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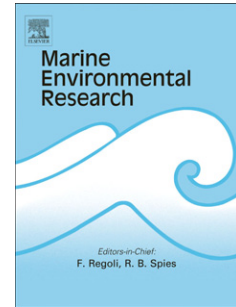
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1 **Physical and biological response of the Arabian Sea to tropical cyclone Phyan**
2 **and its implications**

3

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24 **Physical and biological response of the Arabian Sea to tropical cyclone Phyan** 25 **and its implications**

26

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30

31 **Abstract.**

32 The response to the tropical cyclone Phyan, which developed in the eastern Arabian Sea during
33 9-11 November 2009, was rapid cooling of sea surface temperature (SST), enhancement of
34 chlorophyll *a* and two-fold increase in net primary productivity (NPP). Cooling of SST was
35 immediate in response to the strong wind mixing, and the subsequent upward Ekman-pumping
36 sustained the cooling even after the dissipation of Phyan. The biological response mediated by
37 the upward Ekman pumping driven vertical transport of subsurface nutrient showed a time lag of
38 3-4 days. The CO₂ flux to the atmosphere associated with Phyan was 0.123 Tg C, which
39 accounted for ~85% of the total out-gassing from the eastern Arabian Sea during November.
40 Thus, an increased occurrence of cyclones in a warming environment will lead to an enhanced
41 biomass production and also increase in CO₂ out-gassing.

42 Key words: Tropical cyclone, Arabian Sea, Sea surface temperature, Ekman-pumping, Wind-
43 mixing, Chlorophyll, Primary production, CO₂ out-gassing, Biogeochemical cycle, Nutrients.

44

45 **1. Introduction**

46

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

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

57 air releases a large quantity of latent heat, which is the necessary fuel for the development and
58 intensification of a cyclone. So in a warming environment it is expected that the frequency and
59 severity of tropical cyclones will also increase (Trenberth, 2005; Emanuel, 2005; Webster et al.,
60 2005). However, factors other than sea surface temperature (SST), such as vertical wind shear,
61 and relative humidity have been cited for their role in regulating cyclone characteristics as well
62 as its genesis (Gray, 1979). It has been reported that the Arabian Sea warmed by about 0.5°C
63 during 1904-1994 (Rupakumar et al., 2002). In a recent study Prasanna Kumar et al. (2009)
64 speculated that the Arabian Sea is experiencing a regional climate shift since 1995, which is
65 accompanied by a five-fold increase in the occurrence of the most intense cyclones. Even though
66 cyclones are known for their destruction of life and property on the land, they often augment life
67 in the ocean (Madhu et al., 2002; Subrahmanyam et al., 2002; Hema Naik et al., 2008; Rao et al.,
68 2006) through upward pumping of nutrients into the euphotic zone. Thus, in a warming scenario,
69 the Arabian Sea could become more productive (see Goes et al., 2005; Prasanna Kumar et al.,
70 2010), which has implications for regional biogeochemistry. For example, increased biological
71 productivity will exert pressure on the already existing mid-depth oxygen minimum zone (OMZ)
72 in the central Arabian Sea and the severe hypoxia experienced along the eastern Arabian Sea
73 (Naqvi et al., 2000). Studies have shown that the Arabian Sea is a perennial source of ocean to
74 atmosphere CO₂ flux in all seasons (Goyet et al., 1998; Sarma et al., 1998; Sabine et al., 2000)
75 and strong wind can increase the flux. It is in this context that we present the upper ocean
76 response of the eastern Arabian Sea to the tropical cyclone Phyan and its impact on biological
77 productivity.

