The referee comments are italicized. Answers in regular typeface. Actions taken in red.

Interactive comment on "Physical control of the interannual variations of the winter chlorophyll bloom in the northern Arabian Sea" by M. G. Keerthi et al.

Anonymous Referee #2
Received and published: 7 November 2016

General Comments:
The study, using multiple datasets and a model, examines the processes related to the interannual variability of winter chlorophyll in the northern Arabian Sea. The Arabian Sea, especially the coastal-open ocean upwelling regions are subjected to an interplay of oceanic processes, such as coastal upwelling, Ekman pumping, mixing, entrainment and lateral/vertical advection (Vialard et al 2012). Other than these physical processes, changes in light penetration and nutrient supply also regulate the chlorophyll content in this basin. Hence it is an interesting task to investigate the biophysical interactions over this region, which result in the observed chlorophyll variations. However, other than presenting several correlation analysis between the mixed layer depth and chlorophyll variations, the study does not delve in depth into the processes governing the chlorophyll changes. The paper is neatly written but it is difficult for the reviewer to comprehend what the prime objectives of the study are, or if there is anything novel in the results. Due to these shortcomings, and as detailed below, I do not recommend the manuscript for publication at its current state.

As underlined by the first reviewer, our study "*assumes importance because, while the seasonal chlorophyll variations in the Arabian Sea are rather well described, their interannual variability is largely unexplored because of the limitation in long time-series data.*" As we pointed out in the introduction (P3 L1-13), there have indeed been to date only two studies addressing the interannual chlorophyll variations in the northern Arabian Sea in winter and their related mechanisms (Prasanna Kumar et al., 2001 and Wiggert et al., 2002). These studies proposed different mechanisms on the basis of a very limited temporal sampling (two one-month-long in-situ time series in February 1995 and 1997 for Prasanna Kumar et al., 2001) and three consecutive winters from 1998 to 2000 for Wiggert et al., 2002). Our study tests the hypotheses of those two studies based on a much longer dataset (12 winters in observations and 20 winters in the model). In addition, while Wiggert et al. (2002) derived interannual thermocline variations from a model simulation, we derive these variations directly from in-situ (Argo) observations. Both our observational and model results support the Prasanna Kumar et al. (2001) hypothesis rather than the one of Wiggert et al. (2002). It hence better ascertain the mechanisms at stake in driving the chlorophyll interannual variability in the northern Arabian Sea. Another added value of the present study is to provide for this first time an intercomparison of all existing remotely sensed chlorophyll products in this region. We thus believe that our study brings new insights for this highly productive region with no consensus on the mechanisms responsible for year-to-year variations. We underline those points better in the introduction and discussion sections of the revised manuscript.

The referee comments are italicized. Answers in regular typeface. Actions taken in red.

Related References:

Prasanna Kumar, S., Ramaiah, N., Gauns, M., Sarma, V., Muraleedharan, P.M., Raghukumar, S., Kumar, M.D., Madhupratap, M. : Physical forcing of biological productivity in the northern Arabian Sea during the Northeast Monsoon, Deep-Sea Research II 48, 1115–1126, 2001.

Wiggert, J. D., Murtugudde, R., and McClain, C. R.: Processes controlling interannual variations in wintertime (northeast monsoon) primary productivity in the central Arabian Sea, Deep Sea Res., Part II, 47,2319 – 2343, 2002.

Specific Comments:

1. The study revolves around a hypothesis put forward by Wiggert et al (2002) that the interannual variations of chlorophyll intensity is regulated by diurnal mixing.

As pointed above, we examine two previously proposed mechanisms: that proposed by Wiggert et al. (2002) but also that suggested by Prasanna Kumar et al. (2001).

The current study, using correlation analyses, points out that the winter chlorophyll variability is tied to the mixed layer depth anomalies, which are associated with the surface heat flux anomalies. However, this factor has already been pointed by studies like Prasanna Kumar et al (2002), where they point out that surface cooling (due to evaporation) in the northern Arabian Sea, combined with reduced incoming solar radiation and high salinity, drives convective mixing, resulting in the upward transport of nutrients in the mixed layer. Similar to the current study, this study also compares two anomalous years and describe the processes involved.

