HAL
open science

Physical and biological response of the Arabian Sea to tropical cyclone Phyan and its implications

P. Byju, S. Prasanna Kumar

To cite this version:

P. Byju, S. Prasanna Kumar. Physical and biological response of the Arabian Sea to tropical cyclone Phyan and its implications. Marine Environmental Research, 2011, 10.1016/j.marenvres.2011.02.008 . hal-00703489

HAL Id: hal-00703489

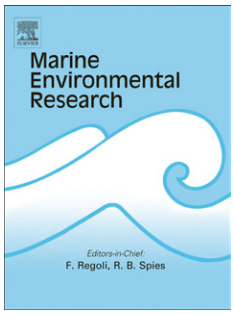
https://hal.science/hal-00703489

Submitted on 2 Jun 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript



Title: Physical and biological response of the Arabian Sea to tropical cyclone Phyan and its implications

Authors: P. Byju, S. Prasanna Kumar

PII: S0141-1136(11)00035-3

DOI: 10.1016/j.marenvres.2011.02.008

Reference: MERE 3514

To appear in: *Marine Environmental Research*

Received Date: 31 May 2010

Revised Date: 25 February 2011

Accepted Date: 25 February 2011

Please cite this article as: Byju, P., Prasanna Kumar, S. Physical and biological response of the Arabian Sea to tropical cyclone Phyan and its implications, Marine Environmental Research (2011), doi: 10.1016/j.marenvres.2011.02.008

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

Physical and biological response of the Arabian Sea to tropical cyclone Phyan and its implications

P. Byju and S. Prasanna Kumar*

National Institute of Oceanography (CSIR), Dona Puala, Goa-403 004, India

P. Byju : byjupbhaskar@gmail.com

S. Prasanna Kumar : prasanna@nio.org

***Corresponding Author:**

S. Prasanna Kumar
National Institute of Oceanography
Dona-Paula, Goa-403004, India.
Tel: +91(832) 2450300
Fax: +91(832) 2450608

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Physical and biological response of the Arabian Sea to tropical cyclone Phyan and its implications

P. Byju and S. Prasanna Kumar*
National Institute of Oceanography (CSIR), Dona Puala, Goa-403 004, India
*Corresponding author

Abstract.

The response to the tropical cyclone Phyan, which developed in the eastern Arabian Sea during 9-11 November 2009, was rapid cooling of sea surface temperature (SST), enhancement of chlorophyll *a* and two-fold increase in net primary productivity (NPP). Cooling of SST was immediate in response to the strong wind mixing, and the subsequent upward Ekman-pumping sustained the cooling even after the dissipation of Phyan. The biological response mediated by the upward Ekman pumping driven vertical transport of subsurface nutrient showed a time lag of 3-4 days. The CO_2 flux to the atmosphere associated with Phyan was 0.123 Tg C, which accounted for ~85% of the total out-gassing from the eastern Arabian Sea during November. Thus, an increased occurrence of cyclones in a warming environment will lead to an enhanced biomass production and also increase in CO_2 out-gassing.

Key words: Tropical cyclone, Arabian Sea, Sea surface temperature, Ekman-pumping, Wind-mixing, Chlorophyll, Primary production, CO_2 out-gassing, Biogeochemical cycle, Nutrients.

1. Introduction

The global tropical cyclone statistics shows that only about 7% of tropical storms form in the north Indian Ocean (comprising of the Bay of Bengal and the Arabian Sea) and, compared to the Bay of Bengal, the ratio of the frequency of occurrence of tropical cyclones over the Arabian Sea is about 4:1 (Dube et al., 1997). Though this number appears to be small in the context of global occurrence, they cause far more damage and misery to the adjoining Asian continent which houses a quarter of humanity most of whom live in the low-lying coastal plain. In the Arabian Sea, tropical cyclones form predominantly during pre-monsoon/spring-summer transition (May-June) and post-monsoon/fall-winter transition (October-November) periods.

The sun heats the ocean surface and the water evaporates over the hot ocean surface, while it condenses in the atmosphere as it rises. If the heating and evaporation is intense, the condensing

ACCEPTED MANUSCRIPT

air releases a large quantity of latent heat, which is the necessary fuel for the development and intensification of a cyclone. So in a warming environment it is expected that the frequency and severity of tropical cyclones will also increase (Trendberth, 2005; Emanuel, 2005; Webster et al., 2005). However, factors other than sea surface temperature (SST), such as vertical wind shear, and relative humidity have been cited for their role in regulating cyclone characteristics as well as its genesis (Gray, 1979). It has been reported that the Arabian Sea warmed by about 0.5^{o}C during 1904-1994 (Rupakumar et al., 2002). In a recent study Prasanna Kumar et al. (2009) speculated that the Arabian Sea is experiencing a regional climate shift since 1995, which is accompanied by a five-fold increase in the occurrence of the most intense cyclones. Even though cyclones are known for their destruction of life and property on the land, they often augment life in the ocean (Madhu et al., 2002; Subrahmanyam et al., 2002; Hema Naik et al., 2008; Rao et al., 2006) through upward pumping of nutrients into the euphotic zone. Thus, in a warming scenario, the Arabian Sea could become more productive (see Goes et al., 2005; Prasanna Kumar et al., 2010), which has implications for regional biogeochemistry. For example, increased biological productivity will exert pressure on the already existing mid-depth oxygen minimum zone (OMZ) in the central Arabian Sea and the severe hypoxia experienced along the eastern Arabian Sea (Naqvi et al., 2000). Studies have shown that the Arabian Sea is a perennial source of ocean to atmosphere CO_2 flux in all seasons (Goyet et al., 1998; Sarma et al., 1998; Sabine et al., 2000) and strong wind can increase the flux. It is in this context that we present the upper ocean response of the eastern Arabian Sea to the tropical cyclone Phyan and its impact on biological productivity.

