following a major international conference organised by WGSIP in 2007, three scientific areas were identified as potentially holding significant further improvements in skill which could enhance seasonal prediction capability: **sea-ice, the stratosphere** and the **land surface**. The CLIVAR WGSIP is now involved in specific experiments on each of these three topics with reforecast experiments being carried out to address each specifically. For example, several centres are starting specific hindcast tests where sea-ice observations are added or withheld from initial conditions to test whether this impacts forecasts in the following months. Further details of these experiments are available at the WGSIP web site: http://www.clivar.org/organization/wgsip/wgsip.php and it is hoped that over the coming years this group will help to answer some of the many questions about potential forecast improvements.

2. Global Seasonal Forecasts from the UKMO Hadley Centre

In 2009 the UKMO introduced its Global Seasonal Forecast System 4 into operations. The new system is described by Arribas et al. (2011). It has double the horizontal resolution of the previous forecast system and shows increased skill scores over most regions of the Earth. The forecast skill for ENSO is similar to that in other leading forecast systems and importantly, GloSea4 is able to reproduce most of the well known ENSO teleconnections throughout the tropics.

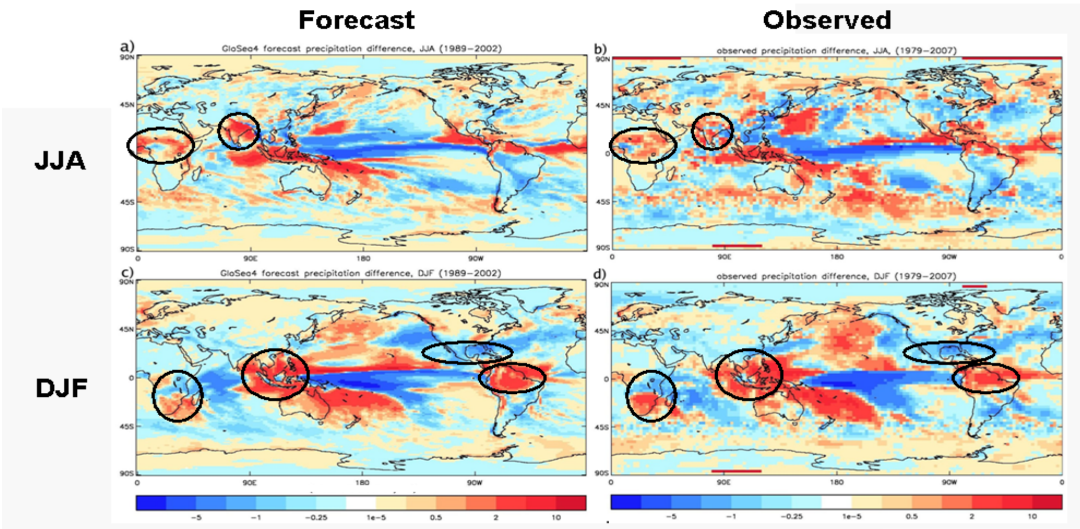

Figure 1: Differences in seasonal mean rainfall between La Niña and El Niño in seasonal forecasts (left) and observations (right). Blue implies more rainfall during El Niño than La Niña. Black circles highlight some of the better known tropical ENSO teleconnections. Units are mm/day. Figure from Arribas et al., Mon. Wea. Rev. 2011.

Figure 1 shows forecast and observed ENSO anomalies across the globe where it can be seen that rainfall anomalies are well reproduced in the forecast composites. In contrast, and in common with other leading forecast systems, it shows only very low predictability of the North Atlantic Oscillation/Arctic Oscillation (NAO/AO) on seasonal timescales (Fig.2).

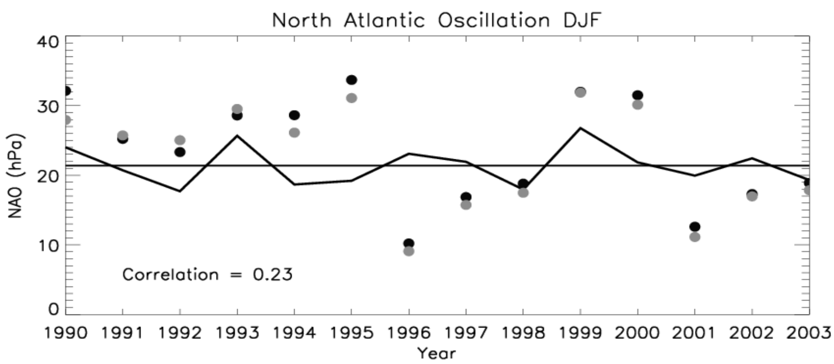

Figure 2: Hindcast values of the NAO showing observational values (grey and black dots) and ensemble mean values (black line). Units are hPa. Figure from Arribas et al., Mon. Wea. Rev. 2011.

Forecasting the NAO/AO remains a key limitation and a major challenge for extratropical predictability over land.

A recent upgrade has increased the vertical resolution to 85 levels to span the middle atmosphere and include potentially important processes such as the QBO and sudden stratospheric warmings which appear, for example, to connect ENSO to the NAO/AO in the extratropics (e.g. Ineson and Scaife 2009). Although there is no doubt a large degree of internal variability in extratropical winter climate, these kinds of physical links with potential predictability of the NAO/AO do exist and are a focus at UKMO (e.g. Folland et al. 2011) to try to gain the maximum seasonal predictability for extratropical climate. We hope in future to add further resolution improvements and to also improve the physical drivers through better initialization and external forcing to deliver better forecast skill on both seasonal and decadal timescales. Our raw forecasts are also delivered to the WMO under our obligations as a designated Global Producing Centre and can be viewed at: http://www.metoffice.gov.uk/science/specialist/long-range/

3. Climate Model Development for Seasonal Forecasting

The UKMO Hadley Centre has an active program of model development. In recent years this has been lead from within the Monthly to Decadal Prediction team to ensure that developments can be fed directly into updating the GloSea seasonal forecast system described above. Figure 3 shows two recent highlights. In Fig 3a we show the ENSO pattern in our new climate model against that in our existing operational model. Note the reduction in the extension of the ENSO anomaly into the West Pacific. This error has been present in all previous versions of this model. Large improvements are also found in the frequency of Atlantic blocking in our latest model (Fig.3b). By correcting a mean Westerly bias in the model, the blocking statistics over the Atlantic are greatly improved. Of course there are remaining errors in our model but we hope eventually to port this model into operations and to improve seasonal forecast skill.

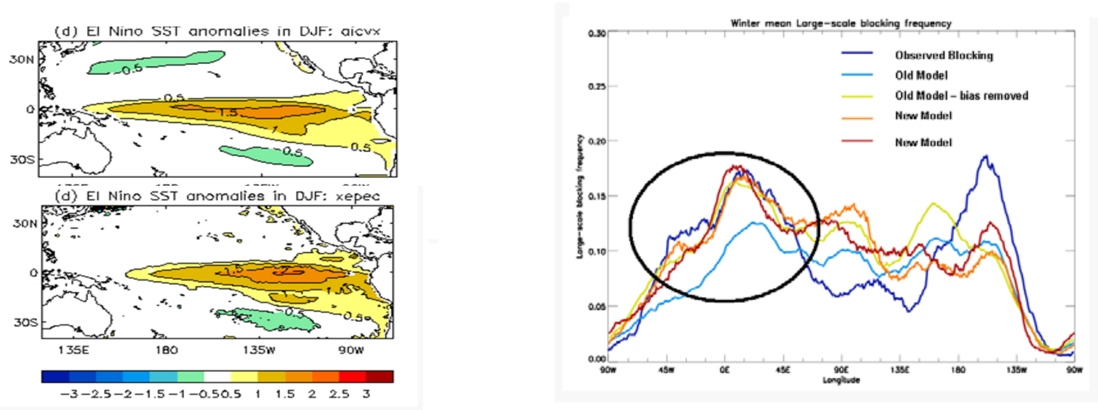

Figure 3: Improvement in model errors at the UKMO Hadley Centre. The left panels show the improvement in simulated ENSO patterns between long control simulations of the model currently used for seasonal forecasts (upper) and the new model (lower, units K). The right hand panel shows the frequency of blocking in the same models.

References

Arribas A. , M. Glover, A. Maidens, K. Peterson, M. Gordon, C., MacLachlan, R. Graham, D. Fereday, J. Camp, A.A. Scaife, P. Xavier, P. McLean, A. Colman, S. Cusack (2011). The GloSea4 ensemble prediction system for seasonal forecasting. *Mon. Wea. Rev.*, in press.

Folland C.K., A.A. Scaife, J.Lindesay and D. Stephenson (2010). How predictable is European winter climate a season ahead? *Int. J. Clim.*, submitted.

Ineson S. and Scaife A.A. (2009). The role of the stratosphere in the European climate response to El Nino. *Nature Geoscience*, 2, 32-36.

Improvements in Seasonal Forecasting by Introducing CGCM

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1. Introduction

The new JMA seasonal ensemble prediction system (Takaya, this volume), which began operating in February 2010, improved the JMA's operational seasonal forecast in some respects. In this paper, key points of improvement are described from the standpoint of seasonal forecasters.

2. Improved prediction skill

Since ENSO and related variabilities in the ocean and the atmosphere are the most important predictable sources for seasonal predictions, the primary requirement for a seasonal numerical prediction system is to adequately predict such variability. In this sense, the new JMA seasonal ensemble prediction system has good capability. Figure 1 shows predicted SST anomalies and precipitation anomalies in the winter of 1997/1998 (DJF) using this prediction system. The strongest El Niño in the twentieth century and related SST anomalies were well predicted; positive SST anomalies in the equatorial central-eastern Pacific, negative SST anomalies in the tropical western Pacific, as well as positive SST anomalies in the tropical Indian ocean and in the tropical Atlantic. Associated precipitation anomalies in the tropics, sub-tropics, and mid-latitudes are well predicted. It is not only the 1997/1998 El Niño, but other El Niños such as in 1986/1987 that are well predicted by this prediction system. A thirty-year (1979–2008) hindcast (Takaya, this volume) confirmed that the prediction system has better prediction skills for ENSO and related variability compared with the old prediction system, which had been used for operations until January 2010.

It is worthy of special mention that the lingering effect of El Niño on the western North Pacific climate variability through the Indian Ocean warming (Xie et al., 2009) is also well predicted. This means that not only the instantaneous impact, but also the delayed impact of El Niño is well predicted. As an example of the prediction of the lingering effect, the prediction for the summer of 2010 is shown. In that year, after El Niño had disappeared in the spring, positive SST anomalies in the Indian Ocean continued until summer, and La Niña started in the summer. Corresponding to these climate system variabilities, characteristic SLP anomalies are observed; negative anomalies in the Indian Ocean extending to the equatorial western Pacific, and positive anomalies in the sub-tropical western North Pacific (Fig. 2). This SLP anomaly pattern is well predicted by the prediction system.

3. Improved explanation on grounds for forecasts

In addition to issuing forecasts, operational forecasters must explain the grounds for their forecast to the public. The new prediction system, which has improved prediction skills, enabled forecasters to give physically consistent explanations regarding the grounds of their forecasts. In this section, an example of an explanation of the grounds for a specific forecast is shown.

The JMA seasonal forecast for the winter of 2010/2011 issued on November 25, 2010 is characterized by DJF below normal temperatures with 40% probability in western Japan and Okinawa/Amami. The grounds for the forecast are as follows. Figure 3 shows predicted fields such as SST and precipitation for the 2010/2011 winter (DJF). The initial date is November 12, 2010. Predicted SST anomalies show that La Niña conditions are likely to persist throughout the winter. Associated with the predicted SST anomalies, positive precipitation anomalies are predicted over the eastern Indian Ocean and the Maritime Continent. In the upper troposphere, negative 200 hPa velocity potential anomalies (i.e. divergent flow anomalies) are predicted reflecting positive precipitation anomalies in the region. The predicted stream function at 200 hPa shows an anti-cyclonic anomaly over Southeast Asia and a cyclonic anomaly over Japan. These rotational flow anomalies will likely form a stationary Rossby wave train forced by the above mentioned divergent flow; low potential vorticity advected by the divergent flow forced a stationary Rossby wave packet which propagated westward along the Asian jet stream. Corresponding to the cyclonic anomaly over Japan, negative temperature anomalies at 850 hPa from western Japan to the South China Sea are predicted. This means that due to the La Niña, there tends to be below normal temperatures in western Japan and Okinawa/Amami. On the other hand, the spread among each ensemble member for temperature prediction in western Japan is very large due to the atmospheric internal variability (Fig. 4). In addition, the prediction system can hardly predict the Arctic Oscillation which impacts Japan's winter climate. Considering all of the above, the JMA issued a DJF temperature forecast for western Japan and Okinawa/Amami with a 40% chance of below normal, a 40% chance of near normal, and a 20% chance of above normal temperatures.

4. Future subjects

Although the new prediction system improved the JMA’s seasonal forecast in some respects as mentioned earlier, several problems remain from the viewpoint of operational use for seasonal forecasts as follows.

1. Over confident predictions. The slope of the reliability diagram of the probability prediction is smaller than that of the diagonal line.
2. Deformed ENSO predictions and its influences. The shape of predicted El Niño and associated teleconnections are deformed.
3. Weak and fast MJO. Activities of predicted MJO are weaker than those observed, and the phase speed of predicted MJO is faster than that observed.
4. No sea ice inter-annual variation. Sea ice is treated as normal in the system and variability caused by sea ice variation is not predicted.

Improvements of the prediction system in the future promise to provide more useful seasonal forecasts to the public.

Reference

Xie, S.-P., K. Hu, J. Hafner, H. Tokinaga, Y. Du, G. Huang, and T. Sampe, 2009: Indian Ocean Capacitor Effect on Indo–Western Pacific Climate during the Summer following El Niño. J. Climate, 22, 730–747.

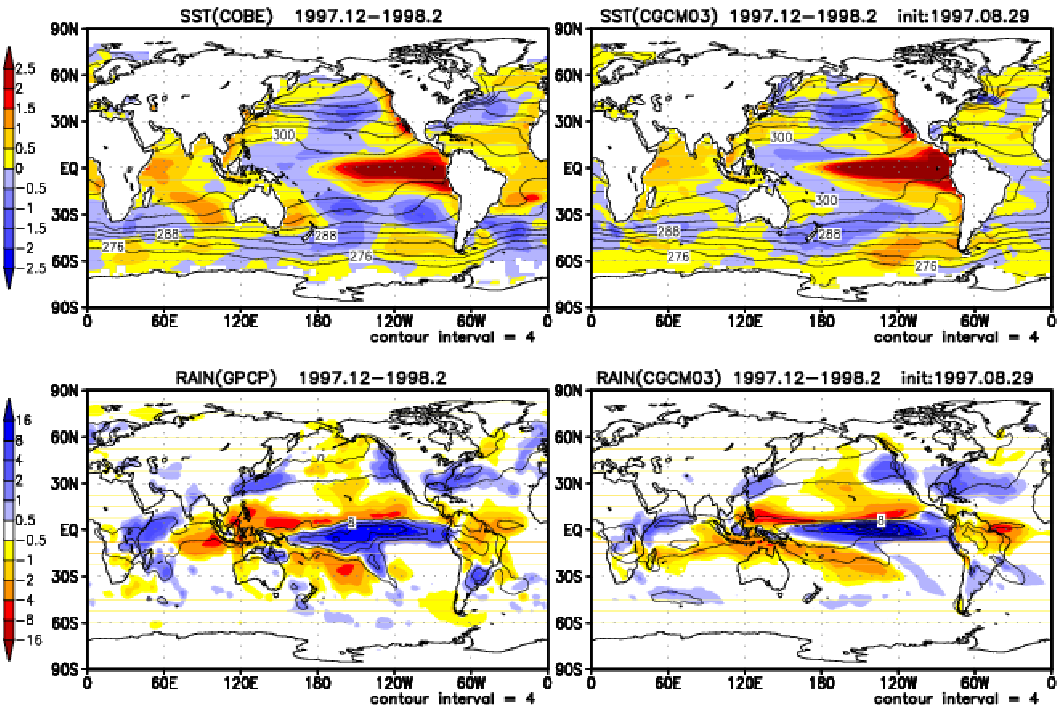

Figure 1. SST and precipitation in DJF 1997/1998.

Left: Observation (COBE SST and GPCP); right: Ensemble mean prediction. Initial date is 08.29.1997

Upper: SST (contour) and anomaly (shading); lower: Precipitation (contour) and anomaly (shading)

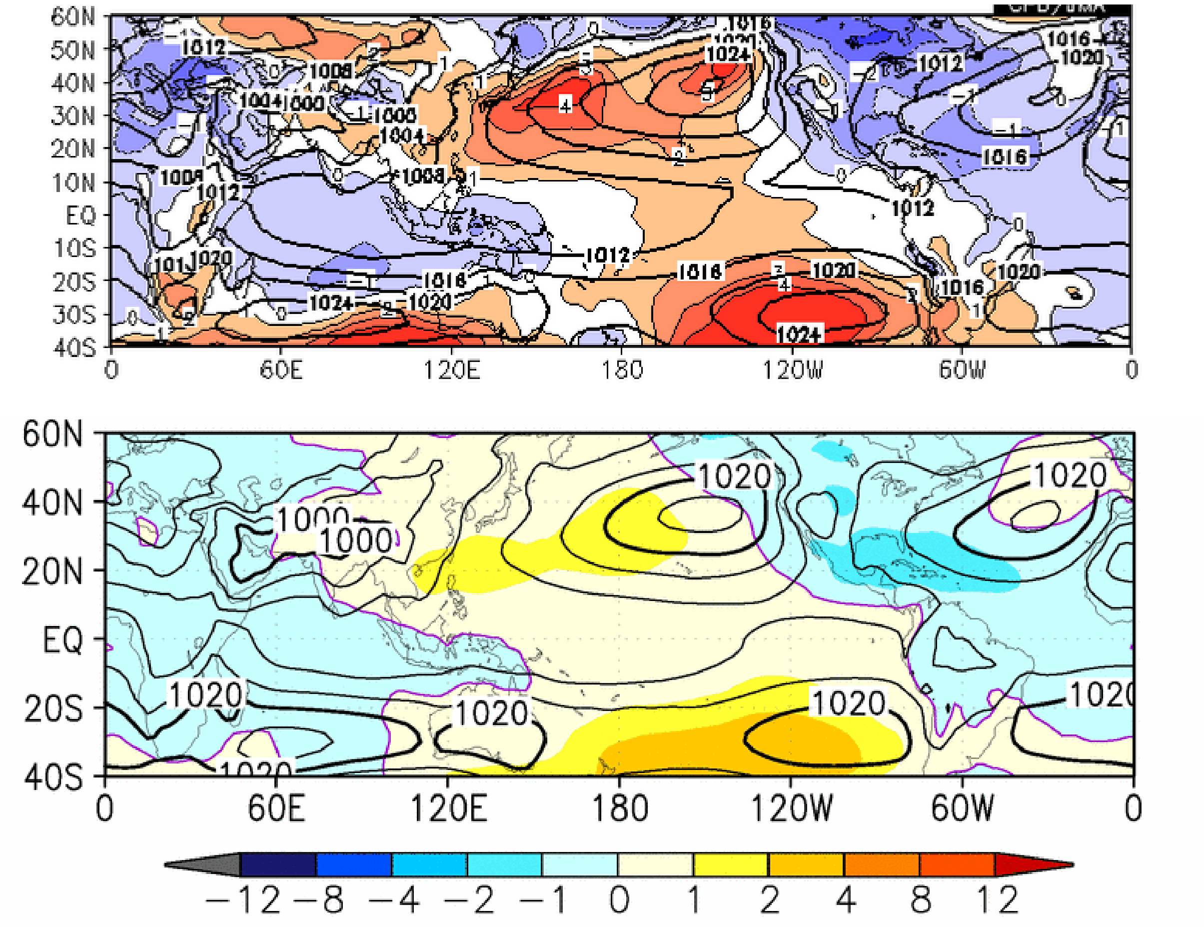

Figure 2. Sea level pressure in JJA 2010.

Upper: Observation (JCDAS); lower: Ensemble mean prediction. Initial date is 5.11.2010

Contours are sea level pressure. Shading is its anomalies.

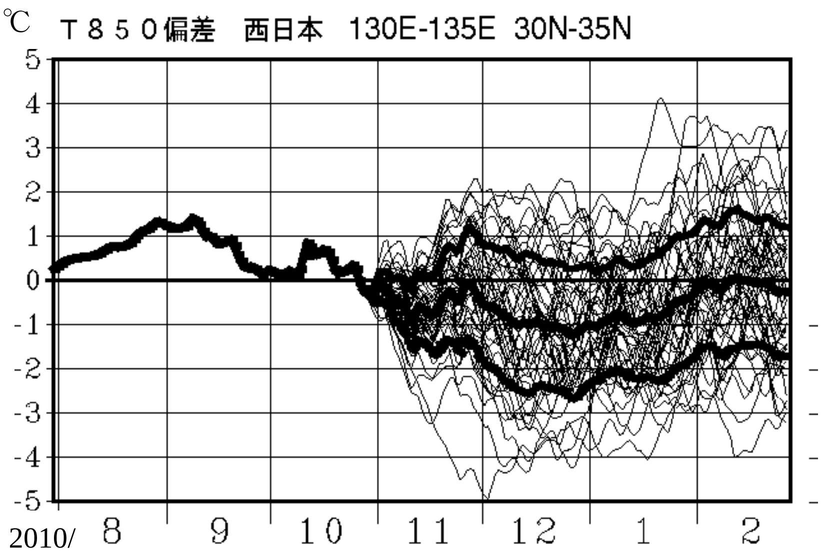

Figure 3. Time series of observed and predicted 30-day running mean 850 hPa temperature anomalies in western Japan (area averaged in 130E-135E,30N-35N). Initial date is 5.11.2010

(Thick lines): Observation (JCDAS), ensemble mean, ensemble mean + spread, ensemble mean - spread

(Thin lines): Each ensemble member

Medium- and extended-range prediction at ECMWF

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1. ECMWF operational medium- and extended-range probabilistic systems

In the past decade several centres have started producing operational extended-range probabilistic forecasts. Building on the implementation in the early 1990s of ensemble-based medium-range systems (say with a forecast range up to 30 days), and their subsequent continuous improvements, attention has been shifting towards the extended forecast range (say with a forecast range up to 1 year). Evidence of recent developments and achievements in the extended-range was presented in December 2010 at two international workshops. The UK Met Office hosted a WCRP[1]/THORPEX[2] workshop on 'Sub-seasonal to seasonal prediction', where current capabilities, open issues and ongoing plans were discussed. The Japanese Meteorological Agency (JMA) hosted this workshop on 'Development of atmosphere-ocean coupled models towards improvement of long-range forecasts', where similar topics were discussed.

ECMWF has been producing operational ensemble-based, probabilistic forecasts covering the medium- and extended-range for many years (see Table 1):

- In the medium-range ECMWF has been running its Ensemble Prediction System (EPS) since 1992. Since 2008, the EPS has been merged with the former ECMWF Monthly prediction system, and is now running with a variable-resolution, coupled to an ocean model from day 10 (*Buizza et al* 2008, *Vitart et al* 2008). EPS forecasts are used to produce 15-day forecasts twice-a-day, and up to 32 days once a week (at 00UTC on Thursdays).