We think that the current study has several merits:

- There are currently two contradictory hypotheses about the physical control of interannual chlorophyll variability in winter in the Northern Arabian Sea (Wiggert et al., 2002 vs Prasanna Kumar et al., 2001), which we examine separately, finding more support for the latter than for the former.
- Wiggert et al. (2002) and Prasanna Kumar et al. (2001) work are respectively based on 3 and 2 winters. As opposed to the reviewer statement, we do not only analyse two anomalous years but examine long datasets that span 2002-2013 (12 years) derived from in-situ observations for MLD and thermocline and several satellite datasets for chlorophyll along with outputs from a model simulation that spans 1993-2012 (20 years), which considerably strengthens the robustness of our results.
- We also provide an intercomparison of chlorophyll datasets in this region, which was necessary, given the large differences among the datasets. Stating that chlorophyll datasets generally agree for the phase of signals but not their amplitude is an important and useful information for studying chlorophyll variability in the Arabian Sea.

2. Also, apart from the correlation analyses between mixed layer depth (and nutrients) and chlorophyll concentrations, the manuscript does not examine how the oceanic processes such as the Ekman pumping, offshore advection etc plays a role on the interannual variability.

The referee comments are italicized. Answers in regular typeface. Actions taken in red.

To address the reviewer comment, we performed composite analysis similar to Figure 10 but looking at the wind stress curl (i.e. the driver of Ekman pumping) and surface currents (which could induce advective changes) anomalies associated with enhanced winter blooms. As shown on Figure R2-1 below, this analysis show that interannual chlorophyll fluctuations are not associated with coherent Ekman pumping and surface currents variations in the northern Arabian Sea (while there is a clear MLD signal, see Figure 10b). We also found no significant correlations between interannual anomalies of the wind curl and surface currents with chlorophyll anomalies in the northern Arabian Sea box. These extra-analyses hence suggest that advection of chlorophyll and/or nutrient is unlikely to play a strong role on the interannual fluctuations of the winter bloom in the Arabian Sea. These analyses are mentioned explicitly in the updated version of the manuscript, referring to Figure R2-1 as not shown.

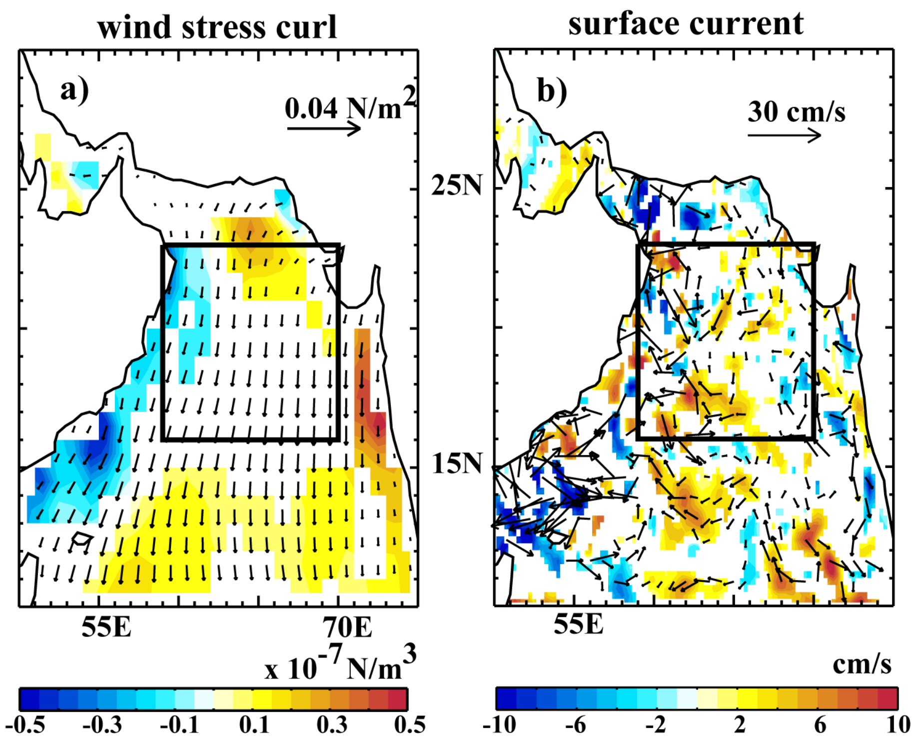

Figure R2-1: Observed interannual anomalies of **(a)** ERAI wind stress curl (color) and wind stress (vectors) for composite surface chlorophyll blooms (highlighted on Figure 8). Like for MLD and TCD composites, wind stress curl and wind stress composite are built from the months of February of the same year. (**b**) Same as left, but for surface currents anomalies derived from GEKCO product (Bonjean and Lagerloef, 2002). Regions where composite values are less than the standard error are displayed in white.

