

Impact of the Indian Ocean temperature - phytoplankton feedback on simulated South Asia climate

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Key Points:

- Marine biogeochemical feedback leads to the decline of the SST during the phytoplankton bloom and significant cooling of subsurface layers occurs
- The feedback leads to a drying over most of the area during the monsoon season
- The feedback's impact has cascading effects upon the model ocean physics which further translates into altered atmosphere dynamics

Abstract

A regional Earth System Model has been implemented for the South Asia region. We investigate the effect of the marine biogeochemical feedback which affects the attenuation of the short-wave radiation upon the regional climate. In the experiment where the feedback is activated the average SST is lower over most of the domain. The greatest deviations (more than 1°C) in SST between the two runs observed in the summer period during the phytoplankton bloom. A significant cooling of subsurface layers occurs and the thermocline shifts upward compared to the Jerlov type absorption. The phytoplankton primary production and its deviation in the feedback-based simulation turned out to be higher, especially during periods of winter and summer phytoplankton blooms. The marine biogeochemistry feedback also affects the amount of precipitation in the model in particular during the monsoon season. The associated SST cooling leads to a reduction of the precipitation but affects it in different ways. In the Arabian Sea, the reduction of the transport of humidity across the equator leads to a reduction of the large scale precipitation in the eastern part of the basin, reinforcing reduction of the convective precipitation. In the Bay of Bengal, the feedback increases the large scale precipitation, contouring the decrease of convective precipitation. Thus, the main impacts of including the biogeochemical coupling in the Indian Ocean include the enhanced phytoplankton primary production, a shallower thermocline and decreased SST, with cascading effects upon the model ocean physics which further translates into altered atmosphere dynamics.

Plain Language Summary

The effect of the marine biogeochemical feedback on the South Asian regional climate has been investigated. In the experiment where the feedback is activated the average surface temperature is lower over most of the ocean. The greatest deviation is in the summer period during the phytoplankton

bloom. A cooling of subsurface layers occurs and the thermocline shifts upward compared to the Jerlov type absorption. The phytoplankton primary production and its deviation in the feedback-based simulation turned out to be higher, especially during periods of winter and summer phytoplankton blooms. The marine biogeochemistry feedback also affects the amount of precipitation in particular during the monsoon season. In the Arabian Sea, the reduction of the transport of humidity across the equator leads to a reduction of the large scale precipitation in the eastern part of the basin, reinforcing reduction of the convective precipitation. In the Bay of Bengal, the feedback increases the large scale precipitation, contouring the decrease of convective precipitation. Thus, the main impacts of including the biogeochemical coupling in the Indian Ocean include the enhanced phytoplankton primary production, a shallower thermocline and decreased sea surface temperature.

1. Introduction

The vulnerability and the ability of society and natural systems to adapt to the impact of climate change vary greatly according to geographic regions and populations. The Indian subcontinent and adjacent area, where a fifth of humanity lives, is one of the regions where the impacts are strong both in the present time and future climate projections (Turco et al, 2015; Szabo et al., 2016). The strongest impacts are related to changes in the intensity and frequency of extreme events (such as floods, droughts, tropical cyclones, storm surges, phytoplankton blooms, ocean heat waves, avalanches, etc.) which can inflict significant damage on ecosystems, human populations, infrastructure and property. In particular, the intensity of extreme events over India is increasing continuously, a fact which can be observed every year when one or other region gets affected by floods causing enormous socio-economic losses (IPCC AR5, 2014).

