Asia-Pac. J. Atmos. Sci., 53(3), 393-401, 2017
DOI:10.1007/s13143-017-0035-2

pISSN 1976-7633 / eISSN 1976-7951

NOTES and CORRESPONDENCE

# Comparison of Extended Medium-Range Forecast Skill Between KMA Ensemble, Ocean Coupled Ensemble, and GloSea5

**Sangwook Park[1], Dong-Joon Kim[1], Seung-Woo Lee[1], Kie-Woung Lee[2], Jongkhun Kim[2], Eun-Ji Song[3], and Kyong-Hwan Seo[3]**

[1]*Numerical Model Development Division, Korea Meteorological Administration, Seoul, Korea*
[2]*Environment Prediction Research Inc., Seoul, Korea*
[3]*Departmet of Atmospheric Sciences, Division of Earth Environmental Systems, Pusan National University, Pusan, Korea*

(Manuscript received 1 February 2016; accepted 1 November 2016)
© The Korean Meteorological Society and Springer 2017

**Abstract:** This article describes a three way inter-comparison of forecast skill on an extended medium-range time scale using the Korea Meteorological Administration (KMA) operational ensemble numerical weather prediction (NWP) systems (i.e., atmosphere-only global ensemble prediction system (EPSG) and ocean-atmosphere coupledEPSG) and KMA operational seasonal prediction system, the Global Seasonal forecast system version 5 (GloSea5). The main motivation is to investigate whether the ensemble NWP system can provide advantage over the existing seasonal prediction system for the extended medium-range forecast (30 days) even with putting extra resources in extended integration or coupling with ocean with NWP system. Two types of evaluation statistics are examined: the basic verification statistics - the anomaly correlation and RMSE of 500-hPa geopotential height and 1.5-meter surface temperature for the global and East Asia area, and the other is the Real-time Multivariate Madden and Julian Oscillation (MJO) indices (RMM1 and RMM2) - which is used to examine the MJO prediction skill. The MJO is regarded as a main source of forecast skill in the tropics linked to the mid-latitude weather on monthly time scale. Under limited number of experiment cases, the coupled NWP extends the forecast skill of the NWP by a few more days, and thereafter such forecast skill is overtaken by that of the seasonal prediction system. At present stage, it seems there is little gain from the coupled NWP even though more resources are put into it. Considering this, the best combination of numerical product guidance for operational forecasters for an extended medium-range is extension of the forecast lead time of the current ensemble NWP (EPSG) up to 20 days and use of the seasonal prediction system (GloSea5) forecast thereafter, though there exists a matter of consistency between the two systems.

**Key words:** Extended medium-range forecast, ensembles, seasonal prediction, MJO

## 1. Introduction

There is growing interest in the area of seamless prediction filling the gap between medium-range numerical weather prediction (NWP) up to 10 days and seasonal long-range forecast. However, this is a difficult time range, since the time scale is sufficiently long so that much of the memory of the atmosphere initial conditions is lost, and it is probably too short for the variability of the ocean to be large enough, which makes it difficult to beat persistence (Vitart, 2013). The forecast skill of this sub-seasonal or extended medium-range (from 10 days to 30 days) is explored by many research institutes and operational organizations (Brunet et al., 2010; Vitart, 2013; Vitart et al., 2014). At the European Center for Medium-range Weather Forecast (ECMWF), an experimental monthly forecasting system was set up in 2002 and ran routinely every 2 weeks from March 2002 to October 2004. This system became operational in October 2004 and was merged to the ECMWF Ensemble Prediction System in 2008 (Vitart, 2013).

The demand from operational forecaster about the current reliability of the extended medium-range NWP is the main motive of this investigation. The ensemble prediction system is considered to be a proper tool for the forecast guidance of this range. To meet the demand, a three way inter-comparison is prepared. The first one is simply extending integration of the Korea Meteorological Administration (KMA) operational global ensemble prediction system (EPSG) up to 30 days. The second one is a coupling of ocean and sea ice module to EPSG and integration up to 30 days (Coupled-EPSG). The third is to use the first 30 days of integration results out of seven months prediction output from the KMA operational seasonal prediction system, Global Seasonal forecast system version 5 (GloSea5; Won et al., 2015).

Recent studies have shown that the potential source of forecast skill for this time range can be improved through better representation of Madden Julian Oscillation (MJO; Madden and Julian, 1971; Ferranti et al., 1990; Wheeler and Hendon, 2004), and coupling with ocean-sea ice-land modules (Vitart et al., 2014; MacLachlan, 2015). The feedback from those coupled modules to atmosphere in this relatively short period can be positive or negative on this time scale. Although it is difficult to diagnose explicitly the cause and effect of the coupled module (ocean, sea ice, and land surface conditions) on forecast skill, it is worth to investigate quantitatively how those three approaches differ in forecast skill. If the forecast skill of the GloSea5 is similar to the first or the second approach mentioned above, there is little reason to invest

---

Corresponding Author: Sangwook Park, Numerical Model Development Division, Korea Meteorological Administration, 61 Yeouidaebang-ro 16-gil, Dongjak-gu, Seoul 07062, Korea.
E-mail: swpark@kma.go.kr

additional expenses from the perspective of operational center.

The goal of the present study is to examine the forecast skill of three extended medium-range forecast outputs. Section 2 introduces a brief description of EPSG, Coupled-EPSG, and GloSea5. Section 3 describes experimental design and the data for statistical evaluation including MJO indices. Section 4 shows the forecast skill of three approaches. The concluding remarks are given in section 5.