2. Materials and methods

2.1. Data

It is very difficult to carry out ship borne observations during violent atmospheric processes like cyclones with great variation in trajectory and strength. With the advent of the satellite era, remote sensing satellites with radiometers at visible, infra-red and microwave frequencies provide a real-time recognition and diagnosis of tropical cyclone development. But ocean colour sensors are obscured by clouds, which are often present during and after the passage of a cyclone, therefore it can capture only a very small part of the entire event. In the present study the track of the cyclone was taken from the Indian Meteorological Department (IMD)

ACCEPTED MANUSCRIPT

Preliminary Report (http://www.imd.gov.in/section/nhac/dynamic/cyclone.htm). We used an Optimally Interpolated sea surface temperature (SST) from the remote sensing satellites Tropical Rainfall Measuring Mission Microwave Imager (TMI), Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer-Earth observing system (AMSR-E) (ftp://ftp.misst.org/ L4/mw_ir) with a spatial resolution of 9km, to elucidate evolution of surface ocean thermal variation due to the cyclone. We also used 3-day composite ocean colour data by NASA's MODIS-Aqua (http://oceandata.sci.gsfc.nasa.gov/MODISA/), which captured only a part of the chlorophyll *a* bloom patch because of the overcast sky. A tropical cyclone releases its energy in the form of strong winds which are significant to ocean mixing resulting in cooling, increased biological productivity and enhanced emission of CO_2. A blended wind product provided by IFREMER/CERSAT derived from the near-real-time measurements by QuikSCAT and SSMI with a spatial and temporal resolution of 25 km and 6 hours respectively, was used for the calculation of Ekman pumping velocity. Since this data is available only till 22nd November 2009 (ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/ mwf-blended/) we used data from NOAA's National Climatic Data Center, (http://www.ncdc.noaa.gov/oa/rsad/ blendedseawinds.html) to calculate wind-dependent, gas-transfer velocity for TCO_2 flux for November 2009. We have also used the climatological sea-air difference in partial pressure of CO_2 (Takahashi et al., 2009a) to calculate total CO_2 flux over the eastern Arabian Sea before, during and after the passage of the cyclone.

2.2. Developmental stages of Phyan

The tropical cyclone formed during 9-11 November 2009 over the Arabian Sea, named as 'Phyan' by Indian Meteorological Department, had some special characteristics. A low pressure system that initially formed over the Comorin area (8.08^{o}N & 77.56^{o}E) on 7th November 2009 became well marked over Lakshadweep area (10.57^{o}N & 72.62^{o}E) on 8th November (not shown in Figure 1) and developed into a depression on 9th November 2009 over the south-east Arabian Sea centered at 11°N and 72°E (Figure 1). It moved initially in a north-northwesterly direction till 10th November and then re-curved to north-northeastward. It intensified into a deep depression at 0830 hrs Indian Standard Time (IST) and into a cyclonic storm 'Phyan' at 2330 hrs IST on 10th November 2009 (see also Joseph et al., 2010). Continuing its north-northeastward movement, the cyclonic storm 'Phyan' crossed the coast (near Mumbai, 18.98^{o}N & 72.83^{o}E, Figure 1) between 1530 and 1630 hrs IST on 11th November causing a wide range of

ACCEPTED MANUSCRIPT

destruction. The central pressure and maximum sustained surface wind speed was estimated to be 988 hPa and 83 km/hour respectively during 11th November 2009. The maximum intensity of 'Phyan' was T 3.0 according to Dvorak's technique (http://www.ssd.noaa.gov/PS/TROP/CI-chart.html).

3. Results and discussions

3.1. SST response

Tropical cyclones form in warm ocean water (Gray, 1979). Once formed the strong wind-stress curl associated with the cyclone drives the upward Ekman-pumping and the resultant entrainment and mixing cools the upper ocean (Price, 1981; Pudov, 1992; DeMaria and Kaplan, 1994; Sadhuram, 2004). Ocean thermal condition was well favoured for the genesis of cyclone Phyan in the eastern Arabian Sea with a SST in excess of 29.4^{o}C. To understand the thermal response of the upper ocean to the passage of Phyan, we plotted SST along the cyclone track. At each latitude along the track, the SST was averaged over 1 degree longitude and was plotted during 3 periods - before (6-8 November 2009), during (9-11 November 2009) and after (12-13 November 2009) the passage of the cyclone (Figure 2).

Before the passage of tropical cyclone Phyan the SST, in general, was in excess of 29.4^{o}C at its origin while it was ~2°C colder towards the north (Figure 2). The colder condition in the north (north of 17°N) before the arrival of the cyclone was due to the winter cooling under the influence of cold and dry winds of continental origin (Prasanna Kumar and Prasad, 1996). During the formation and passage of the cyclone (9-10 November 2009), a strong surface cooling of about 2°C was noticed. Cooling predominantly occurred between the latitude 11°N and 14°N where the cyclone veered from north-west to north-east. Notice the cold pool to the right of the cyclone track in Figure 1. Similar cooling at the right side of the cyclone track has been reported earlier by several authors (Price 1981; Pudov, 1992; Sadhuram, 2004). Price (1981) attributed this right-side bias of SST reduction to non-linear mixed-layer current response and the stronger winds located on the right side of the storm track due to storm motion. In the present study even after the passage of cyclone Phyan, the cooling of SST persisted in the south up to 14°N. In the north (north of 14°N), however, the cooling of SST was gradual. To further understand the mechanism of cooling and the occurrence of cold pool associated with the cyclone Phyan, we calculated the wind-stress curl and the vertical velocity in a box EFGH (0.5-

ACCEPTED MANUSCRIPT

degree latitude x 1-degree longitude) located within the cold pool (see Figure 1) during the first fortnight of November. The value of wind-stress curl was near zero before the formation of Phyan and it suddenly peaked during the period of cyclone (9-11 November 2010) with the highest value of 7.5 x 10^{-6} N/m^3 (Figure 3) on 10th November. The vertical velocity also showed a similar pattern with upward (negative) velocity during the period of cyclone. The highest upward velocity of 2.4 x 10^{-4} m/s occurred on 10th November which coincided with the time of maximum strength of wind-stress curl. Note that the SST cooled from the pre-cyclone value of 29.9^{o}C to 27.9^{o}C on 11th November 2010. This time lag between the maximum strength of wind-stress curl (and the vertical velocity) and the occurrence of the maximum cooling indicates the thermal response time of the water column associated with diffusion. Though the wind stress curl diminished rapidly after 10th November when the cyclonic storm moved away from the cold pool location, the momentum imparted by wind stress could sustain the upward transport of cold water. This clearly indicated that the maximum cooling and hence the cold pool, at the right side of cyclone track, was generated by the cyclonic wind-stress curl and the associated upward Ekman-pumping. The enhanced evaporation under the influence of strong winds can also lead to decrease in the SST, but its magnitude is much less (Price, 1981). The SST prior to the formation of Phyan was 1°C higher than the climatological SST computed from TMI during 1998 to 2009. This higher SST could be one of the factors that triggered the cyclone.