Atmospheric extreme events contribute to the emergence of extreme situations in the ocean and vice versa. For example, the strengthening of the southwestern monsoon in the Arabian Sea leads to abnormal coastal upwelling and increased mixing of the upper ocean layer, the subsequent supply of nutrients into the upper layer from the deep ocean and anomalous blooms of phytoplankton (Ryabchenko et al., 1998). In turn, the changes in sea surface temperature (SST) and surface fluxes of heat and momentum caused by monsoons can feedback to atmospheric circulation. It is known that the Bay of Bengal is one of the main tropical cyclogenesis areas in the world (Dube et al., 1997). Strong cyclones forming here lead to catastrophic storm surges during which hundreds of thousands of people lose their lives (Tasnim et al., 2015). Another example of the relationship between atmospheric and oceanic processes is associated with river runoff and nutrient loading which is projected to be maximum in southern and eastern Asia due to the growth of population and increased industrialization (Seitzinger et al., 2002). The Ganges–Brahmaputra estuary is strongly vulnerable to high nutrient load from river discharges (Seitzinger et al., 2005; Mukhopadhyay et al., 2006). Global warming can enhance the freshwater river runoff and the nutrient flux thus enhancing the primary production in coastal areas. It was stated that the estuarine ecosystem experiences a complete change in terms of phytoplankton during monsoon (De et al., 2011) and that the eastern Indian coast is affected by localized eutrophication which directly influences the nutrient level of coastal water and phytoplankton abundance (Choudhury & Pal, 2010). Recent assessments (Sattar et al., 2014) of the impact of food production upon the river flux of nutrients into the Bay of Bengal coastal waters in the past and the future show that the coastal eutrophication potential is high in the Bay of Bengal thus elevating the risk for oxygen deficiencies (d'Asaro et al., 2019). The above examples of interactions between atmospheric and oceanic processes underscore the need to create a unified high-resolution modeling system for the region to be able to study these interactions in detail.

Earth System Models (ESMs) include coupled representations of the ocean, atmosphere, land use, vegetation, biogeochemistry, atmospheric chemistry, and the hydrological cycle. They are very

effective tools for the study of the Earth's climate system and are used to investigate the complex systems and associated mechanisms in climate and environmental sciences in the past and future, driven by assumptions on the evolution of climate change (Taylor et al., 2012). However, they usually lack the resolutions that are necessary for regional studies. Dynamical downscaling with Regional Climate Models (RCMs) is used to translate the global climate information generated by ESMs down to regional scales at a higher resolution. RCMs take the initial conditions and time-dependent boundary conditions from the global models and provide dynamically downscaled climate information within the region of interest (Giorgi, 2006).

We have implemented a new version of the high-resolution Regional Earth System Model (RESM) ROM (Sein et al., 2015) for South Asia and the northern Indian Ocean. The model includes ocean, atmosphere, hydrological cycle and marine biogeochemistry components. Such a modeling system is required for the study of extreme events in the atmosphere and the ocean in the India region for seasonal and decadal predictions, climate change projections and advanced monsoons modeling. It will help to better describe their interaction with the ocean and glaciers, calculate their statistical characteristics and fulfill projections for the future.

In this study we will use the model to assess the impact of marine biogeochemical feedback upon the simulation of the present climate over the Indian subcontinent and the adjacent ocean using the South Asia CORDEX domain. To this end, we compare two simulations carried out with our RESM. In both simulations, the model is driven by data from CMIP5 20th century simulation with the Max Planck Institute Earth System Model (MPI-ESM). These two simulations differ only in the influence of the ocean biochemistry module on the shortwave solar radiation penetration into the ocean. In the first simulation, we use a light attenuation parameterization based on the Jerlov water types, when the attenuation coefficient depends on the water type specified but does not vary in time. The use of Jerlov water types is the standard case in ocean modelling although it has several shortcomings. Firstly, the dynamics of phytoplankton blooms on the light climate is completely neglected, which is highly problematic in regions which are subject to a strong seasonal cycle and in regions with strongly varying nutrient supply. Secondly, coastal characteristics, especially in front of large rivers with high nutrient load and limited exchange with the open ocean, are not resolved which is however important in high resolution downscaling simulations. In the second simulation, we introduce the marine biogeochemical feedback by calculating the attenuation coefficient using the phytoplankton concentration simulated by the ocean biogeochemistry module and allow to feedback onto the absorption of shortwave radiation by the physical module (MPIOM). Hence, the presence of a strong local phytoplankton bloom in the surface layer will increase the heat absorption in the upper layers and decrease it in deeper layers, with cascading feedbacks on the thermohaline structure of the water column such as the e.g. thermocline intensity and depth. Due to these reasons in regional climate studies, the effect of seasonal and local varying phytoplankton concentration can be expected to be important. The reason why so many ocean models make use of the more simple Jerlov attenuation scheme is not a scientific one but is of economic nature. Including the biogeochemical feedback, as done here, requires online coupling to a biogeochemistry model which leads to a threefold consumption of CPU hours compared to an uncoupled model running with Jerlov water types.