## 2. Model description

### *a. Global ensemble prediction system: EPSG*

The KMA global ensemble prediction system (EPSG) which is based on Unified Model (UM) from the United Kingdom (UK) Met Office has been operated since March 2011. EPSG runs twice a day (0000 and 1200 UTC) up to 12 days to provide guidance for weekly forecast. The spatial resolution is N320L70 (~40 km horizontally and 70 vertical levels up to 80 km) and the ensemble size is 24 members: one for control and 23 perturbed members per running. The Ensemble Transform Kalman Filter (ETKF) is adopted for the generation of initial perturbation. To represent the effects of structural and sub-grid-scale model uncertainties, two stochastic physics schemes are included. One is the Stochastic Kinetic Energy Backscatter (SKEB) which is to backscatter into the forecast model some of the energy excessively dissipated by it at scales near the truncation limit (Shutts, 2005). Another is the Random Parameters (RP) scheme which represents the structural error due to approximations in parameterization (Arribas, 2004). The SST perturbation generated by Ensemble Transformed Kalman Filter (ETKF) is also employed to portray uncertainties of the surface boundary condition. The initial fields of the control member is reconfigured (interpolation of fields between different grid resolution systems) from the operational deterministic global forecast model (GDAPS) which has spatial resolution of N512L70 (~25 km horizontally).

The lead time for prediction is extended up to 30 days with the same configuration of EPSG for this experiment. The computational wall clock time of an EPSG single ensemble member is about five hours for 30-day integration with 648 CPUs in the KMA's third phase supercomputer CRAY XE6.

### *b. Coupled global ensemble prediction system: Coupled-EPSG*

The European ocean circulation and sea ice community model Nucleus for European Modeling of the Ocean (NEMO)/ The Los Alamos Sea Ice Model (CICE; Hunke and Lipscomb, 2010) (ORCA-025; tri-polar grid with 1/4 degree spacing near equator and 75 vertical levels in depth; Madec, 2008) is coupled to EPSG using the OASIS (Name of ocean-atmosphere coupler developed in European Center for Research and Advanced Training in Scientific Computing) (Valcke, 2006) coupler (Coupled EPSG). The coupling configuration is adopted from GloSea5 (See section 2.c for description of GloSea5.) except for the atmospheric model resolution and the number of ensemble members. The schematic diagram of coupling procedure is shown in Fig. 1 (Modified from Hewitt et al., 2011 Fig. 3). The remapping of exchange variables between atmospheric regular grid and ocean and sea ice tri-polar grid in the OASIS coupler is done by the bilinear and first order or second order conservation methods (See Table 1).

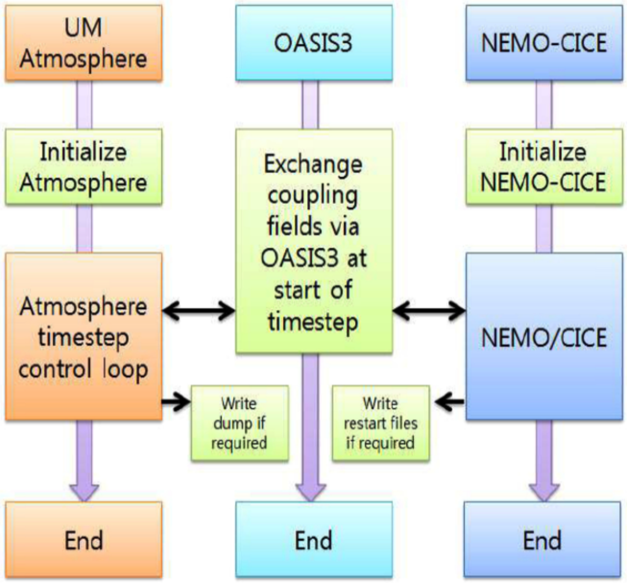

**Fig. 1.** Schematic process flow diagram of Coupled-EPSG and GloSea5 (Modified from Fig. 3 of Hewitt et al., 2011).

**Table 1.** Remapping methods used in the OASIS coupler between UM and NEMO/CICE.

| Remapping | | Method |
|---|---|---|
| Source | Destination | |
| UM T points | NEMO T points | First order conservative |
| UM U, V points | NEMO U, V points | Bilinear |
| NEMO T points | UM T points | Second order conservative |
| NEMO U, V points | UM U, V points | Bilinear |

The NEMO/CICE initial fields are provided from the UK Met Office twice per day at 0000 and 1200 UTC analysis time. The integration time step of EPSG is 12 minutes and that of NEMO/CICE is 20 minutes. The flux exchange interval between ocean and atmosphere is set to three hours. The computational wall clock time of a Coupled-EPSG single ensemble member is about 4.5 hours for 30 days integration with 1296 CPUs for UM, 576 CPUs for NEMO/CICE, and 12 CPUs for OASIS in the KMA's third phase supercomputer CRAY XE6. Coupled-EPSG requires about three times more CPUs than EPSG for similar computational wall clock time.

### *c. Seasonal prediction system: GloSea5*

The UK Met Office Global Seasonal forecast system version

**Table 2.** Summery table of EPSG, Coupled-EPSG, and GloSea5 setups.

| | EPSG | Coupled-EPSG | GloSea5 |
|---|---|---|---|
| atmospheric model | Unified Model | Unified Model | Unified Model |
| atmospheric model resolution | N320L70 (~40 km, 70 levels) | N320L70 (~40 km, 70 levels) | N216L85 (~60 km, 85 levels) |
| ocean model | N/A | NEMO/CICE | NEMO/CICE |
| ocean model resolution | N/A | 1/4 degree near equator, 75 levels | 1/4 degree near equator, 75 levels |
| ensemble generation method | ETKF & SKEB-II, RP, SST | ETKF & SKEB-II, RP, SST | Time-lagged ensemble & SKEB-II |
| ensemble size | 24 | 24 | 28 (14 from monthly + 14 from seasonal forecast) |

5 (GloSea5; MacLachlan et al., 2015) has been employed in KMA since January 2014 as the operational seasonal prediction system. The GloSea5 is a coupled model with components of atmosphere, ocean, land surface, and sea ice. The atmospheric model (UM) has spatial resolution of (~60 km horizontally and 85 vertical levels) which is coarser than Coupled-EPSG. The ocean, land surface, and sea ice model configuration is same as Coupled-EPSG which is described in section 2b. The initial fields of the control member are reconfigured from GDAPS as in EPSG and Coupled-EPSG.

