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Successful prediction of the consecutive IOD in 2006 and 2007

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[1] During 2006 and 2007 boreal fall, two consecutive positive Indian Ocean Dipole (pIOD) events occurred unprecedentedly regardless of the respective El Niño and La Niña condition in the Pacific. These two pIOD events had large climate impacts, particularly in the Eastern Hemisphere. Experimental forecasts using a coupled model show that the two pIOD events can be predicted 3 or 4 seasons ahead. The evolution of the 2006 pIOD is consistent with the large-scale IOD dynamics, and therefore, it has long-lead predictability owing to the oceanic subsurface memory in the South Indian Ocean. The 2007 pIOD event, however, is rather weak and peculiar without a long memory from the off-equatorial ocean. The model has less predictability for this weak event. The results show that seasonal climate anomalies in the Eastern Hemisphere associated with the two pIOD events can be predicted 1–2 seasons ahead. This indicates potential societal benefits of IOD prediction. **Citation:** Luo, J.-J., S. Behera, Y. Masumoto, H. Sakuma, and T. Yamagata (2008), Successful prediction of the consecutive IOD in 2006 and 2007, *Geophys. Res. Lett.*, *35*, L14S02, doi:10.1029/2007GL032793.

1. Introduction

[2] The Indian Ocean Dipole (IOD), an inherent air-sea coupled climate mode in the tropical Indian Ocean (IO), has been extensively studied during the recent decade after the pioneering work of *Saji et al.* [1999]. IOD usually starts to develop in boreal summer, peaks in fall, and terminates rapidly in early winter, subject to the strong seasonal modulation by the Asian monsoon surface winds. Despite the fact that IOD signal is generally weaker than that of El Niño-Southern Oscillation (ENSO), it has large climate impacts particularly in the Eastern Hemisphere, owing to the warm sea surface temperature (SST) background state in the tropical IO.

[3] Figure 1a shows the boreal fall SST anomalies during the 2006 positive IOD (pIOD) event. Cold SST anomalies ($<-1°C$) appeared clearly along the west coast of Sumatra with weak warm ones in the western IO. In the equatorial central and eastern Pacific, a weak El Niño signal co-occurred but with less rainfall there (not shown); this indicates that the El Niño signal should have small or negligible influences on the atmosphere. On the other hand, the IOD signal induced large rainfall deficit in the eastern IO and Indonesia, and floods in western IO, South India, and East Africa (Figure 1b). Besides, its remote influence via the atmospheric bridge caused warm and dry anomalies over large parts of Australia, East Asia, Arabian continent, and Europe during 2006 boreal fall, in agreement with previous studies [e.g., *Saji and Yamagata*, 2003; *Yamagata et al.*, 2004; *Behera et al.*, 2005; *Meyers et al.*, 2007; *Black and Sutton*, 2007]. The 2006 IOD event caused large societal and economical losses, including the severe haze problem in Indonesia due to forest fires, exceptionally long-lasting drought in Australia, and many deaths in East Africa due to floods. This suggests the importance and societal benefits of IOD prediction.

[4] Interestingly, another weak pIOD signal appeared in early fall of 2007 (Figure 1c), together with a La Niña condition in the Pacific. The atmospheric response appears to be similar to that in 2006 fall, with drought in the eastern IO and Indonesia and floods in the western IO, South India, and East Africa (Figure 1d). Australia again suffered from dry and warm anomalies, in contrast to the normal expectation of good rains during La Niña year. This caused an interesting debate about releasing of IOD prediction in the public domain (e.g., The Weekly Times, 24 and 31 October 2007). The peculiar co-occurrence of both pIOD and La Niña clearly suggest that potential predictability of pIOD may reside in the IO itself.

[5] Predicting IOD and its related climate anomalies, however, is rather difficult and still in its infancy. In this study, we present our experimental real time forecasts of the pIOD in both 2006 and 2007 based on an advanced ocean-atmosphere coupled general circulation model (GCM). The possible reasons for successful predictions will be discussed briefly.

2. Model and Forecast Experiments

[6] The model used in this study is the SINTEX-F global ocean-atmosphere fully coupled GCM [e.g., *Luo et al.*, 2005a]. It consists of a high resolution atmospheric component (ECHAM4.6, T106) with 19 vertical levels, and a relatively 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. The SINTEX-F model has been applied to various climate studies and proved to have good performance in simulating and predicting both ENSO and IOD [e.g., *Yamagata et al.*, 2004; *Behera et al.*, 2005; *Luo et al.*, 2005a, 2005b, 2007].