The objectives of this paper can be summed as follows:

1. To evaluate the ability of our model to reproduce the present climate in the South Asia CORDEX region both in the ocean and the atmosphere.
2. To evaluate the quality of corresponding simulated physical and biogeochemical characteristics in the northern part of the Indian Ocean.

- 138 3. To assess the impact of the biochemistry feedback upon the simulated regional climate,
139 both in the atmosphere and the ocean.

140 The layout of the present paper is as follows. In section 2 a description of the coupled modeling
141 system is presented. Section 3 is focused on the verification of the developed RESM and its results.
142 Section 4 contains some discussion. Conclusions are presented in section 5.

144 2. Methods

145 The oceanic component of our RESM ROM is the Max Planck Institute Ocean Model
146 (MPIOM: Marsland et al., 2002; Jungclaus et al., 2013). Via the OASIS coupler, the MPIOM is
147 coupled with the REgional atmospheric MOdel (REMO: Jacob, 2001), the Hamburg Ocean Carbon
148 Cycle model (HAMOCC: Ilyina et al., 2013), and the Hydrological Discharge model (HD: Hagemann
149 and Dumenil, 1998). This coupled modeling system has the distinctive feature that its global ocean
150 module provides the possibility to refine the grid resolution in the region of interest and to avoid the
151 lateral boundary conditions in the ocean while performing calculations. Another feature of the ROM
152 is that the dynamical link between the ocean and the atmosphere (coupling) is implemented only at
153 the chosen subdomain, while outside this region in the uncoupled area the ocean module of the ROM
154 system calculates heat, freshwater, and momentum fluxes from atmospheric fields taken from the
155 same global model used for REMO boundary conditions. A detailed description of the coupled model
156 ROM can be found in (Sein et al., 2015).

157 For this study, we perform two present-time simulations using ROM. The setups used are
158 almost identical and differ only in the activation of the ocean biogeochemistry component. For REMO
159 we use the slightly extended CORDEX (<http://www.cordex.org>) South Asia domain (Fig. 1). The
160 mesh of the global oceanic component has a variable horizontal resolution which reaches up to 15
161 km inside the coupled region. In both simulations, the model is driven by data from a historical
162 simulation with the MPI-ESM LR setup. The model runs were performed for the period 1920–2005,
163 the first 30 years being an adjustment period. Initial conditions for the biogeochemical module were
164 taken from MPIOM/HAMOCC long term simulations (Gröger et al., 2013). For the ocean and
165 atmosphere, the initial conditions were taken from previous spin-up simulations: 50 years MPIOM
166 stand-alone run plus 2 times 40 years (80 years) coupled MPIOM/REMO simulations with ERA-
167 Interim forcing.