There are two types of long-range forecast with GloSea5. One is monthly (60 days) forecast from the most recent previous seven days 14 time lagged ensemble members (two members per day). The other is seasonal (seven months) forecast from the most recent three weeks 42 time lagged ensemble members (two members per day). A 14-year hindcast set (from 1996 to 2009) for a given initialization date (1st, 9th, 17th, 25th day of each month) is also completed in a forecast run. The same hindcast is used to perform a bias correction of seasonal forecast products.

The computational wall clock time of the GloSea5 single ensemble member is about 2.5 hours for 30 days integration with 1296 CPUs for UM, 576 CPUs for NEMO/CICE, and 12 CPUs for OASIS in the KMA's third phase supercomputer CRAY XE6. The different setups of EPSG, Coupled-EPSG, and GloSea5 are summarized in Table 2.

## 3. Experiment design and evaluation methods

Upon available computing resources at KMA, EPSG and Coupled-EPSG start on every Mondays and run four ensemble members each day completing 24 ensemble members within six days. If there are no technical problems, four or five complete simulation sets per month are produced. The experiment period is from Jan. 2015 to Oct. 2015. The actual number of simulation sets which are used for this forecast skill inter-comparison was 29. The missing ensemble members from each simulation were simply omitted from ensemble averaging processes. The main cause of missing is mainly related to numerical instability (blow-up) and file system failure in hardware system. The ensemble mean value from 24 members of interest variables are used for evaluation statistics of EPSG and Coupled-EPSG while GloSea5 uses the ensemble mean of 28 members (from the recent previous seven days: two members per day from monthly forecast plus two members from seasonal forecast ).

Two types of evaluation statistics are examined.

- Basic verification statistics: the RMSE and the anomaly correlation of 500-hPa geopotential height and 1.5-meter surface temperature for global region (0°~360°E, 60°S~60°N) and the East Asia (110°E~160°E, 25°N~50°N)
- The Real-time Multivariate MJO indices (RMM1 and RMM2; Wheeler and Hendon, 2004): combined empirical orthogonal function analysis of anomalies of National Oceanic and Atmospheric Administration (NOAA) outgoing long-wave radiation (OLR) and 850-hPa and 200-hPa zonal winds averaged over the tropical latitudinal band of 15°S~15°N

The National Center for Environment Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis Data (NCEP-R1; Kalnay et al., 1996; Kistler et al., 2001) are used as a validation analysis and the NCEP-R1 climatology (1979~2010) data are used for the calculation of anomaly.

## 4. Inter-comparison of forecast skill

Annually averaged anomaly correlations of 500-hPa geopotential height of three systems and the persistence of initial condition for the global and East Asia areas are shown in Fig. 2a. All three systems exhibit skillful forecast over persistence. If we use a correlation of 0.5 as a cutoff skill measure, EPSG and Coupled-EPSG have about one and half day more skill than GloSea5. It shows little difference in correlation skill between EPSG and Coupled-EPSG. GloSea5 shows some signal that it might provide better prediction skill after 20 days although the correlation is below 0.2. The 2015 annual verification report of KMA showed that the annual average of anomaly correlation of GDAPS 12-day forecast of 850 hPa temperature for the northern hemisphere was 0.26 (no surface temperature verification in WMO standards). The anomaly correlation of surface temperature is expected to be lower than that of 850 hPa. As the anomaly correlation of persistence stays 0.2~0.3 range, the skill of surface temperature forecast from NWP is below persistence. It is not rare that the model forecast skill for higher lead times is less than that of persistence since the model has a poor performance at these lead

