GEOPHYSICAL REASEARCH LETTERS, VOL. 30, NO. 2, 1063, doi:10.1029/2002GL015639, 2003

Modulation of Sri Lankan *Maha* rainfall by the Indian Ocean Dipole

Lareef Zubair,[1] Suryachandra A. Rao, and Toshio Yamagata[2]
Institute for Global Change Research, FRSGC, Kanazawa-ku, Yokohama, Japan

Received 11 June 2002; revised 23 October 2002; accepted 25 November 2002; published 24 January 2003.

[1] Investigating the September to December rainy season in Sri Lanka associated with the *Maha* rice growing season provides insights into the Asian monsoon during the boreal fall. Here, the modulation of the *Maha* rainfall by the tropical air_sea coupled phenomenon referred to as the Indian Ocean Dipole (IOD) is documented. The *Maha* rainfall has a strong and robust association with the IOD from 1869 to 2000. The anomalously warm sea surface in the western Indian Ocean associated with the positive IOD phase induces large scale convergence in the lower troposphere extending to Sri Lanka leading to the preponderant enhancement of *Maha* rainfall. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 9320 Information Related to Geographic Region: Asia; 9340 Information Related to Geographic Region: Indian Ocean. **Citation:** Zubair, L., S. A. Rao, and T. Yamagata, Modulation of Sri Lankan *Maha* rainfall by the Indian Ocean Dipole, *Geophys. Res. Lett.*, *30*(2), 1063, doi:10.1029/2002GL015639, 2003.

1. Introduction

[2] While the boreal summer phase of the Asian monsoon has been well investigated through studies of the Indian summer monsoon rainfall, its behaviour during the other seasons has received less attention [*Pant and Rupa Kumar*, 1997]. During the fall, the zone of maximum rainfall migrates to southern-most India, Sri Lanka and the neighbouring sea. The rainfall during this period is of immense societal significance as it supports the main cultivation season known as *Maha* in Sri Lanka and *Rabi* in India. The *Maha* season cultivation starts sometime in September depending on the region and the harvest is around March. Water for sowing, transplanting and plant growth is supplied from the September to December rains (Figure 1) [*Zubair*, 2002a]. The January to March period is relatively dry. We shall refer to the September to December rains as the *Maha* rains in keeping with local usage. The *Maha* rainfall is a combination of the influences of the monsoon, local thunderstorms from the southward passage [*Zubair*, 2002b] of the inter-tropical convergence zone (ITCZ), depressions and cyclones from the Bay of Bengal and orographic rainfall due to the island's topography.

[3] While the monsoon rainfall during summer in peninsular India usually decreases during El Niño events, quite the opposite happens in Sri Lanka and Southern-most India during the boreal fall [*Rasmusson and Carpenter*, 1983; *Ropelewski and Halpert*, 1987]. The October to December Sri Lankan rainfall shows a strong positive correlation with the basin-wide tropical Indian Ocean (IO) sea surface temperature (SST) which in turn was highly correlated with the El Niño/Southern Oscillation (ENSO) phenomenon [*Suppiah*, 1988].

[4] Recently, an ocean-atmosphere coupled phenomenon referred to as the Indian Ocean Dipole (IOD) has been documented [*Saji et al.*, 1999; *Webster et al.*, 1999]. The IOD is associated with an east-west gradient in the tropical IO SST anomalies. IOD is a seasonally phase-locked phenomenon that initiates in May, peaks in October and wanes by December. The positive phase of the IOD (associated with a warm SST in the West) leads to enhanced rainfall in Eastern Africa and diminished rainfall around Sumatra [*Saji et al.*, 1999; *Behera et al.*, 1999]. The IOD also modulates the relationship between Indian summer monsoon rainfall and ENSO [*Ashok et al.*, 2001].

[5] Sri Lanka lies near the middle of this dipole, and it is not immediately clear what the influence of this dipole mode, if any, will be. Here, we address this question with diagnostic analysis of relationships between the *Maha* rainfall and SST, sea surface heights (SSH) and velocity potential (χ) fields.