78

79 **2. Materials and methods**

80

81 **2.1. Data**

82

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

90 Preliminary Report (<http://www.imd.gov.in/section/nhac/dynamic/cyclone.htm>). We used an
91 Optimally Interpolated sea surface temperature (SST) from the remote sensing satellites Tropical
92 Rainfall Measuring Mission Microwave Imager (TMI), Moderate Resolution Imaging
93 Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer-Earth observing
94 system (AMSR-E) (ftp://ftp.misst.org/L4/mw_ir) with a spatial resolution of 9km, to elucidate
95 evolution of surface ocean thermal variation due to the cyclone. We also used 3-day composite
96 ocean colour data by NASA's MODIS-Aqua (<http://oceandata.sci.gsfc.nasa.gov/MODISA/>),
97 which captured only a part of the chlorophyll *a* bloom patch because of the overcast sky. A
98 tropical cyclone releases its energy in the form of strong winds which are significant to ocean
99 mixing resulting in cooling, increased biological productivity and enhanced emission of CO₂. A
100 blended wind product provided by IFREMER/CERSAT derived from the near-real-time
101 measurements by QuikSCAT and SSMI with a spatial and temporal resolution of 25 km and 6
102 hours respectively, was used for the calculation of Ekman pumping velocity. Since this data is
103 available only till 22nd November 2009 ([ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/mwf-](ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/mwf-blended/)
104 [blended/](ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/mwf-blended/)) we used data from NOAA's National Climatic Data Center,
105 (<http://www.ncdc.noaa.gov/oa/rsad/blendedseawinds.html>) to calculate wind-dependent, gas-
106 transfer velocity for TCO₂ flux for November 2009. We have also used the climatological sea-
107 air difference in partial pressure of CO₂ (Takahashi et al., 2009a) to calculate total CO₂ flux over
108 the eastern Arabian Sea before, during and after the passage of the cyclone.

109

110 ***2.2. Developmental stages of Phyan***

111

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

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

127

128 **3. Results and discussions**

129

130 **3.1. SST response**

131

132 Tropical cyclones form in warm ocean water (Gray, 1979). Once formed the strong wind-stress
133 curl associated with the cyclone drives the upward Ekman-pumping and the resultant
134 entrainment and mixing cools the upper ocean (Price, 1981; Pudov, 1992; DeMaria and Kaplan,
135 1994; Sadharam, 2004). Ocean thermal condition was well favoured for the genesis of cyclone
136 Phyan in the eastern Arabian Sea with a SST in excess of 29.4°C. To understand the thermal
137 response of the upper ocean to the passage of Phyan, we plotted SST along the cyclone track. At
138 each latitude along the track, the SST was averaged over 1 degree longitude and was plotted
139 during 3 periods - before (6-8 November 2009), during (9-11 November 2009) and after (12-13
140 November 2009) the passage of the cyclone (Figure 2).

141 Before the passage of tropical cyclone Phyan the SST, in general, was in excess of 29.4°C at its
142 origin while it was ~2°C colder towards the north (Figure 2). The colder condition in the north
143 (north of 17°N) before the arrival of the cyclone was due to the winter cooling under the
144 influence of cold and dry winds of continental origin (Prasanna Kumar and Prasad, 1996).
145 During the formation and passage of the cyclone (9-10 November 2009), a strong surface
146 cooling of about 2°C was noticed. Cooling predominantly occurred between the latitude 11°N
147 and 14°N where the cyclone veered from north-west to north-east. Notice the cold pool to the
148 right of the cyclone track in Figure 1. Similar cooling at the right side of the cyclone track has
149 been reported earlier by several authors (Price 1981; Pudov, 1992; Sadharam, 2004). Price
150 (1981) attributed this right-side bias of SST reduction to non-linear mixed-layer current response
151 and the stronger winds located on the right side of the storm track due to storm motion. In the
152 present study even after the passage of cyclone Phyan, the cooling of SST persisted in the south
153 up to 14°N. In the north (north of 14°N), however, the cooling of SST was gradual. To further
154 understand the mechanism of cooling and the occurrence of cold pool associated with the
155 cyclone Phyan, we calculated the wind-stress curl and the vertical velocity in a box EFGH (0.5-

156 degree latitude x 1-degree longitude) located within the cold pool (see Figure 1) during the first
157 fortnight of November. The value of wind-stress curl was near zero before the formation of
158 Phyan and it suddenly peaked during the period of cyclone (9-11 November 2010) with the
159 highest value of $7.5 \times 10^{-6} \text{ N/m}^3$ (Figure 3) on 10th November. The vertical velocity also showed
160 a similar pattern with upward (negative) velocity during the period of cyclone. The highest
161 upward velocity of $2.4 \times 10^{-4} \text{ m/s}$ occurred on 10th November which coincided with the time of
162 maximum strength of wind-stress curl. Note that the SST cooled from the pre-cyclone value of
163 29.9°C to 27.9°C on 11th November 2010. This time lag between the maximum strength of wind-
164 stress curl (and the vertical velocity) and the occurrence of the maximum cooling indicates the
165 thermal response time of the water column associated with diffusion. Though the wind stress curl
166 diminished rapidly after 10th November when the cyclonic storm moved away from the cold pool
167 location, the momentum imparted by wind stress could sustain the upward transport of cold
168 water. This clearly indicated that the maximum cooling and hence the cold pool, at the right side
169 of cyclone track, was generated by the cyclonic wind-stress curl and the associated upward
170 Ekman-pumping. The enhanced evaporation under the influence of strong winds can also lead to
171 decrease in the SST, but its magnitude is much less (Price, 1981). The SST prior to the formation
172 of Phyan was 1°C higher than the climatological SST computed from TMI during 1998 to 2009.
173 This higher SST could be one of the factors that triggered the cyclone.

