Study of Cloud and Precipitation Processes Using a Global Cloud Resolving Model

Project Representative

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Numerical experiments using Nonhydrostatic Icosahedral Atmospheric Model (NICAM) with horizontal mesh sizes of 3.5 to 14 km are conducted to better understand cloud and precipitation processes on the Earth and to improve their treatment in climate models. Two topics from major achievements in the FY2014 are reported: (1) Mechanisms of the life cycles of the Madden-Julian Oscillation (MJO) events that occurred during the Cooperative Indian Ocean experiment on intraseasonal variability in the year 2011 (CINDY2011) / Dynamics of the Madden-Julian Oscillation (DYNAMO) were examined by initial date ensemble and sensitivity simulations. The results suggested significant roles of easterly anomalies and sea surface temperature (SST) distribution on the convective initiation and eastward propagation of the MJO through moisture modulations. (2) A prototype of subseasonal to seasonal forecast systems was constructed, where NICAM was forced by the SST predicted by a fully coupled general circulation model. Preliminary results of boreal summer 2014 simulations showed marked impacts of SST evolution on the convective activity over the warm pool region. Potential abilities and limitations of the new forecast system were examined.

Keywords: cloud and precipitation processes, global cloud-resolving model

1. Introduction

In this project, cloud and precipitation processes over the Earth have been investigated by numerical experiments using Nonhydrostatic Icosahedral Atmospheric Model (NICAM, Satoh et al. 2008[1]; 2014[2]; Tomita and Satoh 2004[3]). NICAM have been run on the Earth Simulator since its early developing stage by this group (e.g., Tomita et al. 2005[4]; Iga et al. 2007[5]; Miura et al. 2007[6]; Oouchi et al. 2009[7]; Noda et al. 2010[8]; Yamada et al. 2010[9]), and now widely run on various supercomputing systems (Miyamoto et al. 2013[10]; Miyakawa et al. 2014[11]; Nakano et al. 2015[12]). Our project have intensively dealt with case studies of field observations (Satoh et al. 2010[13], 2011[14], 2012[15], 2013[16], 2014[17]). On the basis of the accomplishments in previous years, a large number of sensitivity experiments have been executed in this year to understand mechanisms of large-scale tropical convective disturbances, such as genesis and development of the Madden-Julian Oscillation (MJO; Madden and Julian 1971[18], 1972[19]) and tropical cyclones. Two highlight topics are reported in the following sections. Major focuses were on the convective responses to sea surface temperature (SST) at subseasonal to seasonal time scale.

2. MJO initiation and regulation during the CINDY2011/DYNAMO

The MJO is a major tropical disturbance characterized by intraseasonal (30–60 day) periodicity and large-scale convective organization with planetary scale (O[10,000 km]) dynamical structure, which propagate eastward over the warm pool region at ~5 m s^{-1}. The MJO draws special attention of modeling communities because of its broad impacts on world weather and climate (Zhang 2013[20]; Klingaman et al. 2015[21]). The convective onset of the MJO in the Indian Ocean is one of the most difficult tasks of MJO forecasting because of limited observations. Moreover, it is affected by stochastic processes including extratropical forcing (Hsu et al. 1990[22]; Nasuno et al. 2015[23]). An international field project, the Cooperative Indian Ocean experiment on intraseasonal variability in the year 2011 (CINDY2011) / Dynamics of the Madden-Julian Oscillation (DYNAMO) was conducted to understand the initiation process and dynamics of the MJO by intensive observations over the Indian Ocean and to improve the representation of the MJO in numerical models (Yoneyama et al. 2013[24]; http://www.jamstec.go.jp/iorgc/cindy/index_e.html).

In our project, simulations of the MJO events that occurred during the CINDY2011/DYNAMO have been conducted, and spontaneous initiation of MJO in the 14-km and 7-km mesh NICAM have been obtained (Satoh et al. 2012[15], 2013[16], 2014[17]). Figure 1 shows a time-longitude section of the daily interpolated observed outgoing longwave radiation (OLR) by National Oceanic and Atmospheric Administraion (NOAA) during the CINDY2011/DYNAMO (October–November 2011) and related fields in National Centers for Environmental Prediction (NCEP) final analysis (NCEP_FNL). Initiation of large envelope of convection in middle October (MJO1) and middle November (MJO2) in the western Indian Ocean (~60°E) and eastward migration of the convection are clearly seen (Fig. 1a).