Related References:

Bonjean, F., Lagerloef, G.S.E. : Diagnostic Model and Analysis of the Surface Currents in the Tropical Pacific Ocean. J. Physical Oceano., 2, 10, 2938-2954, 2002.

Also, to counter the study by Wiggert et al (2002), the current study does not examine the contributions due to diurnal mixing.

We do not explicitly investigate the diurnal cycle in observations because the Argo data are too sparse to be able to analyse the diurnal variability from this dataset. A proper investigation of the impact of diurnal variability on interannual chlorophyll variations from observations would require continuous and long-term temperature and chlorophyll profiles from a fixed location, which are not available to date. Yet, if Wiggert's mechanism was dominating, there should be a negative correlation between interannual variations of chlorophyll and thermocline depth (i.e. a deeper thermocline leading to lower chlorophyll concentrations operating through daily dilution): Table 2, 3 and Figure 8, 9, 10 clearly demonstrates it is not the case in observations, neither over the entire winter period, nor during the beginning (December-January) or the end (February-March) of the winter monsoon period. In addition, despite the absence of a diurnal cycle in the model forcing (i.e. by construction, the model can't reproduce the Wiggert's mechanism), the model shows a good agreement with observed interannual chlorophyll variability in winter in the northern Arabian Sea (see Figures 7a and 10), which is an indirect evidence that the bulk of interannual chlorophyll variations are not linked to the diurnal cycle mechanism. Instead, we find large and statistically significant correlations between MLD and chlorophyll variations at the end of the winter monsoon, suggesting that the mechanism proposed by Prasanna Kumar et al. (2001) (a modulation of nutrient entrainment into the mixed layer, i.e. a mechanism similar to the one proposed at seasonal timescales) dominates during that period. During the early winter monsoon, neither of the two mechanisms appears to drive the weaker interannual chlorophyll anomalies during that season. These points were already mentioned in the submitted version of the paper from P11 L8 to P12 L10 but this discussion is expanded in the revised manuscript to better stress these points out.

In fact, it is not clear to me where Wiggert et al (2012) says that mixed layer variations are not important in controlling the chlorophyll concentrations – though the study says that diurnal changes of mixed layer are important.

The mechanism proposed by Wiggert et al., 2002 might indeed imply a correlation between the MLD anomalies and the chlorophyll anomalies. But it also implies a control of MLD and chlorophyll anomalies by the thermocline depth, which is not seen in our results (see L5-6 of the abstract of Wiggert et al., 2002). We point this out better in the revised version.

3. Page 10, Line 10 says the MLD deepening is controlled by convective overturning, which in turn is controlled by surface heat fluxes. It is not clear to me how the cause and effect is separated here. Surface net heat flux is inversely proportional to the mixed layer depth. Hence it is not surprising as in Fig.10 that they show a good correlation.

There is a misunderstanding here. We agree with the reviewer that the sea surface temperature (SST) tendency induced by atmospheric heat flux forcing into the ocean (the term Qnet/(rho*Cp*MLD)) could be anticorrelated with MLD variations because the MLD appears in the two terms. However, the y axis of Figure 12c does not show Qnet/(rho*Cp*MLD) but the net heat flux at the ocean-atmosphere interface Qnet and there is no reason for the surface net heat flux to be inversely proportional to the mixed layer depth. Indeed surface net heat flux is controlled by atmospheric parameters (wind speed, cloudliness, stability…), which are not controlled by MLD variations. On the other hand the surface heat fluxes exert a strong control on the mixed layer depth. We clarify this in the revised manuscript.