3.2. Biological response

3.2.1. Enhancement of Chlorophyll a

Biological response of the Arabian Sea to the passage of Phyan was explored by analyzing chlorophyll *a* concentration during the first fort-night of November 2009 in the box ABCD (see Figure 1 for location). A major drawback of such a study is the lack of data during the peak of the cyclone activity over the ocean due to thick cloud associated with it. Since *in situ* measurements are extremely difficult in such violent condition and non-existent in the present case, we used the 3-day composite of chlorophyll *a* concentration derived from MODIS-Aqua (Figure 4). The average chlorophyll *a* concentration in the eastern Arabian Sea before the genesis of Phyan was ~1.0 mg/m^3. However, during its genesis, evolution and decay the chlorophyll *a* concentration showed a rapid decline reaching almost 0.45 mg/m^3. This is due to the spare data coverage by MODIS-Aqua because of thick cloud associated with the cyclone as indicated by the percentage of pixel count in Figure 4. During a relatively cloud-free condition the pixel count

ACCEPTED MANUSCRIPT

(3500) was more than 70%. This declined to almost 2% (79 pixels) during the period of cyclone activity (8-11 November 2009). After 11th November when Phyan had dissipated, the chlorophyll *a* concentration showed a continuous increase reaching an average highest value of ~1.5 mg/m^3 (black dotted line in figure 4) on 16th November. Note that the pixel count also showed an increase which indicated the robustness of the chlorophyll estimate. A greater enhancement in the chlorophyll *a* concentration was seen on 16th November at a location close to the Phyan trajectory (e.g., 71.16^{o}E, 16.66^{o}N), but away from the continental shelf, where the value reached more than 6 mg/m^3 (not presented here). This increased biomass seen 3-4 days after the dissipation of tropical cyclone Phyan indicated the response of biology and the following is the probable mechanism.

It is well known that the strong curling winds of cyclone can bring nutrients from the subsurface to the surface by Ekman pumping and entrainment due to the wind stirring at the base of the mixed layer (Subrahmanyam et al., 2002; Lin et al., 2003). An analysis of the monthly mean climatology of nutrient data averaged within the box ABCD showed that the 1μmole nitrate concentration was situated at a depth of ~5m during November (World Ocean Atlas 2005 data, ftp://ftp.nodc.noaa.gov/pub/data.nodc/woa/WOA05nc/monthly/) while the mixed layer depth (MLD) during the same period was ~25m (de Boyer Montegut et al., 2004). From the available Argo data (http://www.nodc.noaa.gov/argo/basins_data.htm) during the first fortnight of November we could identify a float with ID R2901105 which was the closest to the Phyan track, about 100-170 Km away to the left of cyclone track. The MLD computed from the Argo data showed a deepening from 25m on 5th (70.36^{o}E, 15.89^{o}N) to 30m on 9th (70.34^{o}E, 15.78^{o}N) November, consistent with the deepening seen from the November climatology. Earlier it was shown that the strong upward Ekman pumping velocity of above 2x10^{-4} m/s (see Figure 3) driven by the cyclonic wind-stress curl associated with Phyan could produce a cold pool with temperature of about 27.5^{o}C. From the Argo temperature profile it was found that the 27.5^{o}C isotherm (coolest surface temperature depicted by satellite near the track) was located at ~58m depth. For a given vertical velocity of 2 x 10^{-4} m/s it would take about 3.4 days for nutrients to come to surface from about 60 m. Thus, the observed enhanced chlorophyll *a* biomass after 3-4 days of passage of cyclone could be explained in the context of prevailing cyclonic winds and the associated upward pumping of nutrients.

Once the cyclone passes away and the cloudy sky clears off, the availability of sunlight and nutrients will lead to an enhanced biological productivity. This has been explored in the following section.

3.2.2. Enhancement of Primary Production

Estimation of primary production is required to understand the biological process affecting global biogeochemical cycles. Phytoplankton is the dominant primary producer in the marine environment, which synthesises organic material using nutrients, carbon dioxide and light energy with the help of chlorophyll through photosynthesis. We have seen a distinct increase of chlorophyll *a* after the passage of Phyan. The Net Primary Production (NPP) was estimated from the codes of Vertically Generalised Productivity Model (VGPM) (Behrenfeld and Falkoswski, 1997), using the 3-day composite values of surface chlorophyll *a* concentration from MODIS Aqua, Sea-viewing Wide Field-of-view Sensor (SeaWiFs) daily Photosynthetically Available Radiation (PAR) and optimally interpolated TMI-MODIS-AMSRE SST during 7-17 November 2009. The spatial averaged NPP within the box ABCD is presented in figure 5. The NPP in the eastern Arabian Sea before the occurrence of Phyan was ~650mg C m^{-2} day^{-1} and it showed a rapid increase to ~1050mg C m^{-2} day^{-1} on 12th November immediately after the dissipation of the cyclone. The peak NPP value of ~1350mg C m^{-2} day^{-1} was attained on 16th November, 4 days after the cyclone event in agreement with increase in chlorophyll biomass. Thus, the observed 2-fold increase in the NPP resulted from the new production which in turn was mediated by the process of upward Ekman pumping associated with the cyclone. A similar value of new production (~1500 mg C m^{-2} day^{-1}) was reported by Hema Naik et al. (2008), based on a chance *in situ* measurement of chlorophyll and nitrate and using Redfield ratio during a cyclone in Arabian Sea in December 1998. This indicated that the sporadic cyclonic storm in the Arabian Sea, which is showing an increasing trend in recent years (Prasanna Kumar et al., 2009) could support much higher primary productivity in a region which is known for its seasonally high phytoplankton blooms and biological productivity. The elevated primary production will exert additional pressure on already existing OMZ in the Arabian Sea leading to severe anoxic conditions (Naqvi et al., 2000). In addition, the upward Ekman pumping of subsurface cold water could also result in the enhancement and saturation of surface pCO_2 which would finally lead to out gassing of CO_2. This is explored in the following section.