- In the seasonal time scale, ECMWF has been producing ensemble-based seasonal predictions since 1998. Since 2005, ECMWF has been running System-3 (S3, *Anderson et al* 2007). It is worth mentioning that S3 is also part of EUROSIP, a multi-model European Seasonal prediction system that includes forecasts from Météo-France, UKMO and ECMWF.

The ECMWF EPS and S3 systems provide users with top-quality probabilistic forecasts. In the medium-range (say up to 15 days), recent comparisons based on the TIGGE[3] data-base have shown that the ECMWF EPS skill in predicting synoptic-scales is about 1 to 2 days better than its closer competitors (*Park et al* 2008, *Hagedorn et al* 2010). In the monthly time scale, ECMWF is one of the only two centres producing operationally monthly forecasts, the other centres being JMA. *Vitart & Molteni* (2009) have concluded that the latest version of the ECMWF EPS is capable to simulate more accurately than before large-scale events such as the Madden Julian Oscillation (MJO), and to capture to a good degree the tropical/extra-tropical interactions. They have also shown that the MJO has a significant positive impact on medium-range forecast

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[1] WCRP is the World Climate research Programme of the World Meteorological Organization (WMO).
[2] THORPEX is THe Observing system Research and Predictability Experiment of WMO.
[3] TIGGE is the THORPEX Interactive Grand Global Ensemble project, see http://www.ecmwf.int/research/WMO_projects/TIGGE/ for more information.

accuracy. The d15-26 forecast period is particularly interesting, with the model showing almost no skill at all when there is no MJO in the initial conditions, but the forecasts become reliable and skilful when there is an MJO in the initial conditions (Fig. 1). This could represent very useful information for the users of the monthly forecasting system, which can use the presence of an MJO event in the initial conditions to have an a priori estimate of the skill of the day 19-25 forecasts. In the seasonal time range, over the tropics the ECMWF S3 has shown good predictions of SST anomalies in the ENSO region up to 1-year ahead (Fig. 2). Over the extra-tropics,

	Current ensemble-based probabilistic systems	**2011 Planned changes**
32d **EPS**	• Twice a day to 15d, and once a week to 32d (Thu at 00UTC) • T_L639(d0-10)v319(d10-15/32)L62 resolution • Top of the Atmosphere: 5hPa • 50+1 members • Persisted SST anomaly up to d10 and coupled to HOPE[4] (1:1/3 degree resolution, L40) ocean model from day 10 • Continuous model cycle update (now cy36r4) • Initial uncertainties simulated using perturbations generated combining T_L399L91 Ensemble Data Assimilation and T42L62 Singular Vectors • Model uncertainties simulated using SPPT[5] and SPBS[6] stochastic schemes. • Reforecast suite with 5 members run once a week for 18 years	• *Q2-2011*: twice-weekly 32d extension (Thu and Sun at 00UTC) • *Q2-2011*: use of NEMO[7] (tripolar grid with 1:1/3 degree resolution, L42) instead of HOPE ocean model, and NEMOVAR instead of HOPE-OI to initialize the ocean • *Q4-2011*: increase in vertical resolution to about L95 in 2011. • *End of 2011/2012*: possible extension to 46 or 62 days
13m **S3**	• once a month to m7 and every quarter to m13 • T_L159L40 resolution • Top of the atmosphere: 5hPa • 40+1 members • coupled HOPE (1:1/3 degree resolution, L29) ocean model • Frozen model cycle (cy31r1, operational in 2006) • Initial uncertainties simulated using SVs and different SST • Model uncertainties simulated using the old SPPT scheme • Reforecast suite with 11 members run for 25y (1981-2005) • The system is also part or EUROSIP	• *Q3-2011*: S4 - T_L255L91 resolution, top of the atmosphere at 0.01hPa, possibly 51 members, coupled to NEMO (tripolar grid with 1:1/3 degree resolution, L42) ocean model. NEMOVAR to initialize the ocean. Frozen model cycle (cy36r4, operational in 2010-11). New SPPT and SPBS stochastic schemes. Reforecast suite with 11 members run for 30 years (1981-2010).

Table A. Configuration of the ECMWF 32-day Ensemble Prediction System (EPS) and seasonal prediction System-3 (S3) operational at the time of writing (January 2011, middle column) and changes planned for 2011 (right column).

The EPS and the S3 probabilistic systems are parts of the ECMWF operational suite that includes the high-resolution 12h 4D-Var assimilation system and forecast, which since 26 January 2010 have been running with a T_L1279L91 resolution. The high-resolution analysis defines the atmospheric unperturbed initial conditions used to initialize the probabilistic systems, after interpolation to the appropriate resolution. Figure 3 shows the grid-point spacing and the orography of the 4 main resolutions used at ECMWF (T_L1279, T_L639, T_L319 and T_L159).

[4] HOPE is the Hamburg Ocean Primitive Equation model.
[5] SPPT is the Stochastically Perturbed Parameterisation Tendency stochastic scheme.
[6] BS is the stochastic Back Scatter scheme.
[7] NEMO is the Nucleus for European Modelling of the Ocean model.

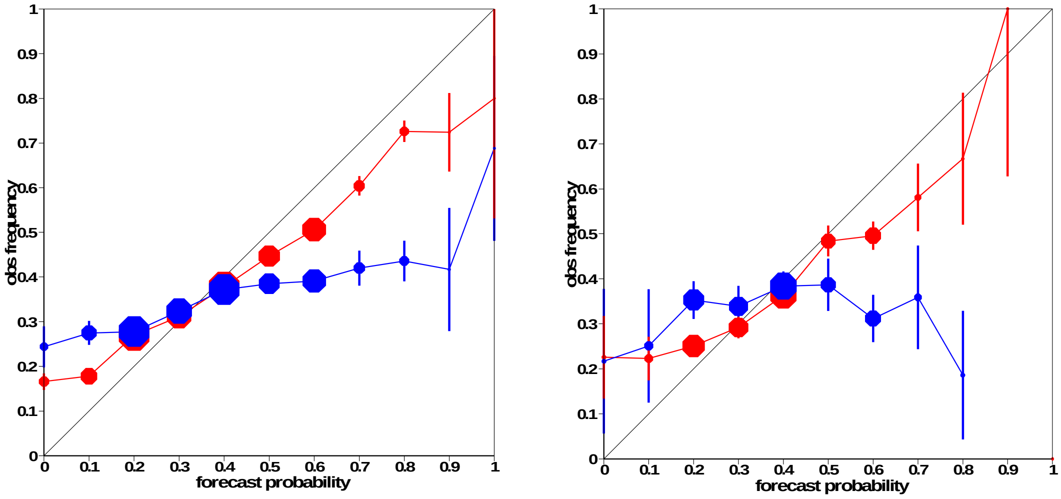

Figure 1. Reliability diagrams of the d15-26 weekly-average probabilistic prediction of 2-meter temperature anomalies in the upper tercile for cases with MJO-in-ICs (red lines) and NO-MJO-in-ICs (blue lines) for the Northern Hemisphere extra-tropics (left panel) and Europe (right panel). The diagrams have been computed considering 45 cases covering the period 1989-2008 (from Vitart & Molteni 2009).

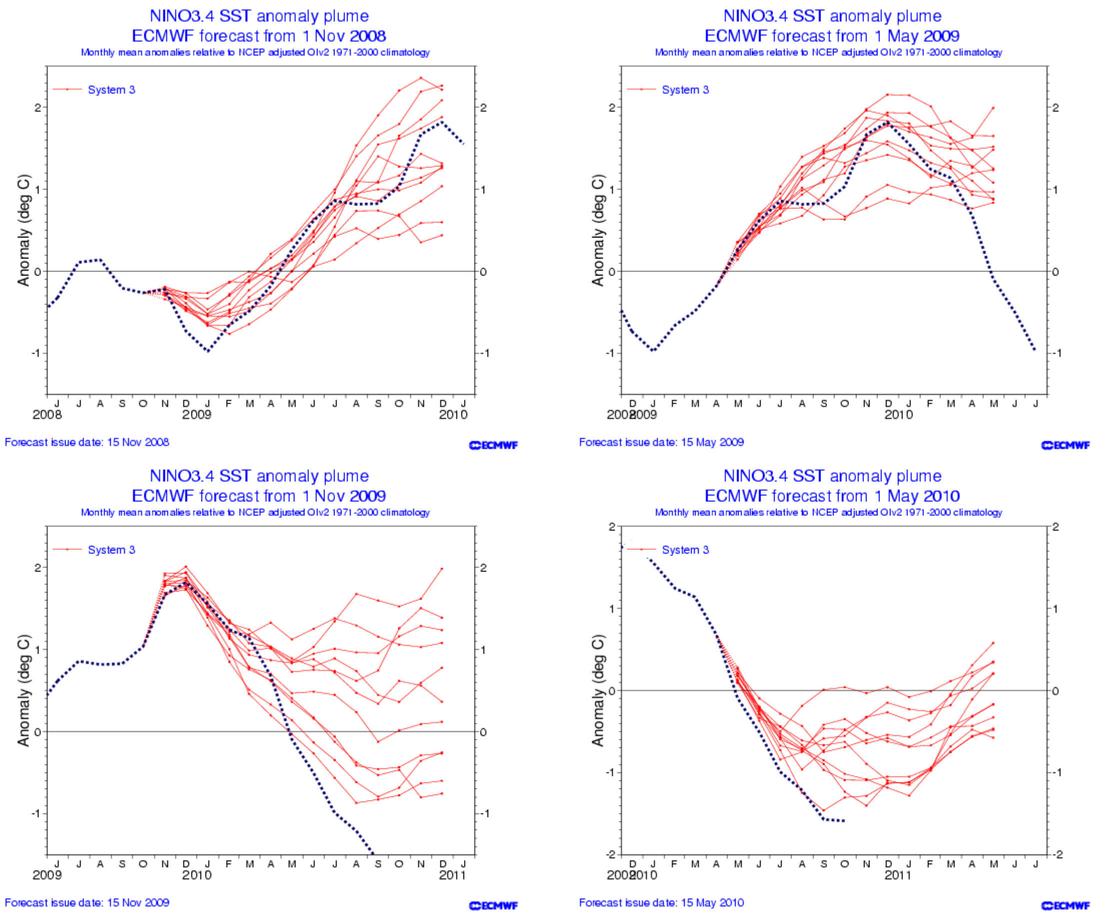

Figure 2.S3 13-month forecasts of nino3.4 SST anomalies (computed with respect to NCEP adjusted OIv2 1971-2000 climatology) issued on 1 Nov 2008 (top-left), 1 May 2010 (top-right), 1 Nov 2009 (bottom-left) and 1 May 2010 (bottom-right). The dotted blue lines show the verifying anomaly.

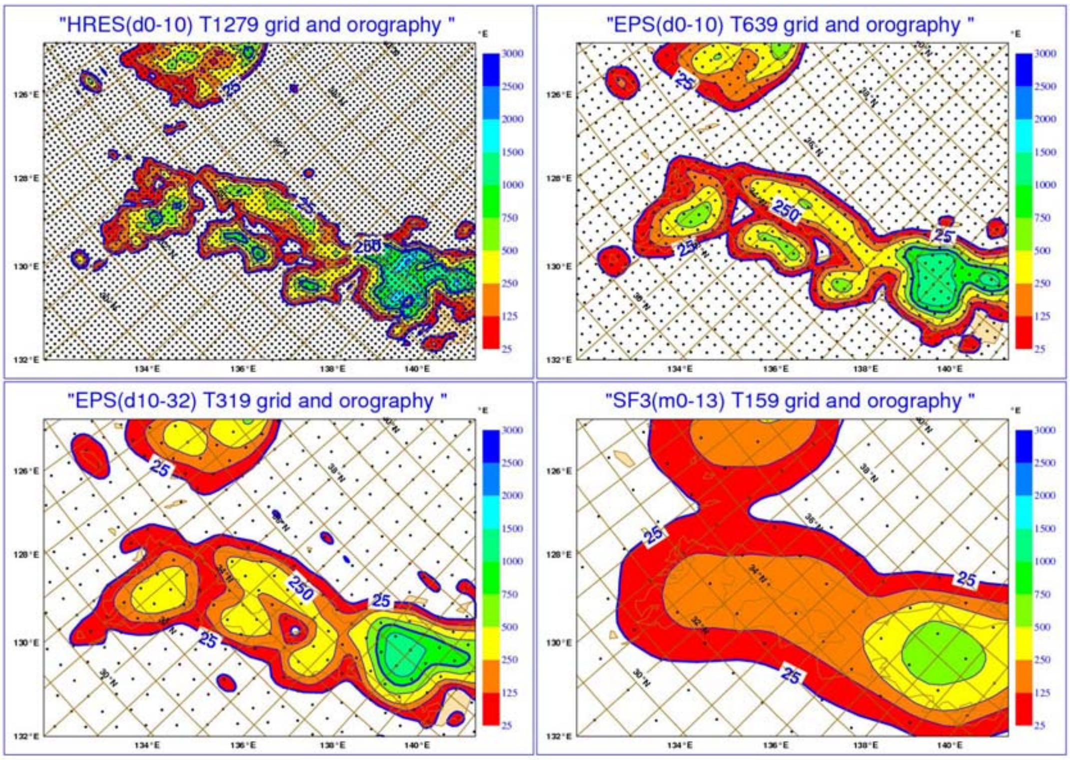

Figure 3. Grid-point resolution and orography over Japan of the 4 main resolutions used at ECMWF to produce the operational T_L1279 HRES analysis and forecasts (top-left), the T_L639 (top right) and T_L319 (bottom left) EPS and the T_L159 S3 (bottom-right) probabilistic forecasts.

2. Future changes of the ECMWF probabilistic systems

In 2011 some of the characteristics of the probabilistic systems will be changed to further improve the quality of the medium- and extended-range probabilistic forecasts:

- The introduction of a second weekly 32-day EPS extension (on Mondays at 00UTC) will also provide users with a more frequent, 'younger' and thus more skilful update of weekly-average forecasts valid for the forthcoming calendar weeks.
- The replacement of the HOPE ocean model with NEMO in the EPS and S4, and the implementation of the 3-dimensional variational ocean assimilation system NEMOVAR to initialize the ocean set the path for future upgrades, and reduce the resources required to run in coupled mode.
- Refinements of the stochastic schemes (SPPT and SPBS, see *Palmer et al* 2010) used to simulate model uncertainties implemented in cycle 36r4 are expected to improve not only the EPS and S4, but also the ECMWF Ensemble Data Assimilation used to generate the EPS initial perturbations.
- The implementation of planned new model cycles, including the vertical resolution increase, should further improve the simulation of the atmospheric circulation in the EPS and the seasonal System-4 (S4), which will use model cycle 36r4 (S3 is based on model cycle 31r1 that was operational in 2006).

Ongoing research in other areas is also expected to lead to improvements to the probabilistic forecasts: these include the simulation of initial uncertainties (e.g. by increasing the number of EDA members and the inclusion of land-surface perturbations) and of model uncertainties (further improvements of the stochastic schemes, SPPT and SPBS), the simulation of the ocean upper levels via a better coupling of the wave/mixed-layer/ocean models and the inclusion of a dynamical sea-ice model.

It is also expected that future atmospheric model improvements, e.g. in the land-surface scheme and in the parameterisation of convection, will improve the quality of the medium- and extended-range ensemble systems, e.g. their simulation of tropical/extra-tropical interactions. Developments of the wave/mixed-layer/ocean model and data assimilation systems should bring better ocean initial conditions, which should lead to better forecasts in the sub-seasonal forecast range. Future increases in the resolution of both the atmospheric and the ocean model should also lead to better long-range forecasts.

In the long-term, following the successful merger of the EPS and monthly systems in 2008, ECMWF will explore the possibility to merge EPS and the seasonal system into a seamless Probabilistic Forecasting System that would provide probabilistic forecasts from days to months ahead. Furthermore, the potential impact of extending the sample size of the re-forecast suite(s) to improve the estimation of the model climate will be assessed.

Acknowledgements

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References

Anderson, D., T. Stockdale, M. Balmaseda, L. Ferranti, F. Vitart, F. Molteni, F. Doblas-Reyes, K. Mogenson and A. Vidard: Development of the ECMWF seasonal forecast System 3. *ECMWF Research Department Technical Memorandum n. 503*, pp. 56 (available from ECMWF, Shinfield Park, Reading RG2 9AX, UK).

Buizza, R., Leutbecher, M., & Isaksen, L., 2008: Potential use of an ensemble of analyses in the ECMWF Ensemble Prediction System. *Q. J. R. Meteorol. Soc.*, **134**, 2051-2066.

Buizza, R., Bidlot, J.-R., Wedi, N., Fuentes, M., Hamrud, M., Holt, G., & Vitart, F., 2007: The new ECMWF VAREPS (Variable Resolution Ensemble Prediction System). *Q. J. Roy. Meteorol. Soc.*, **133**, 681-695.

Hagedorn, R., Buizza, R., Hamill, M. T., Leutbecher, M., & Palmer, T. N., 2011: Comparing TIGGE multi-model forecasts with re-forecast calibrated ECMWF ensemble forecasts. *Mon. Wea. Rev.*, under revision.

Palmer, T. N., Buizza, R., Doblas-Reyes, F., Jung, T., Leutbecher, M., Shutts, G. J., Steinheimer M., & Weisheimer, A., 2009: Stochastic parametrization and model uncertainty. *ECMWF Research Department Technical Memorandum n. 598*, ECMWF, Shinfield Park, Reading RG2-9AX, UK, pp. 42.

Park, Y.-Y., Buizza, R., & Leutbecher, M., 2008: TIGGE: preliminary results on comparing and combining ensembles. *Q. J. R. Meteorol. Soc.*, **134**, 2029-2050.

Vitart, F., Buizza, R., Alonso Balmaseda, M., Balsamo, G., Bidlot, J. R., Bonet, A., Fuentes, M., Hofstadler, A., Molteni, F., & Palmer, T. N., 2008: The new VAREPS-monthly forecasting system: a first step towards seamless prediction. *Q. J. Roy. Meteorol. Soc.*, **134**, 1789-1799.

Vitart, F., & F. Molteni, 2009: Simulation of the MJO and its teleconnections in an ensemble of 46-day EPS hindcasts. *ECMWF Research Department Technical Memorandum n. 597*, pp. 60 (available from ECMWF, Shinfield Park, Reading RG2 9AX, UK).

Expanding the horizon of seasonal prediction using state-of-the-art climate models

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1. Introduction

Division of Climate System Research (former Center for Climate System Research; CCSR) of the Atmosphere and Ocean Research Institute (AORI), the University of Tokyo, is developing a coupled atmosphere-ocean general circulation climate model called MIROC (Model for Interdisciplinary Research on Climate) in collaboration with National Institute for Environmental Studies (NIES) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The model is being used for climate research in general and has participated in coupled model intercomparison project (CMIP) that has been referred extensively in the fourth assessment report of IPCC published in 2007. Recent research highlights are introduced and future perspectives of climate models and prediction are discussed.

2. Research and model development

After many years of MIROC model development, we have recently succeeded, in the most recent version MIROC5 (Watanabe et al. 2010), to replace most of the physics packages by our original schemes. Furthermore, the new model has given us clues to some of the long-standing problems in the coupled ocean-atmosphere modeling; one being improvements in double ITCZ syndrome (Fig.1; Hirota et al. 2011) and another being understanding of convective control of air-sea coupling strength that governs simulated ENSO amplitude (Watanabe et al. 2011a). A new cumulus parameterization scheme developed by Chikira and Sugiyama (2010) plays a central role in these improvements through interactions with boundary layer (Nakanishi and Niino 2004) and stratiform clouds (Watanabe et al. 2009). Comparison of the new model with a previous version has also given us a clue to understand behavior of subtropical low-level clouds (Watanabe et al. 2011b), which is the key in the climate sensitivity problem (Bony and Dufresne 2005).

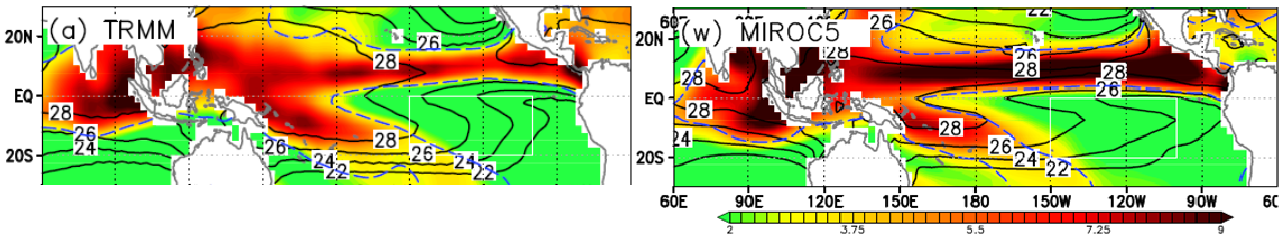

Figure 1 Precipitation (shade; mm day-1) and SST (black contour; ℃) (left) for the observation (TRMM and HadISST), and (right) for MIROC5 in the seasons of SON. Blue dashed lines are contours of ω500 = 0 hPa s-1 indicateing the boundary of the large-scale subsidence regions and ascending regions. (Hirota et al. 2011)

Work on the Earth Simulator gave us an opportunity to learn impact of high resolution; improvements in heavy rain frequency (Kimoto et al. 2005) was one of the most obvious, and perhaps the less is the fact that better representation of tight potential vorticity gradient is the key to the better reproducibility of blocking events (Mori and Kimoto in prep.). Another area of recent surprise, which can be a breakthrough in seasonal predictability, is that ENSO may affect Arctic Oscillation through the stratospheric sudden warming process, which has been proposed by Ineson and Scaife (2009) and confirmed also by a high-resolution version of MIROC (Imada and Kimoto, in prep.). On the other hand, Imada and Kimoto (in prep.) has developed a parameterization of tropical instability waves (TIWs) in the eastern equatorial Pacific based on simulations with high-resolution ocean, which helps us understand TIWs interesting roles to modify ENSO characteristics.

Developing a state-of-the-art climate model requires considerable amount of work, but all of these exciting experience has led us to a belief that forefront research can only be conducted by using state-of the-art models, and that substantial advancement of such an important research tool can only be made based on the understanding obtained through patient model development work.

3. Expanding the scope of prediction: from seasonal to decadal, and from physical to environmental predictions

Validation is an essential component of the model development, and the models should be tested through various modes of predictions. One of the recent topics of interest in research community is the possibility of decadal prediction (Meehl et al. 2009). We are working on experimental decadal hindcasts as a part of new phase 5 of CMIP and the next 5th assessment report of IPCC. Using a low-resolution version of MIROC3, we have found an interesting multi-year predictability in Pacific Decadal Oscillation (Fig. 2; Mochizuki et al. 2010) and in Tropical Atlantic Dipole Mode (Chikamoto et al. in prep.).

