Review of “Progress in understanding of Indian Ocean circulation, variability, air-sea exchange and impacts on biogeochemistry” by Phillips et al.

This is an ambitious effort to summarize scientific advances since the last comprehensive reviews of Indian Ocean dynamics and their role in the climate system by Schott and McCreary (2001) and Schott et al (2009). The paper contains an impressive amount of information compiled by an impressive list of authors. The writing is generally clear and the range of topics comprehensive. I consider myself an Indian Ocean expert and still learned a lot by reading it.

I list specific comments for the authors to consider below. Some are related to missing ideas, references that should be cited, or organizational issues. The biggest concern I have though is the length of the paper and the effort to include a comprehensive review of ocean dynamics with biogeochemistry. I appreciate that the authors are attempting an interdisciplinary synthesis, but in my opinion it doesn’t work. The problem is that the paper is very long (80 pages of text). The sections on biogeochemical processes break the flow of ideas on ocean dynamics, are not complete, and don’t do justice to range of important topics on biogeochemistry. For example, there is almost no meaningful discussion of OMZs and little discussion of how vertical mixing (section 7.3) affects biogeochemistry. You could add more on these and other BGC topics (like the ocean carbon cycle), but that is not the right solution with the paper so long already. My suggestion would be to focus this paper on just ocean dynamics to keep it to a manageable length. Then write a second companion paper using the material in this paper as a start on how ocean circulation and mixing processes affect Indian Ocean biogeochemistry, and what the implications are for ecosystems and fisheries. Some topics on biogeochemistry may still fit in a dynamics paper, like how primary productivity affects penetrative radiation in the mixed layer, but they will be limited and focused.

Specific comments follow in the order in which the occur.

*Abstract and Introduction. Calling out only IIOE-2 is inappropriate. IIOE-2 started in 2015. Much of the progress reviewed in this paper between the Schott and McCreary and Schott et al reviews has been made in programs that predated IIOE-2. Mentioning IIOE-2 to the exclusion of other national, bilateral and international (e.g. CLIVAR, GOOS) programs leaves the impression that it is only IIOE-2 that is responsible for all the wonderful science reported in the paper. This can be easily remedied by removing mention of IIOE-2 from the abstract and being more inclusive of other programs in the introduction. I flag this issue in the final section as well.

*Line 82. Call out the Ningaloo Nino here. This was a major new discovery in the past 10 years that gave rise to the term “marine heat wave” as noted on lines 1593-95.

*Lines 152ff an Lines 194ff. The shallow meridional overturning circulation in the Indian Ocean consists to two distinct cells, the subtropical cell (STC) and the cross-equatorial cell (CEC) (Lee, 2004). The ascending branches of these cells connect to different upwelling zones (e.g. SCTR region in the case of the STC, Somali in the case of the

CEC). These cells and need to be discussed in more detail rather than simply grouped together as part of the “meridional overturning circulation.”

*Line 251 (Section 3.1.1/Fig.6) Indo-Pacific warming trends are warping the life cycle of the MJO, which is spending less time over the Indian Ocean, more time over the Pacific (Roxy et al, 2019). This warped life cycle is projecting onto mean rainfall trends in various parts of the globe and should be mentioned.

*Lines 277ff. Kelvin waves propagate energy not only eastward but downward into the interior ocean; they also propagate into the Indonesian seas where they affect the ITF (Pujiana and McPhaden, 2020). Intraseasonal winds excite Rossby waves directly, but Rossby wave are also excited by reflection of wind-forced Kelvin waves at the eastern boundary (Nagura and McPhaden, 2012; Pujiana and McPhaden, 2020). These points should be mentioned.

*Line 326. Cite Nagura and McPhaden (2014) here. Also, as they point out, it is not just intraseasonal time scale variability that rectifies into mean flows along the equator, but also lower frequencies as well (especially semi-annual time scales). This point should be expanded upon in short subsection at the start of Section 4.1 (see below).

*Line 399-400 Reference Chelton et al (2001) here

*Line 407. “…tropical Indian Ocean” rather than “tropics” for clarity.

*Section 4.1/4.2 Reference Nagura and McPhaden (2018) who used Argo and CTD today to map out the circulation and water masses in density classes associated with the shallow overturning circulation, with emphasis on the southern hemisphere.

*Line 467-70. Imprecise language: “conveys”?? Is this advection, waves, other?