A number of theories on convective initiation and regulation

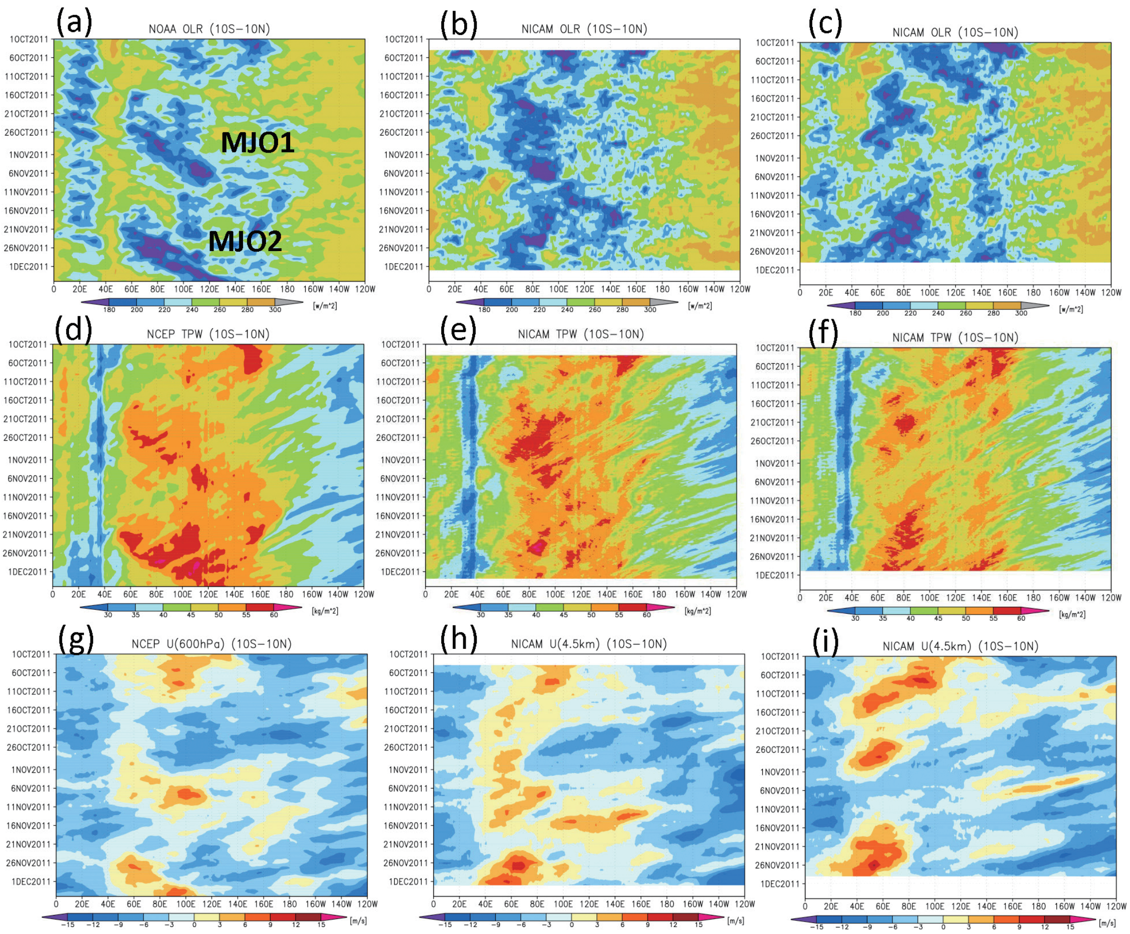

Fig. 1 Time-longitude section of (upper panels) outgoing longwave radiation (OLR), (middle panels) column integrated precipitable water, and (bottom panels) zonal velocity in the middle troposphere in the (left) observations (OLR from NOAA and precipitable water and zonal velocity from NCEP_FNL) and NICAM simulations which initialized on (center) 4 and (right) 1 October 2011, averaged in 10°N–10°S.