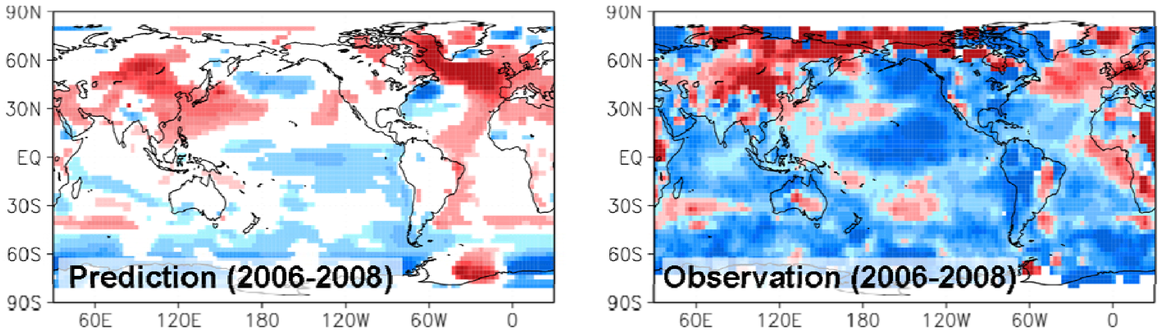

Figure 2 Impacts of initialization on surface air temperature (SAT). (Left) The ensemble-mean SAT deviations (°C) of a hindcast initialized on July 1, 2005 from the externally forced variation during 2006–2008. Shaded regions are the significant areas at 90% confidence levels. (Right) The same except for verifying observed deviation. (Mochizuki et al. 2010)

Climate models are being developed to include biogeochemical processes to become earth system models (ESMs). Such development expands our capability to monitor and predict Earth’s environment, aerosols, chemical species, air pollution, land surface and oceanic biogeochemistry, and carbon cycle, through the assimilation of environment monitoring satellites such as GOSAT. Not only long-term but also short-term prediction capability should be sought such as yellow-sand and chemistry forecasts and estimates of anthropogenic greenhouse gas and aerosol emissions.

4. Remark: Better understanding and prediction with help of process resolving models

Despite a considerable progress made recently by global climate models, the parameterization of sub-grid physics remains one of the central problems in modeling. Cloud parameterizations are recognized as one of the most uncertain components in climate models. The Earth Simulator enabled us to develop a global cloud system resolving model called NICAM (Satoh et al. 2008), which has run up to 3.5 km resolution and has opened a new era of cloud resolving global atmospheric models. NICAM gave a few successful examples of tropical intraseasonal oscillation (Miura et al. 2007) and tropical cyclone formation up to two weeks in advance (Fudeyasu et al. 2008). We plan to make more experiments with NICAM on extended-range predictability and on climate change impact on tropical cyclones on a new 10-peta flops computer, called K computer, scheduled to operate in 2012 (http://www.nsc.riken.jp/index-eng.html).

Experience with cloud and cloud system resolving models should give a breakthrough not only in prediction but also our understanding and parameterization capability of clouds. More generally, we should be able to foresee taking advance of high-speed computer technology to systematically utilize process-resolving models such as large-eddy simulations to improve physics parameterizations used in operational coupled ocean-atmosphere prediction models as has been attempted by Watanabe et al. (2009) in developing a strati-form clouds based on sub-grid scale probability density functions of cloud water.

References

Bony, S., and J.-L. Dufresne, 2005: Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models, *Geophys. Res. Lett.*, **32**, L20806, doi:10.1029/2005GL023851.

Chikira, M., and M. Sugiyama, 2010: A cumulus parameterization with state-dependent entrainment rate. Part I: Description and sensitivity to temperature and humidity profiles. *J. Atmos. Sci.*, **67**, 2171-2193, doi:10.1175/2010JAS3316.1.

Fudeyasu, H., Wang, Y., Satoh, M., Nasuno, T., Miura, H., Yanase, W., 2008: The Global Cloud-Resolving Model NICAM Successfully Simulated the Lifecycles of Two Real Tropical Cyclones. *Geophys. Res. Lett.*, **35**, L22808, doi:10.1029/2008GL036003.

Hirota, N., Y. N. Takayabu, M. Watanabe, and M. Kimoto, 2011: Precipitation reproducibility over tropical oceans and its relationship to the double ITCZ problem in CMIP3 and MIROC5 climate models. *J. Climate*, sub judice.

Ineson, S. and A.A. Scaife, 2009: The role of the stratosphere in the European climate response to El Nino. *Nature Geosci.*, **2**, 32-36.

Kimoto, M., N. Yasutomi, C. Yokoyama and S. Emori, 2005: Projected changes in precipitation characteristics near Japan under the global warming, *Sci. Online Lett. Atmos.*, **1**, 85-88, doi: 10.2151/sola. 2005-023.

Meehl, G. A., L. Goddard, J. Murphy, R. J. Stouffer, G. Boer, G. Danabasoglu, K. Dixon, M. A. Giorgetta, A. Greene, E. Hawkins, G. Hegerl, D. Karoly, N. Keenlyside, M. Kimoto, B. Kirtman, A. Navarra, R. Pulwarty, D. Smith, D. Stammer, and T. Stockdale , 2009: Decadal Prediction: Can it be skillful? *Bull. Amer. Meteorol. Soc.*, **90**, 1467-1485.

Miura,H., Satoh, M., Nasuno, T., Noda, A. T., Oouchi, K., 2007 An Madden-Julian Oscillation event simulated using a global cloud-resolving model. *Science*, **318**, 1763-1765.

Mochizuki, T., M. Ishii, M. Kimoto, Y. Chikamoto, M. Watanabe, T. Nozawa, T. T. Sakamoto, H. Shiogama, T. Awaji, N. Sugiura, T. Toyoda, S. Yasunaka, H. Tatebe, and M. Mori, 2010: Pacific Decadal Oscillation hindcasts relevant to near-term climate prediction. *Proc. Natl. Acad. Sci. USA*, doi: 10.1073/pnas.0906531107.

Nakanishi, M., and H. Niino, 2004: An improved Mellor-Yamada level-3 model with condensation physics: its design and verification. *Bound.-Layer Meteor.*, **112**, 1-31.

Satoh, M., T. Matsuno,T., H. Tomita, H. Miura, T. Nasuno, S. Iga, 2008: Nonhydrostatic Icosahedral Atmospheric Model (NICAM) for global cloud resolving simulations. *J. Comp. Phys.*, **227**, 3486-3514, doi:10.1016/j.jcp.2007.02.006.

Watanabe, M., S. Emori, M. Satoh, and H. Miura, 2009: A PDF-based hybrid prognostic cloud scheme for general circulation models. *Clim. Dyn.*, **33**, doi:10.1007/s00382-008-0489-0.

Watanabe, M., T. Suzuki, R. O'ishi, Y. Komuro, S. Watanabe, S. Emori, T. Takemura, M. Chikira, T. Ogura, M. Sekiguchi, K. Takata, D. Yamazaki, T. Yokohata, T. Nozawa, H. Hasumi, H. Tatebe, and M. Kimoto, 2010: Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity. *J. Climate*, **23**, 6312-6335.

Watanabe, M., M. Chikira, Y. Imada, and M. Kimoto, 2011a: Convective control of ENSO simulated in MIROC. *J. Climate*, in press.

Watanabe, M., H. Shiogama, T. Yokohata, T. Ogura, M. Yoshimori, S. Emori, and M. Kimoto, 2011b: Constraints to the Tropical Low-Cloud Trends in Historical Climate Simulations by MIROC. Geophys. Res. Lett., sub judice.

The influence of ENSO on East Asian and Northwest Pacific summer climate: Tropical Indian Ocean capacitor effect

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1. Introduction

In the summer of 1998 when the strong El Niño of 1997-98 had dissipated, there were many reports of anomalous weather conditions in the East Asia and northwest (NW) Pacific. Examples include suppressed rainfall over the Philippines /NW Pacific and floods in the Yangtze River Valley and some parts of East Asia. These abnormal anomalies have attracted the attention of many researchers since then. It is less clear how these anomalous events occur over the NW Pacific six-months after the peak of El Niño. What maintains the robust precipitation and circulation anomalies over this region during summer (June–August) following El Niño [JJA(1)]? Understanding and predicting these remarkable events over the NW Pacific is critical as the ensuing heavy rainfall caused for devastating consequences human life and livelihood.

2. The Capacitor effect and predictability

Xie et al (2009) showed that the El Niño induced Tropical Indian Ocean (TIO) warming acts like a capacitor anchoring atmospheric anomalies over the Indo–western Pacific Oceans during JJA(1). Significant climate anomalies persist through the summer after El Niño, dissipates in spring over the equatorial Pacific, including the TIO sea surface temperature (SST) warming and an anomalous anticyclone over the subtropical NW Pacific. The TIO warming causes tropospheric temperature to increase by a moistadiabatic adjustment in deep convection, emanating a baroclinic Kelvin wave into the Pacific (Fig. 1). In the northwest Pacific, this equatorial Kelvin wave induces northeasterly surface wind anomalies, and the resultant divergence in the subtropics triggers suppressed convection and the anomalous anticyclone (Fig. 1). The intensified moisture transport on its northwest flank of the anomalous anticyclone causes rainfall to increase over East Asia.

The Capacitor effect discussed above has important implications for the predictability over the Indo–western Pacific summer climate. By replacing TIO SST with climatology, in a forecast coupled ocean-atmosphere general circulation model (CGCM), atmospheric anomalies such as the anticyclonic circulation over the NW Pacific weaken by 50% during JJA(1) (*Chowdary et al*., 2011). An interactive TIO extends the useful prediction of NW Pacific anomalies by 1-2 months with significant anomaly correlation coefficient (> 0.5). In addition to this, analysis of 11 coupled GCMs hindcasts and the associated multi-model ensemble (MME) show that to predict NW Pacific atmospheric anomalies during JJA(1), models need to predict the TIO SST and precipitation well (*Chowdary et al*., 2010). Most coupled models and their MME well predict these EOF modes and circulation patterns with high fidelity in the NW Pacific. The MME

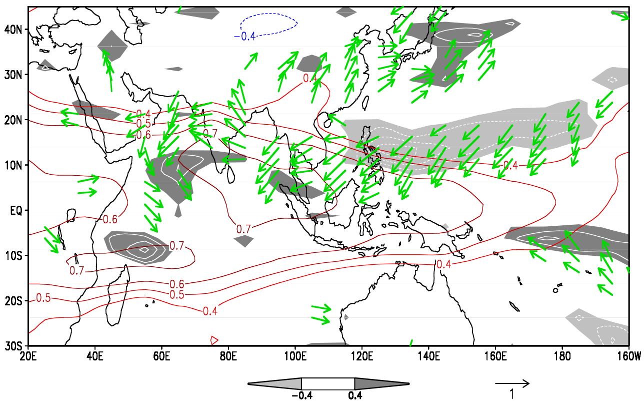

Fig.1. *JJA(1) correlation with the NDJ(0) Nino-3.4 SST index: tropospheric (850–250 hPa) temperature (contours), precipitation (white contours at intervals of 0.1; dark shade . 0.4; light , 20.4), and surface wind velocity (vectors). (Xie et al. 2009)*

shows better skill in temporal correlations of SLP PC than most of individual models (Fig. 2c). The MME analysis generally supports previous findings regarding the TIO Capacitor effect.

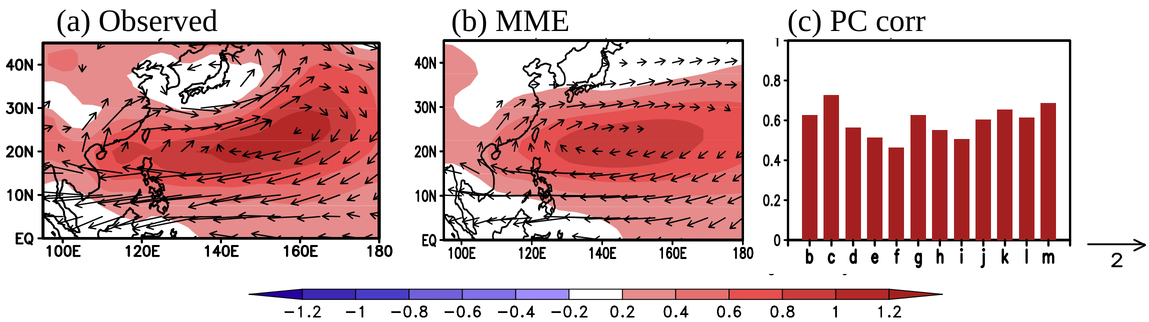

Fig. 2 *The first EOF of JJA SLP anomalies (hPa) obtained from (a) observations and (b) MME (1-month lead prediction). (c) Temporal correlation in PC between observations and individual models (b to l) for MME (m). Vectors represent the 850hPa wind anomalies (ms^{-1}) regressed against the corresponding SLP PC. (Chowdary et al. 2010).*

3. Inter-decadal modulation

There is growing evidence of decadal changes in El Niño–Southern Oscillation (ENSO) teleconnections to the Indo-western Pacific from instrumental records. For examples, Xie et al. (2010) suggested that a slower decay El Niño induces a more robust and long-persistent response over the TIO and NW Pacific after the 1970s regime shift. The Capacitor effect that translates a strong TIO response into a pronounced development of atmospheric anomalies over the NW Pacific in JJA(1) during the recent three decades is strong (after 1970's) and as the TIO SST warming does not persist through JJA(1), atmospheric anomalies over the NW Pacific weaken and are not well organized in space before the 1970's (Fig. 3). An atmospheric GCM forced by the observed history of SST for the period of 1950–2000 is able to reproduce epochal changes in JJA(1) with TIO influence on the summer NW Pacific strengthens in the mid-1970s. The strengthened TIO teleconnection coincides with an intensification of summer SST variability over the TIO (Huang et al. 2010).

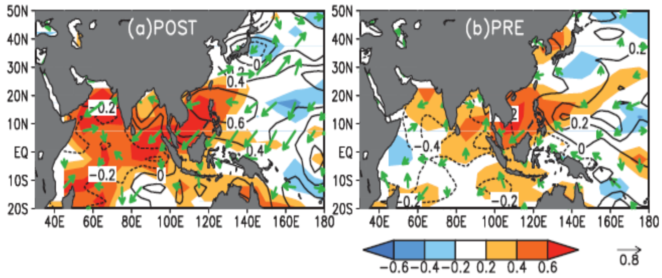

Fig.3 *Correlation of JJA(1) SST (color), SLP (contours), and surface wind velocity (vectors) with the NDJ(0) Nin˜o-3.4 SST index for the (a) POST (1977–2003) and (b) PRE (1950–76) epochs (Xie et al. 2010).*

Summer NW Pacific anticyclone is highly correlated with North Indian Ocean (NIO) SST (Xie et al. 2010; Huang et al. 2010). The SST warming over NIO displays a peculiar double peak structure, one at the mature phase of the El Niño and one during early summer following El Niño peak (Fig. 4). An equatorially antisymmetric pattern of wind anomalies is key to the NIO warming during summer after El Niño (Du et al. 2009). Northeasterlies in the north of the equator and southeasterlies in the south, opposing the prevailing southwesterliy monsoon mean winds, reduce surface evaporation and warming the NIO. The antisymmetric wind pattern is anchored by the persistent SST warming over the Southwest TIO (SWTIO) due to downwelling Rossby waves from the east (Xie et al. 2002; Du et al. 2009). This double peak pattern in NIO warming is strong in the recent epoch after the 1970's and absent before the 1970's epoch (Xie et al. 2010). The second peak in NIO warming in turn plays an important role in maintaining the NW Pacific atmospheric anomalies, through the Capacitor effect, in JJA(1) and to reducing the frequency of tropical cyclones (TC) in the east of

Philippines (Du et al. 2011). The westerly vertical shear associated with the warm Kelvin wave reduces the magnitude of vertical shear in the South China Sea and strengthens it in the NW Pacific, an east-west variation that causes TC activity to increase and decrease in respective regions.

4. Summary

A moderate El Nino took place in 2009-10 and transitioned into a La Nina by the end of 2010 summer. The early 2010 summer looked in many ways like a typical summer following El Nino. Over the NW Pacific, there were only 4 TCs from July 1 to August 26 (compared with the climatology of 8.3). August 27 marks the beginning of a busy late TC season. Japan experienced a hot summer. The new Japan Meteorological Agency (JMA) coupled GCM predicted the development of the anomalous anticyclone over the subtropical NW Pacific but missed the circulation anomalies to the north that gave rise to the hot summer in Japan (S. Maeda et al., this volume). This is consistent with our evaluation of JJA(1) predictions by multi-models (Chowdary et al. 2010); the skills are high in predicting the subtropical circulation but low over the midlatitude region centered over Japan (Fig. 2). More work is necessary to extend the skills to populous East Asia.

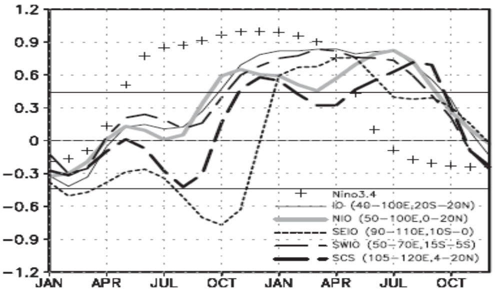

Fig. 4. *Correlation of Tropical Indian Ocean indices with NDJ(0/1) Nino 3.4 index as a function of Calendar month (Du*

References

Chowdary, J. S., S.-P. Xie, J.-J. Luo, J. Hafner, S. Behera, Y. Masumoto, and T. Yamagata (2011), Predictability of Northwest Pacific climate during summer and the role of the tropical Indian Ocean. *Clim. Dyn*., in press, doi: 10.1007/s00382-009-0686-5.

Chowdary, J. S., S.-P. Xie, J.-Y. Lee, Y. Kosaka and B. Wang (2010), Predictability of summer Northwest Pacific climate in eleven coupled model hindcasts: Local and remote forcing. *J. Geophys. Res.-Atmos., 115*, D22121, doi:10.1029/2010JD014595.

Du, Y., L. Yang, and S.-P. Xie (2011), Tropical Indian Ocean influence on Northwest Pacific tropical cyclones in summer following strong El Niño. *J. Climate*, *24*, 315-322.

Du, Y., S.-P. Xie, G. Huang, and K. Hu (2009), Role of air-sea interaction in the long persistence of El Niño-induced North Indian Ocean warming, *J. Climate*, *22*, 2023–2038.

Huang, G., K. Hu, and S.-P. Xie (2010), Strengthening of tropical Indian Ocean teleconnection to the Northwest Pacific since the mid-1970s: An atmospheric GCM study. *J. Climate*, 23, 5294-5304.

Xie, S.-P., H. Annamalai, F. A. Schott, and J. P. McCreary (2002), Structure and mechanisms of South Indian Ocean climate variability, *J. Climate*, *15*, 864–878.

Xie, S.-P., K. Hu, J. Hafner, Y. Du, G. Huang, and H. Tokinaga (2009), Indian Ocean capacitor effect on Indo-western Pacific climate during the summer following El Niño. *J. Climate*, *22*, 730–747.

Xie, S.-P., Y. Du, G. Huang, X.-T. Zheng, H. Tokinaga, K. Hu, and Q. Liu (2010), Decadal shift in El Niño influences on Indo-western Pacific and East Asian climate in the 1970s. *J. Climate*, *23*, 3352-3368.

IndOOS (Indian Ocean Observing System): Present status and recent highlights on air-sea interactions in the Indian Ocean

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1. Introduction

The Indian Ocean has been known as the ocean with strong influence on monsoon systems, which generate distinct seasonal variations in the upper-ocean. In addition, there is a rich spectrum of variability in the Indian Ocean spanning from intraseasonal to interannual, decadal, and much longer time-scale phenomena. Despite an important role of the Indian Ocean for African-Asian-Australian monsoons, climate variability in regions surrounding the Indian Ocean, and its impact on global climate change through atmospheric and oceanic teleconnections, a long-term, sustained observing system in the Indian Ocean had not been started as of about a decade ago, leaving the Indian Ocean as the least observed ocean among the three major basins. Recognizing this observation-gap, a plan for the Indian Ocean Observing System (IndOOS) was developed and has been implemented under the coordination of the CLIVAR/GOOS Indian Ocean Panel.

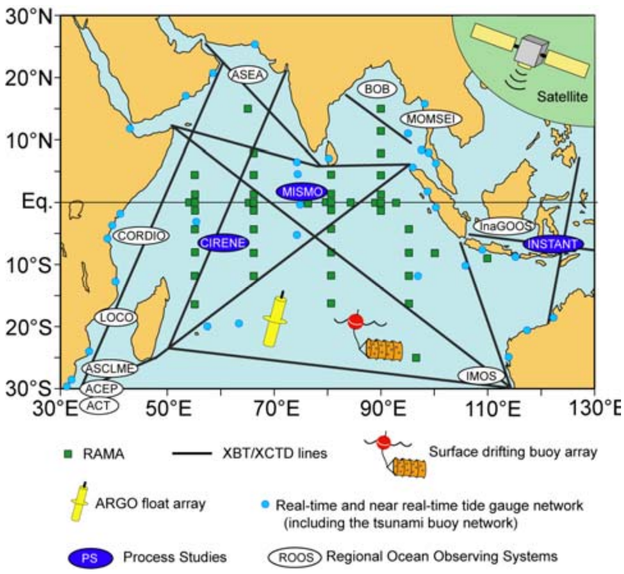

Fig.1: Schematic of IndOOS. Regional observing systems and process studies in the Indian Ocean are also indicated.

2. Indian Ocean Observing System: IndOOS

IndOOS is a multi-platform long-term observing system, which consists of Argo floats, surface drifting buoys, tide gauges, a surface mooring buoy array, VOS based XBT/XCTD sections, and satellite measurements as a backbone observation for sea surface conditions (Fig.1) (ICPO, 2006). The resources for IndOOS come from diverse national and international bodies. The system is designed to provide high-frequency, near real-time climate-related observations, serving the needs of the intraseasonal, interannual and even decadal time-scale climate studies and climate services in many national meteorological agencies.

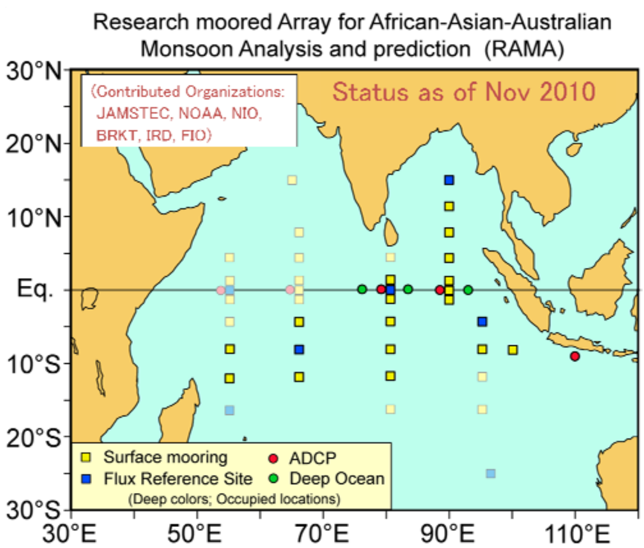

Fig.2: Status of RAMA as of Nov. 2010.