3.3. Effect on CO_2 flux

ACCEPTED MANUSCRIPT

The intense biological activity in the Arabian Sea results in higher sea water pCO_2 than in the atmosphere for all seasons (Sarma et al., 1998), which makes the Arabian Sea a source of CO_2 to the atmosphere (Goyet et al., 1998; Sarma et al., 1998; Sabine et al., 2000). The sporadic cyclone has the potential to intensify this source. The rate of exchange of sea-air CO_2 depends on the solubility of CO_2 in sea water, gas transfer velocity and difference in partial pressure between the Surface Ocean and atmosphere. We can formulate the net CO_2 flux (F) as:

$$F = k.\alpha.(pCO_2^{sea} - pCO_2^{air}) \quad (1)$$

where k is gas transfer velocity and α is the solubility of CO_2 in sea water. The solubility (α) of CO_2 in sea water depends on surface temperature (T) and salinity (S) (Weiss, 1974) as

$$ln\ \alpha = A_1 + A_2\,(100/T) + A_3\,In(T/100) + S\,[B_1 + B_2\,(T/100) + B_3\,(T/100)^2] \quad (2)$$

The transfer velocity (k) is determined from wind speed (Wanninkhof, 1992) as given below,

$$k\ (\text{cm h}^{-1}) = \Gamma.\ U^2.\ (Sc/660)^{-1/2} \quad (3)$$

where U is the wind speed and the value of scaling factor $\Gamma = 0.26$ was taken from Takahashi et al., (2009b). Sc is Schmidt number (kinematic viscosity of water / diffusion coefficient of CO_2 in water) which is 660 for CO_2 in seawater at 20°C. Sc is a function of temperature (T) and is given by

$$Sc = A - BT + CT^2 - DT^3 \quad (4)$$

Refer Weiss (1974) and Wanninkhof (1992) for the values of the constants A, B, C and D.

We calculated the total CO_2 flux associated with Phyan within the box ABCD in the eastern Arabian Sea (10°N-18°N and 70°E-75°E) using (1).

Studies have shown that though the surface ocean cools under the influence of cyclone, strong wind associated with cyclone can intensify out-gassing of CO_2 from ocean to atmosphere (Bates et.al., 1998). A recent time series observation using moored buoy data in the East China Sea by Nemeto et al. (2009) also suggested a similar result that strong wind and dissolved inorganic carbon (DIC) supply from the subsurface during the passage of a cyclone can increase efflux of CO_2 from ocean to atmosphere.

The CO_2 flux to the atmosphere associated with Phyan over the eastern Arabian Sea (10°N-18°N and 70°E-75°E) during 8th to 11th November was about 0.123 Tg C (1Tg=10^{12}g) (Figure 6), which accounted for ~85% of the total out-gassing of CO_2 for the month of November (climatology) calculated by Takahashi et al. (2009a). The total emission of CO_2 during November 2009 was ~0.244 Tg C, which was about 170% of the climatological value (0.144 Tg C) over the area ABCD (see Figure1 for location of box). Based on the Indian JGOFS measurements Sarma et al. (1998) estimated the seasonal variability of CO_2 emission to be 1 to

ACCEPTED MANUSCRIPT

3.5 mmol m^{-2} day^{-1} (excluding south west monsoon period) (Sarma et al., 1998). The present estimate showed that during the course of cyclone Phyan ~8 mmol m^{-2} day^{-1} CO_2 was emitted from ocean to atmosphere, making the eastern Arabian Sea a major source.

4. Conclusion

In this study we investigated the impact of tropical cyclone Phyan to the ocean biology and CO_2 exchange over the eastern Arabian Sea using *in situ* as well as remote sensing data sets. Surface temperature showed an immediate response by way of cooling (2°C) while chlorophyll *a* and net primary production showed a delayed response. The strong wind-mixing associated with cyclonic winds led to the observed rapid cooling, which was sustained even after the dissipation of Phyan by the wind-stress curl induced upward Ekman pumping. Though the SST showed an immediate response, the biological response to Phyan showed a time lag. The peak chlorophyll *a* and the net primary productivity (NPP) occurred 3-4 days after the dissipation of Phyan. The chlorophyll *a* showed an average enhancement of 0.5 mg/m^3 while the NPP showed a two-fold increase. The mechanism that supported increased biological productivity was the vertical transport of subsurface nutrients by the wind stress curl. The upward Ekman pumping transported the cold and nutrient rich waters to the upper ocean which was also enriched in CO_2. The estimated CO_2 flux to the atmosphere associated with Phyan was 0.123Tg C which was 85% of the climatological monthly mean value for November. The above results of our study have implication to the Arabian Sea which already has a mid-depth OMZ. Thus, in the Arabian Sea the increased frequency and intensity of the cyclones in a warming environment are expected to increase manifold the biological productivity as well as CO_2 out-gassing. Increased productivity, in turn, will exert increased demand on mid-depth oxygen exerting additional stress on already existing OMZ.

Acknowledgements

The authors wish to acknowledge Director, National Institute of Oceanography (NIO), Goa as well as Council of Scientific and Industrial Research (CSIR), New Delhi for all the support and encouragement for the successful completion of this work. The funding support of Ministry of Earth Sciences (MoES) through Centre for Marine Living Resources and Ecology (CMLRE), Kochi for the project “Assessment of Myctophid resources in the Arabian Sea” is gratefully acknowledged. This in NIO contribution Number xxxx.

ACCEPTED MANUSCRIPT

References

Bates, N.R., Knap, A.H. and Michaels, A.F., 1998. Contribution of hurricanes to local and global estimates of air-sea exchange of CO_2, Nature 395, 58-61.

Behrenfeld, M.J., Falkoswski, P.G., 1997. Photosynthetic rates derived from satellite based chlorophyll concentration, Limnology and Oceanography 42(1), 1-20.

de Boyer Montegut, C., Madec, G., Fischer, A.S., Lazar, A., Iudicone, D., 2004. Mixed layer depth over the global ocean: an examination of profile data and a profile-based climatology, Journal of Geophysical Research 109, C12003. doi:10.1029/2004JC002378.

DeMaria M., Kaplan, J., 1994. Sea surface temperature and the maximum intensity of Atlantic tropical cyclones, Journal of Climate 7, 1325–1334.

Dube, S.K., Rao, A.D., Sinha, P.C., Murty, T.S., Bahuleyan N., 1997. Storm surge in Bay of Bengal and Arabian Sea: The problem and its prediction, Mausam 48, 288-304.

Emanual, K.A., 2005. Increasing destructiveness of tropical cyclone over the past 30 years, Nature 326, 686-688.

Goes, J.I., Thoppil, P.G., Gomes, H.R., Fasullo, J.T., 2005. Warming of the Eurasian landmass is making the Arabian Sea more productive, Science 308, 545–547.