*Line 826. Section 4.1
The mean circulation along the equator is unique compared to the Pacific and Atlantic and should be highlighted in a subsection at the start of 4.1. Mean westerly winds are downwelling favorable: surface convergence and thermocline divergence that are part of that downwelling circulation have been described in Wang and McPhaden (2017) from Argo and RAMA data (mean downwelling is mentioned in lines 898-900 but would be better to include in a subsection that included other notable interbasin differences in mean equatorial circulation). Also, in the Pacific and Atlantic, easterly winds produce an eastward mean undercurrent in the thermocline but in the Indian Ocean westerly winds do not produce a mean westward undercurrent. The reason is that nonlinear momentum advection drives mean eastward currents in the thermocline that flow up the zonal pressure gradient (Nagura and McPhaden, 2014). The near surface meridional mean flow is southward across the equator in the interior ocean in the surface branch of the cross-equatorial cell (Lee, 2004) consistent with Sverdrup dynamics (Wang and McPhaden, 2017). Also, Horii et al (2013) and Wang and McPhaden (2017) present the first observational evidence for the “equatorial roll”, unique to the Indian Ocean and first

identified in models (Wacogne and Pacanowski, 1996) as reviewed in Schott et al (2009).

*I am surprised that “meridional circulation” (section 4.3.2) does not highlight the seasonal cross-equatorial flow of mass and heat. These variations need to be discussed. In particular, the seasonal cross-equatorial mass flux is oppositely directed along the western boundary and interior (Beal et al., 2013). Flow in the interior is directed from the summer to the winter hemisphere (Horii et al., 2013; Wang and McPhaden, 2017) consistent with monsoon wind forced Ekman and Sverdrup dynamics as proposed in the model study of Miyama et al. (2003). Heat transports associated with these cross equatorial flows help to moderate seasonal climate of the region.

*Section 4.3.2 Meridional Circulation is more than just high frequency biweekly mixed Rossby gravity waves and similar high frequency phenomena. It includes the meridional overturning circulation, which includes the cross equatorial cell and subtropical cell, their means, seasonal, interannual and longer term variations. This section should be retitled as something like 5-30 day ocean waves and instabilities. Note also that the recent studies on the topic of mixed Rossby gravity waves by Arzeno et al (2020) and Pujiana and McPhaden (2021) should be referenced.

In this section you could also include a discussion of convectively coupled atmospheric Kelvin waves (Baranowsky et al, 2016) and how they force ocean Kelvin waves, affect surface heat fluxes, and generate upper ocean turbulence (Pujiana and McPhaden, 2018).

*There are two sections 4.3.4, which is an error in labelling.
Section 4.3.4 (the first one) The undercurrents also undergo significant inter annual variations related to the IOD. These variations are important in the mass and heat balance on IOD time scales, with significant impacts on upwelling and SST (Zhang et al., 2014; Nyadjro and McPhaden, 2014)

*Lines 852-53 and 909-10: Reference Nyadjro and McPhaden (2014)

*Line 1279. For the strong negative IOD event in 2016, the Indian Ocean influence overwhelmed that of the Pacific leading to record low ITF volume transports because of the reduction in the interbasin pressure gradient (Pujiana et al., 2019).

*Line 1281. Reference Pujiana and McPhaden (2020)

*Line 1289-1295. Dong and McPhaden (2016) should be referenced here especially in relation to the recent hiatus in global warming and the interhemispheric contrasts in the Indian Ocean related to Pacific forcing of ITF mass transports

*Line 1433-45 repeats some of the earlier discussion of the ITF

*Line 1446-49. Two recent studies on this topic should be referenced: Volkov et al (2020) and Nagura and McPhaden (2021)

*Line 1496. IOD variability internal to the Indian Ocean resembles recharge oscillator dynamics for ENSO, but equatorial heat content is less effective as a precursor for the IOD than for ENSO because of the strong impact of remote forcing from the Pacific on the IOD. Internal Indian Ocean dynamics however may contribute to the biennial nature of the IOD through the cycling of Kelvin/Rossby wave energy across the basin (McPhaden and Nagura, 2014).

*Section 7.2.3 repeats some of the same material on Wyrtki jets and ISOs presented previously

*Line 1805. Observations have also have captured energetic and consequential 5-20 day convectively coupled Kelvin waves in the atmosphere (Baranowsky et al, 2016) that generate oceanic Kelvin waves, affect surface heat fluxes and generate upper ocean turbulence (Pujiana and McPhaden, 2018).

*Line 1531-41. Not a BGC subsection like for other topics?

*Section 7.3 This section is presumably only about the Bay of Bengal, but mixing and the role of inertial waves in the SCTR should also be discussed (e.g. Cuypers et al, 2013; Sabu et al., 2021) in the paper.

*Line 1834-35. Even longer records (10 years) have been used to infer via inverse methods the seasonal cycle of mixing, Kt and barrier layer effects and how they vary spatially in the Bay of Bengal (Girishkumar et al, 2020).

*Line 1873-75. The influence of barrier layer induced subsurface warm layers on SST is not limited to just cyclone events (e.g. Girishkumar et al, 2013)

*I originally thought Section 7.5 was supposed to be for the entire paper, but then realized that is just about the Bay of Bengal. Section 7 has more subsections than any other part of the paper which was part of my confusion. After almost 80 pages though, I thought other pieces needed to be put together, like how oceanic variability affects monsoon rainfall (see below) and how biogeochemistry affects ecosystems and fisheries.

*Section 8. The big question is how does the Indian Ocean affect the monsoons and on what time/space scales? This is not addressed in a coherent way in the paper. I would have expected Izumo et al (2008) and articles like it on this topic to be discussed somewhere since it is such an important question.

*Line 1964. IIOE-2 contributed to the progress reported in this review, but only beginning in 2015. The way this sentence is worded does not do justice to all the other programs involved.

References

All references beginning with Z are missing
England et al 2014 reference is missing

Additional References

Arzeno, I. B., S. N. Giddings, G. Pawlak, and R. Pinkel, 2020: Generation of Quasi-Biweekly Yanai Waves in the Equatorial Indian Ocean. *Geophys Res Lett*, 47, e2020GL088915. https://doi.org/10.1029/2020GL088915

Baranowski, D. B., M. K. Flatau, P. J. Flatau, and A. J. Matthews (2016), Impact of atmospheric convectively coupled equatorial kelvin waves on upper ocean variability, Journal of Geophysical Research-Atmospheres, 121(5), 2045–2059, doi:10.1002/2015jd024150.

Beal, L. M., Hormann, V., Lumpkin, R., & Foltz, G. R. (2013). The Response of the Surface Circulation of the Arabian Sea to Monsoonal Forcing, Journal of Physical Oceanography, 43(9), 2008-2022. https://journals.ametsoc.org/view/journals/phoc/43/9/jpo-d-13-033.1.xml

Chelton, D.B., S.K. Esbensen, M.G. Schlax, N. Thum, M.H. Freilich, F.J. Wentz, C.L. Gentemann, M.J. McPhaden, and P.S. Schopf, 2001: Observations of coupling between surface wind stress and sea surface temperature in the eastern tropical Pacific. J. Climate, 14, 1479–1498.

Cuypers, Y., X. Le Vaillant, P. Bouruet-Aubertot, J. Vialard and M. J. McPhaden, 2013: Tropical storm-induced near-inertial internal waves during the Cirene experiment: energy fluxes and impact on vertical mixing*. J. Geophys. Res., 118,* 358-380, doi: 10.1029/2012JC007881.

Dong, L. and M.J. McPhaden, 2016: Interhemispheric SST gradient trends in the Indian Ocean prior to and during the recent global warming hiatus. *J. Climate*, *29*, 9077-9095.

Girishkumar, M. S., M. Ravichandran and M. J. McPhaden, 2013: Temperature inversions and their influence on the mixed layer heat budget during the winters of 2006-07 and 2007-08 in the Bay of Bengal. *J. Geophys. Res.,118*, doi:10.1002/jgrc.20192.

Girishkumar, M.S., K. Ashin, M.J. McPhaden, B. Balaji, and B. Praveenkumar, 2020: Estimation of vertical heat diffusivity at the base of the mixed layer in the Bay of Bengal. *J. Geophys. Res.*, *125*, e2019JC015402. http://dx.doi.org/10.1029/2019JC015402.

Horii, T., K. Mizuno, M. Nagura, T. Miyama, and K. Ando (2013), Seasonal and interannual variation in the cross-equatorial meridional currents observed in the eastern Indian Ocean, J. Geophys. Res., 118, 6658–6671, doi:10.1002/2013JC009291.

Izumo, T., C. de Boyer Montegut, J.J. Luo, S.K. Behera, S. Masson, and T. Yamagata, 2008: The role of the western Arabian Sea upwelling in Indian monsoon rainfall variability. J. Clim., 21, 5603–5623, doi:10.1175/2008JCLI2158.1.
McPhaden, M. J. and M. Nagura, 2014: Indian Ocean Dipole interpreted in terms of Recharge Oscillator theory. *Clim. Dyn., 42*, 1569–1586. doi 10.1007/s00382-013-1765-1.

Miyama, T., J. P. McCreary, T. G. Jensen, J. Loschnigg, S. Godfrey, and A. Ishida (2003), Structure and dynamics of the Indian-Ocean crossequatorial cell, Deep Sea Res., Part I, 50(12), 2023–2047.

Nagura, M., and M. J. McPhaden, 2012: The dynamics of wind-driven intraseasonal variability in the equatorial Indian Ocean. *J. Geophys. Res., 115,* C07009, doi:10.1029/2011JC007405.

Nagura, M. and M. J. McPhaden, 2014: Zonal momentum budget along the equator in the Indian Ocean from a high resolution ocean general circulation model. *J. Geophys. Res.*, *119*, 4444-4461, doi:10.1002/2014JC009895.

Nagura, M. and M.J. McPhaden, 2018: The Shallow Overturning Circulation in the Indian Ocean, *J. Phys. Oceanogr., 48*, 413-434.

Nagura, M. and M. J. McPhaden, 2021: Interannual variability in sea surface height at southern mid-latitudes of the Indian. J. Phys. Oceanogr., https://doi.org/10.1175/JPO-D-20-0279.1.

Nyadjro, E. and M. J. McPhaden, 2014: Variability of zonal currents in the eastern equatorial Indian Ocean on seasonal to interannual time scales. *J. Geophys. Res.*, *119*, 7969-7986, doi:10.1002/2014JC010380.

Pujiana, K. and M.J. McPhaden, 2018: Ocean's response to the convectively coupled Kelvin waves in the eastern equatorial Indian Ocean. *J. Geophys. Res., 123*, 5727-5741. https://doi.org/10.1029/2018JC013858.

Pujiana, K. and M.J. McPhaden, 2020: Intraseasonal Kelvin waves in the equatorial Indian Ocean and their propagation into the Indonesian Seas. *J. Geophys. Res*, *25*. https://doi.org/10.1029/2019JC015839.

Pujiana, K. and M. J. McPhaden, 2021: Biweekly mixed Rossby-Gravity waves in the equatorial Indian Ocean. J. Geophys. Res., https://doi.org/10.1029/2020JC016840.

Pujiana, K., M.J. McPhaden, A.L. Gordon, and A.M. Napitu, 2019: Unprecedented response of Indonesian throughflow to anomalous Indo-Pacific climatic forcing in 2016. *J. Geophys. Res*., 124, 3737-3754. https://doi.org/10.1029/2018JC014574.

Roxy, M.K., P. Dasgupta, M.J. McPhaden, T. Suematsu, C. Zhang, and D. Kim, 2019: Twofold expansion of the Indo-Pacific warm pool warps the MJO life cycle. *Nature, 575*, 647-651. https://doi.org/10.1038/s41586-019-1764-4.

Sabu, P., M.P. Subeesh, J.V. George et al., 2021: Enhanced subsurface mixing due to near-inertial waves: observation from Seychelles-Chagos Thermocline Ridge. Ocean Dynamics 71, 391–409. https://doi.org/10.1007/s10236-020-01430-z
Volkov, D.L., S.-K. Lee, A.L. Gordon, and M. Rudko, 2020: Unprecedented reduction and quick recovery of the South Indian Ocean heat content and sea level in 2014-2018. Sci. Adv., 6, eabc1151

Wacongne, S., and R. C. Pacanowski (1996), Seasonal heat transport in a primitive equation model of the tropical Indian Ocean, J. Phys. Oceanogr., 26, 2666–2699.

Wang, Y. and M.J. McPhaden, 2017: Seasonal Cycle of Cross-Equatorial Flow in the Central Indian Ocean. *J. Geophys. Res*., *122*, doi:10.1002/2016JC012537.

Zhang, D., M. J. McPhaden, and T. Lee, 2014: Observed Interannual Variability of Zonal Currents in the Equatorial Indian Ocean Thermocline and Their Relation to Indian Ocean Dipole. *Geophys. Res. Lett*., 41, 7933-7941, doi: 10.1002/2014GL061449.