The main platform for in situ observations in the tropical region is the surface and subsurface mooring array, called Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA) (McPhaden et al., 2009). The proposed RAMA array consists of 8 sub-surface ADCP moorings and 38 ATLAS/TRITON-type surface moorings, of which 7 are selected as surface flux reference sites with enhanced flux measurements (Fig.2). The RAMA array design was evaluated and supported by observing system simulation experiments (Oke and Schiller, 2007; Vecchi and Harrison, 2007). As of November 2010, 27 mooring sites out of 46 planned locations are occupied (59%), and several more moorings are planned to be deployed in 2011. However, implementation of RAMA and securing necessary resources to maintain IndOOS are two major issues in the near future.

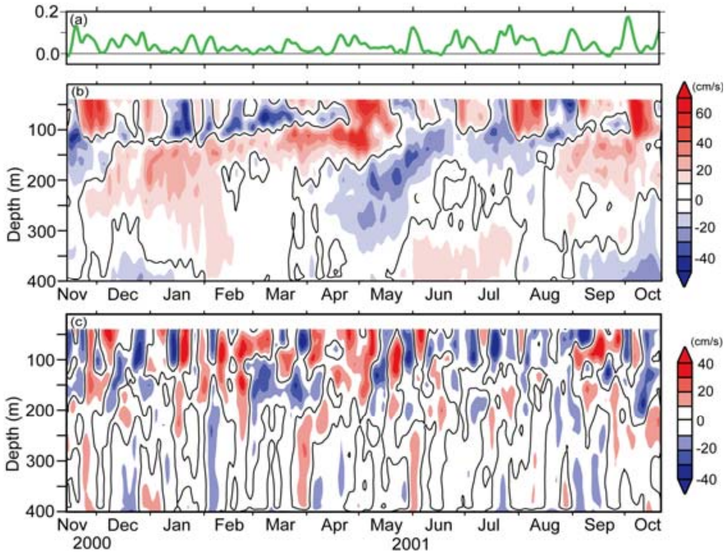

Fig.3: (a) Time series of the zonal wind stress (in N/m^2) at the sea surface on the equator averaged between 80°E and 90°E, observed by the Quick-SCAT satellite. Time-depth sections of (b) the zonal current and (c) the meridional current observed at 90°E on the equator in the Indian Ocean. The eastward (westward) and northward (southward) currents are shaded by reddish (bluish) color, with the black contours for the value of zero. Contour interval is 10 cm/s.

Argo floats are another essential in-situ ocean observing system in the Indian Ocean. The Indian Ocean (north of 40°S) requires 450 floats to meet the Argo design of one float per 3x3 deg. As on 15 November 2010, 674 floats are deployed by various countries and measuring temperature and salinity profiles in the Indian Ocean. The surface drifting buoys are also extensively deployed during the recent decade, and the original surface drifter buoys deployment design, one buoy in every 5-degree box, is almost achieved (e.g. Lumpkin and Goni, 2008). Several SOOP XBT lines obtain frequently repeated and high-density section data, including more than 20 years measurements of IX-1 section between Australia and Indonesia, which can monitor the Indonesian throughflow (Meyers, 1996). Most of the data collected by IndOOS are available through a data portal maintained at INCOIS, India at http://www.incois.gov.in/Incois/iogoos/home_indoos.jsp.

3. Recent Research Highlights

Early observations of IndOOS provide an invaluable data set for analyses on the Indian Ocean variability. For example, a long-term current observation at 90°E on the equator reveals that there is significantly large amplitude intraseasonal variability both in the zonal and meridional components as well as the well-known semiannual and annual variations (Masumoto et al., 2005). The upper-layer zonal current shows 30 to 50 days variability associated with the zonal wind stress variability in a region west to the mooring location, while the meridional current variations are dominated by 10 to 20 days oscillations (Fig.3). Diagnosis of the zonal momentum balance from long term current observations further to the west at 80°E indicates that the seasonal variations in zonal transport are primarily governed by linear wind-driven ocean dynamics (Nagura and McPhaden, 2008). TRITON buoys deployed in the eastern tropical Indian Ocean successfully capture subsurface evolution of the three consecutive Indian Ocean Dipole events from 2006 to 2008, with clear negative temperature anomaly at the thermocline depth that appeared a few months before the surface signatures of the IOD events (Horii et al., 2008), indicating predictability associated with oceanic dynamics (Fig.4). The surface mooring in the Bay of Bengal observed an unusual condition during the passage of cyclone Nargis in May 2008 (McPhaden et al., 2009). The data demonstrate large responses in the upper-ocean and air-sea fluxes, providing a rare opportunity to investigate the responses to such a devastating event. Surface moorings from the RAMA array allowed process studies of the SST seasonal cycle (Foltz et al., 2010) and strong upper ocean response to the MJO in the Seychells-Chagos Thermocline Ridge region (Vialard et al., 2008), a region known for strong ocean atmosphere interaction (Xie et al., 2002). In addition, the data from the RAMA array has been used by Australian farmers, for example, for making their effective plan of agriculture and pasturing (cf. McPhaden et al., 2009).

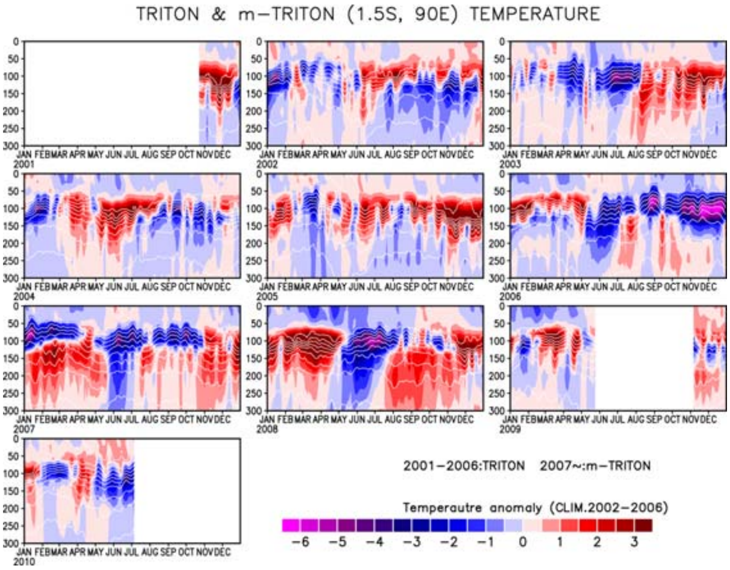

Fig.4: Depth-time sections temperature (white contours) and temperature anomaly (color shade) at 1.5°S, 90°E observed by TRITON and m-TRITON buoys from October 2001 to July 2010. Contour interval for the temperature is 2°C, and anomaly is calculated with reference to the mean conditions during 2002 and 2006.

For more details of and additional information about the interesting scientific results from IndOOS, an extensive list of papers can be found in IndOOS bibliography site at http://www.clivar.org/organization/indian/IndOOS/biblio.php.

Reference

Foltz, G.R., Vialard, J., Praveen Kumar B. & McPhaden, M.J. (2010). Seasonal mixed layer heat balance of the southwestern tropical Indian Ocean, *J. Clim*., **23,** 947-965.

Horii, T., Hase, H., Ueki, I. & Masumoto, Y. (2008). Oceanic precondition and evolution of the 2006 Indian Ocean dipole, *Geophys. Res. Lett.,* **35**, L03607, doi:10.1029/2007GL032464.

International CLIVAR Project Office (2006). *Understanding the Role of the Indian Ocean in the Climate System—Implementation Plan for Sustained Observations.* ICPO Publication Series **100**; GOOS Report No. 152; WCRP Informal Report No. 5/2006, International CLIVAR Project Office, Southhampton UK, 60 pp, 30 fig's.

Lumpkin, R. & Goni, G. (2008). State of the ocean in 2007: surface currents. In "State of the Climate in 2007", *Bulletin of the American Meteorological Society*, **89**.

Masumoto, Y., Hase, H., Kuroda, Y., Matsuura, H. & Takeuchi, K. (2005). Intraseasonal variability in the upper layer currents observed in the eastern equatorial Indian Ocean, *Geophys. Res. Letter,* **32**, L02607, doi:10.1029/2004GL021896.

McPhaden, M.J., Foltz, G.R., Lee, T., Murty, V.S.N., Ravichandran, M., Vecchi, G.A., Vialard, J., Wiggert, J.D. & Yu, L. (2009). Ocean-atmosphere interactions during cyclone Nargis, *EOS*, **90**, 53-54.

McPhaden M.J. & Co-authors (2009). RAMA: The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction, *Bull. Am. Meteorol. Soc.*, **90**, 459-480.

Meyers, G. (1996). Variation of Indonesian throughflow and the El Niño – Southern Oscillation. *J. Geophys. Res.*, **101**, 12,255-12,263.

Nagura, M. & McPhaden, M.J. (2008). The dynamics of zonal current variations in the central equatorial Indian Ocean. *Geophys. Res. Lett.*, **35**, L23603, doi:10.1029/2008GL035961.

Oke, P.R. & Schiller, A. (2007). A Model-Based Assessment and Design of a Tropical Indian Ocean Mooring Array. *J. Climate*, **20,** 3269.

Vecchi, G.A. & Harrison, M.J. (2007). An observing system simulation experiment for the Indian Ocean. *J. Climate*, **20,** 3300–3319.

Vialard, J., Foltz, G., McPhaden, M.J., Duvel, J-P. & de Boyer Montégut, C. (2008). Strong Indian Ocean sea surface temperature signals associated with the Madden-Julian Oscillation in late 2007 and early 2008, *Geophys. Res. Lett.*, **35**, L19608, doi:10.1029/2008GL035238.

Xie, S.-P., Annamalai, H., Schott, F.A. & McCreary, J.P. (2002). Structure and Mechanisms of South Indian Ocean Climate Variability. *J. Climate*, **15,** 864-878.

Air-sea interaction over the Indian Ocean after El Nino in JMA/MRI-CGCM seasonal forecast experiment

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1. Introduction

Sea surface temperature (SST) warming in the Indian Ocean after El Nino has been well recognized (e.g., Klein et al. 1999, Xie et al. 2002, Lau and Nath 2003). Recently, the role of the entire basin of the Indian Ocean on atmospheric fields in the western North Pacific has been emphasized. Xie et al. (2009) proposed an Indian Ocean Capacitor effect on the western North Pacific after El Nino. In the seasonal forecast conducted by JMA/MRI, the prediction skill of summer atmospheric fields in the western North Pacific is high. It is suggested that its high predictability is related to SST prediction in the Indian Ocean. Therefore, it is important to reproduce mechanisms of SST warming in the Indian Ocean for successful seasonal prediction in Japan. In this study, processes of SST warming in the Indian Ocean after El Nino in the JMA/MRI-CGCM seasonal forecast experiment are examined.

2. Seasonal forecast experiment

The atmosphere-ocean coupled model for the seasonal forecast system (JMA/MRI-CGCM) has been developed at the JMA/MRI (Yasuda et al. 2007, Takaya et al. 2010). This system is now used for conducting seasonal forecasts at JMA. The atmosphere component of the CGCM is a recent version of the JMA atmospheric general circulation model. The dynamical framework is a spectral transformed method. The horizontal resolution is TL95 in wave truncation and 196x92 on a transformed Gaussian grid. The vertical configuration consists of a 40-layer sigma-pressure hybrid coordinate with its top at 0.1 hPa. The ocean component is the MRI Community Ocean Model (MRI.COM) which is a z-coordinate ocean general circulation model developed at MRI (Tsujino et al. 2010). The horizontal resolution is 1.0 degree in longitude. Meridional resolution is 1.0 degree (0.3 degrees between 6S and 6N). The vertical resolution is 50 levels, the uppermost layer has a 2 m thickness and the layer thicknesses between 30 to 200 m where equatorial thermoclines exist are 10 m. In order to keep the model climatology to the observed one, we use flux adjustments for heat and momentum during the forecast runs.

We carried out the seasonal forecast experiment that is a part of the Climate-system Historical Forecast Project (CHFP) in WCRP/WGSIP. This experiment is the 10-member ensemble hindcast initiated at 00Z and 12Z in the last five days of January, April, July and October from 1979 to 2006. Annual and global mean CO_2 concentration at the year of initial time is set to last through each experiment. The atmospheric initial conditions are derived from the Japanese Re-Analysis 25 years (JRA-25; Onogi et al. 2007). The data assimilation system for creating ocean initial conditions is the Multivariate Ocean Variational Estimation (MOVE) System developed at MRI (MOVE-G/MRI.COM; Usui et al. 2006).

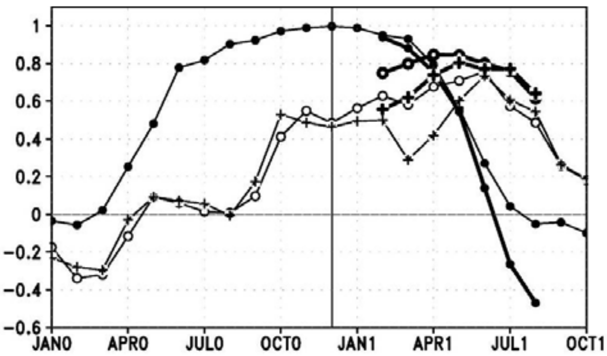
Anomaly correlation of SST prediction exceeds 0.7 in the eastern equatorial Pacific and 0.6 in the Indian Ocean at a lead time of six months. In this study, in order to examine the responses of the Indian Ocean to El Nino, the results of forecast experiments initiated from the end of January are used. The forecast skills in this experiment are verified with the atmospheric data of JRA-25 and subsequent product JMA Climate Data Assimilation System (JCDAS), and oceanic data of COBE-SST and MOVE-G/MRI.COM.

3. Results

Figure 1 shows the lag correlation of SST averaged in the Nino3.4 region (170-120W, 5S-5N: Nino3.4SST), Tropical Indian Ocean (TIO: 40-100E, 20S-20N) and North Indian Ocean (NIO: 40-100E, 0-20N) with Nino3.4SST averaged from November to January (NDJ). After the mature phase of El Nino in December (DEC0 in Fig. 1), the Nino3.4SST anomaly decreased rapidly to zero until spring. On the other hand, the SST anomaly in the Indian Ocean has a positive peak from spring to summer with a lag of two seasons to Nino3.4SST. In JMA/MRI-CGCM forecast experiments initiated at the end of January, these SST lag relationships between El Nino and the Indian Ocean can be well predicted.

Du et al. (2009) showed that SST in the southwestern part of the Indian Ocean increases due to the oceanic downwelling Rossby wave, which is induced in the South Indian Ocean by the equatorial westward wind anomaly corresponding to El Nino (Fig. 2). From February to April in the forecast experiment, the Indian Ocean shows

Figure 1. Lag correlation coefficient of SST averaged in Nino3.4 (closed circle), TIO (open circle) and NIO (Plus) with Nino3.4SST (NDJ). Bold lines denote the seasonal forecast experiment by JMA/MRI-CGCM initiated from the end of January (thin lines are observation). The vertical line indicates the mature phase of El Nino (DEC0).



similar responses to the El Nino wind system (Fig. 3). However, the area (period) of interaction between thermoclines and SST is larger (longer) than those observed. In boreal spring, an anticlockwise wind anomaly from the northern hemisphere toward the south western Indian Ocean generates a negative (positive) surface heat flux anomaly in the North (South) Indian Ocean. As shown in Fig. 2 (May–Jun.), a positive SST anomaly in the South Indian Ocean and an anticlockwise wind anomaly are maintained due to Wind-Evaporation-SST (WES) feedback (Xie and Philander 1994; Kawamura et al. 2001). In the season from boreal spring to summer, the northeasterly Indian monsoon changes to a southwesterly. Since anticlockwise wind anomalies act to reduce southwesterly monsoons in the North Indian Ocean, a positive SST anomaly spreads out there due to the reduced latent heat release to the atmosphere (Jul.-Aug. in Fig. 2; Du et al. 2009). In the CGCM experiment (Fig. 3), the anticlockwise wind anomaly in May and June and the related SST warming in the North Indian Ocean is well predicted, that could affect atmospheric anomalies in the north western Pacific (Xie et al. 2009).

In summary, this examination of the JMA/MRI-CGCM seasonal forecast experiment on SST warming in the Indian Ocean after El Nino has revealed that SST warming in the South Indian Ocean during boreal spring in CGCM is due to a deeper thermocline anomaly induced by a positive wind stress curl anomaly. In boreal spring, the predicted wind anomaly does not induce WES feedback that would prevent SST warming in the western part of the North Indian Ocean as in observation. This is one reason for higher correlation between NIOSST and Nino3.4SST (NDJ) than that in the observation. The wind anomaly in boreal summer tends to weaken summer monsoons in the western North Indian Ocean. This reduces latent heat release to the atmosphere, maintaining a positive SST anomaly in the North Indian Ocean. These results are consistent with studies based on observation. This could be one of the causes of the good forecast skill obtained in the western North Pacific in boreal summer.

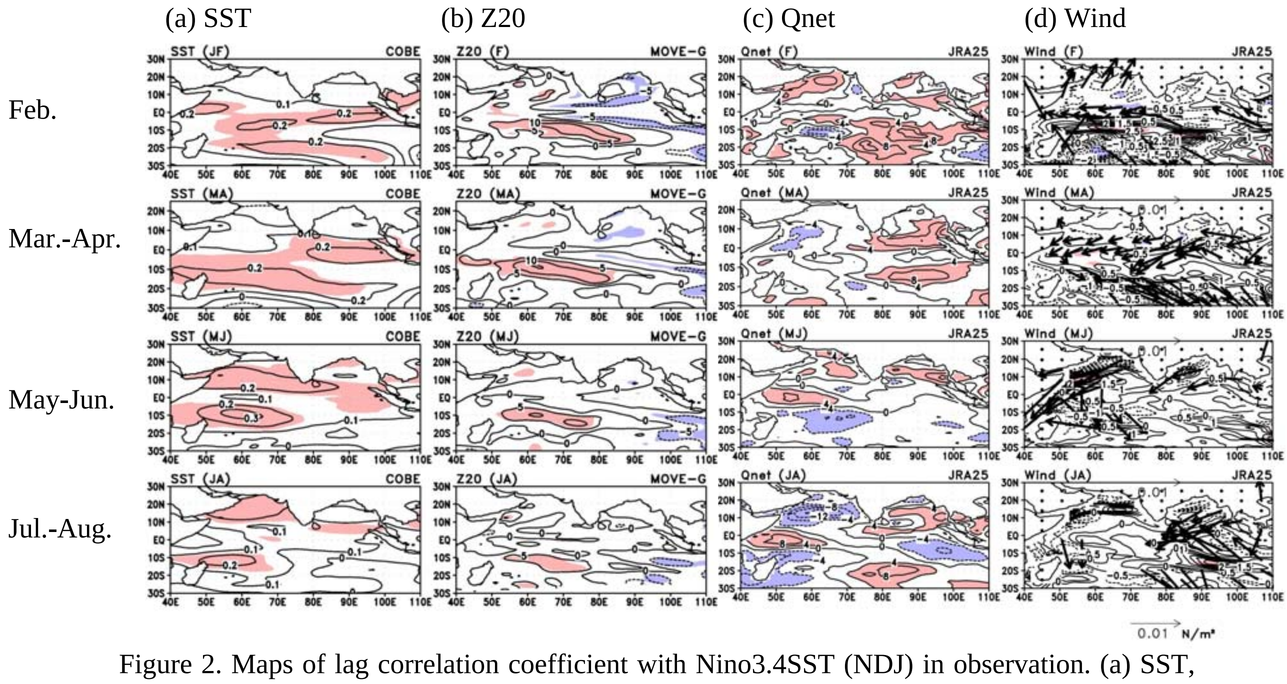


Figure 2. Maps of lag correlation coefficient with Nino3.4SST (NDJ) in observation. (a) SST, (b) depth of 20 degC (Z20), (c) net surface heat flux, and (d) wind stress (vector) and wind stress curl (contour). Contour intervals are (a) 0.1 degC, (b) 5 m, (c) 4 W/m^2 and (d) 10^{-8} N/m^3. Red and blue shades indicate significant areas with a 95% confidence level.

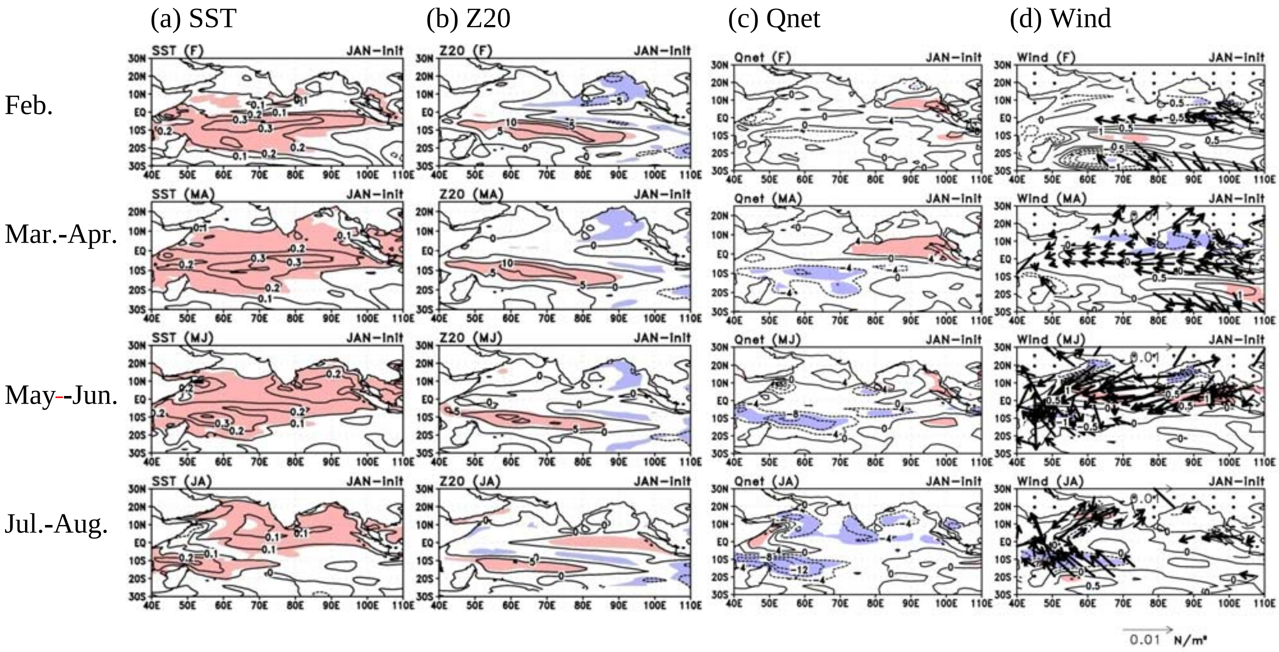


Figure 3. Same as in Fig. 2 but for the JMA/MRI-CGCM seasonal forecast experiment initiated from the end of January.

References

Du, Y., S.-P. Xie, G. Huang, and K. Hu, 2009: Role of air-sea interaction in the long persistence of El Nino induced North Indian Ocean warming. *J. Climate*, **22**, 2023–2038.