Goyet, C., Millero, F.J., O'Sullivan, D.W., Eischeid, G., McCue, S.J., Bellerby, R.G.J., 1998. Temporal variations of pCO_2 in surface seawater of the Arabian Sea in 1995, Deep Sea Research II 45, 609–624.

Gray, W.M., 1979. Hurricanes: Their formation, structure and likely role in the tropical circulation, in: D. B. Shaw (Ed.), Meteorology over the tropical oceans, Royal Meteorological Society, James Glaisher House, Grenville Place, Bracknell, Berkshire, RG121BX, 155-218.

ACCEPTED MANUSCRIPT

Hema Naik, Naqvi, S.W.A., Suresh, T., Narvekar, P.V., 2008. Impact of tropical cyclone on biogeochemistry of the central Arabian Sea, Global Biogeochemical Cycles 22, GB3020. Doi: 10.1029/2007GB003028.

Joseph, A., Prabhudesai, R.G., Mehra, P., Sanil Kumar, V., Radhakrisnan, K.V., Kumar, V., Ashok Kumar, K., Agarwadekar, Y., Bhat, U.G., Luis, R., Rivankar, P., Viegas, B., 2010. Response of west Indian coastal regions and Kavaratti lagoon to the November-2009 tropical cyclone Phyan, Natural Hazards, DOI: 10.1007/s11069-010-9613-7.

Lin, I., Liu, W.T., Wong, C.C., Hu, G.T.F., Chen, C., Liang, Z., Liang, W.D., Yang, Y., Liu, K.K., 2003. New evidence for enhanced ocean primary production triggered by tropical cyclone, Geophysical Research Letters 30, 1718. doi:10.1029/2003GL017141.

Madhu, N.V., Maheswaran, P.A., Jyothibabu, R., Revichandran, C., Balasubramanian, T., Gopalakrishnan, T.C., Nair, K.K.C., 2002. Enhanced biological production off Chennai triggered by October 1999 super cyclone (Orissa), Current Science 82, 1472–1479.

Naqvi, S.W.A., Jayakumar, D.A., Narvekar, P.V., Naik, H., Sarma, V.V.S.S., D'Souza, W., Joseph, S., George, M.D., 2000. Increased marine production of N_2O due to intensifying anoxia on the Indian continental shelf, Nature 408, 346–349.

Nemoto, K., Midorikawa, T., Ogawa, A., Takatani, S., Kimoto,H., Ishii, M., Inoue, H.Y., 2009. Continuous observations of atmospheric and oceanic CO_2 using a moored buoy in the East China Sea: Variations during the passage of typhoons, Deep Sea Research II 56, 542-553.

Prasanna Kumar, S., Prasad, T.G., 1996. Winter cooling in the northern Arabian Sea, Current Science 71, 834-841.

Prasanna Kumar, S., Roshin, R.P., Narvekar, J., Dinesh Kumar, P.K., Vivekanandan, E., 2009. Response of the Arabian Sea to global warming and associated regional climate shift, Marine Environmental Research 68, 217-222.

ACCEPTED MANUSCRIPT

Prasanna Kumar, S., Roshin, R.P., Narvekar, J., DineshKumar, P.K., Vivekanandan, E., 2010. Signatures of global warming and regional climate shift in the Arabian Sea, in: Joseph, A., Nandan, S.B., Augustine, A. (Eds.), Climate change and aquatic ecosystems, Natl. Symp. On Impact Climate Change on Aquatic Ecosystems (NSICCAE 2010), Cochin, India, 55-62.

Price, J.F., 1981. Upper ocean response to hurricane, Journal of Physical Oceanography 11, 153-175.

Pudov, V.D., 1992. The oceans response to the cyclone's influence and its possible role in their track formation, In: Proc. ICSU/WMO Int. Symp. On Tropical Cyclone Disasters, Beijing, China, WMO, 367-376.

Rao, K.H., Smitha, A., Ali, M.M., 2006. A study on cyclome induced productivity in south-western Bay of Bengal during November-December 2000 using MODIS (SST and chlorophyll-*a*)and altimeter sea surface height observations, Indian Journal of Marine Science 35(2), 153-160.

RupaKumar, R., KrishnaKumar, K., Ashrit, R.G., Patwardhan, S.K., Pant, G.B., 2002. Climate change in India: observations and model projections, In: Shukla, P.R.,Sharma, S.K., Venkata Ramana, P., (Eds.), Climate Change and India: Issues, Concerns and Opportunities, TataMcGraw-Hill Publishing Company Limited, New Delhi.

Sabine, C.L., Wanninkhof, R., Key, F.M., Goyet, C., Millero, F.J., 2000. Seasonal CO_2 fluxes in the tropical and subtropical Indian Ocean, Marine Chemistry 72, 33-53.

Sadhuram, Y., 2004. Record decrease of sea surface temperature following the passage of a super cyclone over the Bay of Bengal, Current Science 86, 383-384.

Sarma, V.V.S.S., Kumar, M.D., George, M.D., 1998. The central and eastern Arabian Sea as a perennial source for atmospheric carbon dioxide, Tellus Series B 50, 179-184.

ACCEPTED MANUSCRIPT

Subrahmanyam, B., Rao, K.H., Rao, N.S., Murty, V.S.N., 2002. Influence of a tropical cyclone on chlorophyll a concentration in the Arabian Sea, Geophysical Research Letters 29(22), 2065. doi:10.1029/2002GL015892.

Takahashi, T., Sutherland, S.C., Kozyr, A., 2009a. Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed During 1968–2008 (Version 2008). ORNL/CDIAC-52, NDP-088r. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. doi: 10.3334/CDIAC/otg.ndp088r.

Takahashi, T., Sutherland, S.C., Wanninkhof, R., Sweeney, C., Feely, R.A., Chipman, D.W., Hales, B., Friederich, G., Chavez, F., Watson, A., Bakker, D.C.E., Schuster, U., Metzl, N., Yoshikawa- Inoue, H., Ishii, M., Midorikawa, T., Nojiri, Y., Sabine, C., Olafsson, J., Arnarson, Th.S., Tilbrook, B., Johannessen, T., Olsen, A., Richard Bellerby, Körtzinger, A., Steinhoff, T., Hoppema, M., de Baar, H.J.W., Wong, C.S., Bruno Delille, Bates, N.R., 2009b. Climatological mean and decadal changes in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans, Deep-Sea Research II 56, 554-577.

Trenberth, K.E., 2005. Uncertainty in hurricanes and global warming, Science 308, 1753-1754.

