Anomalous behaviors of Wyrtki Jets in the equatorial Indian Ocean during 2013

Yongliang Duan1,2, Lin Liu1,2, Guoqing Han1, Hongwei Liu3, Weidong Yu1,2, Guang Yang1,2, Huiwu Wang1,2, Haiyuan Wang1, Yanliang Liu1,2, Zahid4 & Hussain Waheed4

In-situ measurement of the upper ocean velocity discloses significant abnormal behaviors of two Wyrtki Jets (WJs) respectively in boreal spring and fall, over the tropical Indian Ocean in 2013. The two WJs both occurred within upper 130 m depth and persisted more than one month. The exceptional spring jet in May was unusually stronger than its counterpart in fall, which is clearly against the previous understanding. Furthermore, the fall WJ in 2013 unexpectedly peaked in December, one month later than its climatology. Data analysis and numerical experiments illustrate that the anomalous changes in the equatorial zonal wind, associated with the strong intra-seasonal oscillation events, are most likely the primary reason for such anomalous WJs activities.

In the tropical Indian Ocean, the equatorial surface currents reverse direction four times a year1. The strong eastward Wyrtki Jets (WJs), forced directly by the equatorial westerlies, occur during the monsoon transition periods of spring and fall2,3. The WJs modulate the zonal distribution of upper ocean mass, heat and salinity flux over the equatorial Indian Ocean4–12 and play key roles in the development of the Indian Ocean Dipole (IOD) events13–18.

Based on satellite and in-situ observations, previous studies of the WJs mostly focused on its dynamics at the sea surface and variations on short timescales. From October 2004, the Research Moored Array for African-Asian-Australian Analyses and Prediction (RAMA) began to provide amount of in-situ ocean current measurements, which revealed the detailed features and multi-timescale variability of the WJs, such as 3D structures, amplitudes, and transport fluxes19. Based on RAMA data, the seasonal to interannual variability of the WJs are widely analyzed. Researchers demonstrated that the interannual variations of the WJs are often associated with IOD and El Niño/Southern Oscillation (ENSO) events20–27. Compared with the seasonal to interannual time scale variation, intra-seasonal variability of WJs is still less studied.

In this paper, we use in-situ observations from the acoustic Doppler current profiler (ADCP) mooring to disclose the intra-seasonal variations of WJs during 2013 and the possible reasons. The rest of the paper is organized as follows: in section 2, observed results from the ADCP in the eastern Indian Ocean are given. We also show the link between currents and the wind forcing based on the data analysis and numerical experiments. In section 3, we provide a summary and discussion of the results of the study. Finally, the data sets and model experiments used in this research are introduced in section 4.

Results

The observed behaviors of WJs. The zonal current evolution at 0°, 85°E observed by the ADCP mooring system is illustrated in Fig. 1c. Two strong eastward WJs occurred in the upper 130 m layer during the boreal spring and fall season of 2013. The strength of 0.5 m s⁻¹ for the zonal velocity had been adopted as the criterion to indicate the jet onset and disappearance. Each of the WJs in 2013 established instantly, prevailed for more than one month, and then decayed quickly. Compared with the climatology (Fig. 1d,e), the WJs in 2013 showed some distinct characteristics. The spring WJ presented mainly in May as expected, and consistent with Iskandar et al.28 and McPhaden et al.25. The fall WJ occurred unexpectedly in the middle of November and peaked in December, which is one month later than the normal period as illustrated in previous observations (Fig. 1d,e) and described in most previous studies (e.g. ref. 22). The late arrival of the fall WJ is also captured by RAMA data. The RAMA

1Center for Ocean and Climate Research, First Institute of Oceanography, State Oceanic Administration, Qingdao 266061, China. 2Laboratory for Regional Oceanography and Numerical Modeling, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China. 3Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China. 4Maldives Meteorological Service, Hulhulé 22000, Maldives. Correspondence and requests for materials should be addressed to L.L. (email: liul@fio.org.cn)
near surface current (Fig. 1b) illustrates that the fall jet of 2013 appeared in late November and then strengthened rapidly in early December.