Ishii, M., A. Shouji, S. Sugimoto, and T. Matsumoto, 2005: Objective analyses of sea-surface temperature and marine meteorological variables for the 20th century using ICOADS and the Kobe Collection. *Int. J. Climatol.*, **25**, 865–879.

Kawamura, R., T. Matsuura, and S. Iizuka, 2001: Role of equatorially asymmetric sea surface temperature anomalies in the Indian Ocean in the Asian summer monsoon and El Niño-Southern Oscillation coupling. *J. Geophys. Res.*, **106**, 4681–4693.

Klein, S.A., B.J. Soden, and N.-C. Lau, 1999: Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. *J. Climate*, **12**, 917–932.

Lau, N.-C., and M.J. Nath, 2003: Atmosphere–ocean variations in the Indo-Pacific sector during ENSO episodes. *J. Climate*, **16**, 3–20.

Onogi, K., J. Tsutsui, H. Koide, M. Sakamoto, S. Kobayashi, H. Hatsushika, T. Matsumoto, N. Yamazaki, H. Kamahori, K. Takahashi, S. Kadokura, K. Wada, K. Kato, R. Oyama, T. Ose, N. Mannoji and R. Taira, 2007: The JRA-25 Reanalysis. *J. Meteor. Soc. Japan*, **85**, 369–432.

Takaya, Y., T. Yasuda, T. Ose, and T. Nakaegawa, 2010: Predictability of the mean location of Typhoon formation in a seasonal prediction experiment with a coupled general circulation model. *J. Meteor. Soc. Japan*, **88**, 799–812.

Tsujino, H., T. Motoi, I. Ishikawa, M. Hirabara, H. Nakano, G. Yamanaka, T. Yasuda, and H. Ishizaki, 2010: Reference manual for the Meteorological Research Institute Community Ocean Model (MRI.COM) Version 3. Tech. Reports MRI, 58, 241pp.

Usui, N., S. Ishizaki, Y. Fujii, H. Tsujino, T. Yasuda, and M. Kamachi, 2006: Meteorological Research Institute Multivariate Ocean Variational Estimation (MOVE) System: Some early results. Adv. Space Res., 37, 806–822.

Xie, X.-P., and S. G. H. Philander, 1994: A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. *Tellus*, **46A**, 340–350.

Xie, S.-P., H. Annamalai, F. A. Scott, and J. P. McCreary, 2002: Structure and mechanisms of South Indian Ocean climate variability, *J. Climate*, **15**, 864–878.

Xie, S.-P., K. Hu, J. Hafner, Y. Du, G. Huang, and H. Tokinaga, 2009: Indian Ocean capacitor effect on Indo-western Pacific climate during the summer following El Nino. *J. Climate*, **22**, 730–747.

Yasuda, T., Y. Takaya, C. Kobayashi, M. Kamachi, H. Kamahori and T. Ose, 2007: Asian Monsoon Predictability in JMA/MRI Seasonal Forecast System, *CLIVAR Exchanges*, **43**, 18–24.

The NCEP Climate Forecast System version 2

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1. Introduction

At the National Centers for Environmental Prediction (NCEP) in USA, we have been running a coupled model for seasonal prediction named the Climate Forecast System (CFS) since 2004. As we are about to introduce an upgrade the entire system, we will name the older version CFS v.1 and the new version CFS v.2. The current plan is to introduce the CFS v.2 into operation in early 2011. In this report, we will describe the make up of the new system and the preparation work that is named the CFS Reanalysis and Reforecast (CFSRR) project.

The CFS v.1 is a coupled forecast model using a version of the NCEP Global Forecast System (GFS) model circa 2003 coupled with the Geophysical Fluid Dynamic Laboratory (GFDL) Modular Ocean Model version 3 (MOM3). The atmospheric model resolution is T62L64 and the ocean model resolution is one degree latitude/longitude with 1/3 latitude in the equatorial region (gradually increase to one degree). The model runs are initialized using the NCEP Reanalysis II system running in real time for atmosphere and the ocean state is derived using the NCEP Reanalysis driven Ocean Data Assimilation System. Sea ice state is taken from climatology and is not predicted.

2. The CFSRR

In preparation for the CFS v.2, we decided to improve the initial condition for the coupled model in addition to an upgrade to the model. The primary reason for this is the desire to bridge the gap of the weather forecast and the seasonal forecast. For weather forecast using the GFS, we do not couple the model with an ocean model. As a result, we should not really run the forecasts beyond 10-15 days as the ocean state change can not be ignored at time range beyond that. The CFS v.1 was designed to forecast primarily seasonal signal of the ENSO so it was deemed that the ocean initial condition is more important than the atmospheric initial condition, which the model could not retain beyond the first two weeks. There is, therefore, a gap for the monthly forecasts for the first month or two. In this time range, we have learned that phenomena such as the Madden-Julian Oscillation are prominent and potentially predictable with the coupled model.

A new reanalysis is planned and performed to provide initial conditions for the reforecast and will also serve as the initial condition provider for the operational CFS v.2 The project to complete the reanalysis and the reforecast for CFS v.2 is named the CFSRR project. The atmospheric model for CFS v.2 is the 2008 version of the GFS with minor upgrades and the ocean model is the MOM4 which also includes interactive sea ice. The two primary components of the CFSRR project are:
a) A reanalysis of the atmosphere, the ocean, the land and the sea ice for 1979-2009 using the CFS v.2 model to provide the first guess for all prognostic variables for atmosphere, ocean, land and sea-ice. The atmospheric analysis is done at the T382L64 as our experience suggests that the large-scale atmospheric circulation in medium range forecast is better captured by the higher resolution for the data assimilation than for the model used in the forecast. It is hoped

that the monthly forecast can be improved with such a tactic as well. The resolution of the ocean model is .5 degree away from the tropics and .25 degree latitude in the equatorial region. In the polar region, the tri-polar grid is employed to enhance the polar region resolution. Observed sea ice fraction is used to initialize the sea ice field and observed precipitation is used to initialized the land moisture field.

b) A reforecast for the period 1981-2009 for CFS v.2 will be used to provide calibration and skill estimates for the real time CFS v.2 forecasts. The resolution of the forecast model is T126L64 for the atmosphere and 1 degree lat/lon for the ocean. Among the major changes to the CFS v.2 is the inclusion of historical CO2, solar cycle and volcanic aerosols to try to capture the effect of the global warming due to these elements.

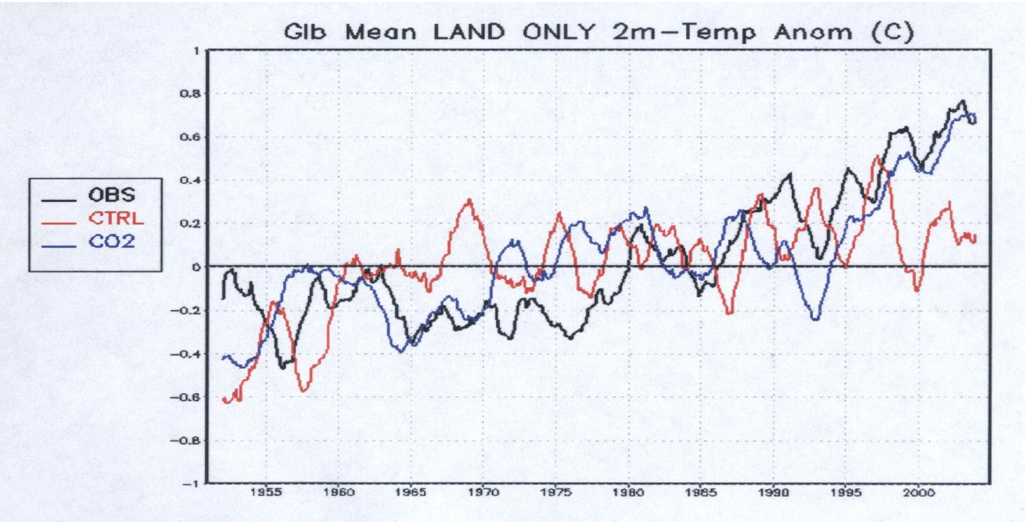


Fig.1. Global land surface mean temperature in long term simulation with and without the CO2 effect compared with observation.

The day-5 anomaly correlation skill scores (a standard measure of medium range operational forecasts) of the reforecasts match the current day GFS skill indicating the reanalysis quality is even as far as medium range forecast is concerned. The real improvement is measured in the skill of the MJO forecasts and the ENSO forecasts. For the ENSO skills, the table below shows that minor improvements are obtained for the CFS v.2:

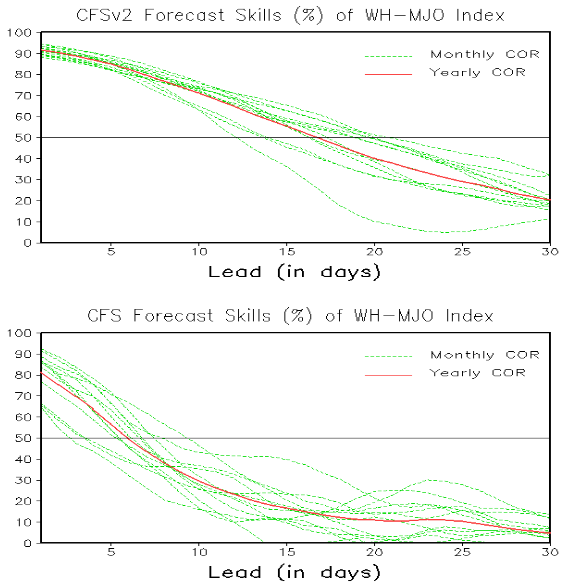
THE BOTTOM LINE FOR CPC

Anomaly Correlation: All Leads (1-8), All Months (10)

Green is good **Red is not good**

Model	US T	US P	Nino34 SST	Nino34 Prate	Global SST (50N-50S)
CFSv2	16.3	9.5	77.2	54.5	42.2
CFSv1	9.5	10.3	71.8	52.8	37.7

For the MJO, the calibrated forecast skill is shown here:



We can see that there are significant improvements in the MJO forecasts between CFS v.2 and CFS v.1.

3. Summary

The CFS v.2 preparation is nearing complete and implementation into operation is planned for early 2011. As we reflect on the strategy we devised for the CFSRR, the MJO forecast improvement is a definite achievement. But there are many questions that have yet been answered:

a) Is coupled data assimilation useful at the present stage? It seems that we could have done the atmospheric reanalysis first (with the land) and then performed the ocean and ice using the fluxes from the atmospheric reanalysis. Given that we placed a strong constraint of the observed Sea Surface Temperature (SST) on the ocean analysis, the alternative method may work as well. The effect of the coupled first guess may not be too important.

b) Is the high resolution for the atmospheric analysis important? The answer appears to be yes. We plan to make a T126L64 reanalysis for a longer period in the next few years and will have a chance to evaluate the answer again.

c) How to merge the efforts for week 1-2 forecasts with the monthly and seasonal forecasts? We have demonstrated that the coupled data assimilation does not hard the medium range forecasts. So the question is really one of cost. For operation, the additional cost of the ocean model is not significant (a few more computer nodes) but it places a burden on the developers who will have to use more resources for all tests in the future.

This may be less of a problem when further computer upgrade comes along.

It looks like we can, in the near future, combine the weather and climate forecast systems into one seamless system. The coupled data assimilation system can provide initial conditions for the weather forecasts as well as for monthly and seasonal forecasts. The idea is to use the best estimates of the state of the atmosphere, the ocean, the land, and the sea ice to initialize all forecasts. Because of the resource demand of the reforecast, the models for seasonal forecasts have to be the same as those used in the reforecast. However, it is not clear the model used in the data assimilation has to be frozen as well. In fact, we advocate testing the hypothesis that better initial conditions always produce better forecasts so the model providing the first guess can be improved continuous while the model providing the forecasts can be frozen.

Reference

Saha et al, 2011: The NCEP Climate Forecast System Version 2, to be submitted for publication to the Journal of Climate.

Saha et al, 2010: The NCEP Climate Forecast System Reanalysis**.** BAMS, 90, 1015-1057.

Seasonal prediction and coupled model development activities at JAMSTEC

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1. Introduction

Predicting the tropical climate anomalies, including El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD), is of great value because of their large climate, environmental and socioeconomic impacts over the globe. Over the past decade, we have developed a fully coupled global climate model (called SINTEX-F, Luo et al. 2003) under the EU-Japan collaboration using the giant Earth Simulator. The SINTEX-F coupled GCM consists of a relatively high-resolution atmospheric component (ECHAM4.6, T106) with 19 vertical levels, and a coarse resolution oceanic component (OPA8.2) with a 2° Mercator horizontal mesh and 31 layers in vertical. The oceanic meridional resolution has been intensified to 0.5° near the equator in order to properly capture the equatorial wave dynamics.

Coupled models have some common biases. One of them is that the cold tongue in the equatorial Pacific extends far too west; the cold sea surface temperature (SST) bias in the western Pacific warm pool region causes a dry bias which can significantly deteriorate model performance in simulating global climate. We have successfully reduced this common model bias by passing the ocean surface current momentum to the atmosphere, namely, the velocity discontinuity across the air-sea interface has been removed. The model with the improved coupling physics showed correct warm-pool cold-tongue sharpness and better ENSO signal and teleconnection pattern in the North Pacific (Luo et al. 2005a). The SINTEX-F model has been applied to various climate studies and shown good performance in simulating and predicting both ENSO and IOD.

Using the SINTEX-F model, we have performed 9-member ensemble retrospective forecasts for the period of 1982–2004. To generate semi-multi-model ensembles, both model coupling physics and initial conditions were perturbed separately in three different ways (Luo et al. 2005a,b, 2007, 2008a). A simple but effective way was adopted to produce realistic and well-balanced ocean–atmosphere initial conditions by assimilating only satellite-observed SSTs into the coupled model (Luo et al. 2005b).

2. Results

Our retrospective forecasts demonstrate useful skill in predicting ENSO and its related impacts on global climate at lead times of up to one years ahead (Luo et al. 2005b, Fig. 1). It is interesting to note that some ENSO events can be well predicted at lead times of up to even 2 years ahead (Luo et al. 2008a). Compared to ENSO, IOD signal is generally weak, and its predictability is limited under the influence of active intraseasonal perturbations in the Indian Ocean. It is found that IOD signal is basically predictable up to about 2 seasons ahead (Luo et al. 2007). Encouragingly, some extreme IOD events and their climate impacts are predictable up to one year lead. The recent three consecutive IOD during 2006-2008, which are unprecedented in historical records, were successfully predicted in a real time manner several seasons in advance (Luo et al. 2008b). It is also found that intrinsic interaction between ENSO and IOD via the equatorial east-west Walker circulation plays an important role in enhancing the predictability of the two climate modes (Luo et al. 2010). Recently, we have found that the rapid global warming over the past 2-3 decades, which may have been predominantly driven by the SST rise, might have significant impact on the seasonal-to-interannual climate predictability of the climate over the globe (particularly in the extratropics) at long-lead times beyond about one year (Luo et al. 2011).

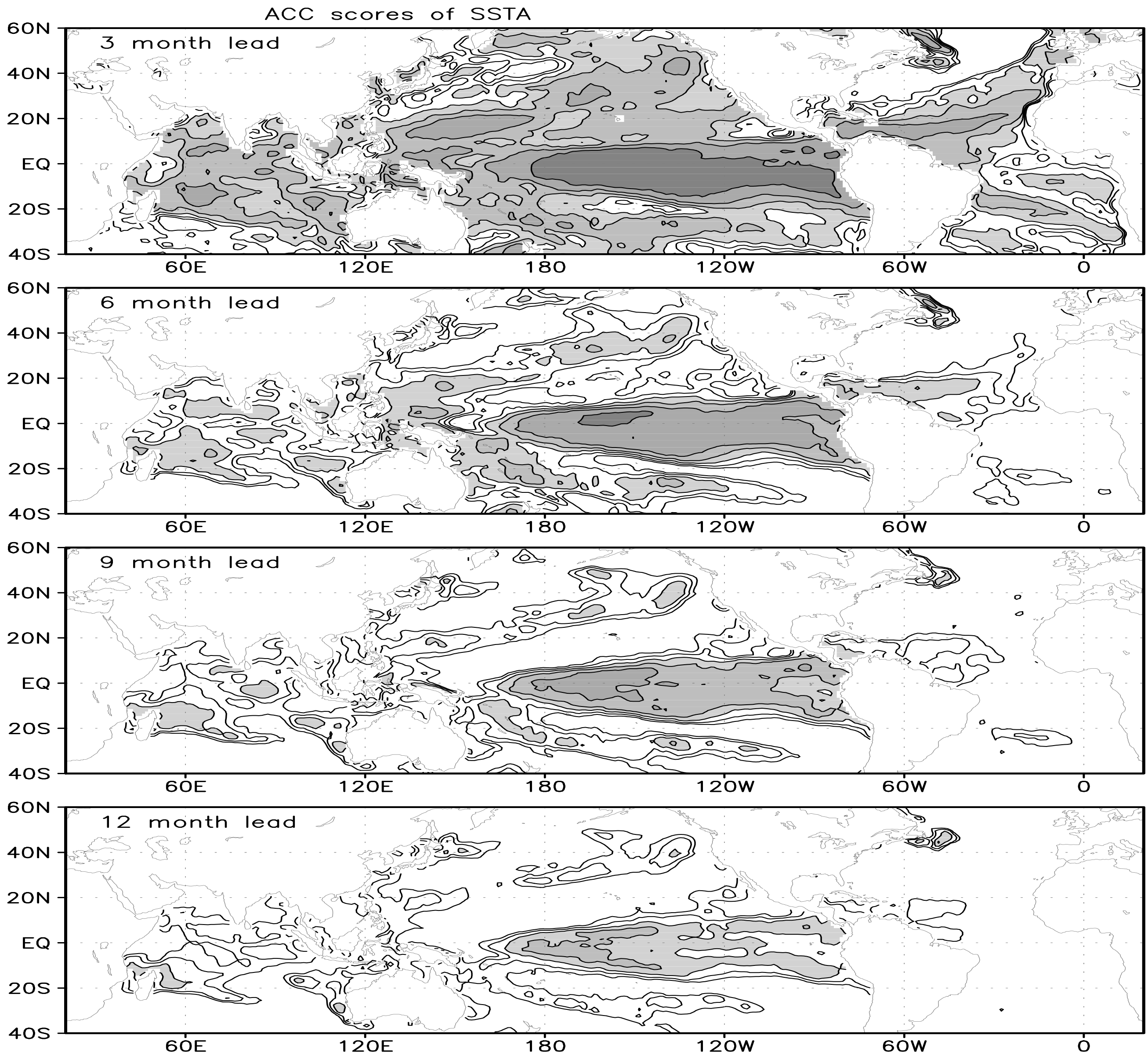

Figure 1: SST anomaly correlations between the NCEP observations and model nine-member ensemble mean predictions at 3-, 6-, 9-, and 12-month lead times for the period 1982–2004. Contour interval is 0.1 and regions with values above 0.6 are shaded. Skills are calculated based on the time series of a 5-month running mean of both the observations and model predictions at each lead time (see Luo et al. 2005b).

Our successful forecasts of the IOD-related drought in Australia during 2006-2008 have caused wide attentions from the society. The JAMSTEC prediction system also shows useful skill in predicting the local climate in South Africa. These results may have important implication for a broad application of the seasonal-to-interannual climate prediction to the society. We are developing some downscaling schemes using regional atmospheric models, aiming to increase the societal values of JAMSTEC seasonal climate forecasts. Real time experimental forecasts are available on http://www.jamstec.go.jp/frcgc/research/d1/iod/sintex_f1_forecast.html.en and updated every month since 2005.

3. Summary and future plans

Using the giant Earth Simulator, we have developed an ocean-atmosphere coupled climate model (i.e., SINTEX-F) which has shown good performance in simulating and predicting the climate variability in the tropical Indian Ocean and Pacific. Based on these, we are further developing various downscaling application schemes in order to enhance the societal values of the climate information. We are also developing a kind of seamless prediction system to improve the quality of intraseasonal-seasonal-interanuual-decadal climate prediction. This will require to assimilate both atmospheric information and available oceanic (particularly in the extratropics) observations to generate better initial conditions, and to incorporate the global warming impacts on climate prediction by inputting anthropogenic and natural external forcing of the earth's climate in the model. Besides, we have also developed a new version of coupled model (SINTEX-F2) with high-resolutions of both atmospheric and oceanic components. After a lot of tuning, the SINTEX-F2 model shows good performance in simulating not only the interannual climate signals in the tropical Indo-Pacific area but also realistic typhoon including its genesis, intensity and movement. This new coupled model will serve as a good tool for climate studies, climate predictions, and societal applications.

References

Luo, J.-J., S. Masson, S. Behera, P. Delecluse, S. Gualdi, A. Navarra, and T. Yamagata, 2003: South Pacific origin of the decadal ENSO-like variation as simulated by a coupled GCM. *Geophys. Res. Lett.,* **30**, 2250, doi:10.1029/2003GL018649.

Luo, J.-J., S. Masson, E. Roeckner, G. Madec, and T. Yamagata, 2005a: Reducing climatology bias in an ocean-atmosphere CGCM with improved coupling physics. *J. Climate*, **18,** 2344–2360.

Luo, J.-J., S. Masson, S. Behera, S. Shingu, and T. Yamagata, 2005b: Seasonal climate predictability in a coupled OAGCM using a different approach for ensemble forecasts. *J. Climate*, **18,** 4474–4497.

Luo, J.-J. , S. Masson, S. Behera, and T. Yamagata, 2007: Experimental forecasts of the Indian Ocean Dipole using a coupled OAGCM. *J. Climate*, **20,** 2178-2190.

Luo, J.-J., S. Masson, S. Behera, and T. Yamagata, 2008a: Extended ENSO predictions using a fully coupled ocean–atmosphere model. *J. Climate*, **21,** 84-93.

Luo, J.-J., S. Behera, Y. Masumoto, H. Sakuma, and T. Yamagata, 2008b: Successful prediction of the consecutive IOD in 2006 and 2007. *Geophys. Res. Lett.*, **35,** L14S02, doi:10.1029/2007GL032793.

Luo, J.-J., R. Zhang, S. Behera, Y. Masumoto, F.-F. Jin, R. Lukas, and T. Yamagata, 2010: Interaction between El Niño and extreme Indian Ocean Dipole. *J. Climate,* **23,** 726-742.

Luo, J.-J., S. K. Behera, Y. Masumoto and T. Yamagata, 2011: Impact of Global Ocean Surface Warming on Seasonal-to-Interannual Climate Prediction, J. Climate, in press.

The Basic Performance of IAP Coupled GCM FGOALS2.0

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1. Introduction

Given the importance of climate models in the atmospheric, oceanic, and even geological sciences, more and more effort has been devoted to their development, especially coupled climate system models. Since the 1990s, five generations of coupled GCMs have been developed, and have been employed in a number of studies in the Earth sciences. The Flexible Global Ocean-Atmosphere-Land System (FGOALS) models are a series of coupled GCMs developed at the State Key Laboratory of Numerical Modeling for the Atmospheric Sciences and Geophysical Dynamics (LASG) at the Institute of Atmospheric Physics (IAP) in China. The latest version of FGOALS is FGOALS2.0, which consists of five component models – atmospheric model, oceanic mode, sea ice model, land model, and flux coupler. This model has been stably integrated for several hundred years, and shows much better performance than its former versions.