Wanninkhof, R., 1992. Relationship between wind speed and gas exchange over the ocean, Journal of Geophysical Research 97, 7373-7382.

Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.R., 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment, Science 309, 1844–1846.

Weiss, R.F., 1974. Carbon dioxide in water and seawater: the solubility of a non-ideal gas, Marine Chemistry 2, 203-215.

Legend to figures

Fig. 1. Track of the cyclone Phyan (black line) over the Arabian Sea during 09th to 11th November 2009. Shading and the filled contours are SST averaged during the above period. Box

ACCEPTED MANUSCRIPT

ABCD denotes the area influenced by the cyclone while box EFGH indicates the location of the cold pool. Blue patches are waters colder than 27.5^{o}C, seen during cyclone period to the right of the cyclone track.

Fig. 2. Time evolution of SST along the track (see Figure 1 for location) before, during and after the passage of cyclone Phyan. A drop in SST by ~2°C between 12°N and 13°N occurred on 10th November.

Fig. 3. Time evaluation of wind-stress curl (red), Ekman-pumping velocity (green), 2009 SST (blue) and SST climatology (black dash line) at the cold pool location EFGH (12.5^{o}N-13°N, 71°E-72°E) indicated in Figure 1. The SST climatology is from TMI during 1998-2009.

Fig. 4. Time series of 3-day composite (centred at the mid-point) of MODIS Aqua derived surface chlorophyll (black) distribution averaged within the box ABCD (longitude 70°E-75°E and latitude 10°N-18°N; see Fig.1). The red coloured plot indicates the number of data pixels that were actually used for the determination of chlorophyll expressed in percentage. Low values of pixel percentage indicate overcast sky and less number of data points for the computation of chlorophyll.

Fig. 5. Net primary production (NPP) values in mg C m^{-2} day^{-1} averaged within the box ABCD (longitude 70°E-75°E and latitude 10°N-18°N).

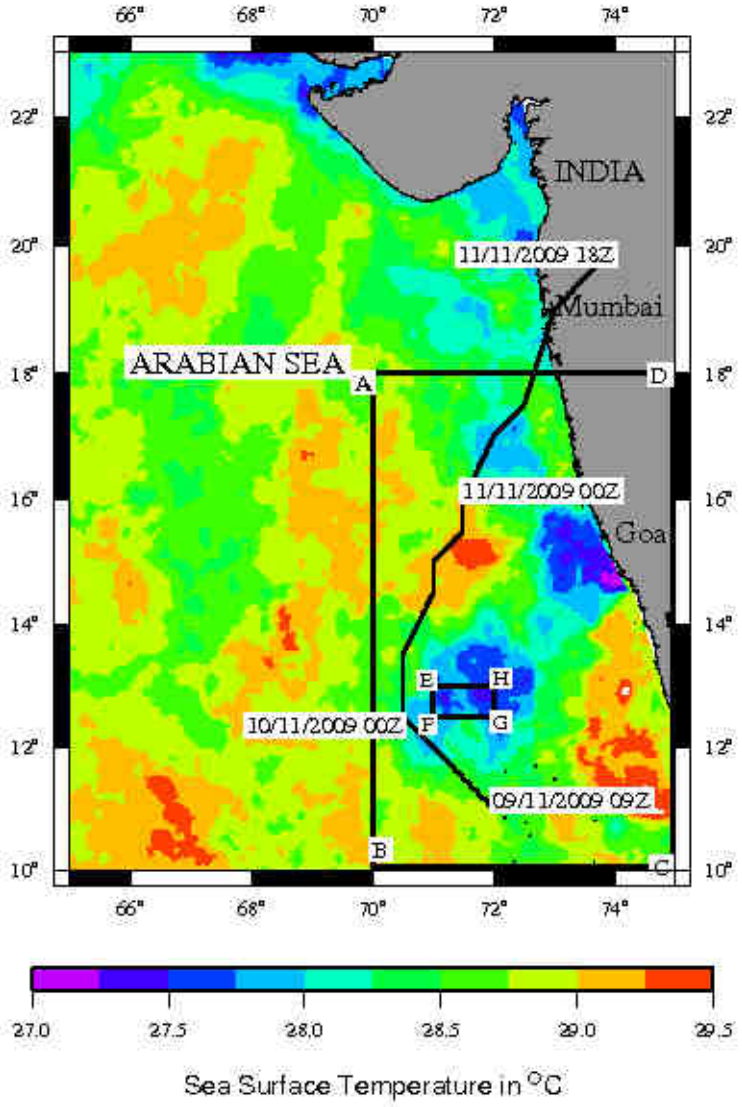
Fig. 6. Total carbon dioxide flux in Tg C (1Tg=10^{12}g) m^{-2} day^{-1} integrated over the box ABCD (see Figure 1 for the location). *T CO_2 values are from Takahashi et al.,(2009a).