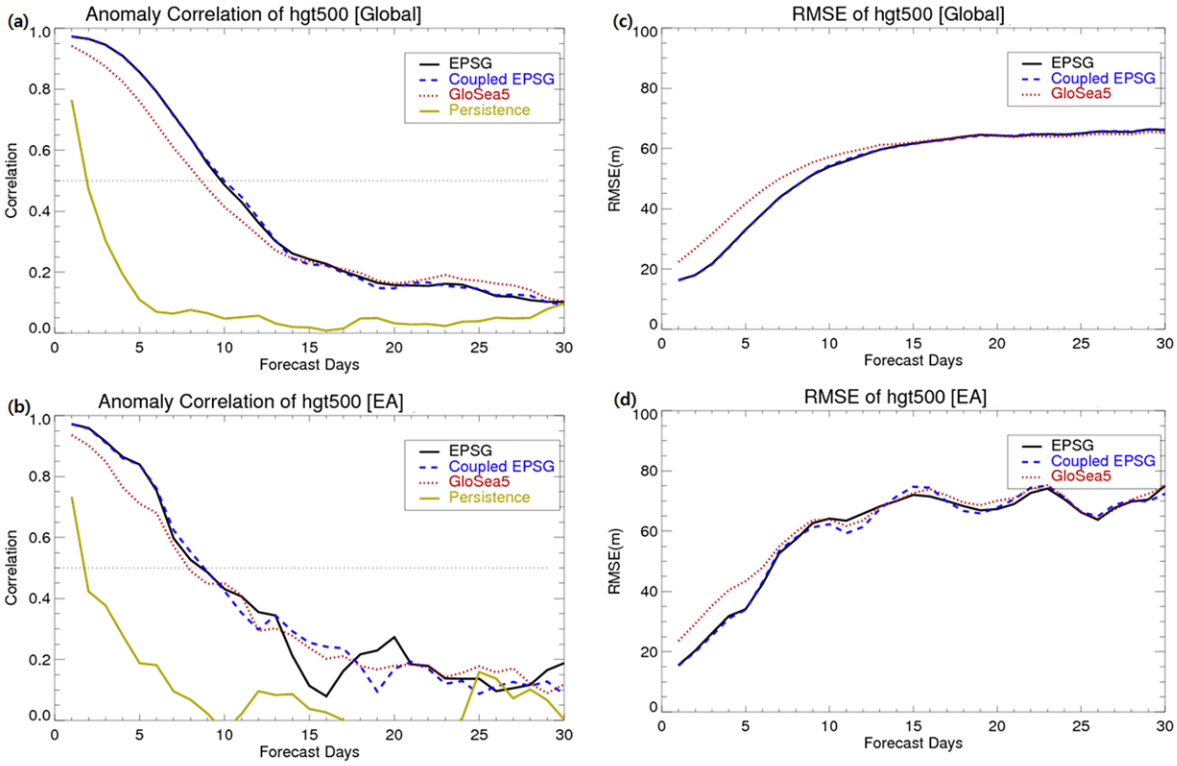

**Fig. 2.** Annually averaged anomaly correlation [(a) global, (b) East Asia] and RMSE [(c) global, (d) East Asia] of 500-hPa geopotential height for EPSG, Coupled-EPSG, GloSea5, and Persistence of initial condition as a function of lead time.

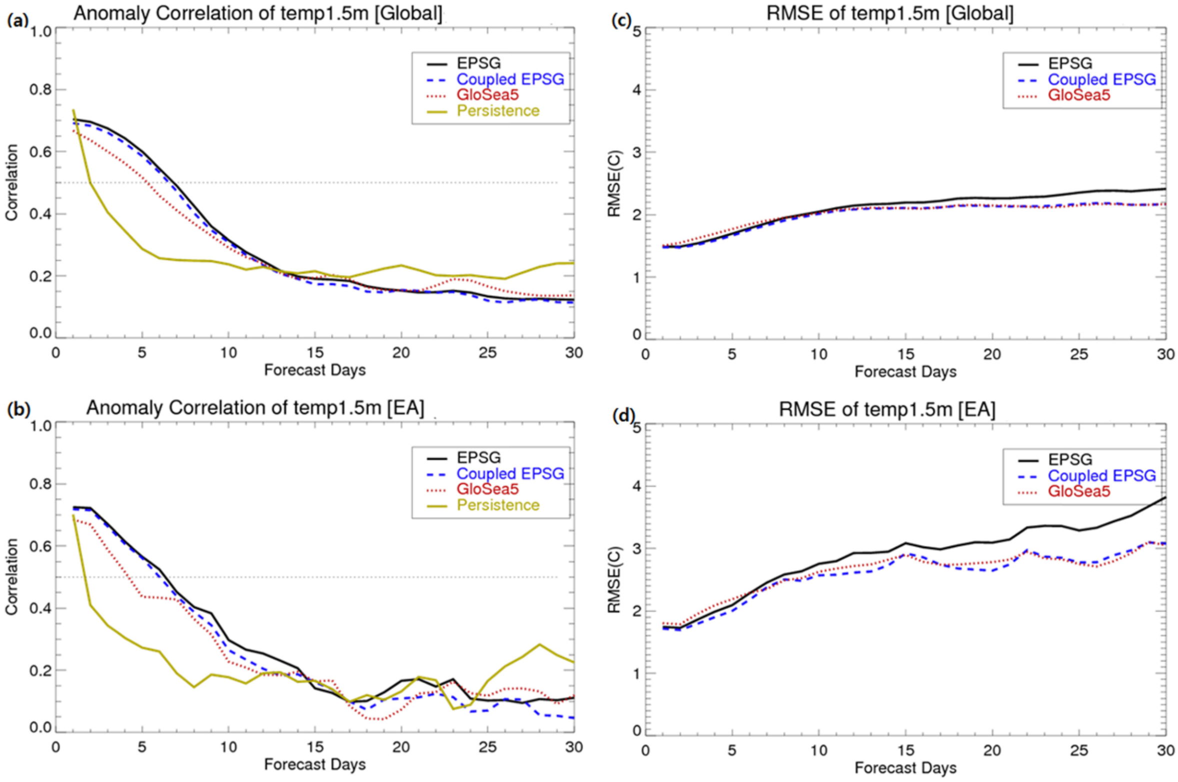

**Fig. 3.** Annually averaged anomaly correlation [(a) global, (b) East Asia] and RMSE [(c) global, (d) East Asia] of 1.5-meter surface temperature for EPSG, Coupled-EPSG, GloSea5, and persistence as a function of lead time.