2. Model Description

FGOALS2.0 is a global fully coupled GCM without any flux correction or adjustment, consisting of atmospheric and oceanic component models developed at LASG/IAP, a sea ice model (CICE4.0) from NASA, and a land model (CLM3.0) and flux coupler (cpl6) from NCAR. Heat, momentum and fresh water fluxes are exchanged at the model interface each model day. The atmospheric component model is a Gridpoint Atmospheric Model of LASG/IAP (GAMIL), and the resolution of the atmosphere model is roughly $2.8^{o}\times2.8^{o}$ in horizontal domain with 26 levels in the vertical. The ocean component is named as LASG/IAP climate Ocean Model version 2 (LIOCM2.0), and it has a horizontal resolution of $1°\times1°$ with an enhanced meridional resolution of 0.5° at the equatorial region. In the vertical direction, there are 30 irregularly spaced levels, of which 10 are in the upper 150m. The main physical parameterizaion schemes of LICOM2.0 include the turbulent mixing by Canuto, the isopycnal meso-sacle eddy-mixing scheme by Gent and Williams, solar radiation penetration scheme, etc. The coupled GCM FGOALS-g2.0 is run for 300 years starting from zero oceanic velocity. In this study, we analyze a 300-yr pre-industrial experiment and a 20th century climate change experiment.

3. Climatologically mean state by FGOALS2.0

There are some significant model biases in the version 1.0 of FGOALS, in particular, cold bias in high latitudes due to very weak thermohaline circulation, and extremely strong ENSO amplitude in the tropical Pacific due to very shallow equatorial thermocline. Through much more modeling efforts, a lot of model biases above were alleviated or reduced in the new version FGOALS2.0. Although the coupled GCM FGOALS2.0 still shows the so-called tropical bias to some extent, for example, cold SST bias in the central and western equatorial Pacific, the realistic double ITCZs etc., the seasonal cycle of SST in the equatorial Pacific is much improved in comparison with earlier versions of FGOALS as well as those from the other IPCC AR4 simulations (Figure1). The observed SST shows obvious annual cycle with westward propagation in the eastern Pacific and semi-annual cycle in the western Pacific, but two earlier versions of FGOALS (g1.0 and g1.1) simulated much weaker annual cycle and incorrect phase. In fact, almost all coupled GCMs from CMIP3 fail to simulate the observed SST annual cycle in the eastern Pacific. However, the new version of FGOALS can reproduce it due to improved physical parameterization schemes in the oceanic and atmospheric models.

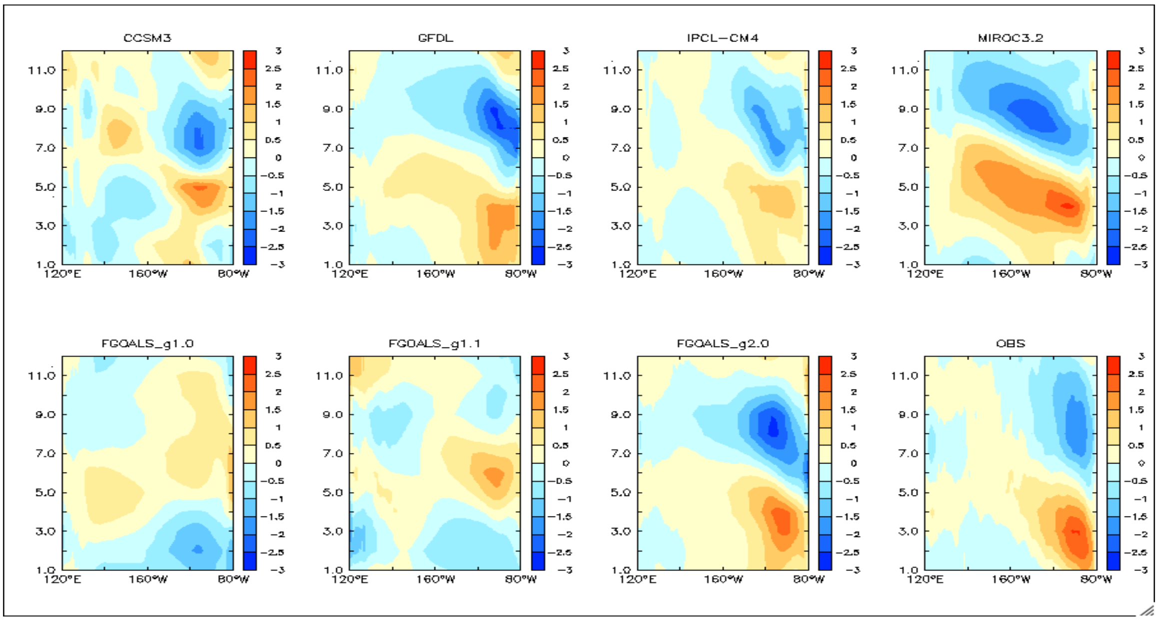

Figure 1 Annual cycle of SST averaged between 2S and 2N as a function of longitude and time. (unit: C)

The seasonal march of East Asian monsoon is also much improved in FGOALS2.0 (Figure2). The observed rain belt shows twice northward jumps, the first is from south China to Yangtze river basin around the mid-June, and the second is from Yangtze river basin to North China around mid-July. The model can reproduce the seasonal march of main rain belt in eastern China as observed, although the precipitation is a bit underestimated. On the other hand, the observed jump of rain belt seems to be more abrupt than the model maybe due to the coarse resolution about 2.8 degrees.

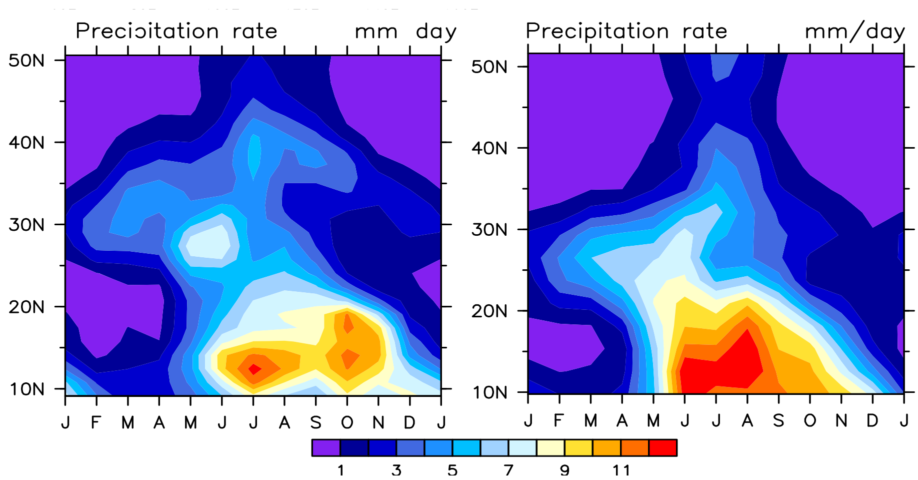

Figure 2 The simulated (left) and observed (right) annual cycle of precipitation averaged between 100E-120E as a function of latitude and calendar month. (unit: mm/day)

4. Climate variability by FGOALS2.0

The first version of FGOALS does not only simulate very strong ENSO event with about twice times of the observed standard deviation of Nino3.4 index, but also produce a very regular period around 3 years (not shown). Figure 3 shows the Nino3.4 time series and the corresponding power spectra from FGOALS2.0 and observation. It is vey clear that the model can simulate the irregular ENSO variability with similar amplitude as observed, especially the power spectra from model shows double peaks, one around 4-5 years and another around 2-3 years, which is also very similar to the observed one.

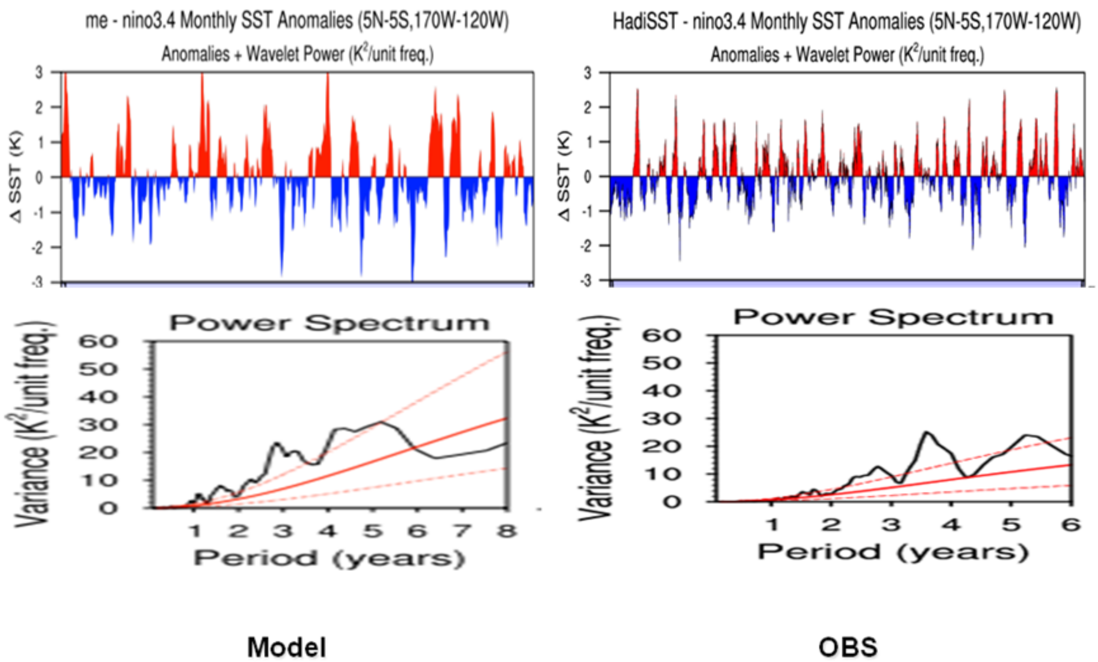

Figure 3 Time series (unit: C) and power spectra of Nino3.4 index from FGOALS2.0 (left) and observed (right).

Using a nudging methodology to restore model SST to the observed one as initialization process in the coupled model, an ENSO hindcasting experiments has been conducted from 1980 to 2002 with the coupled model. Starting from 1st of January, April, July, and October in the each year, the 10-member hindcasting ensemble experiment is integrated for one year. The predicted Nino3.4 indices at 3-, 6-, 9-, and 12-month leading time as well as the anomaly correlation coefficient (ACC) of Nino3.4 index are shown in Figure 4. For strong ENSO events, e.g., 1982-83 El Nino, 1997-98 El Nino and 1998-99 La Nina etc., the model predicts them very well even in 12 month leading time. But for the moderate ENSO events, e.g., 2003 El Nino, the model hardly shows any prediction skill. In addition, the model predicts a false El Nino in 1990. In fact, the ACC skill from FGOALS is much greater than persistence skill, and is comparable with the other coupled GCMs from CliPAS project.

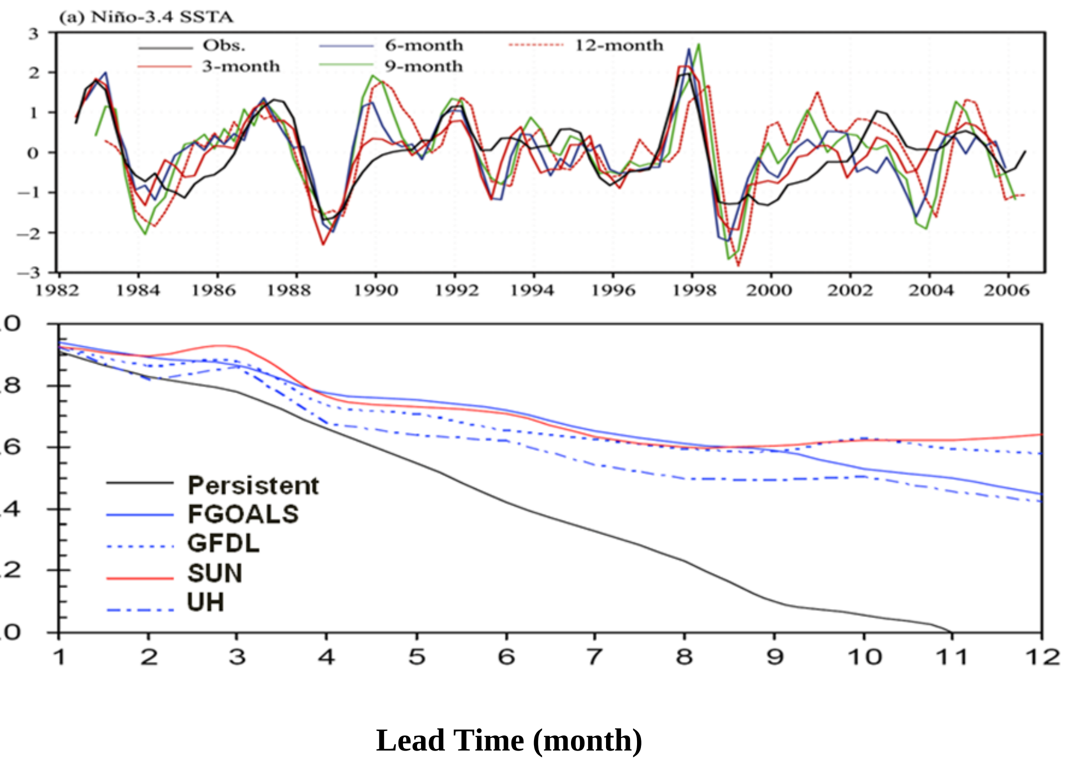

Figure 4 The observed (black) and predicted Nino3.4 indices (upper panel) at 3- (solid red), 6- (solid blue), 9- (solid green), and 12-month (dashed red) lead time, the anomaly correlation coefficient (AAC) from persistence, four coupled GCMs. (FGOALS (solid blue), GFDL (dotted blue), SUN (solid red), UH (dashed blue)).

5. Summary and future plan

The basic performance of the coupled GCM FGOALS2.0 developed at LASG/IAP is evaluated in this study. Compared with the earlier versions of FOALS, a lot of model biases are alleviated or reduced, especially, FGOALS2.0 simulate reasonable seasonal cycle of equatorial SST, the seasonal march of summer rain belt in East Asia, and ENSO variability. It is worthy indicating that the coupled model shows relative high

ACC skill of Nino 3 index in the 1981-2003 ENSO hindcasting experiment even though a very simple initialization process in used. In the next five years, the coupled GCM will be widely applied in many fields of the earth science and will be improved in many aspects as follows:

(1) IPCC AR5 climate change experiments will be conducted with the model FGOALS2.0.
(2) The climate prediction experiments from intra-seasonal, to seasonal, to decadal time scale will be performed, as well as some advanced data assimilation methodology.
(3) Air-sea interaction, especially the impact of air-sea interaction on the East Asian monsoon will be investigated with the coupled GCM.
(4) Based on the FGOALS2.0, we will develop high-resolution model. For example, 1/10 degree for oceanic model, ¼ degree for atmospheric model.
(5) Biogeochemical processes, especially the carbon-nitrogen cycle will be introduced in the coupled GCM.

Current Status and Strategy of CGCM and Ocean Analysis System Developments in Australia

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1. Introduction

POAMA (Predictive Ocean Atmosphere Model for Australia) is an intra-seasonal to inter-annual climate prediction system based on coupled ocean and atmosphere general circulation models. The first version (POAMA-1) was developed jointly between the former Bureau of Meteorology Research Centre (BMRC), the former division of CSIRO Marine Research (CMR) and the Managing Climate Variability (MCV) program. POAMA-1 became operational in October 2002. The main focus for POAMA-1 was the prediction of Sea Surface Temperature (SST) anomalies associated with El Niño/Southern Oscillation, achieved through initializing the model with observed ocean initial conditions. In 2007 a new version, POAMA-1.5, became operational (Wang et al 2008). In this version an Atmosphere-Land Initialization scheme was implemented to provide observed atmospheric initial conditions (Hudson et al 2010). This upgrade made it possible to explore experimental Australian climate forecasts, such as rainfall and surface air temperatures on a range of timescales from weeks to months (Hudson et al 2011a,b; Lim et al 2009; Marshall et al 2011), in addition to oceanographic products (Hendon et al 2009; Spillman 2010, Spillman et al 2010a,b, Zhao and Hendon 2009). The model also has a reasonable level of skill prediction the Madden Julian Oscillation (Rashid et al 2010).

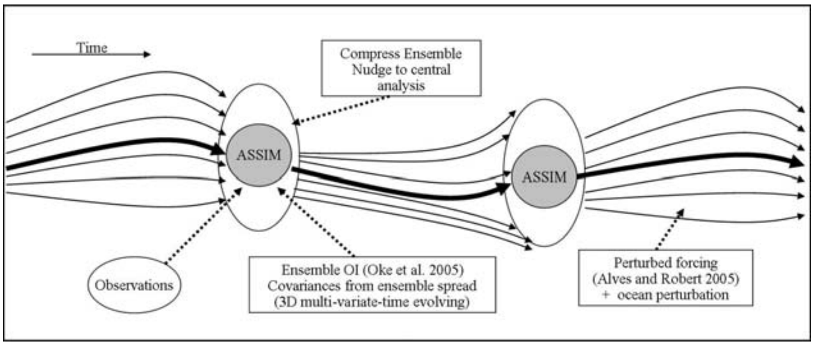

Figure 1: Schematic of the PEODAS ocean assimilation system (from Yin et al 2010)

Recently, a more advanced POAMA Ensemble Ocean Data Assimilation System (PEODAS) has been developed that gives rise to a more superior depiction of observed ocean conditions than previous system (Yin et al 2010). This enhancement forms part of a new POAMA-2 system that will be transferred to Bureau operations in 2010. Preliminary analysis of the POAMA-2 system shows significant improvements in skill (Lim et al 2010).

The main modules in POAMA-2 include the ocean model ACOM2 (Australian Community Ocean Model version 2), the atmospheric model BAM3 (the BMRC Atmospheric Model version 3; T47L17 resolution) and the OASIS (Ocean Atmosphere Sea Ice Soil) coupler. The spatial resolution is approximately 2.5º longitude by 2.5º latitude for the atmosphere and 2º longitude by varying 0.5º~1.5º latitude for the ocean models.

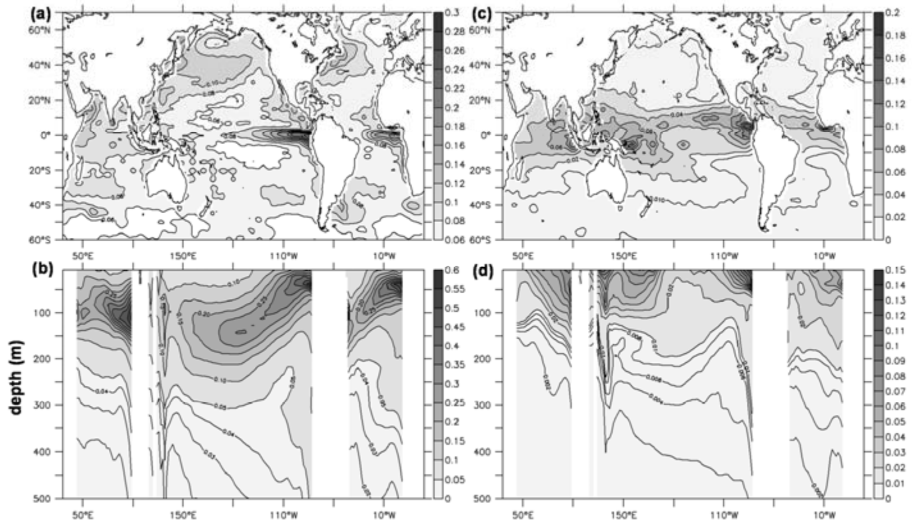

Figure 2: Spread of the ensemble (before assimilation) over the re-analysis period showing fields of (a) SST (°C), (b) Temperature section along the equator (°C), (c) Sea surface salinity (psu) and (d) salinity section along the equator (psu). (From Yin et al 2010). Ensemble spread is calculated relative to a central analysis (see Yin et al for full details).

The ocean assimilation (PEODAS) is based on the Ensemble Kalman Filter and generates an ensemble of ocean states each day (fig 1). These are used to perturb the seasonal forecasts. PEODAS assimilates all available temperature and salinity data, including SHIP, Buoy, XBT, TOGA-TAO array and Argo. The covariances are based on a time evolving model ensemble and as such are multi-variate, 3-dimensional and time dependent. Full details can be found in Yin et al 2010.

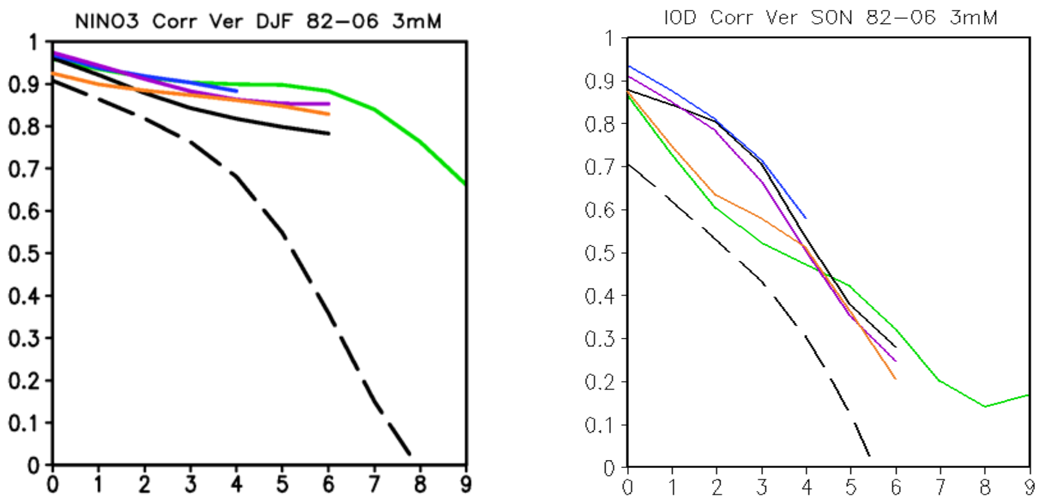

Figure 3: Hind-cast anomaly correlation SST skill with lead time for (left) NINO3 region for Dec-Jan (right) Indian Ocean Dipole for Sep-Nov. Dashed line is persistence, solid colours are as follows: Black – POAMA1.5, Purple – POAMA-2 Multi model, Green – SINTEX, Blue – ECMWF System 4, Orange – NCEP.

The perturbation strategy is further enhanced by creating a pseudo-multi model ensemble by utilizing three different configurations of the coupled model. The ensemble consists of 3 sets of 10-member ensembles, each set from a different model configuration as follows:
p24a – standard coupled model
p24b – as p24a but with explicit bias correction of SST during model integration
p24c – as p24a but with boundary layer settings used in POAMA-1.5

These model configurations give simulations with different characteristics, but complementary levels of skill. Initial results suggest that there is some benefit in creating a multi-model ensemble based on these three different configurations, i.e. errors have different characteristics in each configuration. For example, p24b includes an SST flux correction which leads to a decreased in SST skill, but improved climate teleconnections.