Climatologically, the fall jet is faster and more intense than that in spring as seen in both in-situ observations and in numerical simulations (e.g. refs 1, 25 and 29–31 see also Figs 1d and 2e). Here, our observations show for the first time the evidence that the spring jet in 2013 (~1.8 m s$^{-1}$) is much faster than that in fall (~1.4 m s$^{-1}$), totally different from previous studies. OSCAR data analysis (not shown) and limited available ADCP in-situ observations25 also suggested that the spring jet in 2013 is more likely the strongest event than any other historical spring jets. Furthermore, it is found that the anomalous strengthened spring jet is only constrained in the ocean upper layer and the subsurface current condition remains normal. Figure 1c also shows the transient eastward equatorial undercurrents in the thermocline (50–200 m depth), which takes place in April, August-November in 2013 and March–April in 2014. The undercurrent in boreal spring (~0.7 m s$^{-1}$) is much stronger than that in summer (~0.3 m s$^{-1}$), which is consistent with the previous results (see also Fig. 1d, e25, 28, 32).

Mechanism. The equatorial ocean is able to respond to westerly winds by developing an accelerating eastward jet in a few days33–38). Previous studies have widely described that the WJs in the Indian Ocean are mainly forced by the local equatorial zonal winds during the transition season between Asian summer monsoon and Asian winter monsoon1, 3, 10, 29–31. For year 2013, what affects the anomalous wind along equatorial Indian Ocean? In order to check the influences of local atmospheric circulation, the anomalous equatorial surface zonal wind and ocean surface currents are shown in Fig. 2. The westerly wind in May (December) 2013 is 80% (41%) stronger than the climatological wind in May (December), and in October-November is 23% weaker than the climatological wind in October-November. Strengthened zonal winds are likely to influence the two WJs significantly (Fig. 2g–h).

The fundamental feature of the WJs is linear dynamics associated with wind forcing4, 45 at different timescales37, which reminded us to figure out whether the interannual variability of the zonal wind is responsible for the variability of the WJs. However, the interannual patterns of the zonal wind anomalies in 2013 are more uniform but much weaker (~0.3 m s$^{-1}$) (Fig. 3a), which may suggest that the interannual part of the wind is not sufficient to induce the aforementioned anomalous behaviors of WJs in 2013.

The tropical Indian Ocean region is strongly affected by intra-seasonal oscillations (ISOs) events and the equatorial westerly anomalies are one of the significant features of ISOs46. ISOs are modulated by the fluctuations of the Asian summer monsoon47–50 and Asian winter monsoon. The oceanic responses to this intra-seasonal wind

![Figure 1](http://www.nature.com/scientificreports/)

Figure 1. The topography of the Indian Ocean based on ETOPO5 (a), where the yellow (red) dots indicate the RAMA (FIO) ADCP mooring locations. Time evolution of daily zonal velocities smoothed with a 5 day running mean (shaded with interval 0.1 m s$^{-1}$) observed by (b) the RAMA mooring at (0°, 80.5°E) from July 2013 to April 2014 and (c) FIO ADCP mooring at (0°, 85°E) from April 2013 to April 2014, with zero thick contours. Mean seasonal cycle of daily zonal velocity smoothed with a 5 day running mean (d, e) based on the RAMA moorings at (0°, 80.5°E) for October 2004 to August 2012 and at (0°, 90°E) for November 2000 to June 2012. Maps are generated using MATLAB R2011a (http://cn.mathworks.com/).
Figure 2. Longitude-time diagram of the climatological (a,e), 2013 (b,f) and anomalous (c,g) zonal surface wind (upper panel, m s$^{-1}$) and current (bottom panel, m s$^{-1}$) averaged over 2°S–2°N band. Time evolution of the longitudinal averaged zonal surface wind (d) and current (h). The black lines indicate the climatology, and the red lines are for year 2013 (f). The criterion of 0.3 m s$^{-1}$ is adopted in (h) to indicate the jets occur. The semiannual eastward WJs are marked by gray bars for climatology and by light-blue bars for 2013. Maps are generated using MATLAB R2011a.