of MJO have been proposed, most of which regarded the accumulation of moisture as critical factor (e.g., Blade and Hartmann 1993[25]). In fact, both MJO1 and MJO2 were preceded by increase in the column integrated moisture over the broad Indian Ocean domain (Fig. 1d). Nasuno et al. (2015)[23], who analyzed European Center for Medium-range Weather Forecasting (ECMWF) Reanalyses (ERA)-Interim, found that easterly anomalies contributed to intraseasonal moistening through zonal advection, especially in the middle troposphere. The easterly acceleration in the middle troposphere (600 hPa) was evident even in the raw data (Fig. 1g), in good correspondence with the moisture increase (Fig. 1d).

In order to confirm the validity of the above described processes, two-month long ensemble simulations with varying the initial date (1, 2, 3, 4, and 5 October 2011) were conducted using NICAM with a 14-km horizontal grid size. Each run was initialized using NCEP_FNL (1.0° x 1.0°) at 0000 UTC. The SST was given by the surface temperature in NCEP_FNL. The simulation with the initial date on 4 October (Figs. 1b, e, and h) well captured the convective initiation and eastward propagation of the October MJO event (Fig. 1b). The convective initiation was preceded by significant moistening (Fig. 1e) and easterly acceleration in the middle troposphere (z = 4.5 km; Fig. 1h), although convective envelope was more stagnant in the Indian Ocean with delayed start of eastward migration by several days. A nuance of next MJO is seen in early December around 60°–80°E.

In the simulation initialized on 1 October (Figs. 1c, f, and i), the initial convective activity in the western Pacific spuriously intensified, and MJO signal corresponding to MJO1 or MJO2 did not appear (Fig. 1c). During October, less amount of moisture increase (Fig. 1f) with insignificant easterly acceleration in the middle troposphere (Fig. 1i) was obtained. Meanwhile, another signal of convective organization and moisture increase was formed several days earlier than MJO2 in the real atmosphere (Figs. 1a, c, d and f), which was again preceded by an easterly acceleration (Fig. 1i).

These results are supportive of the role of easterly acceleration in the middle troposphere to facilitate convective onset of MJO during the CINDY2011/DYNAMO. Nasuno et al. (2015)[23] discussed the origin of the easterly anomalies, showing possible contributions of extratropical wave activity. Further analysis is underway.

Another branch of ensemble simulations have been conducted to understand the impacts of SST distribution and its evolution on the regulation and eastward propagation of the MJO. The results suggest possible effects of seasonal evolution of SST on the MJO for the CINDY2011/DYNAMO cases (Miura et al. 2015[26]).

3. Development of a prototype seasonal to sub-seasonal forecast system

During the spring and early summer 2014, development of El Niño was predicted by operational centers and by a JAMSTEC seasonal prediction system based on the Scale Interaction Experiment-Frontier (SINTEX-F) fully coupled global ocean-atmosphere model (Luo et al. 2005[27]; Behera et al. 2013[28]; Doi et al. 2014[29]; http://www.jamstec.go.jp/frcgc/research/d1/iod/seasonal/outlook.html).

On the recognition that the seasonal march and inter-annual variation of the basin scale SST have significant impacts on the boreal summer intraseasonal oscillation (BSISO) / MJO, monsoon, and tropical cyclone activities, the effects of SST forcing on the atmospheric convection were examined by a series of 2–5-month long sensitivity simulations. In a branch of the sensitivity experiments, SST forcing from the SINTEX-F1 seasonal prediction was used, aiming development of a prototype of subseasonal to seasonal forecast system.

A schematic of the forecast system is given in Fig. 2. In this system, monthly mean SST anomalies obtained from seasonal forecasts by the SINTEX-F1 were used to force NICAM, instead of using the SST anomalies at the initial date (Miyakawa et al. 2014[11]; Nakano et al. 2015[12]). The SST anomalies were defined as a long-term (1983–2013 mean) climatology of NOAA Optimum Interpolation (OI) SST. The slab ocean model was not used in this prototype system currently.