174

175 **3.2. Biological response**

176

177 **3.2.1. Enhancement of Chlorophyll *a***

178

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

190 (3500) was more than 70%. This declined to almost 2% (79 pixels) during the period of cyclone
191 activity (8-11 November 2009). After 11th November when Phyan had dissipated, the chlorophyll
192 *a* concentration showed a continuous increase reaching an average highest value of $\sim 1.5 \text{ mg/m}^3$
193 (black dotted line in figure 4) on 16th November. Note that the pixel count also showed an
194 increase which indicated the robustness of the chlorophyll estimate. A greater enhancement in
195 the chlorophyll *a* concentration was seen on 16th November at a location close to the Phyan
196 trajectory (e.g., 71.16°E , 16.66°N), but away from the continental shelf, where the value reached
197 more than 6 mg/m^3 (not presented here). This increased biomass seen 3-4 days after the
198 dissipation of tropical cyclone Phyan indicated the response of biology and the following is the
199 probable mechanism.

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

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

223

224 **3.2.2. Enhancement of Primary Production**

225

226 Estimation of primary production is required to understand the biological process affecting
227 global biogeochemical cycles. Phytoplankton is the dominant primary producer in the marine
228 environment, which synthesises organic material using nutrients, carbon dioxide and light energy
229 with the help of chlorophyll through photosynthesis. We have seen a distinct increase of
230 chlorophyll *a* after the passage of Phyan. The Net Primary Production (NPP) was estimated from
231 the codes of Vertically Generalised Productivity Model (VGPM) (Behrenfeld and Falkowski,
232 1997), using the 3-day composite values of surface chlorophyll *a* concentration from MODIS
233 Aqua, Sea-viewing Wide Field-of-view Sensor (SeaWiFs) daily Photosynthetically Available
234 Radiation (PAR) and optimally interpolated TMI-MODIS-AMSRE SST during 7-17 November
235 2009. The spatial averaged NPP within the box ABCD is presented in figure 5. The NPP in the
236 eastern Arabian Sea before the occurrence of Phyan was $\sim 650 \text{ mg C m}^{-2} \text{ day}^{-1}$ and it showed a
237 rapid increase to $\sim 1050 \text{ mg C m}^{-2} \text{ day}^{-1}$ on 12th November immediately after the dissipation of the
238 cyclone. The peak NPP value of $\sim 1350 \text{ mg C m}^{-2} \text{ day}^{-1}$ was attained on 16th November, 4 days
239 after the cyclone event in agreement with increase in chlorophyll biomass. Thus, the observed 2-
240 fold increase in the NPP resulted from the new production which in turn was mediated by the
241 process of upward Ekman pumping associated with the cyclone. A similar value of new
242 production ($\sim 1500 \text{ mg C m}^{-2} \text{ day}^{-1}$) was reported by Hema Naik et al. (2008), based on a chance
243 *in situ* measurement of chlorophyll and nitrate and using Redfield ratio during a cyclone in
244 Arabian Sea in December 1998. This indicated that the sporadic cyclonic storm in the Arabian
245 Sea, which is showing an increasing trend in recent years (Prasanna Kumar et al., 2009) could
246 support much higher primary productivity in a region which is known for its seasonally high
247 phytoplankton blooms and biological productivity. The elevated primary production will exert
248 additional pressure on already existing OMZ in the Arabian Sea leading to severe anoxic
249 conditions (Naqvi et al., 2000). In addition, the upward Ekman pumping of subsurface cold
250 water could also result in the enhancement and saturation of surface pCO_2 which would finally
251 lead to out gassing of CO_2 . This is explored in the following section.