[7] Though ENSO prediction is not sensitive to ensemble size using the SINTEX-F model, large ensembles are important to improve IOD prediction [*Luo et al.*, 2007]. Based on a kind of semi-multimodel ensemble approach [*Luo et al.*, 2005b, 2007], the ensemble members are increased up to 27 for experimental real time forecasts.

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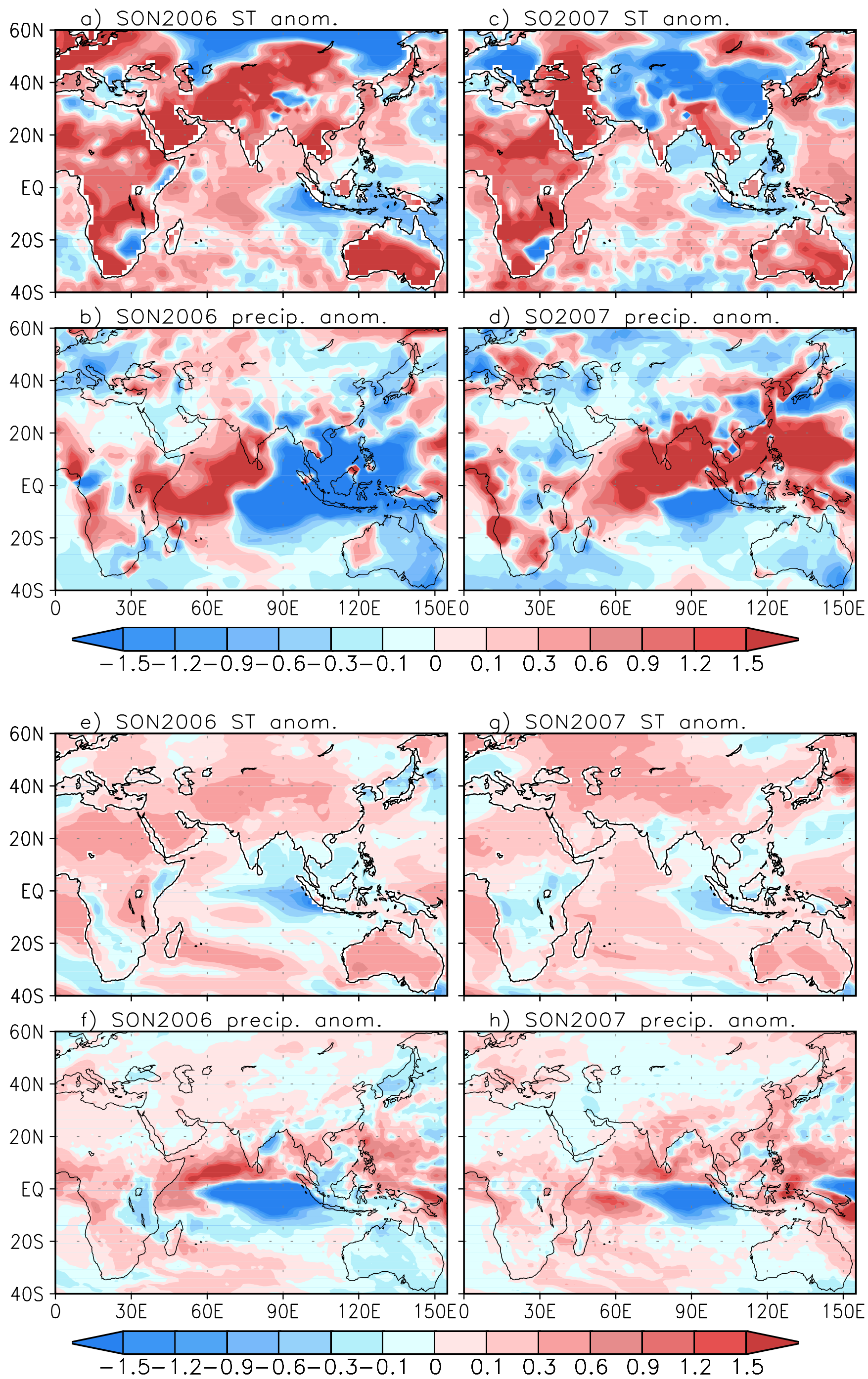

Figure 1. Seasonal mean SST, terrestrial 2-m air temperature (°C), and precipitation (mm/day) anomalies in (a–b) September–November 2006 and (c–d) September–October 2007. These are based on the NCEP OI SST, NCEP/NCAR reanalysis, and NCEP CPC precipitation product. The anomalies were calculated relative to the climatology over the period 1983–2006. (e–h) Same as in Figures 1a–1d, but for the model predictions in 2006 and 2007 boreal fall. These are produced by the average of three 27-member mean consecutive forecasts initiated from 1 May, 1 June, and 1 July in 2006 and 2007, respectively.