In parallel to the development of full ocean-atmosphere coupled system, where NICAM is used for the atmospheric component (Oouchi et al., in this report), the approach proposed here is useful to understand air-sea interactions by extracting the atmospheric responses to the predicted SST anomalies in an one-way coupling framework (Fig. 2). By comparing the simulation results with observed and predicted SST forcing, one can estimate forecast errors originate from SST prediction errors and those from wrong atmospheric responses to the SST forcing. Thus, the new forecst system can serve as a stepping stone to constructing a fully coupled system.

The simulations of boreal summer (June–July) 2014 were

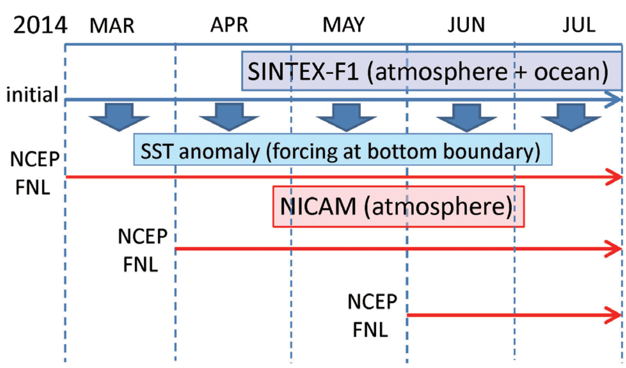

Fig. 2 A schematic of the new sub-seasonal to seasonal forecast system, where NICAM is forced by sea surface temperature (SST) predicted by SINTEX-F1.

initialized using NCEP_FNL on 1 March, 1 April, and 1 June for 5-, 4-, and 2-month simulations, respectively (Fig. 2), with monthly mean SST anomalies in observations (CTL), the SINTEX-F1 forecasts (SIN), and without anomalies (CLM) (Fig. 3). The SINTEX-F1 forecasts that initialized on 1 March were used in all the cases.

Figure 4 presents the observed and predicted distribution of SST anomalies in June and July 2014. Warm anomalies over the equatorial Eastern Pacific were evident in June, which had been developing from spring and were slightly weakened in July (Figs. 4a, b). Warm anomalies were also pronounced over the Western Pacific. Such warm tendency reduced the zonal SST contrast under an El Niño condition and was commonly observed during this decade. The ensemble-mean SST anomalies from the SINTEX-F1 forecasts among the nine members (Figs. 4c, d) captured the major features of the observed SST anomalies including the subtropical cold anomalies in the north Western and south Eastern Pacific, but with generally weaker amplitudes than those observed.

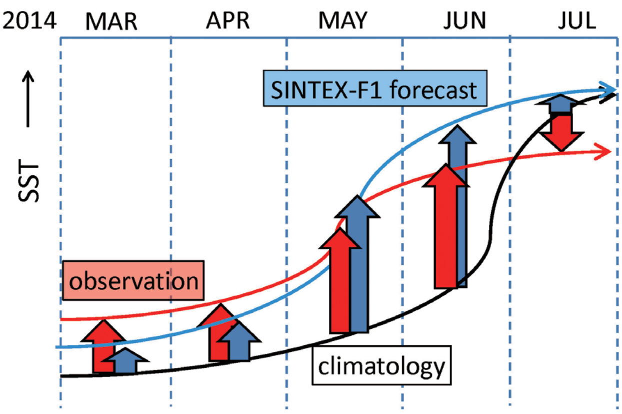

Fig. 3 A schematic of the seasonal evolution of SST observed (red) and predicted by SINTEX-F1 (blue) in 2014, and in a long-term climatology (black).