Each 10-member set is perturbed with different ocean initial conditions from PEODAS. The characteristics of the PEODAS initial conditions are such that they span the uncertainty in the ocean state and the technique used is effectively a simplified breeding method. Ensemble spread from the PEODAS ocean assimilation scheme (Yin et al 2010) is shown in Figure 2. The highest spread in SST (fig 2a) occurs in the eastern equatorial Pacific and along the western boundary currents, as one might expect as these are the regions of highest variability. The highest spread in surface salinity (fig 2b) occurs in regions of highest rainfall, such as along the Inter-Tropical Convergence Zone, the South Pacific Convergence Zone and the high rainfall regions of the West Pacific warm pool. Figure 2c shows the temperature ensemble spread at depth along the equator. Maximum spread occurs along the thermocline, the region of maximum temperature variability. Maximum salinity spread (fig 2d) occurs at the surface.

All members will use the same atmospheric initial conditions, while this is not ideal, proper atmospheric perturbed initial conditions are being developed for POAMA-3, and an initial version is being implemented in the POAMA-2 monthly configuration.

More details about POAMA can be found on a dedicated web site at http://poama.bom.gov.au

2. Summary

The POAMA-2 system has been transferred into the Bureau operations in January 2011 and after operational trials will replace POAMA-1.5 as the Bureau's operational dynamical seasonal forecast model. The key features of POAMA-2 are: a new ocean data assimilation system based on the Ensemble Kalman Filter and a Pseudo multi-model ensemble strategy based on three different configurations of the model.

One of the three model configurations uses a flux correction technique to reduce model SST biases. This led to mixed results, with decreased tropical SST skill but improved teleconnections with Australian rainfall. Each of the three model configurations used in POAMA-2 has advantages and disadvantages when compared to each other. The pseudo-multi model ensemble provides the best skill. Figure 3 shows the anomaly correlation skill in the NINO3 region and for the Indian Ocean Dipole (IOD) index, compared with similar hind-casts from other international centres. The POAMA forecasts for both NINO3 and IOD are comparable to the best international models.

In the longer term, the next version, POAMA-3, will use a new coupled model called the ACCESS (Australian Coupled Climate Earth System Simulator) coupled model. This model is based on the UK Met Office atmospheric model, the GFDL MOM 4 ocean model, the Los Alamos CICE sea ice model, the Australian CABLE land surface model and the OASIS coupler. The exact configuration of model in POAMA-3 has not been finalized, but the atmospheric horizontal resolution will be at least N96.

In POAMA-3, the PEODAS ocean assimilation system will be extended to include the atmosphere and land, in what will be a coupled Ensemble Kalman Filter. This technique will also generate coupled perturbations for the ensemble of forecasts. It will incorporate coupled covariances between the ocean, atmosphere and land.

Reference

Alves, O., C. Robert, 2005: Tropical Pacific Ocean model error covariances from Mont Carlo simulations. Quart. J. Roy. Meteor. Soc., 131, 3643-3658.

Hendon, H.H., E. Lim, G. Wang, O. Alves, and D. Hudson, 2009: Prospects for predicting two flavors of El Nino Geophys. Res. Lett.,36, L19713, doi:10.1029/2009GL040100.

Hudson, D., Alves O., Hendon H.H., Marshall A.G. 2011a. Bridging the Gap between Weather and Seasonal Forecasting: Intraseasonal Forecasting for Australia. Quarterly Journal of the Royal Meteorological Society. Accepted.

Hudson, D., Marshall, A., Alves,O. 2011b. Intraseasonal forecasting of the 2009 summer and winter Australian heat waves using POAMA. Weather and Forecasting (in press)

Hudson, D., O. Alves, H.H. Hendon, G. Wang, 2010: The impact of atmospheric initialisation on seasonal prediction of tropical Pacific SST . Climate Dyn., DOI 10.1007/s00382-010-0763-9.

Lim, E.-P., H. H. Hendon, O. Alves, Y. Yin, G. Wang, D. Hudson, M. Zhao and L. Shi 2010: Dynamical seasonal prediction of tropical Indo-Pacific SST and Australian rainfall with improved ocean initial conditions. CAWCR Tech. Rep. No. 032

Lim, E.-P., H.H. Hendon, D. Hudson, G. Wang, and O. Alves, 2009: Dynamical forecasts of inter-El Nino variations of tropical SST and Australian springtime rainfall . Mon.Wea. Rev. ,137,3796-3810.

Marshall, A.G., D. Hudson, M.C. Wheeler, H.H. Hendon, and O. Alves. 2011. Assessing the simulation and prediction of rainfall associated with the MJO in the POAMA seasonal forecast system. *Clim. Dyn.*, accepted.

Oke, P. R., A. Schiller, G. A. Griffin, G. B. Brassington, 2005: Ensemble data assimilation for an eddy-resolving ocean model. Quart. J. Roy. Meteor. Soc., 131, 3301-3311.

Rashid, H.A., H.H. Hendon, M.C. Wheeler, and O. Alves, 2010: Prediction of the Madden-Julian Oscillation with the POAMA dynamical prediction system. Climate Dyn., DOI 10.1007/s00382-010-0754-x.

Spillman C.M., Hudson D.A. and Alves O., 2010a. Real-time seasonal SST predictions for the Great Barrier Reef during the summer of 2009/2010. CAWCR Research Letters, 4:11-19.

Spillman C.M., Alves O. and Hudson D.A., 2010.b Seasonal prediction of thermal stress accumulation for coral bleaching in the tropical oceans. Monthly Weather Review, DOI: 10.1175/2010MWR3526.1.

Spillman C.M., 2010. Operational real-time seasonal forecasts for coral reef management. Journal of Operational Oceanography, in review.

Wang G., O. Alves, D. Hudson, H. Hendon, G. Liu, and F. Tseitkin: 2008, SST skill assessment from the new POAMA-1.5 System. BMRC Research Letter No.8.

Yin, Y., Alves, O. and Oke, P.R. 2010. An ensemble ocean data assimilation system for seasonal prediction. Mon. Wea. Rev. (in press)

Zhao M. and H. Hendon: 2009, Simulation and prediction of the Indian Ocean Dipole in the POAMA seasonal forecast model. Quarterly Journal of the Royal Meteorological Society. (To appear)

Coupled Model Simulation by Constraining Ocean Fields with Ocean Data through the JMA Operational Ocean Data Assimilation System

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1. Introduction

We developed a “quasi coupled data assimilation system,” i.e., a data assimilation system in which ocean observation data is adopted for constraining the ocean component of a Coupled atmosphere-ocean General Circulation Model (CGCM) (Fujii et al. 2009). The system is called MOVE-C in this report. The CGCM used in MOVE-C is JMA’s current operational CGCM, JMA/MRI-CGCM (Yasuda et al. 2007). MOVE-C also adopts the ocean data assimilation scheme of MOVE/MRI.COM-G (Usui et al. 2006) for constraining the ocean components with observation data.

We expect MOVE-C to be suitable for analyzing the climate variability because it explicitly calculates the interaction between the atmosphere and ocean. It is often pointed out that the forecast skill can be degraded by inconsistency between the initial conditions of the atmosphere and ocean for the coupled model in current seasonal forecasting because they are prepared separately by using non-coupled atmosphere and ocean data assimilation systems. Hence, there is a possibility that seasonal forecasting can be improved by using the coupled atmosphere-ocean analysis as the initial condition. It also enables us to make an ocean analysis that does not depend on any atmospheric reanalysis data and, therefore, is not affected by its errors.

The MOVE-C reanalysis (MOVE-C RA) is conducted for the period of 1940-2006. In the reanalysis, in situ temperature and salinity profiles, satellite altimetry data, and COBE-SST (observation-based SST data in JMA, Ishii et al. 2005) are assimilated into the ocean component of the CGCM. We also performed the AMIP Run, a simulation run of the atmosphere GCM used in MOVE-C. Monthly data of COBE-SST is employed as the ocean boundary condition in the AMIP Run. Here, we compare MOVE-C RA to the AMIP Run and atmospheric reanalysis products.

2. Result

Figure 1 shows the monthly climatological precipitation in MOVE-C RA and the AMIP Run, as well as that in an observation-based precipitation dataset (CMAP: Xie and Arkin 1997). In January, the AMIP Run has an excess peak north of New Guinea, and underestimates in the South Pacific Convergence Zone and the equatorial Indian Ocean. These defects are improved in MOVE-C RA. The overestimates in the African continent and North Atlantic in the AMIP Run are also suppressed in MOVE-C RA. In July, the precipitation is considerably overestimated east of India and underestimated around the Philippines in the AMIP Run. The overestimate east of India is mitigated and precipitation around the Philippines increases in MOVE-C RA. The position of the peak in the Intertropical Convergence Zone in MOVE-C RA is closer to that in CMAP. The overestimate in the equatorial Atlantic in the AMIP run is suppressed in MOVE-C RA. MOVE-C thus improves the precipitation fields over the AMIP Run.

The improvement of the summer precipitation over the Philippine Sea is caused by the reconstruction of the negative feedback between SST and precipitation in MOVE-C RA. This negative feedback has an important role in adjusting precipitation. In particular, it suppresses the overestimated summer precipitation in the Bay of Bengal in the AMIP Run: the convection cools SST by reducing solar heating and enhancing ocean mixing, and the cooled SST, in turn, deactivates the convection in the coupled system. The reduction of the upward transport of the air mass by the convection in the western part of the Bay of Bengal increases the lower westerly wind over the eastern part of the Indian Ocean and the maritime continent, resulting in the improved monsoon trough.

It also suppresses divergence in the upper troposphere over the Bay of Bengal (Fig. 2). In the AMIP Run, the excess precipitation in the ocean east of India generates a spurious divergence maximum, resulting in the suppressed convective activities over the Philippine Sea compensating for the extra divergence. This divergence is weakened in MOVE-C RA, resulting in increased convective (Typhoon) activities and the upper-layer divergence over the Philippine Sea. It also intensifies the zonal contrast of the velocity potential in the upper troposphere and improves the zonal Walker Circulation.

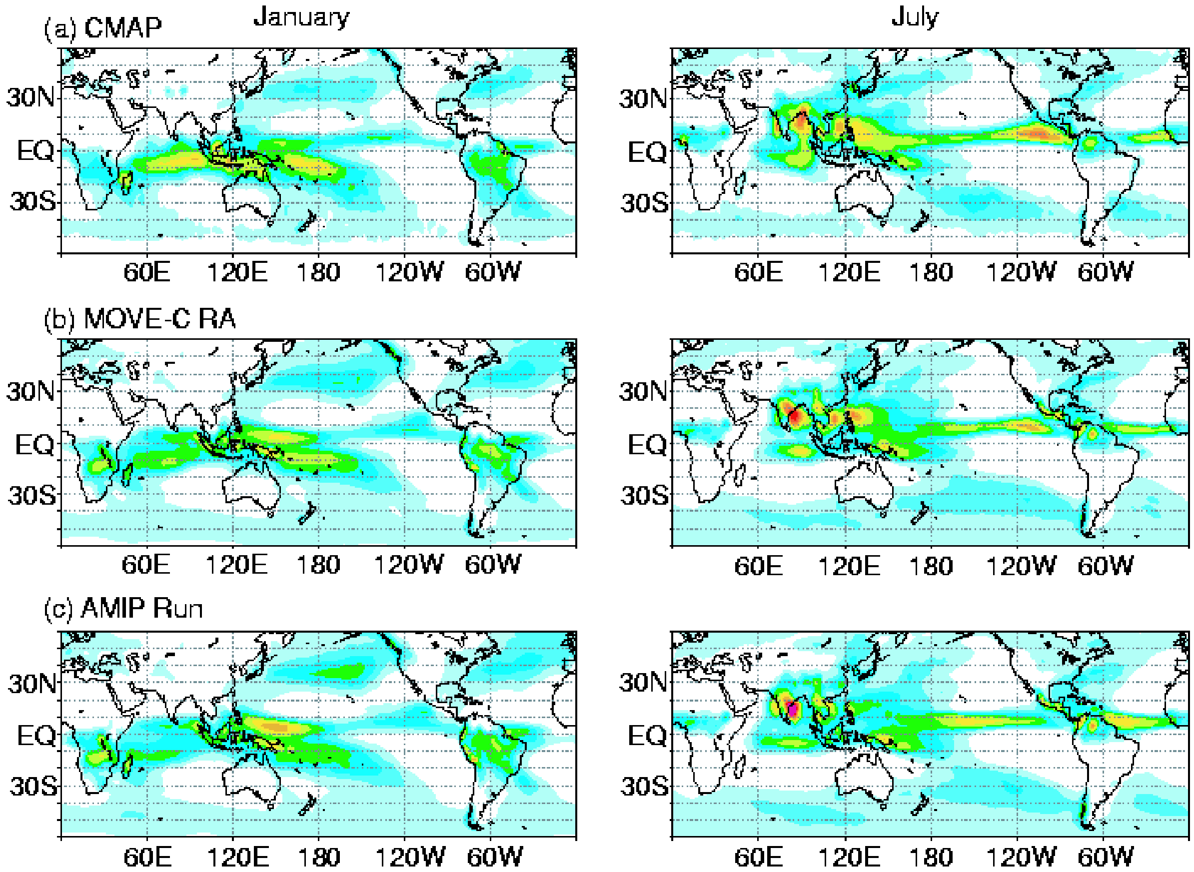

Fig. 1. Global distribution of monthly mean precipitation (mm/day) in (a) CMAP, (b) MOVE-C RA, and (c) AMIP Run (bottom). Left: January. Right: July.

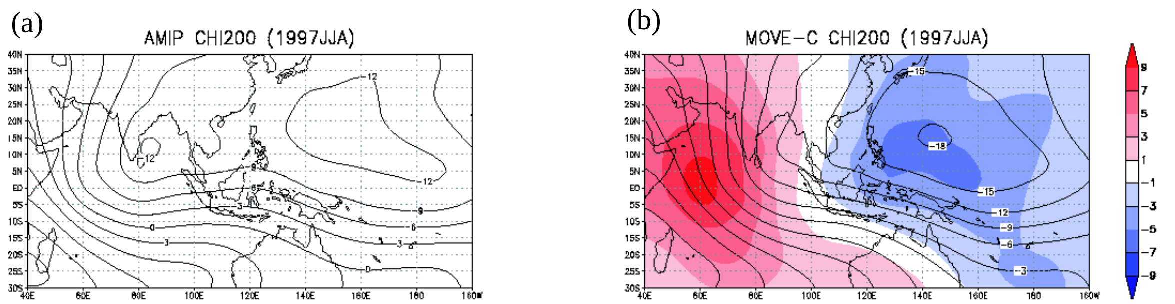

Fig. 2. Velocity potential (contours, m^2s^{-1}) at the 200 hPa surface in June-August of 1997 for (a) AMIP Run, and (b) MOVE-C RA. The shading in (b) shows the difference of (MOVE-C RA07) - (AMIP Run).

Another interesting result of this study is that the trend in precipitation over the Indian Ocean in MOVE-C RA is improved over reanalysis products produced by uncoupled atmospheric data assimilation systems (Figure 3). All reanalysis products show an increasing trend in precipitation responding to the substantial increasing trend in SST. This is, however, a spurious trend because the observation based maps show no increasing trend in precipitation there. This spurious precipitation trend also induces a doubtful decreasing trend in the solar flux. This trend is probably inconsistent with the increasing trend in SST.

In MOVE-C RA, this spurious trend in precipitation has been removed effectively, while the substantial SST trend has not changed. The decreasing trend in the solar flux also disappears responding to the improvement of the precipitation trend. This improvement is also caused by the reconstruction of the negative feedback between SST and precipitation. It decoupled the precipitation change from that of SST. Consequently, the atmospheric fields are adjusted to the increasing SST trend in a more global manner.

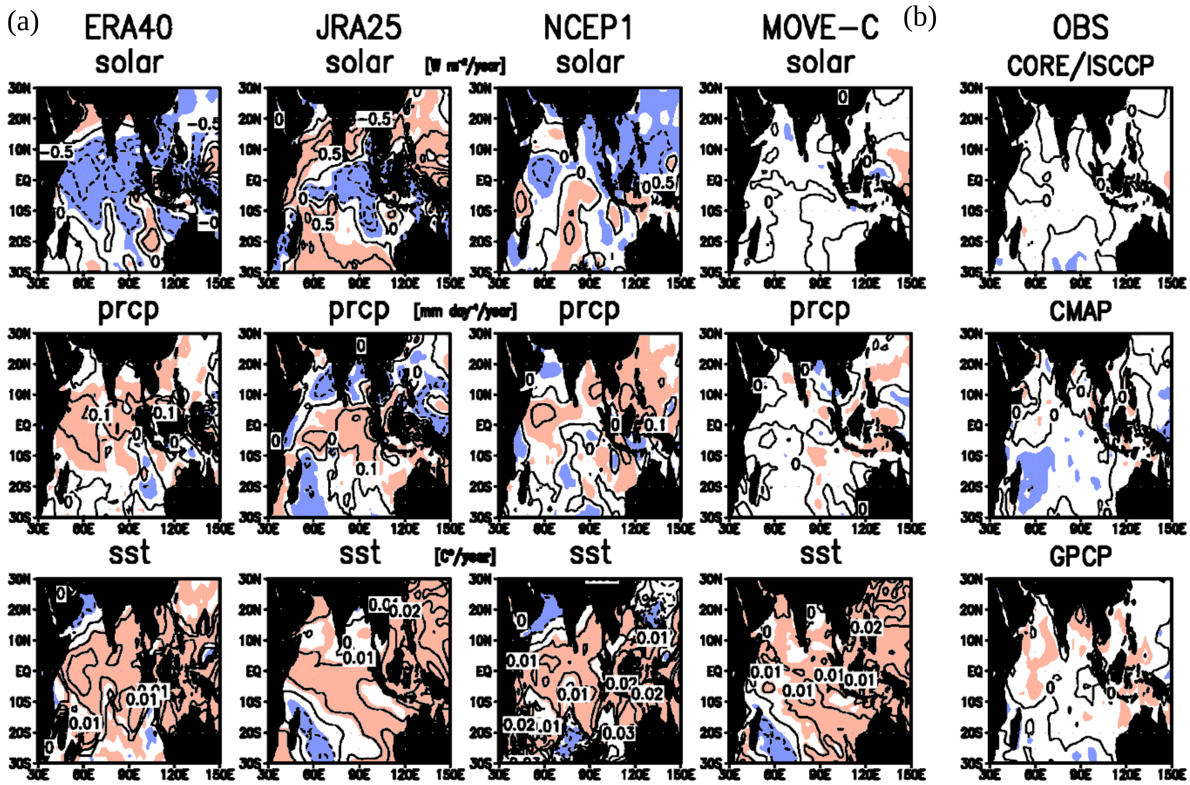

Fig. 3. (a) Comparison of the trends in the solar flux (top), precipitation (middle), and SST (bottom) over the Indian Ocean in 1979-–2001 between atmospheric reanalysis products (ERA-40, JRA-25, NCEP-R1) and MOVE-C RA. (b) Trends in solar flux (top) and in precipitation (middle and bottom over the Indian Ocean in 1979-–2001 derived from observation-based maps (CORE/ISCCP, CMAP, GPCP).

3. Summery

We showed above that the quasi coupled data assimilation system improves atmospheric fields over atmospheric reanalysis products, as well as the AMIP Run, in some aspects. Assimilating ocean data alone, however, is not sufficient for reproducing climate variability completely because not all climate phenomena are controlled by the ocean field alone. It should also be noted that state-of-the-art atmosphere models are not sophisticated enough to reflect ocean variability correctly even if the ocean field is well reconstructed by assimilating ocean observation data. Inadequate reproduction of the atmosphere field may then cause degradation of the ocean field. MOVE-C is, therefore, not likely to exceed the atmosphere and ocean reanalysis products generated by uncoupled atmosphere and ocean models. It is thus essential to assimilate atmosphere observations in addition to ocean data for reconstructing climate variability more effectively in MOVE-C. It is also thought to provide better initial conditions for seasonal and ENSO forecasting. Therefore, our crucial target is to develop a truly coupled data assimilation system in which both atmosphere and ocean observations are assimilated into a CGCM.

Reference

Fujii Y., Nakaegawa, T., Matsumoto, S., Yasuda, T., Yamanaka, G., and Kamachi M. (2009), \Coupled climate simulation by constraining ocean fields in a coupled model with ocean data, J Climate 22, 5541-5557.

Ishii M., A. Shouji, S. Sugimoto and T. Matsumoto 2005: Objective analyses of sea-surface temperature and marine meteorological variables for the 20th century using ICOADS and the Kobe collection. Intl. J. Climatol., 25, 865-879.

Usui N., S. Ishizaki, Y. Fujii, H. Tsujino, T. Yasuda and M. Kamachi 2006: Meteorological Research Institute Multivariate Ocean Variational Estimation (MOVE) System: Some Early Results. Adv. Spa. Res., 37, 806-822.

Xie P. P. and P. A. Arkin 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull. Am. Meteor. Soc., 78, 2539-2558.

Yasuda, T., Y. Takaya, C. Kobayashi, M. Kamachi, H. Kamahori and T. Ose, 2007: Asian Monsoon Predictability in JMA/MRI Seasonal Forecast System. CLIVAR Exchange, 43, 18-24.

Strategy and Issues to be Addressed in Sea Ice Assimilation

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1. Introduction

Current practices of the operational sea ice analysis group in the Japan Meteorological Agency (JMA) rely heavily on human interpretation and analysis of satellite observation data. Ice analysts require extensive experience and specialized knowledge of ice phenomena/physics, climatology and image/data interpretation. The analyst mentally assimilates large volumes of satellite and other data including previous ice charts, weather and ocean information, ice observations and numerical assimilated model information. Satellite data interpretation is particularly labour intensive and subjective due to the volume and variety of data and because required physical quantities must be indirectly inferred (see Carrieres et al., 2003).

According to recent progress in ocean data assimilation (GODAE, 2009) and arctic oceanography (Breivik et al., 2009 and Calder et al., 2009) communities, we need to investigate the feasibility of transitioning from an “observation-based” to a “model/assimilation-based” approach for the development of an operational sea ice analysis system in JMA. In this report, we investigate three recent examples of sea ice assimilation/influence in oceanic/coupled/atmospheric systems: sea ice assimilation in the Okhotsk Sea (OGCM with ocean data assimilation) by Usui et al. (2009), sea ice assimilation in the Arctic Sea (CGCM with ocean data assimilation) by Toyoda et al. (2010), and sea ice thickness impact on the atmosphere (AGCM simulation) by Adachi and Yukimoto (2006). After examining the experiences of the above three research works, we would then like to mention issues (perspectives) related to sea ice operation.

2. Examples

We briefly investigate three examples of recent sea ice assimilation/influence in the oceanic/coupled/ atmospheric systems.