Figure 3. Time-longitude diagram of (a) interannual part (1–5 years band-pass) of zonal wind in 2013 (shaded with interval 0.1 m s$^{-1}$), and (b) intraseasonal part (20–110 days band-pass) of daily zonal wind (shaded with interval 1 m s$^{-1}$) and OLR for 2013 (contours with interval 15 W m$^{-2}$, solid/dashed lines indicating positive/negative values), all averaged between 2°N–2°S. In this figure, different colorbars are used. Figures are plotted using MATLAB R2011a.
forcing in the Indian Ocean have been described based on numerical experiments and in-situ and satellite observations. In order to investigate the mechanisms of the strong zonal wind anomalies in 2013, we analyzed the atmospheric data and conducted three numerical experiments to show the detailed processes associated with these wind anomalies and try to find whether ISOs in the tropical Indian Ocean are able to modulate the surface current anomalies.

As shown in Figs 3b and 2a, the amplitudes of intra-seasonal zonal wind fluctuations in 2013 were as large as the climatological components. During the WJs periods (April-May and October-December), there were several distinct positive and negative ISO events over the tropical Indian Ocean region (Fig. 3b). In particularly, the negative ISOs controlled the tropical Indian Ocean through April and November. The positive phase of ISOs prevailed from late April to mid-May and from late November to mid-December. As a result of ISO events, the surface westerly winds near the equator were particularly strong in mid-May as well as in early December, and the maximum speed is larger than 6 m/s (Figs 2d and 3b).

In the numerical experiments, the Climatology Run (CR) and Main Run (MR) well reproduce the climatological WJs and their anomalous behaviors in 2013 as observation (Fig. 4a,b). However, after removing the ISO-related wind forcing (NoISO), the spring jet in 2013 is similar as the climatology with onset at April and disappearance at June (Fig. 4c,d). The westward propagation phenomena are both visible. Meanwhile, the fall jet begins at early November and strengthens gradually to the peak at December. Both of the WJs in NoISO are much weaker than in MR. It is suggested that the patterns of the anomalous wind associated with the ISOs play important roles on squeezing the WJ into one month (May and December) and enhancing their intensity. In conclusion, the strong ISOs appeared frequently over tropical Indian Ocean and generated significant changes in the surface westerly winds near the equator, which forced the upper ocean and the abnormal WJs occurred.

**Summary and Discussion.** In this study, we present the analysis of observations for the two WJs in the eastern equatorial Indian Ocean during 2013. The results indicate there are remarkably anomalous behaviors of the WJs and the relevant atmospheric circulation in this year. Firstly, the exceptional spring jet is unexpectedly stronger than the fall jet. Secondly, the fall jet peaks in December, one month later than expected. Lastly, there are anomalous equatorial zonal winds over the tropical Indian Ocean, which may contribute to WJ changes.

The two WJs during 2013 both established rapidly, with a four- to five-fold increase in zonal velocity in only 3 days, in early May and late November. Although similar abnormal fall WJs have also been reported for late 2004 and 2011, we have proposed a mechanism for the abnormal event in this study. By conducting a series of numerical experiments, it is suggested that the zonal wind anomalies associated with the strong ISO event is able to modulate the intra-seasonal change of WJ phenomenon. The high-frequency in-situ current data and corresponding satellite remote observations permit us to explore further the detailed micro processes during the whole WJ period. The dynamics and effect of abnormal WJs will be described in a separate publication.
Methods

Measurements from the mooring system. The study utilizes data from an upward-looking 75 kHz RDI ADCP located at 0°, 85°E from 5 April 2013 to 18 April 2014 (Fig. 1c). The instrument head depths ranged between 339–405 m. Hourly averaged horizontal current velocities were recorded at 16 m vertical intervals, then gridded to 10 m resolution in upper 300 m depth. Daily averaged current data were calculated from original data. We neglect near surface measurements in the upper 35 m, which is contaminated by acoustic signals reflected at the surface layer.