Both model coupling physics and initial conditions are perturbed separately in three different ways. Current initial conditions for forecasts are generated using a simple coupled SST-nudging scheme. Because of the uncertainty in SST observations, we have used three different products for the initialization process. One is the National Centers for Environmental Prediction (NCEP) weekly optimum interpolation (OI) analysis available from January 1982 [*Reynolds et al.*, 2002]. The others are daily OI SSTs based on two microwave satellites (TMI and AMSR-E) retrievals available from January 1998 and June 2002 [e.g., *Gentemann et al.*, 2004].

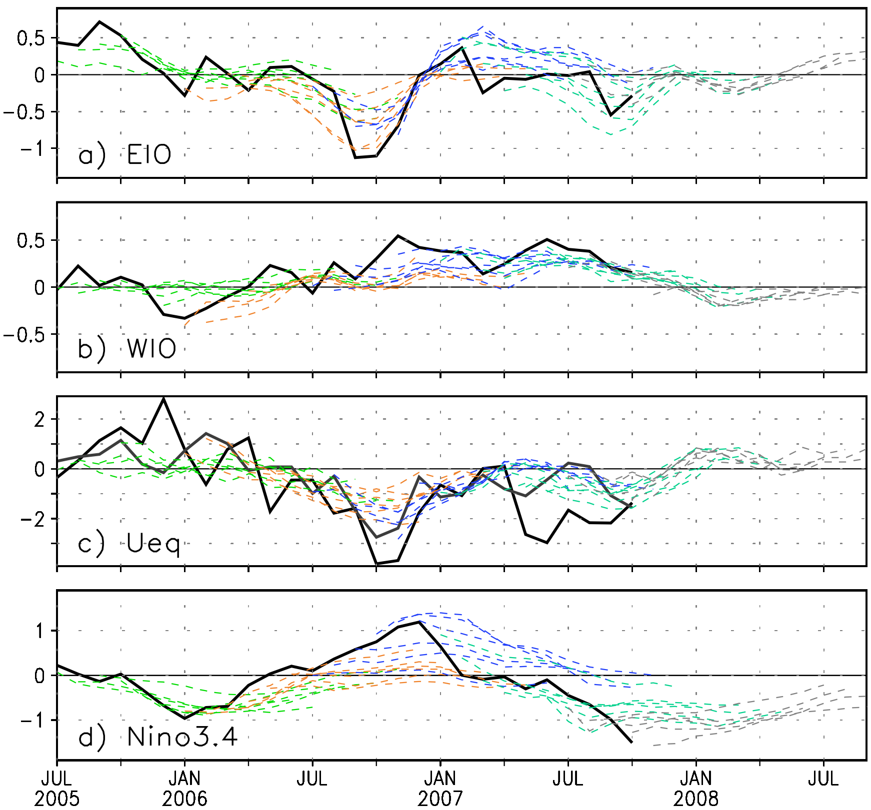

Figure 2. Prediction plumes of the monthly SST anomalies in (a) the eastern pole (EIO, 90°–110°E, 10°S–0°), (b) the western pole (WIO, 50°–70°E, 10°S–10°N), and (d) Niño3.4 region (170°–120°W, 5°S–5°N). The thick solid black lines and colored dashed curves denote the NCEP monthly IO SST anomaly and 27-member ensemble mean forecasts for 12 target months, respectively. Colors for the forecast plumes are changed every 6 start months, starting from 1 July 2005. (c) As in Figure 2a, but for the surface zonal wind anomaly (m/s) in the central equatorial IO (Ueq, 70°–90°E, 5°S–5°N). The thick black line denotes the NCEP/NCAR reanalysis and dark-gray line the 27-member mean Ueq produced by the coupled SST-nudging initialization scheme.