2. Data

[6] The following monthly data sets were used in the analysis; (1) monthly SST reconstructions from 1869 to

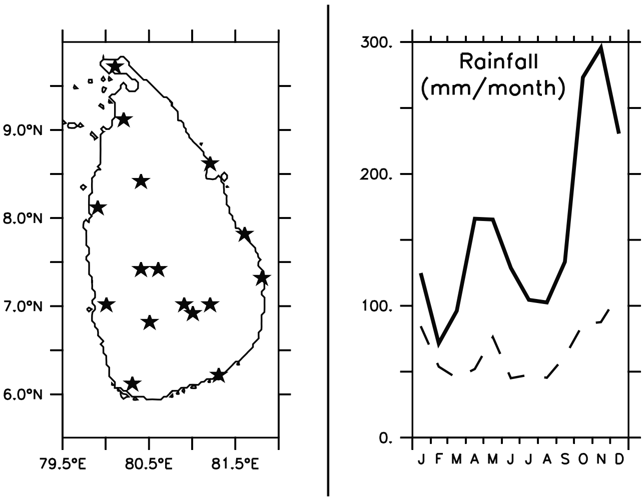

Figure 1. (Left panel) Locations of rain gauges and (right panel) the mean (solid line) and standard deviation (dashed line) of the average rainfall.

---

[1] Also at International Research Institute for climate prediction, P.O. Box 1000, Palisades, New York, NY 10964, USA.

[2] Also at Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan

0094-8276/03/2002GL015639$05.00

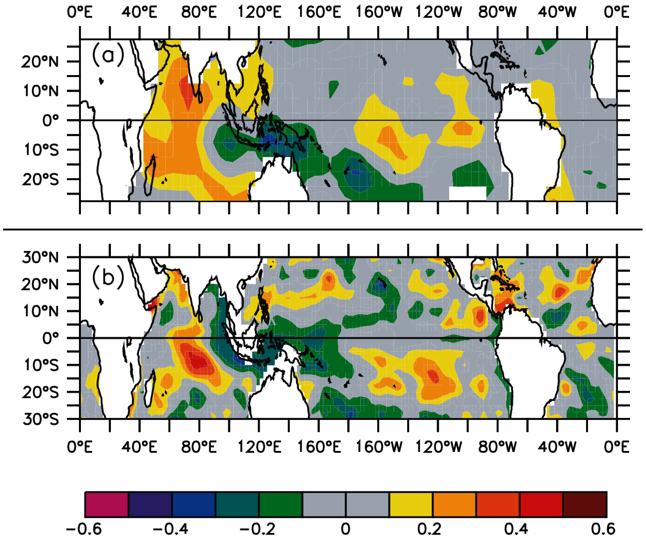

Figure 2. The partial correlation between *Maha* rainfall with (a) SST anomalies from 1869 to 2000 and (b) SSH anomalies from 1950 to 1999 with the variance predictable due to NINO3 removed.

Table 1. Extreme *Maha* Rainfall Occurences Classified by its Simultaneous IODMI and NINO3 Intensity. Wet and Dry Years Refers to *Maha* Rainfall Anomalies That Exceed σ = 45 mm/month

	21 Dry *Maha*		**22 Wet** *Maha*	
Intensity	IOD	ENSO	IOD	ENSO
Strong Positive	0	1	10	9
Weak Positive	2	0	7	8
Neutral	5	7	4	1
Weak Negative	9	8	1	2
Strong Negative	5	5	0	2

See Figure 3 for classifications of intensity.

2000 [*Kaplan et al.*, 1998] (2) SSH from ocean data assimilation from 1950 to 1999 [*Carton et al.*, 2000] (3) χ from NCEP reanalysis [*Kalnay et al.*, 1996]. These data were band-pass filtered between 5 and 90 months to represent the inter-annual variability clearly.

[7] As customary, the ENSO index of NINO3 is defined as the average SST anomaly in the equatorial Pacific (90°W–150°W; 5°S–5°N). The NINO3 index is preferred over the Southern Oscillation Index as it represents the ENSO phenomenon more compactly [*Soman and Slingo*, 1997]. *Saji et al.*, [1999] have defined an Indian Ocean Dipole Mode Index (IODMI) to characterize the IOD as the difference in the SST anomalies in the tropical western IO (50°E–70°E; 10°S–10°N) and the tropical south-eastern IO (90°E–110°E; 10°S–0°). In this paper, the index has been slightly modified by shifting the western pole to an overlapping region towards Sri Lanka (60°E–75°E; 5°N–15°N). This is because the SST observations before the mid-twentieth century in the south-western IO were sparse compared to that for the shipping lanes leading to Sri Lanka and Sumatra [*Kaplan et al.*, 1998.]. The two IODMI indices have a correlation of 0.9 over the last 130 years.