The current data obtained from the RAMA moorings is also considered. Two subsurface upward-looking ADCP moorings have been deployed at 0°, 80.5°E since October 2004 and at 0°, 90°E since November 2000, respectively. Based on RAMA observations, the mean seasonal cycle of the zonal velocity is conducted to present the climatological characteristics of the WJs. The limited near surface current at 0°, 80.5°E measured by the current meter measurements at 10 m and 40 m depths are also derived to support our ADCP observations.

OSCAR current data. As the ADCP observations are not able to provide the near surface current information, we adopt the 5-day averaged surface velocity data from Ocean Surface Current Analyses Real Time (OSCAR) for the current surface analysis. This data is available on a 1° × 1° grid starting from October 1992 and represents the average current at 15 m depth. This product is derived from satellite altimetry measurements of ocean surface height, surface winds, and SST, using a diagnostic model of ocean currents based on frictional and geostrophic dynamics.

Wind and OLR data. The daily surface wind data with 1° × 1° resolution from European Centre for Medium-Range Weather Forecasts Interim Reanalysis (ERA-Interim) and daily interpolated outgoing longwave radiation (OLR) data with 2.5° × 2.5° resolution from the National Oceanic and Atmospheric Administration (NOAA) are used to study the mechanisms associated with the changes of the WJs. The climatological annual cycle is calculated based on the available period for each data and the anomalies are obtained by subtracting the climatological annual cycles from their respective daily mean time series.

Model setup. To assess the role of ISO-related zonal wind forcing on the WJs, three numerical experiments are also performed. The ocean general circulation model used in this study is the Princeton Ocean Model (POM), which is configured to the global ocean with a horizontal resolution of 0.5° × 0.5° and 21 vertical layers with higher resolution in the upper mixed layer. The surface forcing fields include 6-hourly surface wind and evaporation data from ERA-Interim, surface heat flux from COADS, and precipitation data from the Tropical Rainfall Measuring Mission. Taking the WOA09 annual climatology of temperature and salinity as the initial condition, the model is spun up from a state of rest for 35 years using climatological forcing fields, and the mean outputs over last three year are referred to as Climatology Run (CR). Restarting from the spun-up solution, the model is integrated forward from 1 September 2012 to 31 December 2013 with the forcing fields described above. This experiment is referred to as Main Run (MR). In order to measure the ISO-related wind forcing effect in the last experiment, named as NoISO, the 20–110 day bandpass filtered signals of the wind forcing field is subtracted, and the resulting experiment is referred to as Main Run (MR).