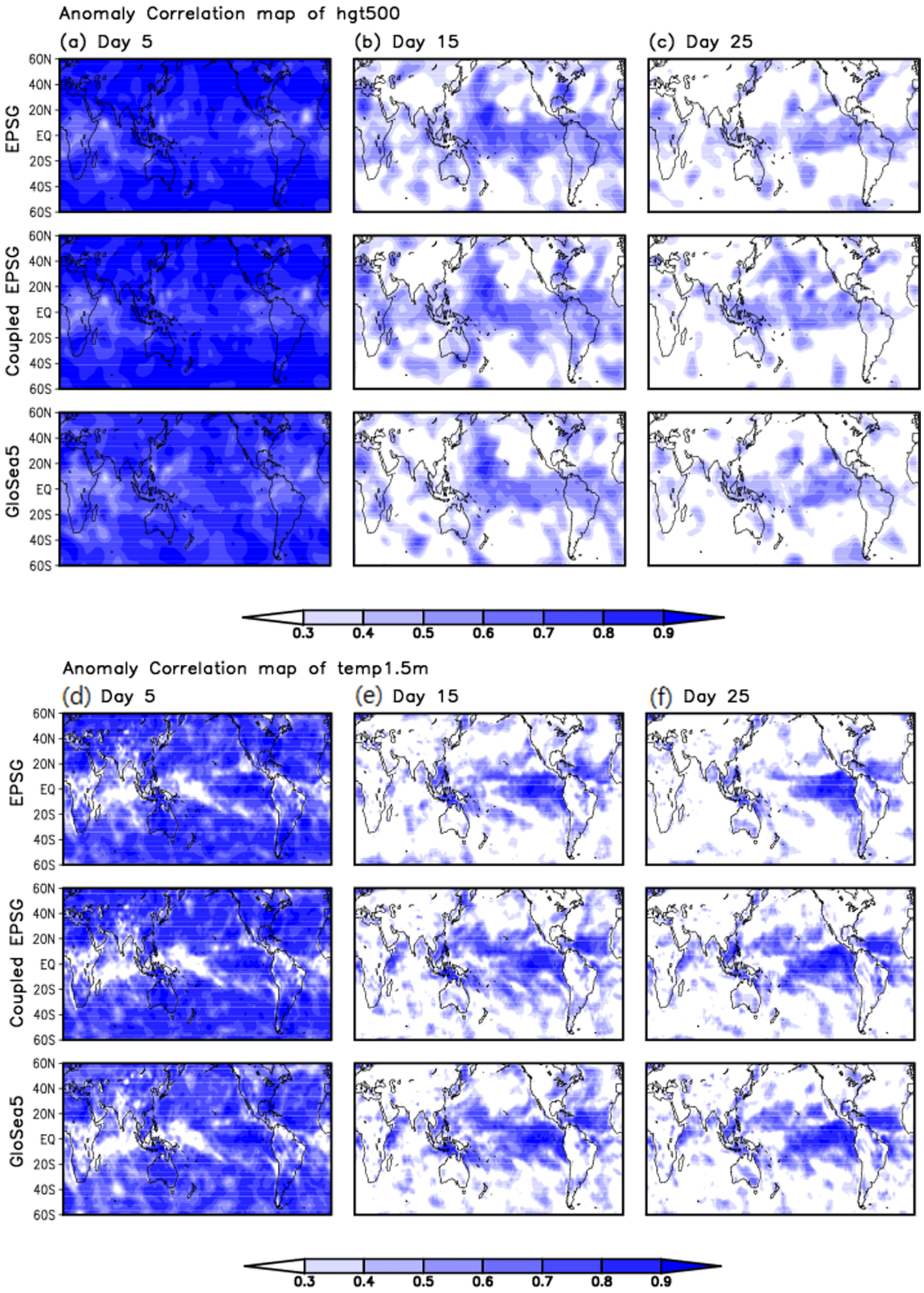

**Fig. 4.** Annually averaged spatial map of anomaly correlation of 500-hPa geopotential height [(a) 5, (b) 15, and (c) 25 days of prediction] and 1.5-meter surface temperature [(d) 5, (e) 15, and (f) 25 days of prediction] for EPSG, Coupled-EPSG, and GloSea5.

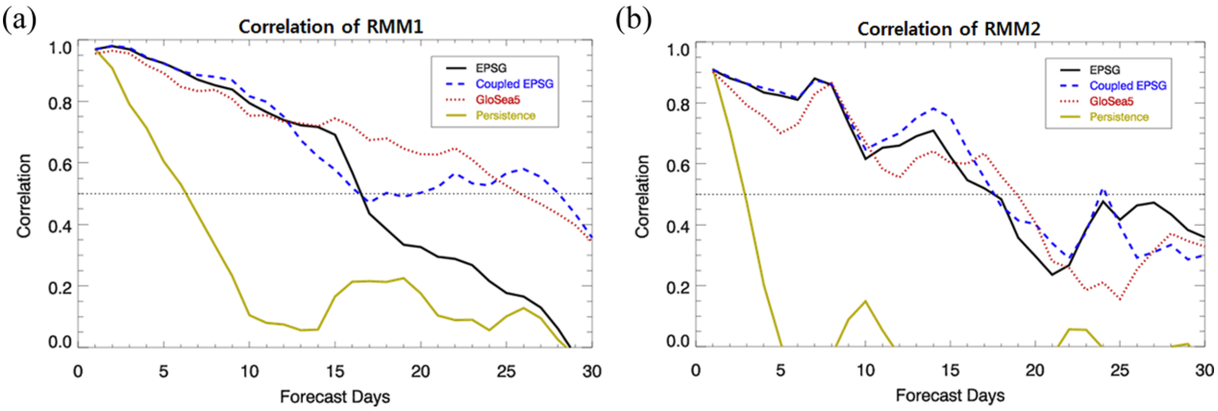

**Fig. 5.** Annually averaged correlation of EPSG, Coupled-EPSG, GloSea5, and persistent for (a) RMM1 and (b) RMM2 as a function of lead time.

times. When we examine the East Asian domain, there is a similar tendency except that the cutoff correlation skill is met earlier than that of the global domain. The RMSE of EPSG and Coupled-EPSG is smaller than that of GloSea5 up to the 14-days prediction and similar to a tendency of saturation (Fig. 2b).