The impacts of the SST forcing on the convective behavior in the NICAM simulations were not dominant against other factors (e.g., initial conditions or model physics) during one-month forecasts (not shown). In the second month of integration, sensitivity of the simulated convective behavior to the SST forcing was more pronounced. Figure 5 compares the July mean precipitation in CTL, SIN, and CLM runs and that in the U. S. Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP). A precipitation peak corresponding to the warm anomalies in the equatorial Eastern Pacific was formed in the observation and CTL run (Figs. 5a, b). In the Western Pacific precipitation associated with boreal summer monsoon was very pronounced (Fig. 5a), presumably reflecting the warm SST anomalies in this region. This enhanced monsoonal convective activity in the Western Pacific was successfully simulated in CTL and SIN runs (Figs. 5b, c), but not in CLM (Fig. 5d). It is noteworthy that the warm anomalies in the Western Pacific were more pronounced in June than in July. Such time lag between SST anomalies and convective activities are suggestive of the relationship among cloud, radiation, and SST specific to this basin (Wang et al. 2005[30]).

As common deficiencies of the NICAM simulations, positive biases of precipitation over the central Pacific along the Equator and northward displacement of convective peaks associated with the Asian summer monsoon are seen (Figs. 5b–d).

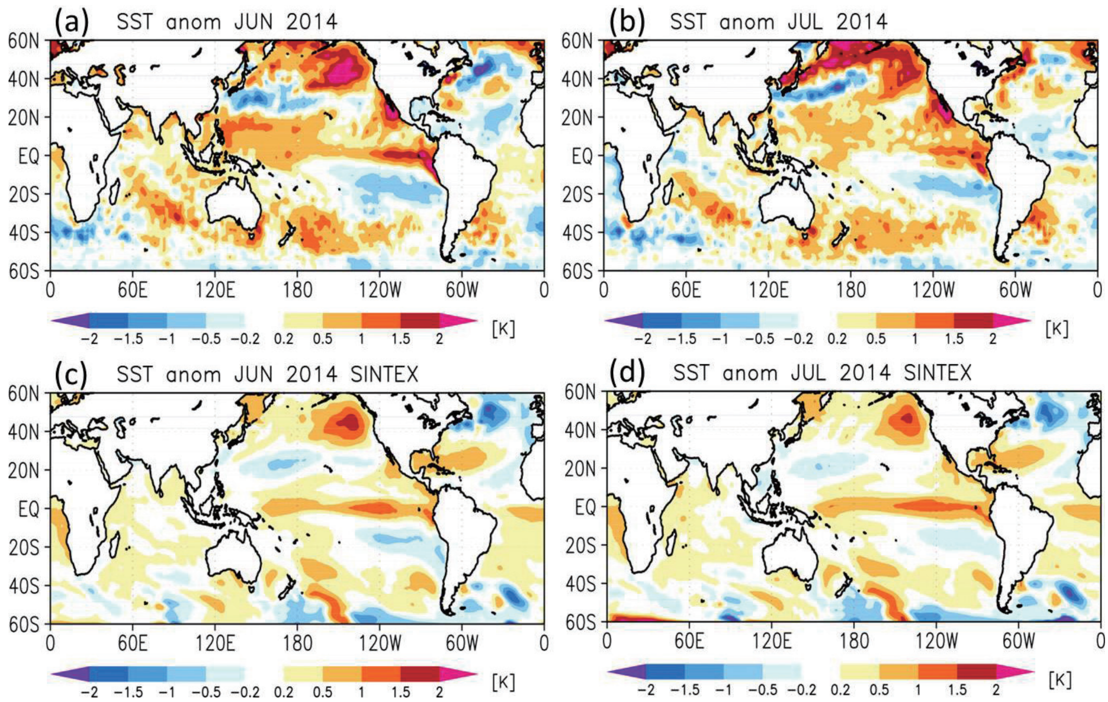

Fig. 4 Monthly mean SST in (a) (b) observation (NOAA OISST) and (c) (d) SINTEX-F1 forecasts (ensemble mean) for (a) (c) June and (b) (d) July 2014.