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

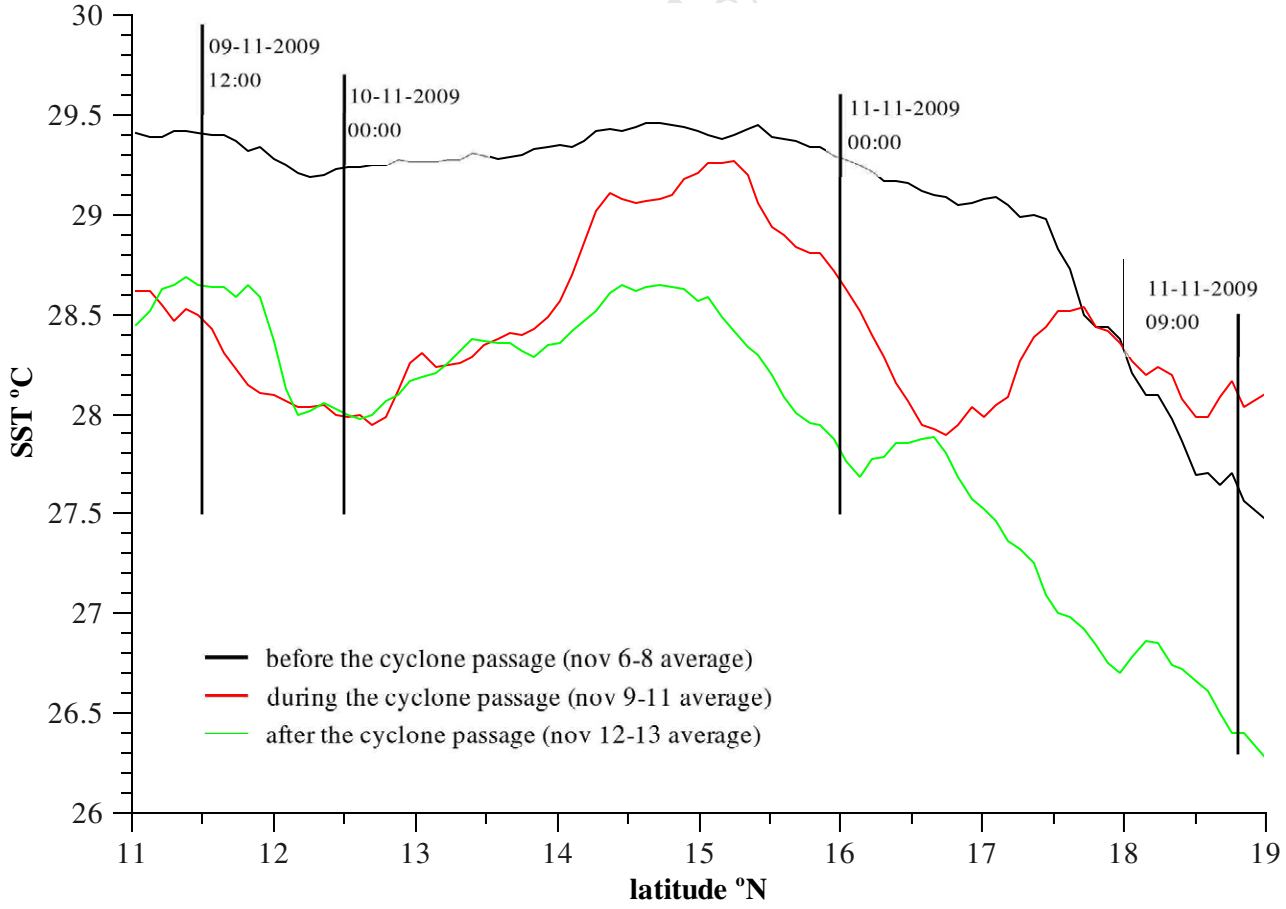
- Impact of tropical cyclone was immediate $2^{o}C$ SST-cooling due to strong wind-mixing
- Biological response was 2-fold increase in productivity with 3-4 days lag time
- Upward Ekman-pumping and associated nutrient transport enhanced chlorophyll-biomass
- Increased CO_2 out-gassing of 0.123 Tg accounts for 85% November climatology

ACCEPTED MANUSCRIPT

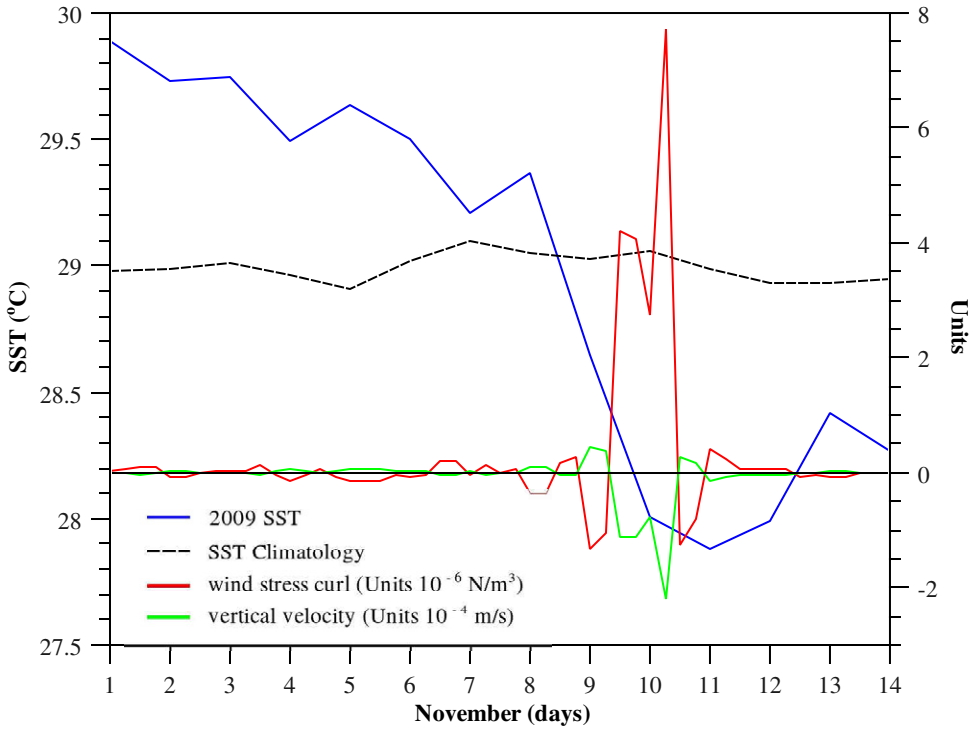

66°
68°
70°
72°
74°
22°
20°
18°
16°
14°
12°
10°
INDIA
11/11/2009 18Z
Mumbai
ARABIAN SEA
A
D
11/11/2009 00Z
Goa
E
H
10/11/2009 00Z
F
G
09/11/2009 09Z
B
C
27.0
27.5
28.0
28.5
29.0
29.5
Sea Surface Temperature in °C