[8] The rainfall data from 1869 to 2000 was obtained from the Sri Lanka Department of Meteorology for 16 stations that have long records (Figure 1) and are distributed in the different climatic zones [*Suppiah*, 1996; *Suppiah*, 1997]. A *Maha* rainfall index was constructed as the average of these measurements from September to December, a period in which the rainfall is fairly evenly distributed [*Thambyapillay*, 1954].

3. Results

[9] The direct relationship of Sri Lankan rainfall with IOD is weaker during summer (r = −0.2 for JJA) than during *Maha*. The ENSO influence on the *Maha* rainfall has been noted before. Hence, we shall describe the *Maha* rainfall-IOD relationship with some commentary on the rainfall-ENSO relationship.

[10] Here, the technique of partial correlations [*Fisher*, 1925] was used to remove the SST patterns predictable from the contemporaneous ENSO state on the correlation between *Maha* rainfall and SST fields in a statistical sense. The partial correlation of variable 1 with 2 after the variance predictable from 3 is removed is estimated as $r_{12.3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{1-r_{13}^2}\sqrt{1-r_{23}^2}}$, where r_{12} refers to the correlation

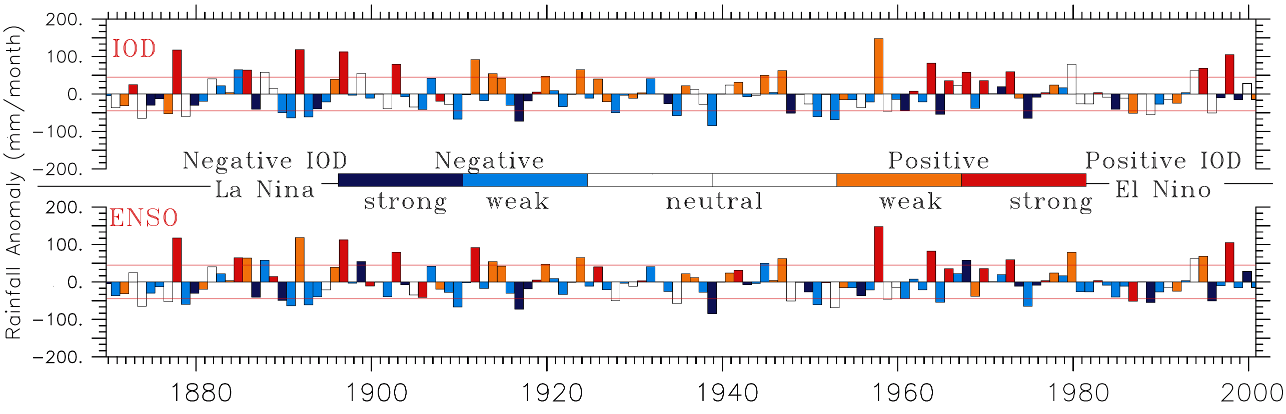

Figure 3. The inter-annual variation of the *Maha* rainfall is shown color-coded as as per the intensity of the IODMI (top) and as per the intensity of NINO3 (bottom). Its standard deviation (σ) is shown as horizontal lines. Weak and strong events are taken to be departures of index exceeding 0.25σ and σ respectively. σ for IODMI and NINO3 is 0.30°C and 0.89°C respectively.

Table 2. The Mean Rainfall Anomaly During Years Where ENSO and IOD Were in Different Phases During *Maha* is Tabulated

ENSO	IOD	Mean Rainfall Anomaly	Years of IOD influence
Positive	Negative	−11 mm	6/8
Negative	Positive	+25 mm	4/5
Neutral	Positive	+10 mm	4/7
Neutral	Negative	−10 mm	8/11

The years in which IOD influence prevailed (negative IOD was associated with lower rainfall and positive with higher rainfall) is also tabulated.

between 1 and 2. The dipole in partial correlation patterns in the tropical IO points to an IOD influence on the *Maha* rainfall (Figure 2a). The presence of a dipole structure in the partial correlation between the *Maha* rainfall and SSH in the tropical IO (Figure 2b) shows that the rainfall anomalies are strongly connected to the air-sea coupling [*Rao et al.*, 2002a, 2002b].