References

1. Han, W. et al. Dynamics of the eastern surface jets in the equatorial Indian Ocean. J. Phys. Oceanogr. 29(9), 2191–2209 (1999).
2. Schott, F. A. & McCreary, J. P. The monsoon circulation of the Indian Ocean. Prog. Oceanogr. 51(1), 1–123 (2001).
3. Wyrski, K. An equatorial jet in the Indian Ocean. Science 181(4096), 262–264 (1973).
4. Masson, S. et al. A model study of the seasonal variability and formation of the barrier layer in the eastern equatorial Indian Ocean. J. Geophys. Res. 107(C12), 8017, doi: 10.1029/2001JC000832 (2002).
5. Masson, S. et al. Impacts of salinity on the eastern Indian Ocean during the termination of the fall Wyrkki jets. J. Geophys. Res. 108(C3), 3067, doi: 10.1029/2001JC000833 (2003).
6. Murtugudde, R. & Busalacchi, A. J. Interannual variability of the dynamics and thermodynamics of the tropical Indian Ocean. J. Clim. 12(8), 2300–2326 (1999).
7. Nyadjo, E. S., Subrahmanyam, B. & Giese, B. S. Variability of salt flux in the Indian Ocean during 1960–2008. Remote Sens. of Environ. 134(5), 175–193 (2013).
8. Nyadjo, E. S. & McPhaden, M. J. Variability of zonal currents in the eastern equatorial Indian Ocean on seasonal to interannual time scales. J. Geophys. Res. 119, 7969–7986 (2014).
9. Rao, R. & Swakumar, R. Seasonal variability of near-surface thermal structure and heat budget of the mixed layer of the tropical Indian Ocean from a new global ocean temperature climatology. J. Geophys. Res. 105(C1), 995–1015 (2000).
10. Reverdin, G., The upper equatorial Indian Ocean: the climatological seasonal cycle. J. Phys. Oceanogr. 17(7), 903–927 (1987).
11. Strutton, P. G. et al. Biogeochemical variability in the central equatorial Indian Ocean during the monsoon transition. Biogeosci. Discuss. 11(4), 6185–6219 (2014).
12. Thompson, B., Granadosadlan, C. & Salvekar, P. S. Variability in the Indian Ocean circulation and salinity and its relation to Indian Ocean Dipole. J. Mar. Res. 64(6), 853–880 (2006).
13. Han, W. et al. Impact of atmospheric intraseasonal variability in the Indian Ocean: Low-frequency rectification in equatorial surface current and transport. J. Phys. Oceanogr. 34, 1350–1372 (2004).
14. Nagura, M. & McPhaden, M. J. Dynamics of zonal current variations associated with the Indian Ocean Dipole. J. Geophys. Res. 115, C11026, doi: 10.1029/2010JC006423 (2010).
15. Vinayachandran, P. N., Saji, N. H. & Yamagata, T. Response of the equatorial Indian Ocean to an unusual wind event during 1994. Geophys. Res. Lett. 26(11), 1613–1616 (1999).
16. Vinayachandran, P. N., Kurian, J. & Neema, C. P. Indian Ocean response to anomalous conditions in 2006. Geophys. Res. Lett. 34, L15602, doi: 10.1029/2007GL030194 (2007).
17. Zhang, D., Mcphaden, M. J. & Lee, T. Observed interannual variability of zonal currents in the equatorial Indian Ocean thermocline and their relation to Indian Ocean Dipole. Geophys. Res. Lett. 41(22), 7933–7941 (2014).
18. Murtugudde, R. et al. Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–1998. Geophys. Res. 105, 3295–3306 (2000).
www.nature.com/scientificreports/