Usui et al. (2009) have developed an assimilation scheme of sea ice concentration in the JMA operational ocean data assimilation and forecasting system (MOVE/MRI.COM-WNP, Usui et al., 2006) for nowcasting and forecasting of sea ice distribution in the Okhotsk Sea. The ice model of the system (Tsujino et al., 2010) is based on the ice-ocean coupled model of Mellor and Kantha (1989) with 5 categories (see Los Alamos sea ice model, CICE; Hunke and Lipscomb, 2006). They used the nudging scheme of JMA sea ice concentration analysis data in the JMA MGDSST dataset in an OGCM (ocean general circulation model, MRI.COM). They compared assimilation, free simulation and observation, and showed improvements in the assimilated field. The scheme tries to conserve the volume of sea ice before and after the assimilation. Category 1 (thinner ice) is corrected, and sea ice volume does not change very much after assimilation. We need to continue to examine the conservation of volume before and after assimilation. Ice thickness data is needed in order to perform such an examination. In this scheme, multivariate (ocean state estimation, sea ice concentration, and water flux optimization) assimilation is adopted and is better than a univariate scheme. We expand the assimilation method in the Okhotsk sea to the Arctic and Antarctic regions in the operational global system MOVE/MRI.COM_G for seasonal prediction in JMA/MRI.

Toyoda et al. (2010) investigated the effects of assimilating sea ice concentration data in a simulation of Arctic Ocean climate using an atmosphere-ocean-sea ice coupled model (CGCM). The overestimation of summertime sea ice concentration in the East Siberian Sea and the Beaufort Sea in free simulations (i.e., without sea ice data input) can be reduced by assimilating sea ice observation. This improvement is also evident in a following hindcast experiment for 3–4 years after the initialization with the assimilation. In the hindcast experiment, the improved heat storage in both sea ice and the ocean surface layer plays a central role in improving the accuracy of sea ice distribution, particularly in summer. The ice-albedo feedback and the feedback associated with the atmospheric pressure pattern work more effectively to retain the heat signal after initialization for a coupled atmosphere-ocean-sea ice system prediction. In addition, comparison with field observations confirms that the ice-cloud feedback and the feedback via the Beaufort Gyre circulation fail to reproduce a realistic feedback loop due to inadequacies in the model. Thus, further development of coupled models is required to better define Arctic Ocean climate processes and to improve accuracy of their prediction.

In Adachi and Yukimoto (2006), the influence of sea ice thickness on the winter Arctic atmosphere is investigated using an atmospheric general circulation model (AGCM), focusing on heat fluxes at the sea ice surface. Due to heat conduction from the sea ice bottom, the sea ice surface temperature increases when the sea ice becomes thin. However, the heat balance among net longwave cooling, sensible and latent heat fluxes, and heat conduction changes with sea ice thickness. When the sea ice is thick, longwave cooling is balanced with the heating of heat conduction and downward sensible heat flux. On the other hand, when the sea ice is sufficiently thin, cooling by sensible and latent heat fluxes plays a large role in heat balance at the sea ice surface, canceling the increase of downward longwave heating associated with cloud change. Thinner sea ice (2–4m, then larger surface temperature) leads to warming of a large part of the troposphere in the Arctic region, causing a weakening of upper westerly wind in the sub-arctic region. The magnitude of such a wind response to possible sea ice thickness variability can be 10–20% of interannual variability. They recommend sea ice thickness information into atmospheric reanalysis, although the thickness data is really needed.

3. Issues

We investigated three examples of research works related to sea ice: (1) Sea ice assimilation in the Okhotsk Sea using OGCM and ocean data assimilation, (2) Sea ice assimilation in the Arctic Sea using CGCM and ocean data assimilation, and (3) Sea ice thickness impact on the atmosphere using AGCM free simulation. From the examples and other community white papers in international projects/symposiums such as Carrieres et al. (2003), Breivik et al. (2009) and Calder et al. (2009), we summarized issues related to sea ice in three categories (observation, model, and assimilation) for future strategic development of sea ice operation.

Observation Issues:

- Operational automated extraction/analysis algorithms of sea ice states and related fields should be developed.
- The shortage of in-situ observations and their inconsistency with other (e.g. satellite) data complicates matters.
- Error information is essential to analysis and data assimilation for producing ice charts.
- Higher resolution data (e.g. SAR) may be better although data management then becomes an issue. The resolution is related to the aim of the operation (ocean-weather vs. seasonal predictions).
- A mix of measurements may provide the most useful information as in the GHRSST project for sea surface temperature.
- Sea ice thickness data is needed as is sea ice concentration data (need more cooperation with the satellite community).

Model Issues:

- Operational ice forecasting as a part of ocean-weather forecasting is more of an initial value problem. But for seasonal forecasting with CGCM, boundary value problem (air-sea flux optimization) may also be needed.
- Many complex processes have been modeled, but very few ice characteristics are observed. How do we deal with this gap (e.g. ice concentration vs. thickness/volume)?

Data Assimilation Issues:

- We have to process sea ice state optimization, and at the same time, deal with the air/sea/ice interface where the boundary interactions are complex.
- Heat and water fluxes and oceanic/atmospheric states should be consistent with each other, not only sea ice concentration.
- Anisotropy and inhomogeneity in the background/observation error variance/covariance (B & R) matrices are needed because sea ice is a discontinuous and deformable complex medium.

- A multivariate assimilation scheme is important: sea temperature consistent with ice extent, ice variability with salinity/water flux optimization, and ice concentration optimization with/without ice volume (and consistent observation too).
- The approach of incremental data assimilation may be useful, where a simpler model may be used as part of a 4D assimilation procedure. The resulting analysis increment is used to correct the full state of a more sophisticated model that is used to produce the forecasts, as is done in incremental 4DVAR.
- Improvement of the observation operator for direct satellite assimilation (e.g. radiance), or a relationship between concentration and thickness (or other variables) should be developed.
- More developments should be done with international cooperation such as intercomparison (Garric 2004).

Reference

Adachi, Y. and S. Yukimoto (2006): Influence of Sea Ice Thickness on the Atmosphere in the Winter Arctic Region in an Atmospheric General Circulation Model. SOLA, vol. 2, 076–079.

Breivik L.-A. and coauthors (2009): Remote Sensing of Sea Ice. Ocean Obs09. 9 pp.

Calder J. and coauthors (2009): Community White Paper: An Integrated International Approach to Arctic Ocean Observations for Society. Ocean Obs09. 13 pp.

Carrieres T. and coauthors (2003): White Paper on An International Collaborative Effort Towards Automated Sea Ice Chart Production. JCOMM/IICWG, 13 pp.

Garric G. (2004): Sea Ice Intercomparison Project. GODAE-MERSEA Intercomparison Project Draft. 5 pp.

GODAE (2009): The Revolution in Global Ocean Forecasting – GODAE: 10 Years of Achievement. Oceanography, vol. 22, No. 3, 272 pp.

Hunke, E.C. and W.H. Lipscomb (2006): CICE: the Los Alamos Sea Ice Model Documentation and Software User’s Manual. 59 pp.

Mellor, G.L. and L. Kantha (1989): An Ice-Ocean Coupled Model, J. Geophys. Res., 94, 10937–10954.

Toyoda, T. and 23 coauthors (2010): Impact of the Assimilation of Sea Ice Concentration Data on an Atmosphere-Ocean-Sea Ice Coupled Simulation of the Arctic Ocean Climate. SOLA (under revision).

Tsujino, H. and coauthors (2010): Reference Manual for the Meteorological Research Institute Community Ocean Model (MRI.COM) Version 3. Tech. Rep. of MRI, No. 59, 241 pp.

Usui, N., T. Imaizumi, H. Tsujino (2009): Toward to implementation of sea ice concentration data into MOVE/MRI.COM-G. JMA Annual Ocean Weather Technical Workshop.

Usui N., S. Ishizaki, Y. Fujii, H. Tsujino, T. Yasuda and M. Kamachi (2006): Meteorological Research Institute Multivariate Ocean Variational Estimation (MOVE) System: Some Early Results. Adv. Spa. Res., 37, 806–822.

CFES: Coupled GCM for the Earth Simulator
—Current status and future directions—

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1. Introduction

A global, high-resolution, coupled atmosphere–ocean general circulation model (GCM) has been developed to efficient computational performance on the Earth Simulator (ES). The model, named CFES (Coupled Atmosphere–Ocean GCM for the ES), consists of AFES (Atmospheric GCM for the ES) and OFES (Oceanic GCM for the ES) with multiple program/multiple data technique and fully parallelized coupling schemes. CFES is used to study mechanisms and predictability of high-impact phenomena especially in the mid-latitudes and their relation to the global-scale circulations In addition, CFES will be used as a platform for observing system (simulation) research using ensemble-based data assimilation methods such as local ensemble transform Kalman filter (LETKF).

2. Model Development and Simulation Research

AFES is adopted from CCSR/NIES AGCM 5.4 (Numaguti et al., 1997) and rewritten for massively parallel computation on the ES (Ohfuchi et al., 2004). Some improvements for high-resolution and coupled simulations are then applied to AFES (Enomoto et al., 2008), and now it has better reproducibility of marine boundary-layer clouds (Kuwano-Yoshida et al., 2010). OFES is based on GFDL MOM 3.0 (Pacanowski and Griffies, 1999) and optimized for vector parallel architecture of the ES (Masumoto et al., 2004). A dynamic–thermodynamic sea-ice model is incorporated into OFES for global and coupled simulations (Komori et al., 2005).

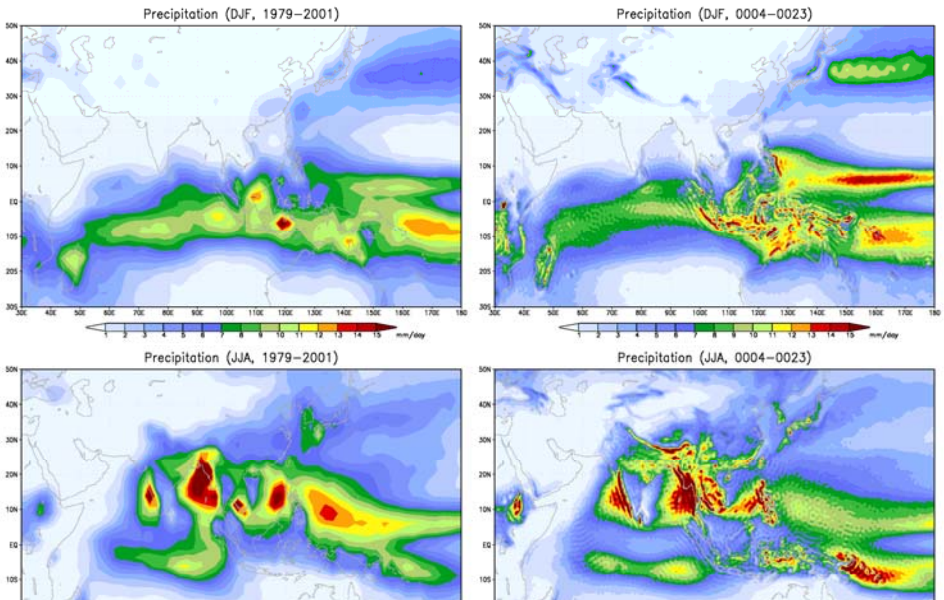

Figure 1: Climatology of the seasonal mean precipitation calculated from (left) CMAP (Xie and Arkin, 1999) and (right) CFES for (top) December–January–February and (bottom) June–July–August.

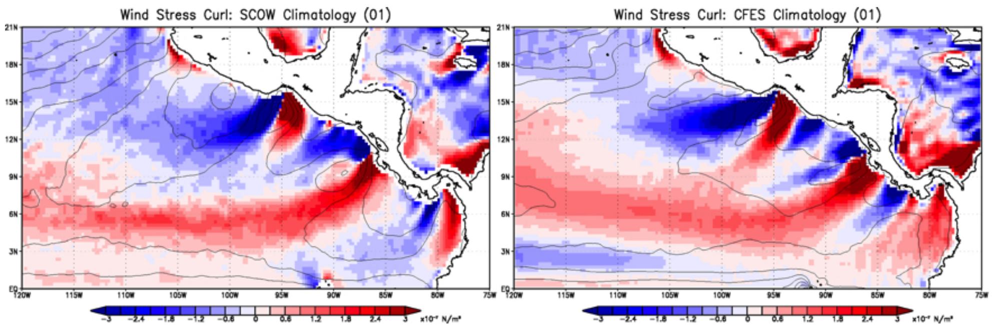

Figure 2: Climatology of the wind stress curl (color) and SST (contour) in January calculated from (left) SCOW (Risien and Chelton, 2008) and (right) CFES.

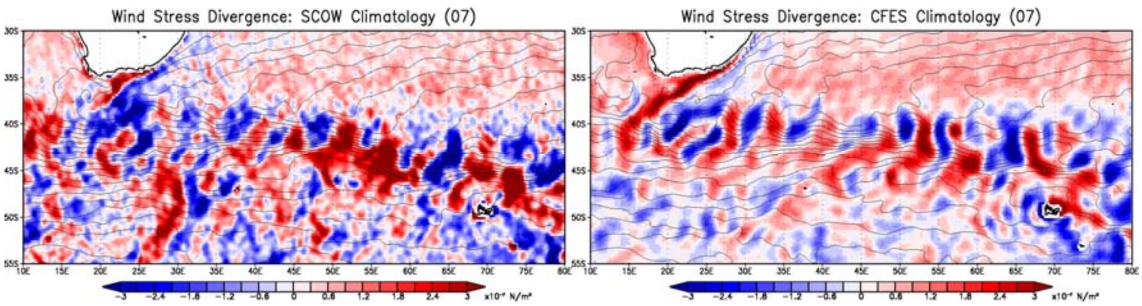

Figure 3: Same as in Figure 2 but for the wind stress divergence in July.

We have two settings of CFES. The higher resolution version, called "CFES standard," has the resolutions of T239 (about 50 km) and L48 for the atmosphere and 0.25º (about 25 km) and 54 levels for the ocean (Komori et al., 2008a). The lower resolution version, called "CFES mini," has half the horizontal resolution of CFES standard. The earlier version of CFES standard was used to investigate deep ocean inertia-gravity waves induced by high-frequency winds (Komori et al., 2008b) and air–sea heat exchanges characteristic of a mid-latitude SST front (Nonaka et al., 2009).

Using the latest version of CFES standard, 23 years of integration was carried out. CFES exhibits good reproducibility of the seasonal mean precipitation of CMAP (Xie and Arkin, 1996) climatology, particularly over the tropical Indian Ocean, one of the key regions for successful seasonal to interannual prediction for Japan (Fig. 1). In addition, both the atmospheric and oceanic components are fine enough to resolve local orography (e.g., narrow passes of Central American cordillera; Fig. 2) and to create ocean surface structures including meandering SST fronts (e.g., the Agulhas Return Current; Fig. 3), respectively. These fine-scale signatures are clearly reflected in the wind stress derivative fields (Komori et al., 2011) as found in high-resolution satellite observations such as Scatterometer Climatology of Ocean Winds (SCOW; Risien and Chelton, 2008).

A 150-year simulation using CFES mini has recently been examined on the triggering of Benguela Niños (Richter et al., 2010) and on seasonal evolutions of atmospheric response to North Pacific decadal SST anomalies (Taguchi et al., 2011). As such, CFES mini is used for studying climate variability on interannual to decadal time scales. It also serves as a platform for coupled sensitivity experiments and ensemble simulations for data assimilation described below.

3. Ensemble Data Assimilation and Observing System Research

AFES–LETKF data assimilation system was developed by Miyoshi and Yamane (2007), and one-half year of AFES–LETKF experimental ensemble reanalysis, ALERA, was performed (Miyoshi et al., 2007a; data are available from the Earth Simulator Center, http://www.jamstec.go.jp/esc/afes/). Based on ALERA, several observing system studies has been conducted: impact of observations from Arctic drifting buoys (Inoue et al., 2009); precursory signals in ensemble spread (Enomoto et al., 2010); propagation of observation impact through tropical waves (Moteki et al., 2011). Currently ALERA 2 is underway with the latest version of AFES and LETKF (Miyoshi et al., 2007b), and AFES–LETKF will be extended to CFES–LETKF in future to assimilate oceanic, sea-ice, and land-surface observations as well as atmospheric observations.

Reference

Enomoto, T., M. Hattori, T. Miyoshi, and S. Yamane (2010): Precursory signals in analysis ensemble spread. *Geophys. Res. Lett.*, **37**, L08804, doi:10.1029/2010GL042723.

Enomoto, T., A. Kuwano-Yoshida, N. Komori, and W. Ohfuchi (2008): Description of AFES 2: Improvements for high-resolution and coupled simulations. In *High Resolution Numerical Modelling of the Atmosphere and Ocean*, ed. by K. Hamilton and W. Ohfuchi, chap. 5, pp. 77–97, Springer, New York.

Inoue, J., T. Enomoto, T. Miyoshi, and S. Yamane (2009): Impact of observations from Arctic drifting buoys on the reanalysis of surface fields. *Geophys. Res. Lett.*, **36**, L08501, doi:10.1029/2009GL037380.

Komori, N., A. Kuwano-Yoshida, T. Enomoto, H. Sasaki, and W. Ohfuchi (2008a): High-resolution simulation of the global coupled atmosphere–ocean system: Description and preliminary outcomes of CFES (CGCM for the Earth Simulator). In *High Resolution Numerical Modelling of the Atmosphere and Ocean*, ed. by K. Hamilton and W. Ohfuchi, chap. 14, pp. 241–260, Springer, New York.

Komori, N., W. Ohfuchi, B. Taguchi, H. Sasaki, and P. Klein (2008b): Deep ocean inertia-gravity waves simulated in a high-resolution global coupled atmosphere–ocean GCM. *Geophys. Res. Lett.*, **35**, L04610, doi:10.1029/2007GL032807.

Komori, N., B. Taguchi, A. Kuwano-Yoshida, H. Sasaki, T. Enomoto, M. Nonaka, Y. Sasai, M. Honda, K. Takaya, A. Ishida, Y. Masumoto, W. Ohfuchi, and H. Nakamura (2011): A high-resolution simulation of the global coupled atmosphere–ocean system using CFES: 23-year surface climatology. *Ocean Dyn.*, under revision.

Komori, N., K. Takahashi, K. Komine, T. Motoi, X. Zhang, and G. Sagawa (2005): Description of sea-ice component of Coupled Ocean–Sea-Ice Model for the Earth Simulator (OIFES). *J. Earth Simulator*, **4**, 31–45.

Kuwano-Yoshida, A., T. Enomoto, and W. Ohfuchi (2010): An improved PDF cloud scheme for climate simulations. *Q. J. R. Meteor. Soc.*, **136** (651), 1583–1597, doi:10.1002/qj.660.

Masumoto, Y., H. Sasaki, T. Kagimoto, N. Komori, A. Ishida, Y. Sasai, T. Miyama, T. Motoi, H. Mitsudera, K. Takahashi, H. Sakuma, and T. Yamagata (2004): A fifty-year eddy-resolving simulation of the world ocean—Preliminary outcomes of OFES (OGCM for the Earth Simulator). *J. Earth Simulator*, **1**, 35–56.

Miyoshi, T., and S. Yamane (2007): Local ensemble transform Kalman filtering with an AGCM at a T159/l48 resolution. *Mon. Wea. Rev.*, **135** (11), 3841–3861, doi:10.1175/2007MWR1873.1.

Miyoshi, T., S. Yamane, and T. Enomoto (2007a): The AFES-LETKF experimental ensemble reanalysis: ALERA. *SOLA*, **3**, 45–48, doi:10.2151/sola.2007-012.

Miyoshi, T., S. Yamane and T. Enomoto (2007b): Localizing the error covariance by physical distances within a local ensemble transform Kalman filter (LETKF). *SOLA*, **3**, 89–92, doi:10.2151/sola.2007-023.

Moteki, Q., K. Yoneyama, R. Shirooka, H. Kubota, K. Yasunaga, J. Suzuki, A. Seiki, N. Sato, T. Enomoto, T. Miyoshi, and S. Yamane (2011): The influence of observations propagated by convectively coupled equatorial waves. *Q. J. R. Meteor. Soc.*, accepted.

Nonaka, M., H. Nakamura, B. Taguchi, N. Komori, A. Kuwano-Yoshida, and K. Takaya (2009): Air–sea heat exchanges characteristic of a prominent midlatitude oceanic front in the South Indian Ocean as simulated in a high-resolution coupled GCM. *J. Climate*, **22** (24), 6515–6535, doi:10.1175/2009JCLI2960.1.

Numaguti, A., M. Takahashi, T. Nakajima, and A. Sumi (1997): Description of CCSR/NIES atmospheric general circulation model. In *Study on the Climate System and Mass Transport by a Climate Model*, ed. by A. Numaguti, S. Sugata, M. Takahashi, T. Nakajima and A. Sumi, CGER's Supercomputer Monograph Report 3, pp. 1–48, Center for Global Environmental Research, National Institute for Environmental Studies.

Ohfuchi, W., H. Nakamura, M. K. Yoshioka, T. Enomoto, K. Takaya, X. Peng, S. Yamane, T. Nishimura, Y. Kurihara, and K. Ninomiya (2004): 10-km mesh meso-scale resolving simulations of the global atmosphere on the Earth Simulator—Preliminary outcomes of AFES (AGCM for the Earth Simulator). *J. Earth Simulator*, **1**, 8–34.

Pacanowski, R. C., and S. M. Griffies (1999): *The MOM3 Manual*. GFDL Ocean Group Technical Report 4, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, NJ.

Richter, I., S. K. Behera, Y. Masumoto, B. Taguchi, N. Komori, and T. Yamagata (2010): On the triggering of Benguela Niños: Remote equatorial versus local influences. *Geophys. Res. Lett.*, **37**, L20604, doi:10.1029/2010GL044461.

Risien, C. M. and D. B. Chelton (2008): A global climatology of surface wind and wind stress fields from eight years of QuikSCAT scatterometer data. *J. Phys. Oceanogr.*, **38** (11), 2379–2413, doi:10.1175/2008JPO3881.1.

Taguchi, B., H. Nakamura, M. Nonaka, N. Komori, A. Kuwano-Yoshida, K. Takaya, and A. Goto (2011): Seasonal evolutions of atmospheric response to decadal SST anomalies in the North Pacific subarctic frontal zone: Observations and a coupled model simulation. *J. Climate*, submitted.

Xie, P. and P. A. Arkin (1996): Analyses of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions. *J. Climate*, **9** (4), 840–858.

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5	Oscar Alves	CAWCR[*4]	Invited
6	Yongqiang Yu	IAP[*5]	Invited
7	Jing-Jia Luo	JAMSTEC[*6]	Invited
8	Masahide Kimoto	University of Tokyo	Invited
9	Yukio Masumoto	JAMSTEC	Presenter
10	Nobumasa Komori	JAMSTEC	Presenter
11	Shuhei Maeda	JMA/CPD[*7]	Presenter
12	Tamaki Yasuda	JMA/MRI[*8]	Presenter
13	Yousuke Fujii	JMA/MRI	Presenter
14	Masafumi Kamachi	JMA/MRI	Presenter
15	Yuhei Takaya	JMA/MRI	Presenter
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18	Akira Yoshida	JAMSTEC	Observer
19	Hiroaki Takebe	JAMSTEC	Observer
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