Annually averaged anomaly correlation of 1.5-meter surface temperature of three systems and persistence of initial condition for the global and East Asian regions are shown in Fig. 3a. After 12 days, skills of all three systems are exhibited below the persistence. The anomaly correlation skill is below the skill measure to five days in GloSea5, and six to seven days in EPSG and Coupled-EPSG. These skill score is four to five days shorter than the middle atmosphere geopotential height case. A slightly lower correlation of Coupled-EPSG compared to EPSG seems persistent throughout the 30 days prediction. The RMSE of EPSG and Coupled-EPSG (Fig. 3b) is smaller than that of GloSea5 up to ten days, and thereafter Coupled-EPSG and GloSea5 show smaller error than EPSG. In the East Asia domain, the RMSE differences between the ocean coupled system and the atmosphere-only system becomes larger after the 20 days of prediction.

Figures 4a, b, c shows the annually averaged spatial map of anomaly correlation of 500-hPa geopotential height after 5, 15, and 25 days of prediction. GloSea5 shows less correlation skill than the other two in both high and low latitudinal areas in the five-days prediction while there is little difference among the three after 15 days. Relatively higher correlation appears in the tropics than at mid-latitudes in extended periods (More specifically, the AC of EPSG in the area of tropical East Indian and Atlantic oceans is higher than the ocean coupled systems, however, the AC in the area of tropical Maritime Continent and western Pacific is shown higher from the ocean coupled systems.). The annually averaged spatial map of anomaly correlation of 1.5-meter temperature (Figs. 4d, e, f) clearly shows that the large portion of forecast skill after 15 days comes from tropical ocean area around the globe. The low anomaly correlation of the surface temperature in tropical oceans within five-days time scale may caused from rather rapid changes in sea surface temperature in respond to the rainfall in convectively active region - mainly tropical Indian ocean and western Pacific ocean warm pool area. The higher correlation in sub-tropics of the western Indian Ocean and western North Pacific in Coupled-EPSG and GloSea5 implies the advantage of ocean coupled system compared to the atmosphere only EPSG system in a monthly-range prediction. However, it should be cautious that the correlation of EPSG is higher in the tropical western Pacific where deep convection occurs.

The MJO is considered to be a main source of forecast skill in the tropics on monthly time scales (Madden and Julian, 1971; Seo et al., 2009; Kang and Kim, 2010; Vitart et al., 2014), which also links to mid-latitude weather and climate (e.g., Seo et al., 2012). The first (explaining about 17.5% variation) and second (explaining about 13.0% variation) modes of the combined Empirical Orthogonal Function (EOF) of the OLR and 850, and 200-hPa zonal winds over the tropical belt (RMM1 and RMM2; Wheeler and Hendon, 2004) are investigated for EPSG, Coupled-EPSG, and GloSea5. RMM1 (RMM2) is characterized by convection center located over the Maritime continent (the Western Pacific, respectively). The prediction skill of RMM1 and RMM2 is shown in Fig. 5. The annually averaged correlation of RMM1 decreases to below the cutoff skill (0.5) after day six for the persistence. It extends to day 16 for EPSG, day 26 for GloSea5, and day 28 for Coupled-EPSG (although the correlation dropped more quickly than the one with EPSG after day 12, and there is a short drop around day 16 below 0.5 and gain again over 0.5 up to day 28 in Coupled-EPSG). The correlation of RMM2 dropped faster than that of RMM1. The similar correlation skill up to 15 days implies that there is little impact of SST variation in those time scale from the ocean coupled systems. However, there is a clear signal of better forecast skill in the ocean coupled systems (Coupled-EPSG and GloSea5) for the second 15 days. As noticed in the higher anomaly correlation spatial pattern in the surface temperature on the tropical ocean area (the Indian and Pacific Ocean) in the coupled systems in Fig. 4, the ocean-