[11] The interannual variation of *Maha* rainfall anomalies shows the strong relationship between IODMI and rainfall during both wet and dry years (Figure 3). The *Maha* rainfall preponderantly increases with El Niño and positive IOD phases and declines in the opposite phases. These rules are violated slightly more frequently for ENSO than IOD (Table 1). To establish the relative influence of IOD and ENSO, consider the variability of *Maha* rainfall when opposing influences from ENSO and IOD are expected. This would happen when one is negative and the other is positive. Of 13 such instances, the IOD influence is dominant preponderantly during 10 occasions (Table 2).

[12] The overall correlation of IODMI with the *Maha* rain ($r = 0.59$) exceeded the 99% significance level from 1869 to 2000. The correlation of *Maha* rainfall with the original IODMI index was similar ($r = 0.54$). The relationship held at a decadal scale with slight declines to the 95% level in the 1920s' and 1980s' (Figure 4). These declines were during periods of relative inactivity of the IOD phenomenon [*S.A. Rao et al.*, manuscript in preparation, 2002]. The precise cause for this inactivity is not established as yet. The IOD can contribute to skillful probablistic predictions of the *Maha* rainfall one season in advance, as the summer IODMI correlates highly ($r = 0.47$) with *Maha* rainfall, well exceeding the 99% significance level. The IOD influence on the *Maha* rainfall has exceeded that of ENSO with the exception of 1920s. The Maha rainfall has a 130 year-long correlation with NINO3 ($r = 0.50$) which exceeds the 99% significance level as well. However this relationship declines at the decadal scale in the 1890s', 1910s', 1930s' and after 1950. These observations hold for shorter sliding-window lengths as well.

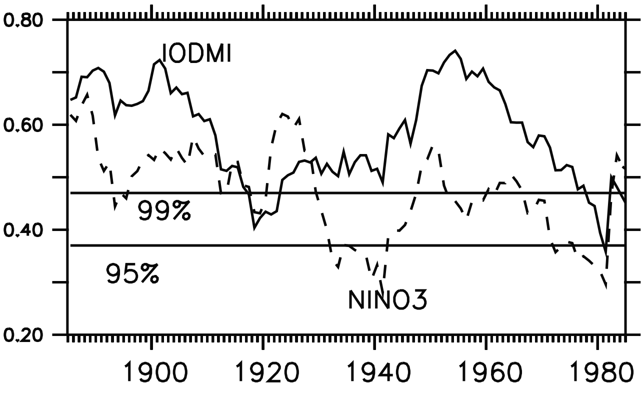

Figure 4. The 31-year windowed sliding correlation of the *Maha* rainfall with NINO3 (dashed line) and IODMI (solid line).