| 6:29688 | DOI: 10.1038/srep29688 |

19. McPhaden, M. J. et al. RAMA: The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. Bull. Am. Meteorol. Soc. 90, 459–480 (2009).
20. Chu, P. C. Observational studies on association between eastward equatorial jet and Indian Ocean dipole. J. Oceanogr. 66(3), 429–434 (2010).
21. Gnanaseelan, C., Deshpande, A. & McPhaden M. J. Impact of Indian Ocean Dipole and El Niño/Southern Oscillation wind-forcing on the Wyrtki Jets. J. Geophys. Res. 117, C08005, doi:10.1029/2012JC007918 (2012).
22. Grodsky, S. A., Carton, J. A. & Murtugudde, R. Anomalous surface currents in the tropical Indian Ocean. Geophys. Res. Lett. 28(22), 4207–4210 (2001).
23. Joseph, S. et al. Weakening of spring Wyrtki Jets in the Indian Ocean during 2006–2011. J. Geophys. Res. 117(C4), 76–85 (2012).
24. Manthali, R. R. et al. Numerical simulation of seasonal and interannual Indian Ocean upper layer circulation using Miami Isopycnic Coordinate Ocean Model. J. Geophys. Res. 108(C7), 352–367 (2003).
25. McPhaden, M. J., Wang, Y. & Ravichandran, M. Volume Transports of the Wyrtki Jets and Their Relationship to the Indian Ocean Dipole. J. Geophys. Res. doi: 10.1002/2015JC010901 (2015).
26. Nagura, M. & McPhaden, M. J. The dynamics of zonal current variations in the central equatorial Indian Ocean. Geophys. Res. Lett. 35, L23603, doi:10.1029/2008GL035961 (2008).
27. Reppin, J. et al. Equatorial currents and transports in the upper central Indian Ocean: Annual cycle and interannual variability. J. Geophys. Res. 104(C7), 15,495–15,514 (1999).
28. Iskandar, I., Masumoto, Y. & Mizuno, K. Subsurface equatorial zonal current in the eastern Indian Ocean. J. Geophys. Res. 114, C06005, doi:10.1029/2008JC005188 (2009).
29. Knox, R. A. On a long series of measurements of Indian Ocean equatorial currents near Addu Atoll. Deep Sea Res. 23, 211–221 (1976).
30. McPhaden, M. J. Variability in the central equatorial Indian Ocean. Part I: Ocean dynamics. J. Mar. Res. 40, 157–176 (1982).
31. Qiu, Y., Li, L. & Yu, W. Behavior of the Wyrtki Jet observed with surface drifting buoys and satellite altimeter. Geophys. Res. Lett. 36(18), 120–131 (2009).
32. Chen, G. X. et al. Seasonal-to-interannual time-scale dynamics of the Equatorial Undercurrent in the Indian Ocean. J. Phys. Oceanogr. 45, 1532–1553 (2015).
33. Yoshida, K. A theory of the Cromwell Current and equatorial upwelling. J. Oceanogr. Soc. Jpn. 15, 154–170 (1959).
34. Liu L. et al. Dynamic and Thermodynamic Air-Sea Coupling Associated with the Indian Ocean Dipole Diagnosed from 23 WCRP CMIP3 Models. J. Clim. 24, 4941–4958 (2011).
35. Liu L. et al. Indian Ocean variability in the CMIP5 multi-model ensemble: the zonal dipole mode. Climate Dyn. 43(5–6), 1715–1730 (2014).
36. McPhaden, M. J. & Foltz G. R. Intraseasonal variations in the surface layer heat balance of the central equatorial Indian Ocean: The importance of zonal advection and vertical mixing. Geophys. Res. Lett. 40, doi:10.1002/2013GL05536 (2013).
37. Moun J. N. et al. Rapid Acceleration of the Wyrtki Jet in the Central Indian Ocean by a Cyclone-Assisted Wind Burst Embedded within an MJO Event. American Meteorological Society, 18th Conference on Air-Sea Interaction/the 20th Symposium on Boundary Layers and Turbulence. Joint Session 8 (2012).
38. Shinoda, T. et al. Large-scale oceanic variability associated with the Madden-Julian Oscillation during the CINDY/DYNAMO field campaign from satellite observations. Remote Sens. 5(5), 2072–2092 (2013).
39. Cané, M. A. on the dynamics of equatorial currents, with application to the Indian Ocean. Deep Sea Res. I 27(7), 525–544 (1980).
40. Jensen, T. G. Equatorial variability and resonance in a wind-driven Indian Ocean model. J. Geophys. Res. 98(C12), 22533–22552 (1993).
41. O’Brien, J. J. & Hurlburt, H. E. Equatorial jet in the Indian Ocean: theory. Science 184(4141), 1075–1077 (1974).
42. Reverdin, G. & Cané, M. A. The near surface equatorial Indian Ocean in 1979. Part I: linear dynamics. J. Phys. Oceanogr. 14(12), 1817–1828 (1984).
43. Senan, R., Sengupta, D. & Goswami, B. N. Intrinsic ”monsoon jets” in the equatorial Indian Ocean. Geophys. Res. Lett. 30(14), 1750, doi:10.1029/2003GL017583 (2003).
44. Masumoto, Y. et al. Intraseasonal variability in the upper layer currents observed in the eastern equatorial Indian Ocean. Geophys. Res. Lett. 32, L02607, doi: 10.1029/2004GL021896 (2005).
45. Han W. et al. Basin resonances in the equatorial Indian Ocean. J. Phys. Oceanogr. 41, 1252–1270 (2011).
46. Madden, R. A., & Julian, P. R. Observations of the 40–50 day tropical oscillation: A review. Mon. Weather Rev. 112, 814–837 (1994).
47. Goswami, B. N. & Ajaia Mohan, R. S. Intraseasonal oscillations and interannual variability of the Indian Summer Monsoon. J. Clim. 14(6), 1180–1198 (2001).
48. Sengupta, D., Goswami, B. N. & Senan, R. Coherent intraseasonal oscillations of ocean and atmosphere during the Asian Summer Monsoon. Geophys. Res. Lett. 28(21), 4127–4130 (2001).
49. Sikka, D. & Gadgil, S. On the maximum cloud zone and the ITCO over Indian longitudes during the southwest monsoon. Mon. Weath. Rev. 108, 1840–1850 (1980).
50. Webster, P. J. et al. Monsoons: Processes, predictability, and the prospects for prediction. J. Geophys. Res. 103(C7), 14451–14510 (1998).
51. Han, W. et al. Dynamical response of equatorial Indian Ocean to intraseasonal winds: Zonal Flow. Geophys. Res. Lett. 28, 4215–4218 (2001).
52. Sengupta, D. et al. Intraseasonal variability of equatorial Indian Ocean zonal currents. J. Clim. 20, 3036–3055 (2007).
53. Waliser, D. E., Murtugudde, R. & Lucas, L. E. Indo-Pacific Ocean response to atmospheric intraseasonal variability: 1. Austral summer and the Madden-Julian Oscillation. J. Geophys. Res. 108(C5), 249–260 (2003).
54. Iskandar, I. & McPhaden, M. J. Dynamics of wind-forced intraseasonal zonal current variations in the equatorial Indian Ocean. J. Geophys. Res. 116(C6), 102–108 (2011).
55. Bonjean, F. & Lagerloef, G. S. E. Diagnostic model and analysis of the surface currents in the tropical Pacific Ocean. J. Phys. Oceanogr. 32(10), 2938–2954 (2002).
56. Dee, D. P. et al. The ERA-Interim Reanalysis: configuration and performance of the data assimilation system. Q. J. Roy. Meteor. Soc. 137, 553–597 (2011).
57. Liebmann, B. & Smith C. A. Description of a Complete (Interpolated) Outgoing Longwave Radiation Dataset. Bull. Am. Meteorol. Soc. 77, 1273–1277 (1996).
58. Rummukainen, C. et al. The Tropical Rainfall Measuring Mission (TRMM) sensor package. J. Atmos. Oceanic Technol. 15(3), 809–817 (1998).

Acknowledgements

We thank the anonymous reviewers for constructive comments and suggestions on the earlier versions of this manuscript. The authors duly acknowledge the various data sources for the freely available data: RAMA data from http://www.pmel.noaa.gov/tao/rama/, OSCAR surface currents from http://www.oscar.noaa.gov/index.html, ERA-Interim reanalysis data from http://www.ecmwf.int/en/research/climate-reanalysis/era-interim, and
interpolated OLR data from http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html. L.L. is supported by National Basic Research Program of China (2012CB955601), National Natural Science Foundation of China (41376037), NSFC-Shandong Joint Fund for Marine Science Research Centers (U1406404), and Global Change and Air-Sea Interaction Program (GASI-03-01-03-03, GASI-IPOVAI-02). Y.D. appreciates the supports from Shandong Provincial Natural Science Foundation, China (ZR2014DP011), Basic Scientific Research Fund for National Public Institutes of China (2015G05), and Open Fund of the Key Laboratory of Ocean Circulation and Waves, Chinese Academy of Sciences (KLOCAW1405). H.L is supported by National Natural Science Foundation of China (41406012).

**Author Contributions**

Y.D. and L.L. designed the study and wrote the draft of the manuscript. G.H. performed the model running. Y.D., H.W., H.W. and Y.L. carried out the fieldwork. H.L., W.Y., G.Y., Z. and H.W. contributed to interpreting results, discussion of the associated dynamics and improvement of this paper.

**Additional Information**

**Competing financial interests:** The authors declare no competing financial interests.

**How to cite this article:** Duan, Y. et al. Anomalous behaviors of Wyrtki Jets in the equatorial Indian Ocean during 2013. *Sci. Rep.* 6, 29688; doi: 10.1038/srep29688 (2016).

This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/