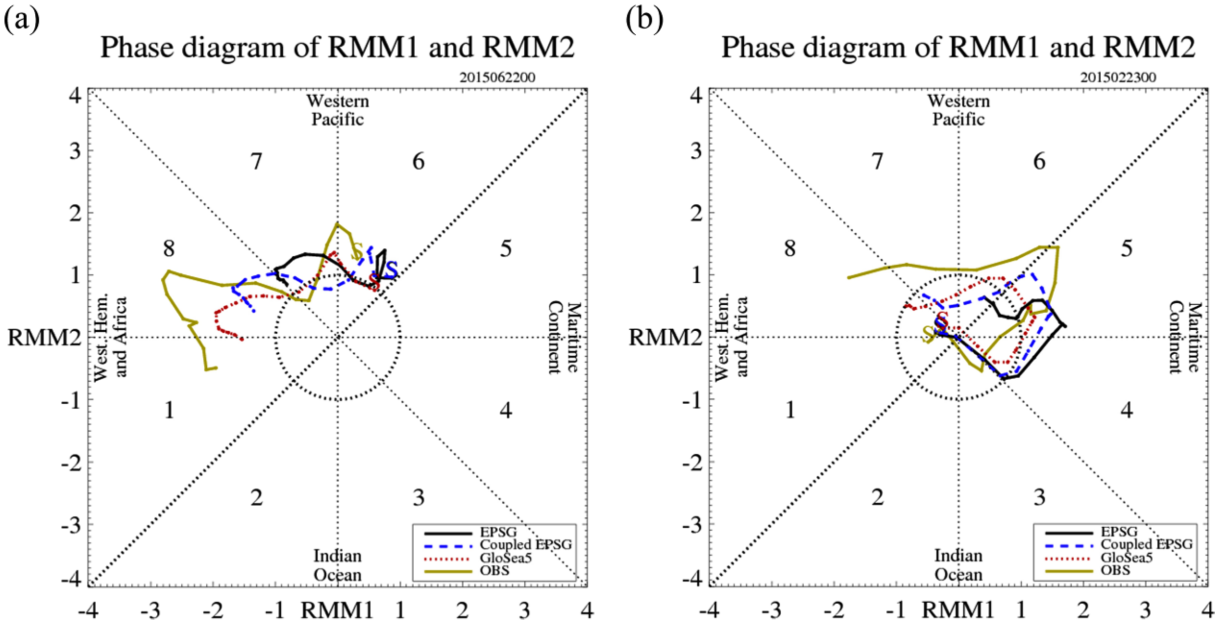

**Fig. 6.** Thirty day MJO forecast phase diagram for EPSG, Coupled-EPSG, and GloSea5 with initial day of (a) 22 Jun, 2015 and (b) 23 Feb, 2015. Eight defined regions of the phase space are labeled, and the inner circle region is considered to signify weak MJO activity. Also labeled are the approximate locations of the enhanced convective signal of the MJO for that location of the phase space, e.g., the "Indian Ocean" for phases 2 and 3 (Wheeler and Hendon, 2004).

atmosphere coupling process plays an important role in the week three or four MJO forecast skill.

An example of actual MJO 30-day RMM1 and RMM2 forecast for EPSG, Coupled-EPSG, and GloSea5 against observation is presented in Fig. 6a (for the northern summer case) and Fig. 6b (for the northern winter case). The MJO forecast phase diagram demonstrates the speed of the convectively active phase (wet condition) movement and its amplitude (larger amplitude with longer distance from the center point of the diagram). The summer case (22 Jun, 2015 initial date) starts at boundary between phases 5 and 6 (between the Maritime Continent and western North Pacific) and traces counter-clockwise (eastward propagation) with a sequential 30 days forecast ending between phase 8 and 1 (the Western Hemisphere and Africa). The dynamic general circulation model prediction of MJO phase speed and amplitude is generally known slower and weaker than the observed. The three systems of our experiment are no exception. However, there is deviation in the performance of systems. The GloSea5 shows better forecast skill than the other two in terms of phase speed and amplitude. EPSG phase speed is slow (thus, it is about two thirds of the observed one) and weaker in amplitude. Coupled-EPSG prediction is better than EPSG but still slower than GloSea5. The corresponding location of high amplitude occurrence (in between phases 6 and 7, and at phase 8) matches well with GloSea5 prediction though the amplitude is smaller than the observed. The winter case (23 Feb, 2015 initial date; Fig. 6b) shows much faster movement of the MJO comparing to the summer case - almost double the speed with the convective center moving from phase 1 to phase 8 areas within 30 days. Similar to the summer case, GloSea5 has better forecast skill than the other two in terms of phase speed and amplitude. Though relatively strong MJO activity was observed in the western Pacific (phases 6 and 7), prediction from all three systems remained weak.

## 5. Concluding remarks

This study describes a three way inter-comparison of forecast skill on extended medium-range forecast using the KMA operational ensemble NWP systems (atmosphere-only: EPSG, ocean-atmosphere coupled: Coupled-EPSG) and the KMA operational seasonal prediction system GloSea5. The main motive is to investigate whether the ensemble NWP system can provide advantage over the current seasonal prediction system for the extended medium-range forecast after extra resources are invested in extended integration or coupling with ocean with NWP system.

The error statistics (anomaly correlation and RMSE) of 500 hPa geopotential height and 1.5-meter surface temperature shows that there is little difference up to 10~12 forecast days between EPSG and Coupled-EPSG while GloSea5 shows less correlation and larger RMSE than the other two. However, this tendency changes in week three and four forecast. Although it is difficult to distinguish prediction skill of three systems from the anomaly correlation after two weeks, the lower RMSE of 1.5 meter surface temperature in the ocean coupled system is clear. And the ocean coupled systems gain better spatial correlation in subtropical ocean area than the atmosphere-only system in the second half of monthly forecast. One of the possible reasons behind this forecast skill reverse may lie in the differently tuned physics parameters between NWP system and seasonal prediction system depending on their forecast lead time, and the time-lagged ensemble member construction of GloSea5 may degrade the forecast skill of initial two weeks. The NWP systems (EPSG and Coupled-EPSG) are optimized on several days of weather phenomena while the seasonal prediction system (GloSea5) is optimized on atmosphere and ocean coupled variation of several months.

The MJO prediction of GloSea5 and Coupled-EPSG shows better skill than that of EPSG. The correlation of RMM1 decreases to below a cutoff skill after day six for the persistence of initial condition, day 16 for EPSG, day 26 for GloSea5, and day 28 for Coupled-EPSG. The dynamical variation of SST in tropical ocean seems to have little impact up to the two week time scale, but the atmosphere-ocean coupled process begins to play an important role after two weeks in MJO prediction. GloSea5 performs best in the MJO phase speed and amplitude when the actual 30-days forecast of RMM1 and RMM2 in the MJO phase space is examined.

The present work started with a curiosity about how the NWP, the coupled NWP, and the seasonal prediction system differ in forecast skill on monthly time scale. The coupled NWP tends to extend the forecast skill of the NWP by a few more days and such forecast skill is overtaken by that of the seasonal prediction system thereafter. In lieu of this fact, it seems that there is little gain from the coupled NWP even after investing more than double the resources. However, authors of this study assume that there are some areas for further research regarding the coupled NWP system which can improve extended medium-range forecast skill by adopting atmosphere and ocean coupled data assimilation for initial condition if large portion of this period prediction is matter of initial value problem. As a demonstration analysis/forecast project, research continues on assessing the benefits of ocean-atmosphere interactions on NWP forecast skill, with current results showing improvement in the Tropics (Shelley et al., 2014).