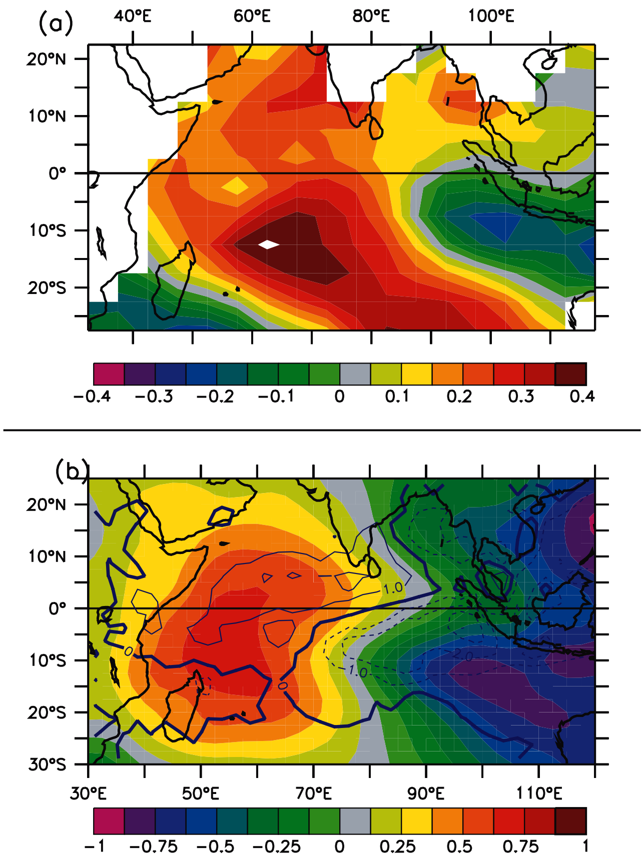

Figure 5. Composites of the (a) SST anomalies (°*C*) (b) χ anomalies ($\times\ 10^{-6} m^2 s^{-1}$) at 1000 hPa from September to November for six recent wet *Maha* seasons (1967, 1972, 1979, 1993, 1994, 1997). The composite rainfall anomalies [*Xie and Arkin*, 1996] for the four recent wet years are shown as contours in mm/day.

[13] The correlation between the IODMI and NINO3 from September to December is 0.61. The partial correlation between *Maha* rainfall and IODMI after removing the NINO3 contribution is 0.42 which exceeds the 99% significance level. The partial correlation between *Maha* rainfall and NINO3 after removing the IODMI contribution is 0.22 which is at the 95% significance level. This analysis brings out the significant role of IOD in modulating the *Maha* rainfall.

[14] To understand the dynamics that are involved in the *Maha* rainfall-IOD relationships, we constructed composite maps of the SST and χ for the six recent wet *Maha's* (Figure 5). These maps bring out features in the tropical IO reminiscent of the canonical IOD structures [*Saji et al.*, 1999] in the SST field (Figure 5a) and in the χ field (Figure 5b). In response, convection is enhanced over the western IO extending to Sri Lanka and suppressed over the eastern IO (correlation analysis of *Maha* rainfall with vertical velocity obtained from NCEP reanalyses bears this out). This results in an anomalous Walker-type circulation over

the tropical IO leading to an increase in the *Maha* rainfall. The modulation of rainfall due to the IOD is brought out by superimposing the seasonal rainfall anomalies over the composite velocity potential during recent wet years (Figure 5b). During years with IOD but no ENSO, much the same SST and χ anomalies prevail. Note, that simulations of the IOD with a coupled general circulation model [*Iizuka et al.*, 2000] also led to a similar anomalous Walker-type circulation in the tropical IO and enhancement of Sri Lanka rainfall in the fall.

4. Conclusions

[15] We have documented the strong modulation of the *Maha* rainfall by the IOD phenomenon. The *Maha* rainfall-IOD correlation has exceeded the 99% significance level and has only diminished to the 95% level during the 1920s' and 1980s'. The influence of the IOD on the *Maha* rainfall exceeded that of ENSO except during the 1920s' a period of diminished IOD activity. The influences of IOD and ENSO is statistically inter-linked but we have shown that the IOD influence remains highly significant even if the influence of ENSO were removed and that its influence prevails preponderantly over that of ENSO when the two are in competition.

[16] The enhancement of *Maha* rainfall by positive IOD events is due to the anomalously warm SST's in the western IO and the associated large-scale convergence extending to Sri Lanka. The convection arising from this convergence leads to enhanced rainfall over Sri Lanka. The opposite mechanism is at work during negative IOD events (not described entirely). These results show the direct influence of the IOD phenomenon on the Asian monsoon during the boreal fall: the season with the strongest IOD intensity. Work is continuing to extend these findings to neighbouring regions, to interrogate coupled global circulation model output along these lines and to develop predictions for the *Maha* rainfall.

[17] **Acknowledgments.** The work was supported by the Frontier Research System for Global Change of JAMSTEC/NASDA under MEXT and the International Research Institute for climate prediction. Data from the Sri Lanka Department of Meteorology and useful comments from Z. Guan, S. Masson, S.K. Behera, K. Ashok, C. Ropelewski and S. Zebiak is acknowledged. Ingrid and FERRET freeware were used.

References

Ashok, K., Z. Guan, and T. Yamagata, Impact of the Indian Ocean dipole on the decadal relationship between Indian monsoon rainfall and ENSO, *Geophys. Res. Lett.*, *28*(23), 4499–4502, 2001.

Behera, S. K., R. Krishnan, and T. Yamagata, Unusual ocean-atmosphere conditions in the tropical Indian Ocean during 1994, *Geophys. Res. Lett.*, *26*(19), 3001–3004, 1999.

Carton, A. N., G. Chepurin, and B. Giese, A simple ocean data assimilation analysis of the global upper ocean 1959–1995, part 1: Methodology, *Geophys. Res. Lett.*, *30*, 294–309, 2000.

Fisher, R. A., *Statistical Methods for Research Workers*, Oliver and Boyd, London, 1925.

Iizuka, S., T. Matsuura, and T. Yamagata, The Indian Ocean SST dipole simulated in a coupled general circulation model, *Geophys. Res. Lett.*, *27*, 3369–3372, 2000.

Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull Am. Meteorol. Soc.*, *77*, 437–471, 1996.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan, Analyses of global sea surface temperature: 1856–1991, *J. Geophys. Res.*, *103*, 18,567–18,589, 1998.

Pant, G. B., and K. Rupa Kumar, *Climates of South Asia*, John Wiley and Sons, Chichester, England, 1997.

Rao, S. A., S. K. Behara, Y. Masumoto, and T. Yamagata, Interannual variability in the subsurface tropical Indian Ocean, *Deep Sea Res. Part II*, *49*, 1549–1572, 2002a.

Rao, S. A., V. V. Gopalakrishna, S. R. Shetye, and T. Yamagata, On the absence of cool sea surface temperature anomalies in the Bay of Bengal during the 1997 dipole mode event, in press, *Geophys. Res. Lett*, 2002b.

Rasmusson, E. M., and T. H. Carpenter, The relationship between eastern equatorial Pacific sea surface temperature and rainfall over India and Sri Lanka, *Mon. Weather Rev.*, *110*(3), 354–384, 1983.

Ropelewski, C. F., and M. S. Halpert, Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation, *Mon. Weather Rev.*, *115*, 1602–1626, 1987.

Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, A dipole mode in the tropical Indian Ocean, *Nature*, *401*, 360–363, 1999.

Soman, M. K., and J. M. Slingo, Sensitivity of the Asian summer monsoon to aspects of sea surface temperature anomalies in the tropical Pacific ocean, *Q. J. R. Meteorol. Soc.*, *123*, 309–336, 1997.

Suppiah, R., Relationships between the Indian Ocean sea surface temperatures and the rainfall of Sri Lanka, *J. Meteorol. Soc. of Japan*, *66*, 103–112, 1988.

Suppiah, R., Spatial and temporal variations in the relationships between the Southern Oscillation phenomenon and the rainfall of Sri Lanka, *Int. J. of Climatology*, *16*, 1391–1407, 1996.

Suppiah, R., Extremes of the Southern Oscillation phenomenon and the rainfall of Sri Lanka, *Int. J. of Climatology*, *17*, 87–101, 1997.

Thambyahpillay, G., The rainfall rhythm in Ceylon, *University of Ceylon Review*, *12*, 224–273, 1954.

Webster, P. J., A. M. Moore, J. P. Loschnigg, and R. R. Leben, The great Indian Ocean warming of 1997-98: Evidence of coupled oceanic-atmospheric instabilities, *Nature*, *401*, 356–360, 1999.

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

Zubair, L., El-Niño-Southern Oscillation influences on rice production in Sri Lanka, *Int. J. of Climatology*, *22*, 242–250, 2002a.

Zubair, L., Diurnal and seasonal variations in surface winds at Sita Eliya, *Sri Lanka, Theor. App. Climatology*, *71*(1–2), 11–127, 2002b.

L. Zubair, S. A. Rao, and T. Yamagata, Institute for Global Change Research, FRSGC, 3173-25 Showamachi, Kanazawa-ku, Yokohama 236-0001, Japan. (lareef@iri.columbia.edu; scrao@jamstec.go.jp; yamagata@eps.s.u-tokyo.ac.jp)