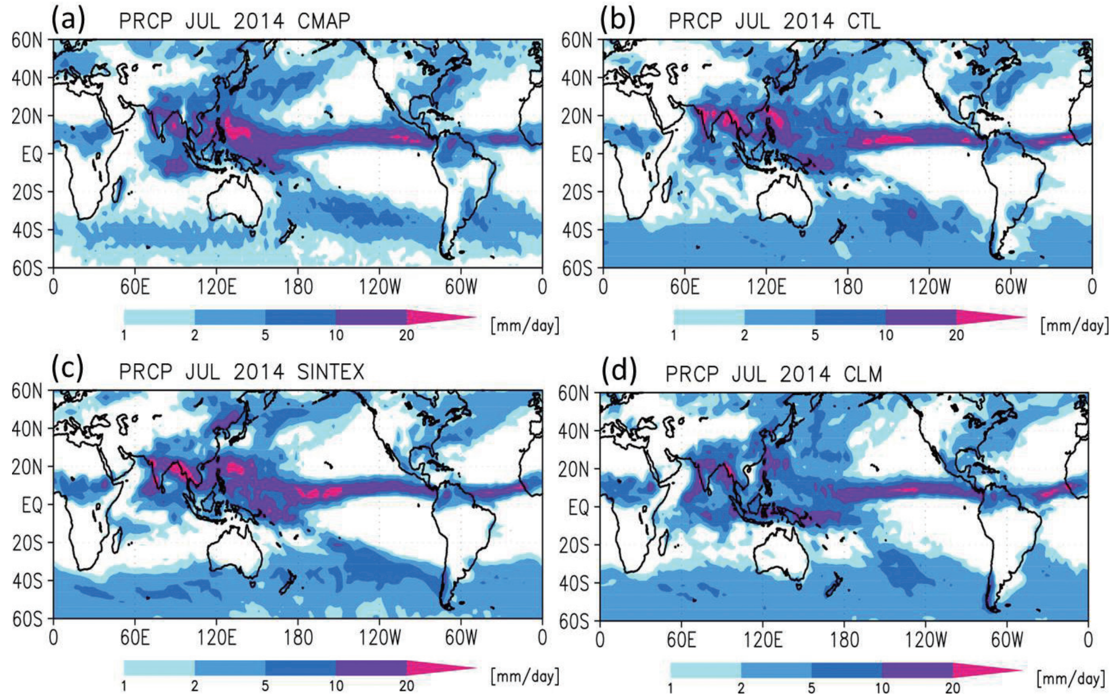

Fig. 5 Surface precipitation rate for July 2014 in (a) observation (CMAP), and 14-km mesh NICAM simulations (initialized on 1 Jun 2014) with SST forcing from (b) NCEP_FNL, (b) SINTEX-F1 forecasts (ensemble mean), and (d) a 30-year climatology (1983–2013).

Further investigations including the remote processes (e.g., teleconnection in response to the SST anomalies) and air-sea interactions are required to deepen our understanding and to improve the forecast system.

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全球雲解像モデルを用いた雲降水プロセス研究

課題責任者

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全球的な雲降水プロセスの理解を深め、それらの気候モデルにおける扱いを改善することを目的として、全球雲解像モデルによる数値計算を行う。2014 年度の主な成果のうち以下の 2 件について報告する。(1) 国際集中観測プロジェクト Cooperative Indian Ocean experiment on intreaseaonal variability in the year 2011 (CINDY2011) / Dynamics of the Madden-Julian Oscillation (DYNAMO) 期間に発生したマッデン・ジュリアン振動（MJO）を対象とする初期値アンサンブルおよび感度計算を行い、MJO の発生・発達のメカニズムについて調べた。その結果、東風偏差や海面水温分布が、水蒸気変動を通して MJO に伴う対流の開始や東進に影響を及ぼすことが分かった。(2) 全球雲解像モデルを海面水温の予測値（大気海洋結合モデルによる季節予測の結果）によって強制する新しい季節内～季節予測システムの原型を構築した。2014 年北半球夏季を対象とする予備計算では、暖水域の対流活動の海面水温に対する応答が顕著に見られた。新しいシステムの利用可能性や限界について検討を行う。

キーワード : 雲降水プロセス , 全球雲解像モデル