252

253 **3.3. Effect on CO_2 flux**

254

255 The intense biological activity in the Arabian Sea results in higher sea water $p\text{CO}_2$ than in the
 256 atmosphere for all seasons (Sarma et al., 1998), which makes the Arabian Sea a source of CO_2 to
 257 the atmosphere (Goyet et al., 1998; Sarma et al., 1998; Sabine et al., 2000). The sporadic cyclone
 258 has the potential to intensify this source. The rate of exchange of sea-air CO_2 depends on the
 259 solubility of CO_2 in sea water, gas transfer velocity and difference in partial pressure between the
 260 Surface Ocean and atmosphere. We can formulate the net CO_2 flux (F) as:

$$261 \quad F = k \cdot \alpha \cdot (p\text{CO}_2^{\text{sea}} - p\text{CO}_2^{\text{air}}) \quad (1)$$

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

$$264 \quad \ln \alpha = A_1 + A_2(100/T) + A_3 \ln(T/100) + S [B_1 + B_2(T/100) + B_3(T/100)^2] \quad (2)$$

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

$$266 \quad k \text{ (cm h}^{-1}\text{)} = I \cdot U^2 \cdot (Sc/660)^{-1/2} \quad (3)$$

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

$$271 \quad Sc = A - BT + CT^2 - DT^3 \quad (4)$$

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

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

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

281 The CO_2 flux to the atmosphere associated with Phyan over the eastern Arabian Sea (10°N -
 282 18°N and 70°E - 75°E) during 8th to 11th November was about 0.123 Tg C (1Tg= 10^{12} g) (Figure 6),
 283 which accounted for ~85% of the total out-gassing of CO_2 for the month of November
 284 (climatology) calculated by Takahashi et al. (2009a). The total emission of CO_2 during
 285 November 2009 was ~0.244 Tg C, which was about 170% of the climatological value (0.144 Tg
 286 C) over the area ABCD (see Figure1 for location of box). Based on the Indian JGOFS
 287 measurements Sarma et al. (1998) estimated the seasonal variability of CO_2 emission to be 1 to

288 3.5 mmol m⁻² day⁻¹ (excluding south west monsoon period) (Sarma et al., 1998). The present
289 estimate showed that during the course of cyclone Phyan ~8 mmol m⁻² day⁻¹ CO₂ was emitted
290 from ocean to atmosphere, making the eastern Arabian Sea a major source.

291

292 4. Conclusion

293

294 In this study we investigated the impact of tropical cyclone Phyan to the ocean biology and
295 CO₂ exchange over the eastern Arabian Sea using *in situ* as well as remote sensing data sets.
296 Surface temperature showed an immediate response by way of cooling (2°C) while chlorophyll *a*
297 and net primary production showed a delayed response. The strong wind-mixing associated with
298 cyclonic winds led to the observed rapid cooling, which was sustained even after the dissipation
299 of Phyan by the wind-stress curl induced upward Ekman pumping. Though the SST showed an
300 immediate response, the biological response to Phyan showed a time lag. The peak chlorophyll
301 *a* and the net primary productivity (NPP) occurred 3-4 days after the dissipation of Phyan. The
302 chlorophyll *a* showed an average enhancement of 0.5 mg/m³ while the NPP showed a two-fold
303 increase. The mechanism that supported increased biological productivity was the vertical
304 transport of subsurface nutrients by the wind stress curl. The upward Ekman pumping
305 transported the cold and nutrient rich waters to the upper ocean which was also enriched in CO₂.
306 The estimated CO₂ flux to the atmosphere associated with Phyan was 0.123Tg C which was 85%
307 of the climatological monthly mean value for November. The above results of our study have
308 implication to the Arabian Sea which already has a mid-depth OMZ. Thus, in the Arabian Sea the
309 increased frequency and intensity of the cyclones in a warming environment are expected to
310 increase manifold the biological productivity as well as CO₂ out-gassing. Increased productivity,
311 in turn, will exert increased demand on mid-depth oxygen exerting additional stress on already
312 existing OMZ.

313

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445 **Legend to figures**

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

448 ABCD denotes the area influenced by the cyclone while box EFGH indicates the location of the
449 cold pool. Blue patches are waters colder than 27.5°C, seen during cyclone period to the right of
450 the cyclone track.

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

454 **Fig. 3.** Time evaluation of wind-stress curl (red), Ekman-pumping velocity (green), 2009 SST
455 (blue) and SST climatology (black dash line) at the cold pool location EFGH (12.5°N-13°N,
456 71°E-72°E) indicated in Figure 1. The SST climatology is from TMI during 1998-2009.

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

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

465 **Fig. 6.** Total carbon dioxide flux in Tg C (1Tg=10¹²g) m⁻² day⁻¹ integrated over the box ABCD
466 (see Figure 1 for the location). *T CO₂ values are from Takahashi et al.,(2009a).

- Impact of tropical cyclone was immediate 2°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 CO₂ out-gassing of 0.123 Tg accounts for 85% November climatology

MANUSCRIPT