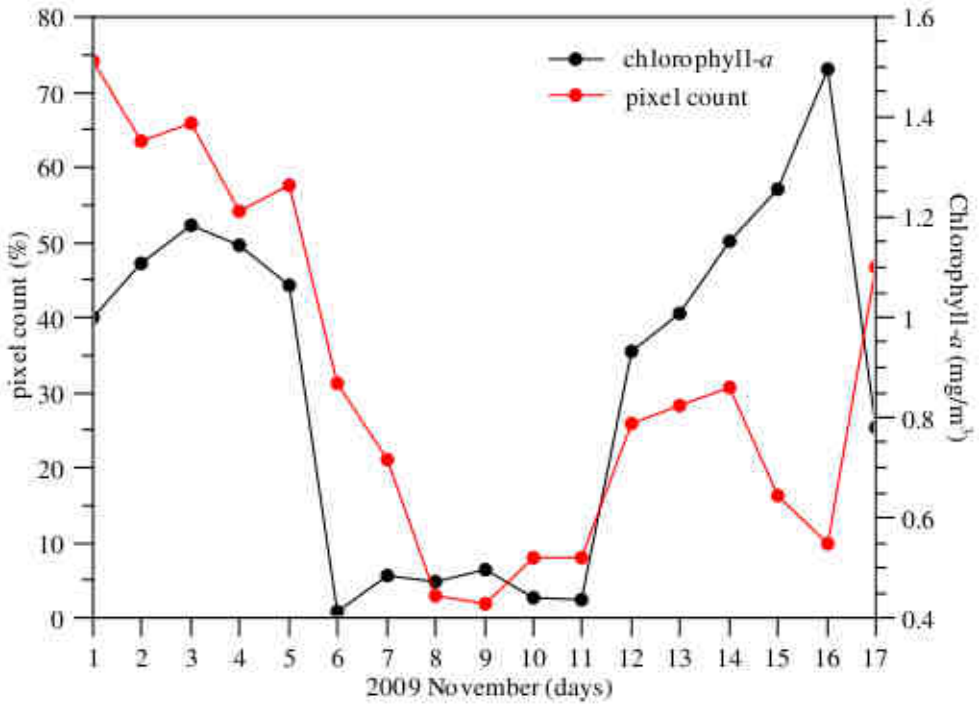
MANUSCRIPT

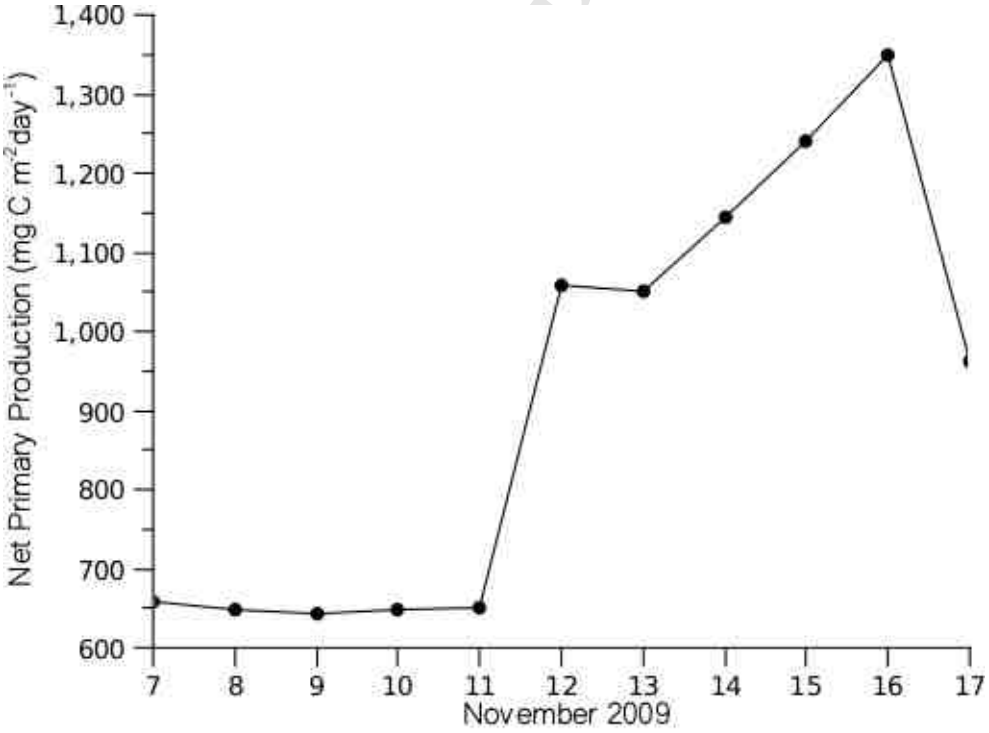
ACCEPTED MANUSCRIPT



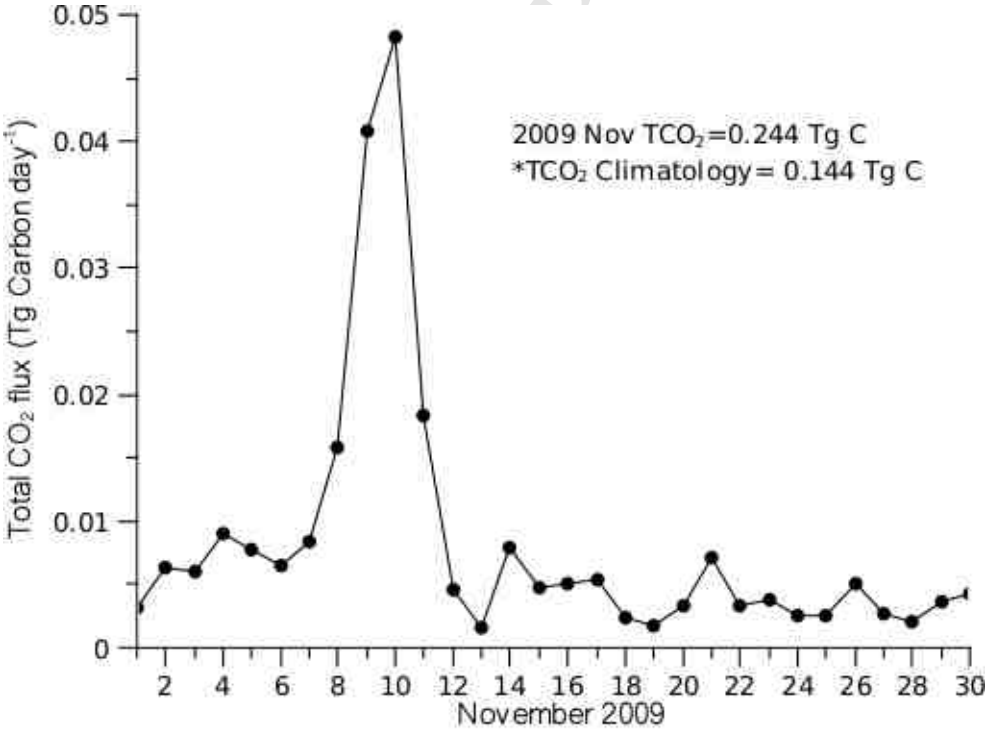
ACCEPTED MANUSCRIPT




chlorophyll-a
pixel count
pixel count (%)
Chlorophyll-a (mg/m3)
2009 November (days)
0
10
20
30
40
50
60
70
80
0.4
0.6
0.8
1
1.2
1.4
1.6
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17



ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT