Study on the Predictability of Climate Variations and Their Mechanisms

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The SINTEX-Frontier coupled general circulation model version 1 (SINTEX-F1) has been developed under the EU-Japan collaborative framework to study the variability in global climate and its predictability. The seasonal prediction system on a basis of the SINTEX-F1 GCM has so far demonstrated high performance in predicting the occurrences of El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole Mode (IOD) events in the tropics. However, it is still very challenging to predict their teleconnections and the occurrences of subtropical climate variations such as the Indian Ocean Subtropical Dipole (IOSD) and the Atlantic Ocean Subtropical Dipole (AOSD) by the SINTEX-F1 seasonal prediction system.

In order to overcome those challenges in predictions, we successfully developed a new high-resolution SINTEX-F2 model, with sea ice processes, and implemented it on the Earth Simulator. Using results from a long-term simulation of the new model, we explored three topics in this fiscal year: 1) roles of tropical SST variations on the formation of the subtropical dipoles, 2) the influence of ENSO on the equatorial Atlantic precipitation through the Walker circulation, and 3) impacts of the equatorial Atlantic sea surface temperature on the tropical Pacific. Those outcomes contribute to deepen our understanding of and to improve prediction skill of the Atlantic-Pacific teleconnection patterns and the occurrence of the subtropical climate variations.

In addition to conduct those process studies, we developed a proto-type system of the real-time seasonal climate predictions with the new SINTEX-F2. Preliminary analyses showed that the new seasonal prediction system improves the prediction skill of the subtropical dipoles, ENSO-Modoki, and the Ningaloo Niño relative to the SINTEX-F1 seasonal prediction system.

Keywords: SINTEX-F2 GCM, Seasonal Prediction, Subtropical Dipole Modes, Tropical Atlantic-Pacific Teleconnection

1. Introduction

We have been conducting seasonal predictions every month using the SINTEX-F1 seasonal prediction system on the Earth Simulator and providing a real-time outlook of seasonal to interannual climate predictions on JAMSTEC website (http://www.jamstec.go.jp/frcgc/research/d1/iod/e/seasonal/outlook.html). In this fiscal year, these real-time seasonal prediction experiments were conducted by another new project (Project representative: Swadhin K. Behera, APL/JAMSTEC; "Study on the real-time ensemble seasonal prediction system and its application") so as to focus on the process studies and model development parts under this project.

The SINTEX-F1 seasonal prediction system has demonstrated its outstanding performance of predicting El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole Mode (IOD). In addition, Doi et al (2013) recently showed that the SINTEX-F1 prediction system is also highly skillful in predicting regional climate phenomenon known as the Ningaloo Niño/Niña off the west coast of Australia.

While the model has done extremely well to predict the tropical climate phenomena, it is still a challenge to predict the teleconnections arising from ENSO and IOD in addition to the subtropical climate variations such as the Indian Ocean Subtropical Dipole (IOSD) and its Atlantic counterpart, the Atlantic Ocean Subtropical Dipole (AOSD). To tackle those difficulties, we had successfully developed a new high-resolution version of SINTEX-F with an embedded sea-ice model, the SINTEX-F2. Some preliminary works show that the SINTEX-F2 GCM is better in reproducing realistic mean atmosphere/ocean conditions, tropical/subtropical climate variations and extreme events, including tropical cyclones, relative to the SINTEX-F1. We are hence expecting significant contributions of the SINTEX-F2 for better understanding of finer-scale climate processes, mid-latitude climate variations, and interactions among climate modes in tropics and mid-latitude regions.

In the following sections, we introduce several important results obtained from our research activities in the fiscal year of 2013. In Section 2, three process studies with SINTEX-F2 sensitivity experiments are discussed. In Section 3, we show that preliminary results with a proto-type of new SINTEX-F2 seasonal prediction system.

2. Climate process studies with SINTEX-F2 experiments

2.1 Role of tropical SST variability on the formation of subtropical dipoles

The subtropical dipole is an interannual climate phenomenon over the mid-latitude ocean basin in the Southern Hemisphere, which accompanies in its positive phase a warmer-than-normal sea surface temperature (SST) in the southwestern part of each basin and a colder-than-normal SST in the northeastern part. The subtropical dipole develops typically during austral summer (December-February) and causes a rainfall increase in

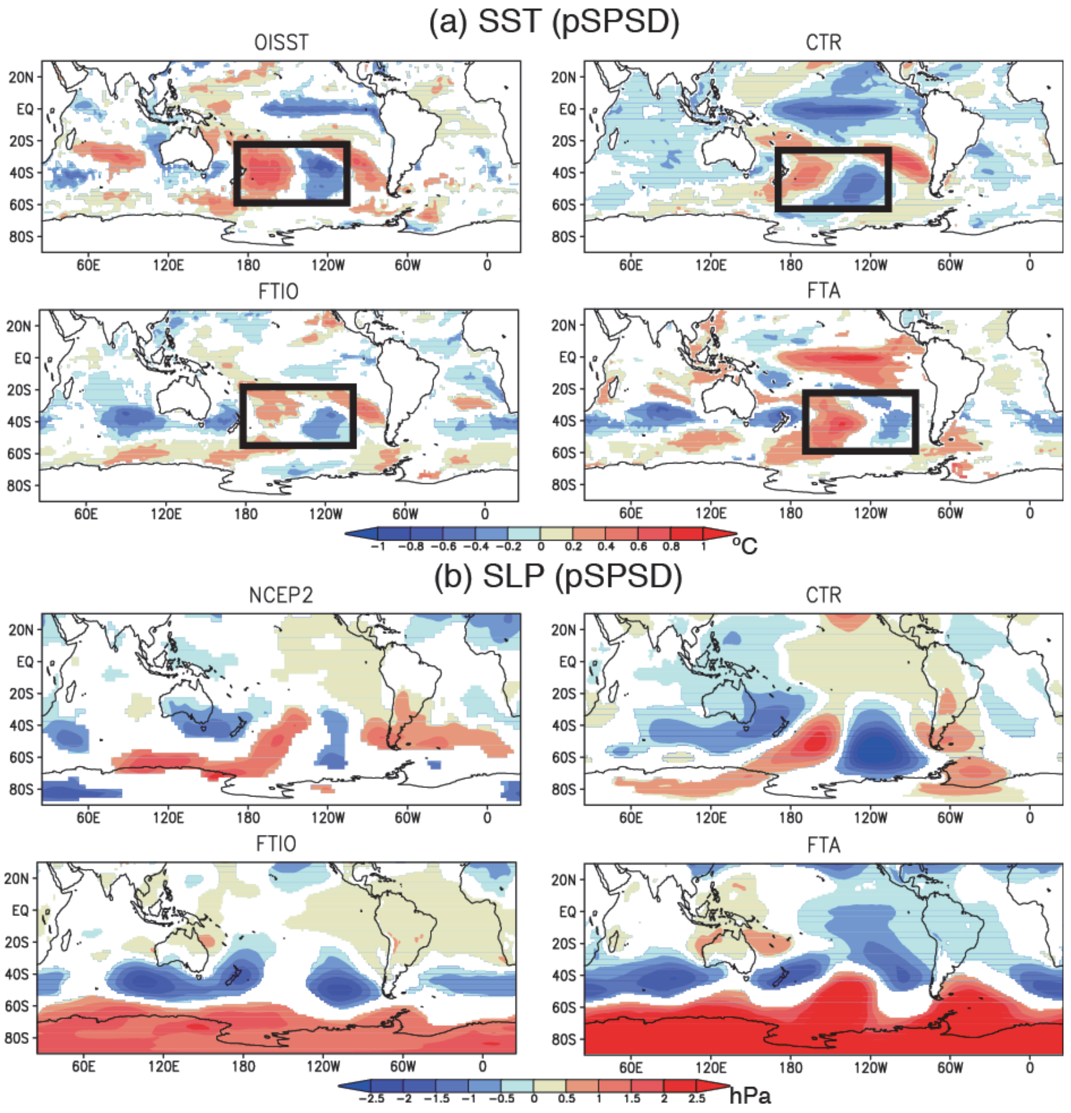

Fig. 1 (a) Composite SST anomalies (in ºC) during December-February of the positive South Pacific subtropical dipole (pSPSD). The OISST, the CGCM (CTR, FTIO, and FTA) experiments are shown. In the FTIO (FTA) experiment, the interannual SST variation in the tropical Indian (Atlantic) Ocean is suppressed. The boxes indicate positions of the dipole SST anomalies associated with the pSPSD. (b) Same as in (a), but for the sea level pressure anomalies during November-January. The NCEP Reanalysis-2 (NCEP2) is shown in the top left panel.

the southern Africa, the southeastern Brazil, and New Zealand. Since prediction of the rainfall variations are closely linked to natural disaster prevention, major crop yield management, and water resources management, detailed understanding of generation mechanisms of the subtropical dipole and improvement of their prediction skills are essential.

The generation mechanism of the subtropical dipole has been identified in our previous studies. During October-December when the subtropical dipole starts to develop, the subtropical high anomalously strengthens in its southern part. Over the northeastern part of the subtropical high, anomalously dry southeasterly wind from the high latitude enhances evaporation. This results in colder-than-normal SST, causing the surface water to mix with water underneath and hence deepening the surface mixed-layer. Although the solar radiation acts to warm the mixed-layer, its contribution becomes smaller due to the thicker-than-normal mixed-layer depth. This leads to development of the northeastern pole with the colder-than-normal mixed-layer temperature. The mechanism for the southwestern pole development is found to be a mirror image to that for the northeastern pole.

However, the variation of the subtropical high during the development of the subtropical dipole remains unclear. Previous studies suggest that ENSO in the tropics and the climate phenomenon in the higher latitudes of the Southern Hemisphere, called the Antarctic Oscillation (AAO), may contribute to the interannual variation in the subtropical high. To investigate the relative role of the lower and higher latitude climate phenomena in the formation of the subtropical dipole, we have conducted a series of experiments by using a coupled general circulation model (SINTEX-F2) that is executed on the Earth Simulator (Morioka et al. 2014[1]). In the experiment, where the interannual SST variation in each tropical basin is suppressed, the subtropical dipole occurs in association with the strengthening of the subtropical high in its southern part (see Fig. 1a for the South Pacific subtropical dipole case). The occurrence frequency and amplitude of the subtropical dipole do not significantly change compared to the case with the interannual SST variation. In addition, the variation in the subtropical high is found to be strongly related to the AAO (Fig. 1b). These results imply that even in the absence of the tropical climate phenomena, the AAO induces the variation in the subtropical high and hence the subtropical dipole.

Detailed understanding of generation mechanisms of the subtropical dipole contributes to better prediction skill of the phenomenon. Results obtained in this study suggest that accurate representations of climate phenomena in the higher latitudes of the Southern Hemisphere, as well as in the tropics, need to be included in prediction models. Since the higher latitude climate phenomena are in turn influenced by other processes such as sea-ice distribution and the ozone amount over Antarctica, it is also important to incorporate these elements appropriately in a climate model. Efforts to provide reliable prediction information to international communities by developing such a climate model are in progress.

2.2 The influence of ENSO on the equatorial Atlantic precipitation

The link between ENSO and the equatorial Atlantic precipitation during boreal spring (March–April–May) is explored using the SINTEX-F2 GCM (Sasaki et al. 2014a[2]). Simulated interannual variability of the equatorial Atlantic SST in the SINTEX-F2 is excluded by nudging the modeled SST toward the climatological monthly mean of observed SST in the equatorial Atlantic, but full air–sea coupling is allowed elsewhere. We found that the equatorial Atlantic precipitation is reduced (increased) during El Niño (La Niña) event, although the interannual variability of the equatorial Atlantic SST is disabled in the model. The precipitation anomalies in the equatorial Atlantic during ENSO are not strongly associated with the meridional migration of the Atlantic Intertropical Convergence Zone (ITCZ). We found that the reduced precipitation in the equatorial Atlantic during El Niño is due to an enhanced Atlantic Walker circulation associated with strengthened low-level easterlies and anomalous dry, downward winds over the equatorial Atlantic, while the Pacific Walker circulation is weakened. The upper-level anomalous westerlies over the equatorial Atlantic are consistent with a *Matsuno–Gill-type* response to heating in the eastern equatorial Pacific. Our results of the CGCM experiments suggest that changes to the Walker circulation induced by ENSO contribute significantly to changes in precipitation over the equatorial Atlantic (Fig. 2).

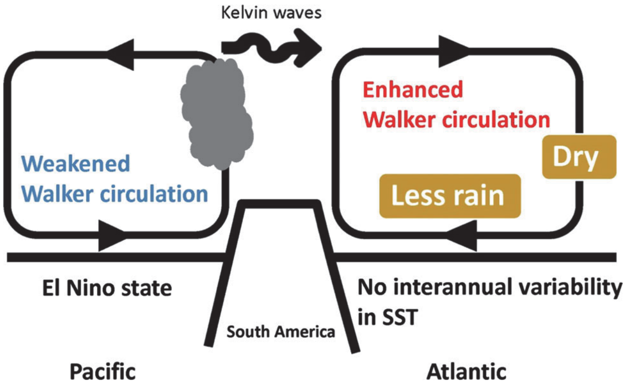

Fig. 2 Schematic diagram of the El Niño impact on the equatorial Atlantic precipitation in the SINTEX-F2 without interannual variability of the equatorial Atlantic SST (Fig. 10 in Sasaki et al. 2014a[2]).

2.3 Impact of the equatorial Atlantic SST on the tropical Pacific

Many CGCMs suffer from serious model bias in the zonal gradient of SST in the equatorial Atlantic. The bias of the equatorial Atlantic SST (EASST) may affect the interannual variability of the equatorial Atlantic, which in turn may influence the state of the tropical Pacific. Therefore, we explore the impact of the EASST bias and the interannual variability of the EASST on the tropical Pacific by the SINTEX-F2 GCM (Sasaki et al. 2014b[3]). To determine the impact of the interannual variability of the EASST on the tropical Pacific, we compare a run in a fully coupled mode (CTL run) and a run in which the EASST is nudged toward the climatological monthly mean of the SST in the CTL run, but full air-sea coupling is allowed elsewhere (AT_m run). We found that, when the interannual variability of the EASST is excluded, the thermocline depth in the eastern equatorial Pacific is deepened, and the amplitude of the ENSO is reduced by 30% relative to the CTL run (Fig. 3).

The impact of the bias of the EASST on the tropical Pacific is investigated by comparing the AT_m run and a run in which the EASST is nudged toward the observed climatological monthly mean SST (AT_o run). It is found that, when the bias of the EASST is removed (i.e. AT_o run), the *Matsuno–Gill type* response to the warm SST anomalies in the western equatorial Atlantic induces low-level cyclonic anomalies in the eastern South Pacific, which leads to a deeper thermocline and colder SST in the South Pacific through the Ekman pumping relative to AT_m. The colder SST in the South Pacific reduces the precipitation along the South Pacific convergence zone (Fig. 4).

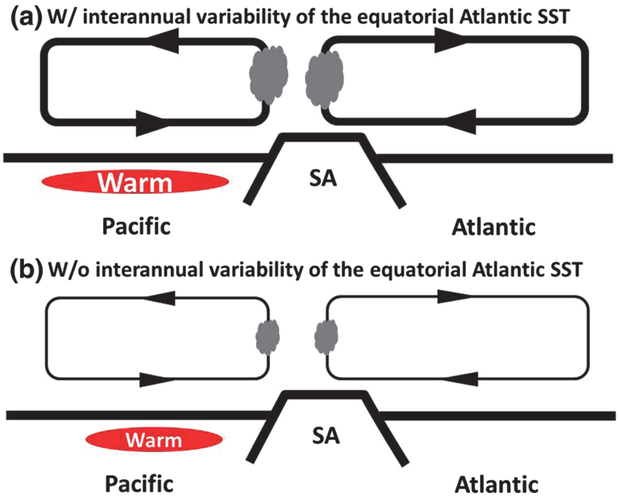

Fig. 3 Schematic diagram showing the difference in the atmosphere–ocean response to the inter-Pacific-Atlantic SST gradient caused by the presence or absence of the interannual variability in the equatorial Atlantic in the SINTEX-F2. (Fig. 13 in Sasaki et al. 2014b[3])

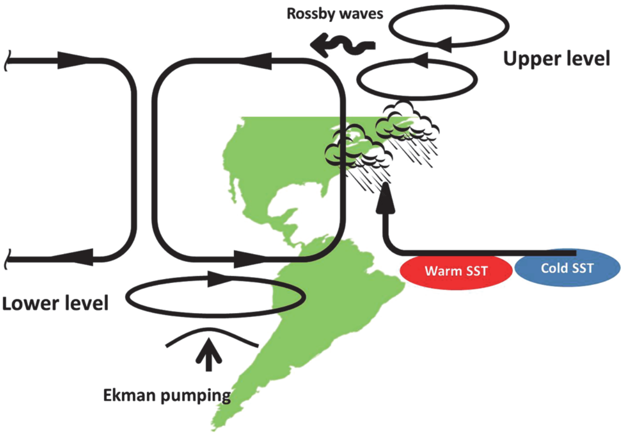

Fig. 4 Schematic diagram showing the atmosphere–ocean response when the equatorial Atlantic SST bias is reduced in the SINTEX-F2. Observed SST in the equatorial Atlantic is warmer (colder) in the west (east) compared to the SST in the CTL run of the SINTEX-F2. (Fig. 14 in Sasaki et al. 2014b[3])

Our results of the model experiments demonstrate the importance of the EASST to the tropical Pacific climate.

3. A proto-type of new SINTEX-F2 seasonal prediction system

3.1 Differences between SINTEX-F1 and SINTEX-F2 seasonal prediction system

We developed the SINTEX-F2 GCM for better representation of several physical processes and to resolve relatively fine-scale phenomena in the ocean. Table 1 briefly summarizes major differences between the SINTEX-F1 and the new SINTEX-F2 GCMs (there are also some differences in numerical schemes and parameterizations). Owing to these differences, model biases in climatological fields are much reduced in SINTEX-F2 compared with those in SINTEX-F1, particularly in mid-latitudes. As a next step, we have been trying to develop a new seasonal prediction system on the basis of SINTEX-F2. In this fiscal year, we successfully developed a proto-type of the new SINTEX-F2 seasonal prediction system and similar to the SINTEX-F1 system, a SST-nudging coupled initialization scheme is adopted. 6 ensemble members with 6-month lead are now available for the SINTEX-F2 seasonal prediction experiments (Table 2).

Table 1 Main differences between SINTEX-F1 and SINTEX-F2

	AGCM	OGCM	Coupling	Sea Ice
SINTEX-F1	ECHAM4.6 T106L19	OPA8.2 2×2 L31	Every 2 hour No flux correction	No
SINTEX-F2	ECHAM5 T106L31	OPA9 0.5×0.5 L31	Same as F1	Yes

Table 2 A proto-type of seasonal prediction system with SINTEX-F1 and F2

	Initialization	Ensemble size	Lead time	Period
SINTEX-F1	SST-nudging, every month	9~27	1~2yr	1982~
SINTEX-F2	Same as F1	6	6mo	2000~

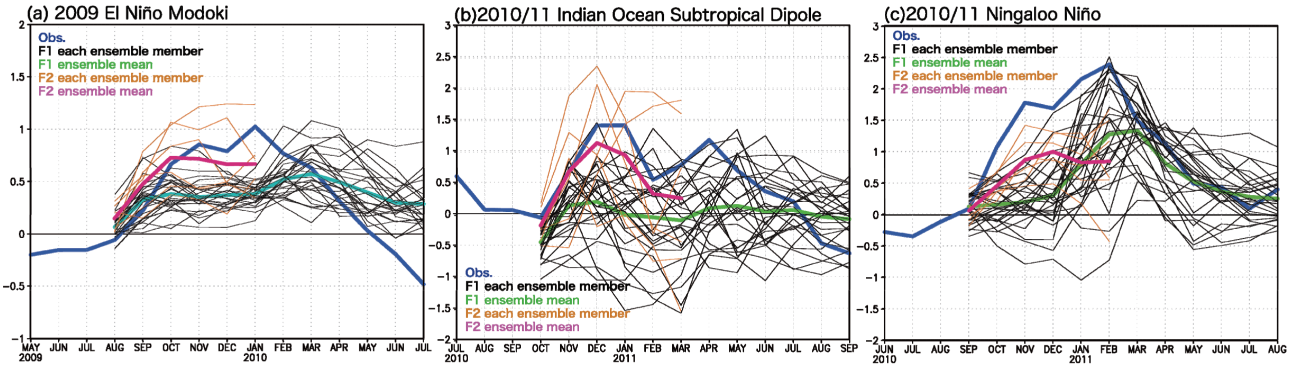

Fig. 5 (a) Monthly El Nino Modoki Index in 2009, defines as SST anomaly in 165°E-140°W, 10°S-10°N minus the half of SST anomaly in 110°W-70°W, 15°S-5°N minus the half of SST in 125°E-145°E, 10°S-20°N. (b) Monthly Indian Ocean Subtropical Dipole Index in 2010/11, defined as SST anomaly in 55ºE-65ºE, 37ºS-27ºS minus SST anomaly in 90ºE-100ºE, 28ºS-18ºS. (c) Monthly Ningaloo Niño Index in 2010/11, defined as SST anomaly in 108º-116ºE, 28º-22ºS.

3.2 Preliminary results with the SINTEX-F2 seasonal prediction system

The preliminary results from the SINTEX-F2 seasonal prediction experiments are shown in Fig. 5. The predicted indices are the ENSO-Modoki, IOSD, and the Ningaloo Niño. It is noted that the SINTEX-F2 system has better skill to predict 2009 El Nino-Modoki and 2010/11 IOSD (Figs. 5a and b). This might be due to the better simulation of the mean state in the mid-latitude and interactions between the tropics and subtropics in the SINTEX-F2 CGCM. Fig. 5c shows the prediction of a newly identified regional climate phenomena off the west coast of Australia, the Ningaloo Niño. The early development stage of the 2010/11 Ningaloo Niño was better predicted by the SINTEX-F2 system relative to the SINTEX-F1 system. This might be due to the high-resolution of the ocean component of the SINTEX-F2 that better resolves the coastally trapped ocean current such as the Leeuwin Current, and its local air-sea feedback - key to develop the Ningaloo Niño. Further analysis is necessary for deep understanding why the SINTEX-F2 successfully improved their prediction skills relative to the SINTEX-F1.

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大気海洋結合モデルを用いた短期気候変動のプロセス研究とその季節予測可能性研究

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数ヶ月から数年スケールで発生する気候変動の理解ならびにその予測可能性研究のため、SINTEX-F 大気海洋結合大循環モデルを日欧研究協力に基づき開発および改良してきた。その第一版である SINTEX-F1 は、リアルタイムの季節・経年変動予測実験に長く用いられており、近年発生したインド洋ダイポールモードやエルニーニョ・南方振動（ENSO）現象のほとんどを現実的に予測している。今年度は、このリアルタイム季節・経年変動予測実験の計算は新規課題（課題責任者 : JAMSTEC/APL スワディヒン・ベヘラ）で行うこととし、本課題では更なる気候変動プロセスの研究と、高度化させた第二版 SINTEX-F2 の開発を中心に実施した。

従来の SINTEX-F1 では、特に中緯度の気候変動現象である亜熱帯ダイポールモード現象の予測や、熱帯海盆を跨いだ気候変動現象同士の相互作用の予測に問題があった。そこで、新しく開発に成功した SINTEX-F2 を用いて、1）亜熱帯ダイポールモード現象の発生プロセスに熱帯域の気候変動がどの程度重要なのか、2）太平洋の ENSO 現象はどのように大西洋の気候変動現象に影響を与えるのか、3）大西洋の気候変動現象やモデルバイアスが太平洋の気候にどの程度影響を与えるのか、を調べた。その結果、1）亜熱帯ダイポールモード現象は ENSO などの熱帯域の現象が無くても発生しうること、2）大気のウォーカー循環を通じて ENSO が大西洋上の降水過程に影響を及ぼしていること、3）大西洋の海面水温バイアスは松野 – ギルパターンの形成を通じて太平洋の風系と海洋表層の変動をもたらしていることが明らかになった。これらの成果は国際誌で発表され、世界の気候変動研究を先導するモデルとして SINTEX-F の地位を確立する礎となっている。

更に新しい高度化モデル SINTEX-F2 を用いたアンサンブル気候予測実験のプロトタイプを開発した。この SINTEX-F2 予測システムでは、近年頻発してきたエルニーニョモドキ現象や、亜熱帯に現れるインド洋亜熱帯ダイポール現象、オーストラリア西岸に現れる地域気候変動現象であるニンガルーニーニョ現象等の予測精度が向上していることが確認できた。SINTEX-F2 での高解像度化や海氷モデルの導入により、中緯度域や海洋の比較的小さな現象の再現性が SINTEX-F1 より向上していることが主な原因と考えられる。

キーワード : SINTEX-F2, 新季節予測システム , 亜熱帯ダイポールモード , 熱帯太平洋－大西洋テレコネクション