[8] We note that SST anomalies in the western and eastern IO can be predicted up to about 2 seasons ahead with correlation skill of about 0.65 and 0.55 respectively, according to our 9-member hindcast experiments for the period 1982–2004 [*Luo et al.*, 2007]. Since 2005 we have performed experimental real time forecasts for 12 target months starting from the first day of each calendar month. Parts of the experimental forecasts are available on the FRCGC IOD web-site (i.e., http://www.jamstec.go.jp/frcgc/research/d1/iod/index.html).

3. Results

[9] Figure 2 shows the 27-member ensemble mean prediction plume of SST anomalies in the eastern and western IOD poles. The strong cooling along the west coast of Sumatra and weak warming in the western IO during 2006 boreal fall were correctly predicted up to about 1-year lead (Figures 2a and 2b, the yellow and last three green lines; see also *Luo et al.* [2007] for the real time forecasts). The predicted magnitudes, however, are generally weaker than the observed due to the ensemble average. The observed intensity was actually captured in some ensemble members (see the FRCGC IOD web for verification). IOD is usually characterized by a quasi-biennial frequency as shown in both the observations [*Saji et al.*, 1999] and the SINTEX-F model long-term simulations [*Yamagata et al.*, 2004; *Behera et al.*, 2006]. The phase transition from a weak negative IOD in 2005 fall to a strong pIOD in 2006 was predicted well. Correspondingly, the transition from westerly wind anomalies to easterly ones in the central IO was also captured and predicted (Figure 2c).

[10] In the equatorial Pacific, a La Niña occurred in 2005/06 winter, and gradually decayed in early 2006. Then it was replaced by a weak El Niño in late 2006 (Figure 2d). The ENSO phase transition was predicted but with a significant phase delay. In particular, the El Niño strength was considerably underestimated in the model predictions from early 2006 (see the yellow lines in Figure 2d), despite that some ensemble members did capture the real intensity. This is probably related to the fact that westerly wind bursts in the western Pacific primarily drove this weak El Niño (see http://www.pmel.noaa.gov/tao/jsdisplay/). The concurrent occurrence of El Niño and pIOD has usually been observed in historical records.

[11] The evolutions of ENSO and IOD in 2007, however, were exceptional. The weak El Niño peaking in November 2006 decayed rapidly in 2006/07 winter, and a La Niña started to develop since 2007 summer (Figure 2d). The short-lived nature of this El Niño was not correctly predicted (Figure 2d, the blue lines), as in most existing forecast systems (see http://iri.columbia.edu/climate/

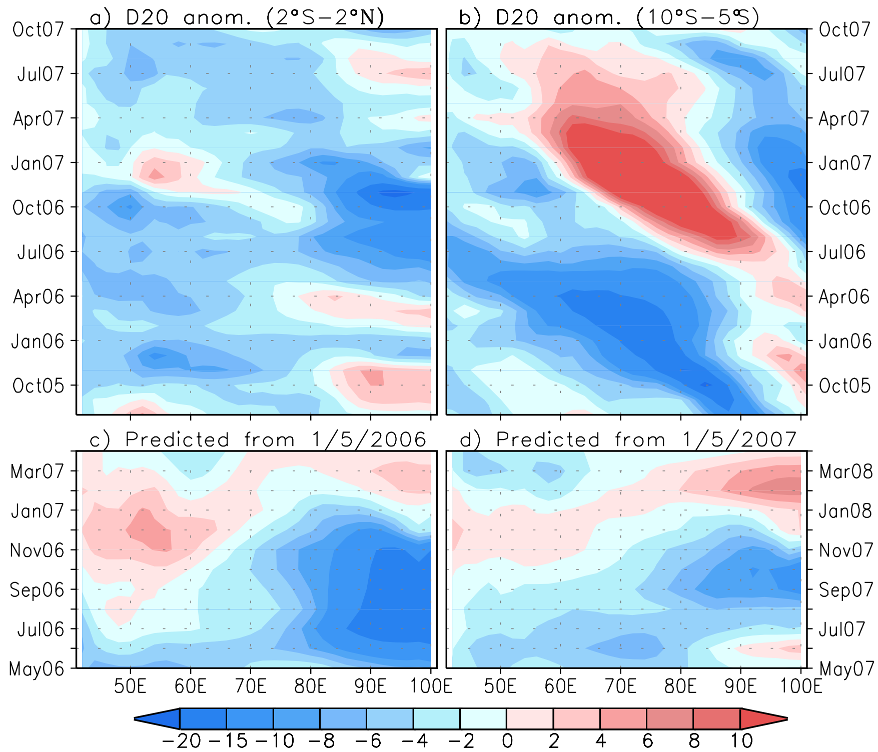

Figure 3. 20°C isotherm depth (D20, meter) anomalies in (a) the equatorial IO and (b) off-equatorial South IO. These are 27-member mean model initial conditions produced by the coupled SST-nudging scheme. We note that subsurface signals induced by stochastic intraseasonal forcing are seen in some members; they are largely filtered out in the model ensemble mean products. (c–d) As in Figure 3a, but for the equatorial D20 anomalies (2°S–2°N) predicted from 1 May 2006 and 1 May 2007, respectively.

ENSO/index.html). Possibly, the atmosphere in reality did not feel much the weak El Niño condition and hence excited little positive feedback to enhance and sustain the oceanic signal. The La Niña in 2007 was well predicted since early 2007 (Figure 2d, the light blue lines).

[12] In the eastern IO, the strong cooling related to the 2006 pIOD demised in early winter of 2006/07 as observed in normal cases (Figure 2a). SSTs there reached to a neutral condition by 2007 summer. Then another cooling appeared near the Java coast in August 2007. The signal was gradually strengthened during its evolution and expanded toward the equator. In September 2007, a weak cold signal appeared along the west coast of Sumatra. In the western IO, weak warming persisted to 2007 spring and summer (Figure 2b), despite the La Niña condition in the Pacific. The prolonged warming in the west and the cooling in the east led to another weak pIOD in 2007 boreal fall.

[13] Mechanisms for the 2006 and 2007 pIOD events appear to be different. According to the NCEP/NCAR reanalysis, stable anomalous surface southeasterly winds started to appear in May 2006 along the west coast of Sumatra in the case of 2006 (not shown). The along-shore winds gradually intensified and extended toward the central equatorial IO via air-sea interactions, under the influence of active intraseasonal disturbances inherent in the IO [*Horii et al.*, 2008; S. A. Rao et al., Activation, maturation and termination of Indian Ocean Dipole events in 2003, 2006 and 2007, submitted to *Climate Dynamics*, 2007]. The peak of the easterly anomaly in the central region lagged the cold SST anomaly in the eastern IO for about 1 month (Figures 2a and 2c). The evolution in 2006 is consistent with the canonical pIOD [*Saji et al.*, 1999].

[14] In 2007, however, strong anomalous easterlies suddenly appeared in the central IO in May–June 2007 (Figure 2c), driving eastward-propagating upwelling Kelvin waves as observed by JAMSTEC TRITON buoys in the eastern IO. The active easterlies appear to be related to strong convective activities in the western IO including the Arabian Sea, partly associated with the prolonged warmer SST there (see Figure 2b). Anomalous southeasterly winds west of Sumatra started later in July 2007 and grew up in following months. The model ensemble mean with the observed SST forcing reproduced the easterly anomalies in the central IO during May–June 2007, but the magnitudes are much weaker than the observed (Figure 2c, the dark gray line). This suggests that this strong easterly event might also be partly linked to the atmospheric internal processes. The weak cooling in the eastern IO, warming in the west, and the easterly anomaly in the central region in 2007 boreal fall were predicted from the early 2007 (Figures 2a–2c, the light blue lines). Compared to the 2006 event, predictability of this weak pIOD is low and large spreads exist among the 27 members (not shown, see the FRCGC IOD web). We note that the easterly anomalies in the central IO during July–August 2007 were not captured with the observed SST forcing (Figure 2c), probably due to exaggerated La Niña influence in the model. This failure led to worse predictions initiated from 1 August and 1 September 2007.

[15] Memories that make the long-range seasonal prediction possible primarily reside in the subsurface ocean.

Figure 3a shows the 20°C isothermal depth (D20) anomaly along the equatorial IO generated by the coupled SST-nudging initialization approach. Cold/warm subsurface signal appeared in the western/eastern IO in late 2005 with a slight phase delay in the west; this dipole pattern was driven directly by the equatorial westerly wind anomalies associated with the weak negative IOD in 2005 fall. The cold signal in the west persisted and extended to the east during 2006 spring–summer, leading to the development of a strong pIOD in 2006 fall. This is related to the arrival of a strong cold westward-propagating Rossby wave in the South IO (Figure 3b) [see also *Luo et al.*, 2007]. The Rossby wave may be forced by the surface wind anomalies associated with both the negative IOD in 2005 fall and La Niña in 2005/06 winter [e.g., *Rao et al.*, 2002; *Chambers et al.*, 1999]. The above evolution is consistent with the IOD dynamics [e.g., *Rao et al.*, 2002; *Yamagata et al.*, 2004; *Behera et al.*, 2006]. This was predicted well in the model (Figure 3c).

[16] The warm signal in the western IO in late 2006 associated with the 2006 pIOD, however, is rather short-lived (Figure 3a); the strong warm Rossby wave in the South IO does not seem to play a role to maintain a warm signal in the western equatorial IO (Figure 3b). The cold signal in the western IO in early 2007 tends to propagate eastward and lead to another weak pIOD event in 2007 fall, as predicted in the model (Figure 3d). We note that the model initial D20 conditions are generally similar to the NCEP ocean reanalysis (not shown). The equatorial upwelling Kelvin wave signal in May–June 2007, however, is weak in the model due to the weak anomalous easterly forcing in the central IO. Besides, the model ensemble mean cold signal in the western equatorial IO in early 2007 appears to be related with a large decadal cooling tendency during the past two decades (not shown). The decadal cooling trend, however, is not clear in the NCEP reanalysis. The underlying reasons need to be clarified in further study.

[17] The dipole structure of the SST anomalies in the tropical IO during 2006 and 2007 boreal fall and their impacts on the Eastern Hemisphere climate were predicted reasonably well at 1–2 seasons lead (Figures 1e–1h). Compared to the observations, the cold SST anomaly and drought in the eastern IO extend far too west. This is related to the common model bias, namely, the equatorial thermocline is too flat associated with too weak mean westerly winds in the model (see *Luo et al.* [2007] for more details). The drought in Indonesia, floods in East Africa and South India, and the dry and warm anomalies in Australia, East Asia, Arabian continent, and Europe during 2006 fall were basically predicted (Figures 1e and 1f), albeit with some local discrepancies. Successful prediction can also be seen in 2007 fall despite that this IOD signal is weak and La Niña may have large influences. In particular, the dry and warm anomalies in South Australia and Arabian continent, and the floods in East Africa and South India are predicted well (Figures 1g and 1h). The results suggest a potential predictability for not only the IOD signal itself but also its remote climate influences.

4. Summary and Discussion

[18] The strong pIOD event in 2006 boreal fall, which co-occurred with a weak El Niño, caused tremendous climate and societal impacts in Australia, East Asia, Indonesia, East Africa, and Europe. In 2007 fall, another weak pIOD appeared but with a La Niña condition in the Pacific. The occurrence of pIOD events during two consecutive years is unprecedented. The concurrent La Niña and pIOD in 2007 fall supports the idea that IOD may be originated from the internal physical processes in the IO. The co-occurrence of pIOD and La Niña is rare; a similar case was in 1967. The pIODs in both 2007 and 1967 caused severe drought in Australia, particularly in its southeast part. Indeed, the drought in 2007 has cost about $2 billion in Victoria alone according to the estimation by Australia Bureau of Meteorology. This suggests the importance of IOD prediction.

[19] Our seasonal forecast system based on the SINTEX-F coupled GCM successfully predicted both the 2006 and 2007 pIOD events up to 3 or 4 seasons ahead. Evolution of the 2006 pIOD event is consistent with that of canonical one. The results suggest that the strong cold subsurface signal in the South IO, associated with the off-equatorial Rossby wave propagation, provides long-lead predictability for this pIOD event. The 2007 pIOD event, however, is rather weak and peculiar. The model shows less predictability for it. The NCEP reanalysis suggests that the strong easterly wind disturbances in the central IO during May–June 2007 might drive equatorial upwelling Kelvin waves and trigger the weak 2007 pIOD. Both the wind anomaly and Kelvin wave signal, however, are weak in the model. Nevertheless, they may contribute to the model forecasts from May–June 2007. The cold subsurface anomalies in the western equatorial IO in early 2007, presumably related to a decadal cooling trend there, may lead to the model success in predicting this weak event up to 3 seasons ahead.

[20] It is encouraging that the IOD-related climate anomalies in the Eastern Hemisphere can be predicted 1–2 seasons ahead using numerical models. This implies potential societal benefits of IOD prediction. Further efforts are required for assimilating available subsurface observations and proper downscaling of the large scale information into regional areas; this will increase the quality and value of seasonal prediction.

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