4. Page 12, Line 20 suggests that the interannual variations in the surface flux are modulated by ENSO (strong correlations). The connection with ENSO was shown by Murtuggude et al (1999), which examined the chlorophyll changes in the Indian Ocean with respect to the 1997-1998 El Niño and the 1998 La Niña. The El Niño – La Niña episodes were accompanied by changes in chlorophyll over the Arabian Sea, with low Chl concentrations during the El Niño period, followed by anomalously high concentrations during the La Niña episode. These changes were attributed to local ocean-atmospheric dynamics linked to the shifts in the Walker circulation. On a similar case, the authors compare 2007 and 2008 MLD and chlorophyll. 2006/7 was a weak El Niño year and 2007/8 was a La Niña year, which is clearly reflected in the Chl anomalies, with the former resulting in negative anomalies and the latter in positive anomalies. Going by correlations as in the current study, I can say that ENSO is a major component in driving both the surface flux and chlorophyll anomalies in the Arabian Sea, on interannual timescales.

Thanks for pointing this out. We have expanded the discussion about the remote control of ENSO onto the Arabian Sea climate and biogeochemistry in winter in the revised discussion. We will now refer to Murtuggude et al. (1999) who showed that surface chlorophyll was anomalously high during December 1997 and January 1998, consistent with the elevated entrainment flux of nutrients into the euphotic zone expected during stronger than usual northeast monsoons. This indeed suggests from a single event that the 1997/98 El Niño could be responsible for this. We will however also refer to Wiggert et al. (2009) results that show a contrasted biological response of the western Arabian Sea to the 1997/1998 and 2006/2007 El Niño events, with an overall decrease of productivity during the earlier and a slight increase during the latter. Finally, we will also discuss the results from Currie et al. (2013) that showed ENSO control on chlorophyll interannual variations in the Arabian Sea during fall and winter is larger than that of the IOD. In line with these results, our analysis shows that interannual variations of the 2-m air temperature in winter in the northern Arabian Sea box is partly correlated with El Nino-Southern Oscillation (ENSO) index and weakly correlated with Indian Ocean Dipole (IOD) index. The positive correlation sign is however opposite to Murtuggude et al. (1999) results as it indicates that an El Niño event should lead to a reduced winter monsoon. To further explore this aspect, Table R2-1 shows the winter T2m correlation with ENSO index for two different periods: it illustrates that the influence of ENSO on the AS in winter is not very stable in time with large correlations when calculated over the recent 2002-2011 period (0.77) and far weaker correlations when performing this analysis over the extended 1993-2011 period (0.27). This table also shows that all observed and model chlorophyll products do show a negative correlation between ENSO and interannual fluctuations of the winter bloom, consistent with the hypothesis that an El Niño event drive a weaker winter monsoon and hence a weaker bloom. The level of correlation is however modest in all datasets (ranging from -0.11 in AVW to -0.44 in GSM), indicating that ENSO is not the only driver of the interannual winter bloom variations in this region. These new results along with their consistency with previous literature will be discussed in a new paragraph that details ENSO influence on the Arabian Sea in winter.

	IOD (SON)	**ENSO (NDJ)**
T2a (DJFM 1993-2011)	-0.06	0.27
T2a (DJFM 2002-2011)	0.05	**0.77**
SChla_OC-CCI (2002-2011)	0.07	-0.34
SChla_MODIS (2002-2011)	0.26	-0.39
SChla_MERIS (2002-2011)	0.04	-0.37
SChla_GSM (2002-2011)	0.24	-0.44
SChla_AVW (2002-2011)	0.05	-0.11
SChla_Model (2002-2011)	0.02	-0.30
MLDa_Argo (2002-2011)	0.21	-0.38
MLDa_Model (2002-2011)	0.08	-0.29

Table R2-1: Correlation of IOD and ENSO index with NAS box averaged winter (DJFM) surface temperature anomaly (T2a), surface chlorophyll anomaly (SChla) derived from different satellite products and model, and in-situ and model MLD anomalies (MLDa).

Related References:

Currie, J., Lengaigne, M., Vialard, J., Kaplan, D., Aumont, O., Maury, O.: Indian Ocean Dipole and El Niño/Southern Oscillation impacts on regional chlorophyll anomalies in the Indian Ocean. Biogeosciences 10: 5841– 5888, 2013.

Murtugudde, R., McCreary, J. P., and Busalacchi, A. J.: Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997 –1998, J. Geophys. Res., 105, 3295–3306, 2000.

Wiggert, J. D., Vialard, J., and Behrenfeld, M. J.: Basinwide modification of dynamical and biogeochemical processes by the positive phase of the Indian Ocean Dipole during the SeaWiFS era, in: Indian Ocean Biogeochemical Processes and Ecological Variability, vol. 185, edited by: J. D. Wiggert, R. R. Hood, S. Wajih, A. Naqvi, K. H. Brink, and S. L. Smith, p. 350, 2009.

5. Also, how do the changes in Eurasian winds (Page 13, Line 8, Goes et al 2005) compare with the ENSO impact? Are the winds increasing, and do they have an impact on the Chl in the Arabian Sea? If so, how does it ride on the interannual variability imposed by ENSO?

To have a preliminary look into the long-terms trends in winter in the Arabian Sea, Table R2-2 provides the linear trends of wind and chlorophyll in the Arabian Sea. This Table indicate that winds exhibit an increasing trend over the 2002-2011 period. When calculated over an extended period (1993-2011), these winds however show a decreasing trend. Regarding the chlorophyll trends, there is no consistent trend amongst products, some of them showing a decreasing trend (OC-CCI, MERIS, AVW) some others showing an increasing trend

(MODIS, GSM). These discrepancies and uncertainties related to the short data length prevent a robust assessment of these trends. We however performed the analyses in the paper using detrended data and found that our results regarding the interannual variability are robust. This is illustrated on Figure R2-2 that shows an analysis similar to that of Figure 9 but for detrended data. This is pointed out in the revised version.

Dataset	Period	Trend
Wind-ERAI	1993-2011	-0.006
Wind-ERAI	2002-2011	0.04
SChla_OC-CCI	2002-2011	-0.005
SChla_MODIS	2002-2011	0.015
SChla_MERIS	2002-2011	-0.007
SChla_AVW	2002-2011	-0.042
SChla_GSM	2002-2011	0.03
SChla_Model	1993-2011	-0.0015
SChla_Model	2002-2011	0.0023

Table R2-2: Linear trends for NAS box averaged winter (DJFM) surface wind speed anomaly from ERA-Interim and surface chlorophyll anomaly (SChla) derived from different satellite products and model.

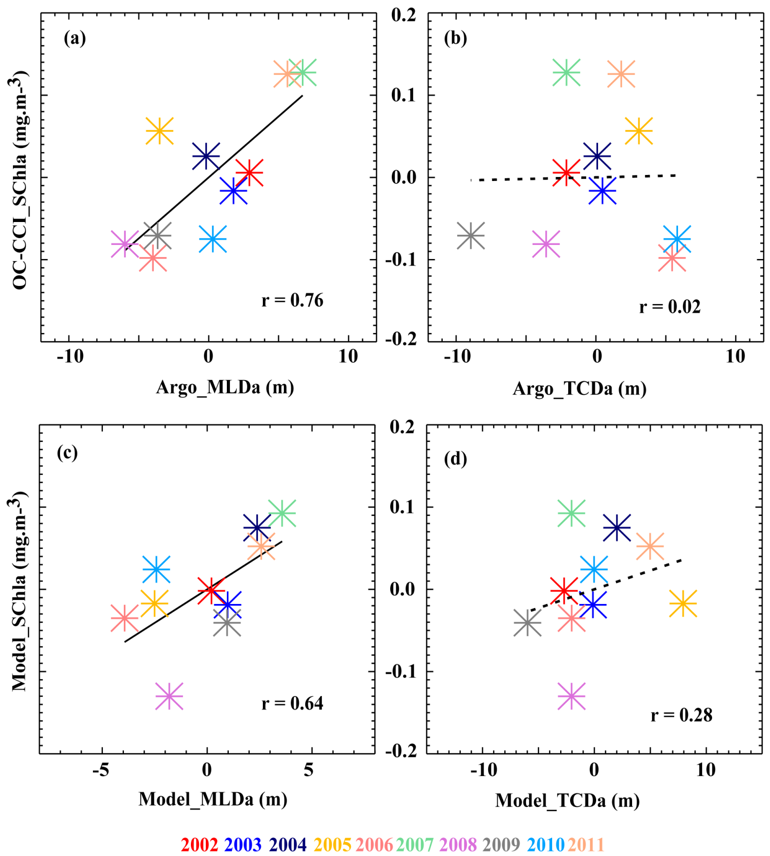

Figure R2-2: Scatterplot of winter (DJFM), NAS-averaged detrended OC-CCI surface chlorophyll anomalies (OC-CCI_SChla) against observed detrended (a) MLD anomalies (Argo_MLDa) and (b) thermocline depth anomalies (Argo_TCDa). (c-d) Idem for Model.