In addition, by employing the method of giving weight on averaging process over each ensemble members to make ensemble mean (simply averaged in this study), the forecast skill can be improved. The ensemble member clustering method is newly adopted in operational centers like ECMWF to summarize large amount of information from EPS (Ferranti and Corti, 2011). The clustering can give us an overview of different synoptic flow patterns. The major cluster pattern can be identified by categorizing abundant ensemble members of similar flow pattern forecast. If we can group the ensemble members in this way, we can give different weight in different clusters in making ensemble mean value.

The best combination of numerical product guidance to operational forecasters for an extended medium-range is at the present stage the extension of the forecast lead time of the current ensemble NWP (EPSG) up to 20 days and the use of the seasonal prediction system (GloSea5) forecast thereafter, though there exists a matter of consistency between the two systems. If there is room for improving the forecast skill of GloSea5 in two to three weeks via increasing the horizontal resolution of the atmosphere from N216 to N320 (upcoming GloSea5 upgrade plan) and adjusting current physics configuration more directed to sub-seasonal range without degrading the seasonal performance, there would be little necessity of extending the current NWP's 12-day lead forecast time.

***Acknowledgements.*** The authors thank to the operational model management team, the global ensemble forecast team, and the long-range forecast team of Numerical Model Development Division and Supercomputing Center of KMA for providing resources and exchanging their opinions. Thanks also go to Dr. D. K. Lee for his comments on the manuscript. We are grateful to the reviewer's helpful suggestions contribute towards improving this paper. This work was supported by the KMA information infrastructure improvement fund. KHS was supported by the National Research Foundation of Korea (NRF) grants funded by the Korea government (MISP) (No. NRF-2015R1A2A2A01006663).

**Edited by:** Chun-Chieh Wu

## References

Arribas, A., 2004: Results of an initial stochastic physics scheme for the Met Office Unified Model. Forecasting Research Technical Report No. 452, 26 pp.

Brunet, G., and Coauthors, 2010: Collaboration of the weather and climate communities to advance subseasonal to seasonal prediction. *Bull. Amer. Meteor. Soc.*, **91**, 1397-1406, doi:10.1175/2010BAMS3013.1.

Ferranti, L., T. N. Palmer, F. Molteni, and E. Klinker, 1990: Tropical-extratropical interaction associated with the 30-60 day oscillation and its impact on medium and extended range prediction. *J. Atmos. Sci.*, **47**, 2177-2199.

Ferranti, L., and S. Corti, 2011: New clustering products. *ECMWF Newsletter*, **127**, 6-11.

Hewitt, H. T., D. Copsey, I. D. Culverwell, C. M. Harris, R. S. R. Hill, A. B. Keen, A. J. McLaren, and E. C. Hunke, 2011: Design and implementation of the infrastructure of HadGEM3: The next-generation Met Office climate modelling system. *Geosci. Model Dev.*, **4**, 223-253, doi:10.5194/gmd-4-223-2011.

Hunke, E. C., and W. H. Lipscomb, 2010: CICE: the Los Alamos sea ice model, documentation and software user's manual, Version 4.1. Tech. Rep. LA-CC-06-012, 76 pp.

Kistler, R., and Coauthors, 2001: The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.*, **82**, 247-267.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.

Kang, I.-S., and H. M. Kim, 2010: Assessment of MJO predictability for boreal winter with various statistical and dynamical models. *J. Climate*, **23**, 2368-2378, doi:10.1175/2010JCLI3288.1.

MacLachlan, C., and Coauthors, 2015: Global Seasonal forecast system version 5 (GloSea5): A high-resolution seasonal forecast system. *Quart. J. Roy. Meteor. Soc.*, **141**, 1072-1084, doi:10.1002/qj.2396.

Madden, R. A., and P. R. Julian, 1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **5**, 702-708.

Madec, G., 2008: NEMO reference manual, ocean dynamics components. note du Pole 1619, 217 pp.

Seo, K.-H., and S.-W. Son, 2012: The global atmospheric circulation response to tropical diabatic heating associated with the Madden-Julian oscillation during northern winter. *J. Atmos. Sci.*, **69**, 79-96, doi: 10.1175/2011JAS3686.1.

Seo, K.-H., W. Wang, J. Gottschalck, Q. Zhang, J.-K. E. Schemm, W. R. Higgins, and A. Kumar, 2009: Evaluation of MJO forecast skill from several statistical and dynamical forecast models. *J. Climate,* **22**, 2372-2388.

Shelly, A., P. Xavier, D. Copsey, T. Johns, J. M. Rodríguez, S. Milton, and N. Klingaman, 2014: Coupled versus uncoupled hindcast simulations of the Madden-Julian Oscillation in the Year of Tropical Convection. *Geophys. Res. Lett.*, **41**, 5670-5677, doi:10.1002/2013GL059062.

Shutts, G., 2005: A kinetic energy backscatter algorithm for use in ensemble prediction systems. *Quart. J. Roy. Meteor. Soc.*, **612**, 3079-3102.

Valcke, S., 2006: OASIS3 User Guide. PRISM-Support Initiative Report No. 3, 68 pp.

Vitart, F., 2013: Evolution of ECMWF sub-seasonal forecast skill scores over the past 10 years. ECMWF Technical Memorandum, No. 694, 28 pp.

______, G. Balsamo, R. Buizza, L. Ferranti, S. Keeley, L. Magnusson, F. Molteni, and A. Weisheimer, 2014: Sub-seasonal predictions. ECMWF Technical Memorandum, No. 738, 45 pp.

Wheeler, M. C., and H. H. Hendon, 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea. Rev.*, **132**, 1917-1932.

Won, D., Y. S. Lee, Y. H. Kang, and H. J. Ham, 2015: Operational system description of GloSea5 in KMA and verification result of 2014. KMA Technical Report, 2015-04, 142 pp.