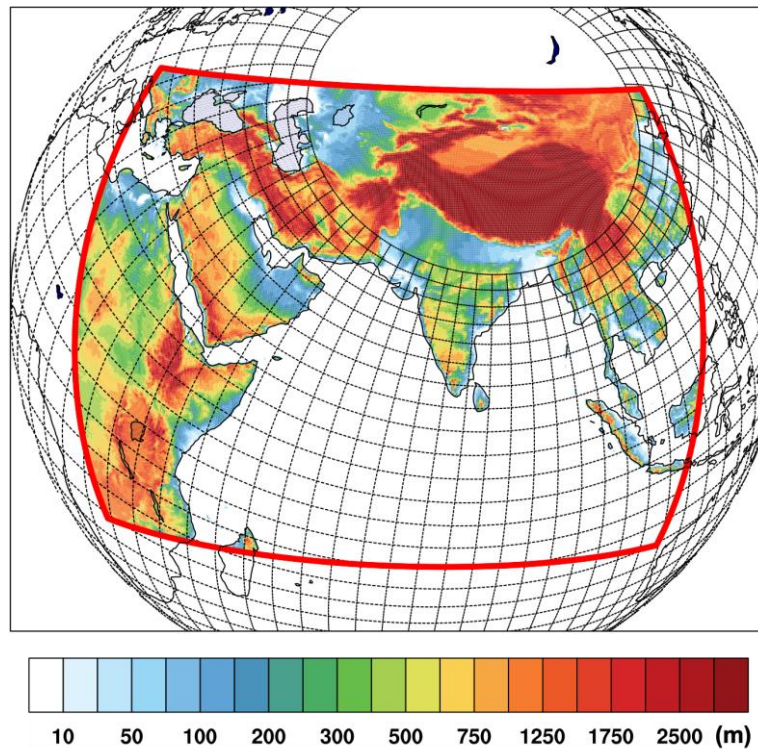


Figure 1. ROM configuration. The red frame shows the coupled ocean-atmosphere CORDEX domain. The black lines indicate the grid of the MPIOM/HAMOCC models (only every 12th line is shown). Color scale represents orography.

The two ROM simulations (labeled as INDJ and INDB hereafter) differ by various parameterizations of the attenuation of short-wave radiation (SWR) penetrating into the ocean and its influence on water temperature. In the INDJ experiment, the model utilized a simple classical light attenuation parameterization based on the Jerlov water types (Jerlov, 1976). In this case, the attenuation coefficient depends on the water type specified in the model, but does not vary in time. This light attenuation parameterization was used both for the evolutionary equation for water temperature and in the HAMOCC marine biogeochemical module which is forced by the ocean but does not have the feedback to the ocean. In the INDB experiment, the biogeochemical feedback between the ocean and the atmosphere through the marine ecosystem was implemented by making the light attenuation coefficient a function not only of water attenuation itself but also phytoplankton concentration (Gröger et al., 2013). In the INDB run, this parameterization was implemented in both the physical and biogeochemical blocks of the ocean model. Therefore, in the INDB experiment, the presence of phytoplankton in the water reduces the amount of SWR penetrating into the deeper layers thus affecting the water column temperature and, through water temperature, the heat flux between the ocean and the atmosphere.

3. Results

3.1 Ocean

To verify the model we use the temperature, salinity, dissolved nitrates and dissolved phosphates data from the World Ocean Atlas 2013 (WOA13), and chlorophyll concentration from the satellite data (SeaWiFS and MODIS-Aqua).

According to the India Meteorological Department, we distinguish the following seasonal periods used for the verification procedure based on the monsoon activity in the northern part of the Indian Ocean:

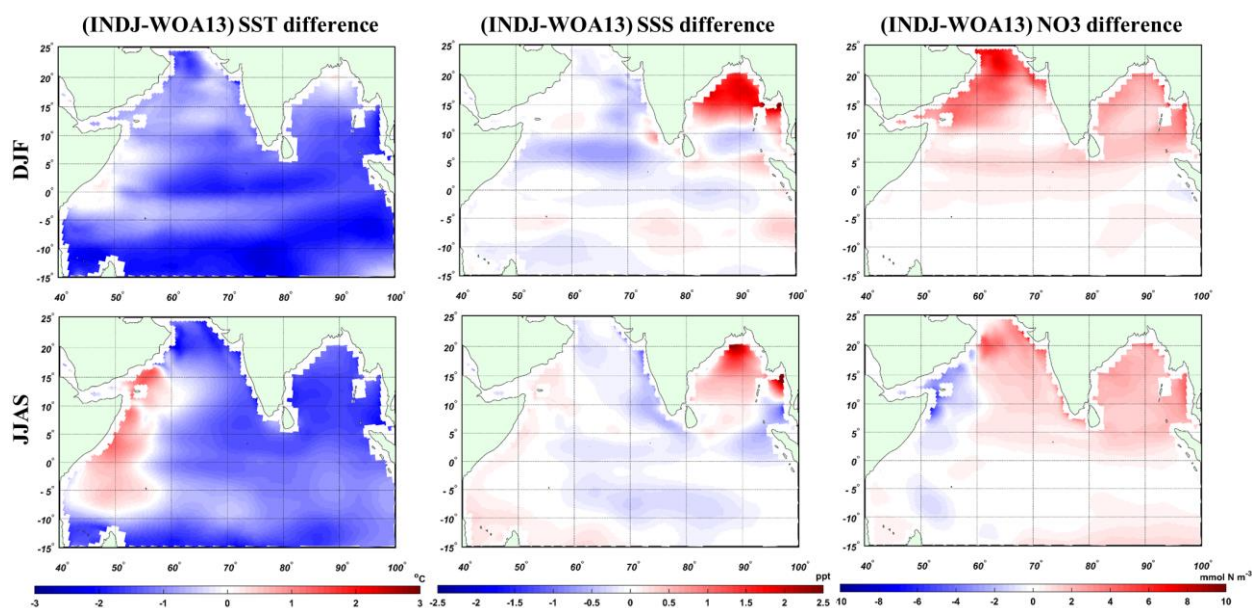
- 198 • DJF: December–February (winter season, NE winds);
- 199 • MAM: March–May (pre-monsoon season);
- 200 • JJAS: June–September (monsoon season, SW winds);
- 201 • ON: October–November (post-monsoon season);

202 In the following, we compare the model results and observations for winter (DJF) and summer
 203 (JJAS) seasons time-averaged over 1975–2004, since the phytoplankton impact is expected to be
 204 maximal during the bloom periods.

206 3.1.1 Sea surface

207 *Sea surface temperature and salinity (SST and SSS).* Figure 2 shows the spatial distribution of
 208 the difference between the modeled SST, SSS and corresponding WOA13 data for the winter (DJF)
 209 and summer (JJAS) climatic seasons time-averaged over 1975–2004. It can be seen that the model
 210 generally underestimates the SST relative to the observational climatic data, the exception being the
 211 region located off the coast of the Somali peninsula. The largest deviations in SSS from the WOA13
 212 are observed in the Bay of Bengal, salinity being overestimated by the model by 0.5–2‰ in the
 213 surface layer. The largest discrepancy in SSS occurs in winter (DJF), while in pre-monsoon and
 214 monsoon seasons the maximum difference is about 0.5‰ and 1.5‰, respectively. Off the western
 215 Indian coast, calculations show somewhat lower SSS than that in the WOA13 surface salinity field,
 216 the largest discrepancy here between ROM and WOA13 occurring in autumn and being up to 1‰
 217 (not shown).

218



219

220 **Figure 2.** Spatial distribution of the difference between experiment INDJ and WOA13 for SST (left column),
 221 SSS (middle column) and NO3 in the surface layer (right column). SST, SSS and NO3 are time-averaged for
 222 winter (DJF) and summer (JJAS) for the period 1975–2004.

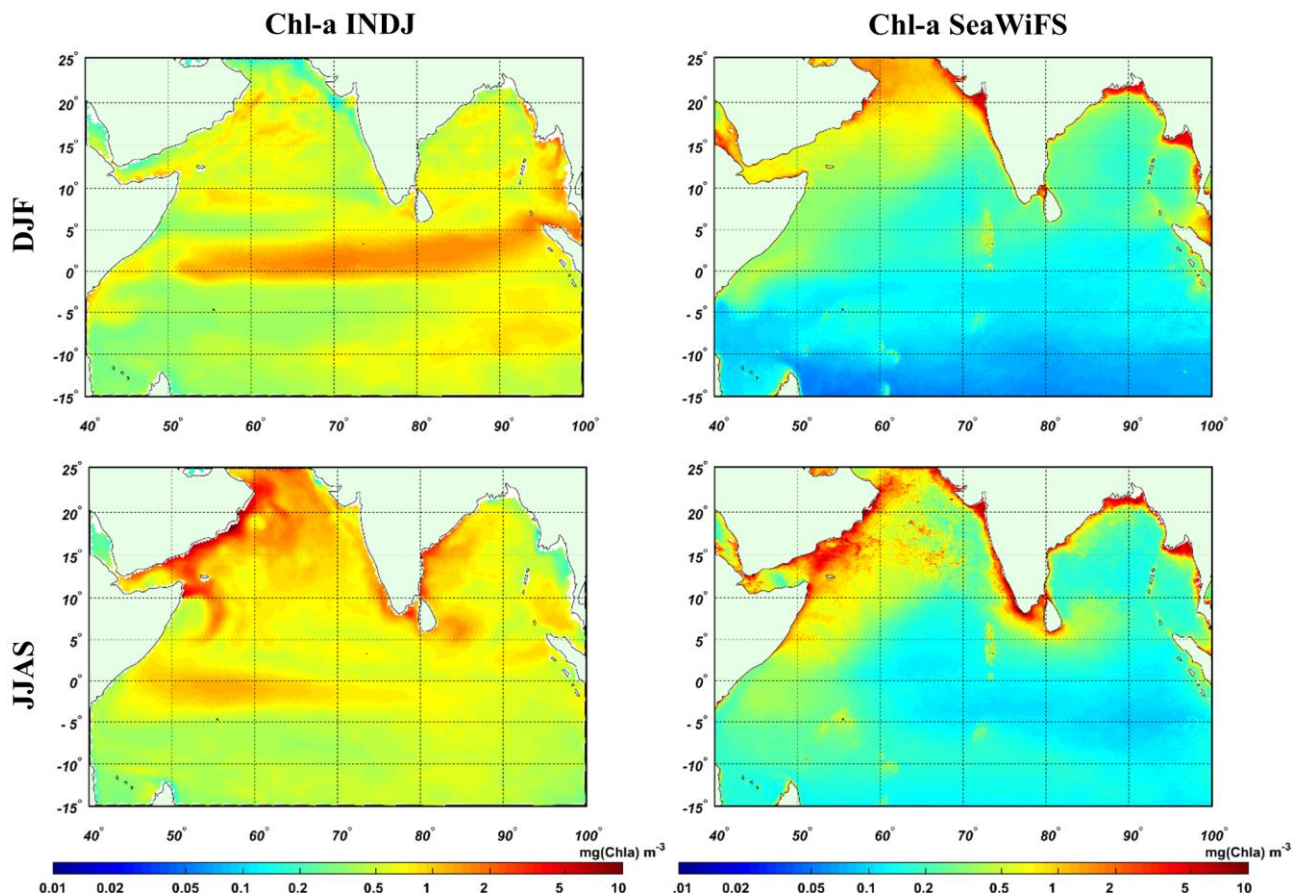
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224 *Sea surface concentration of dissolved nitrate.* It was found that, compared to WOA13, the
 225 HAMOCC biogeochemical model somewhat overestimates the surface concentration of nitrates
 226 (NO3), especially during winter (Fig. 2). The strongest deviations are located along the coasts and
 227 are related to uncertainties in nutrient supply originating from rivers and point sources as we apply a
 228 rough climatological estimate for external nutrient supply (Gröger et al., 2013). With more distance
 229 from the coasts, the model bias reduces showing the model’s capability to correctly simulate the

230 biogeochemical cycling of the open Indian ocean which is the main purpose of this study. In front of
 231 NE Africa and South Arabia, the modeled too high SSTs and too low nitrate concentrations during
 232 the summer monsoon season may indicate too weak upwelling in response to the predominant SW
 233 wind regime. At a depth of 50 m, the agreement between WOA13 and the model is somewhat better
 234 and the main features of the spatial distribution of nitrates are reproduced correctly. The only serious
 235 exception is the overestimated concentration of nitrates in autumn off the southwest coast of India.
 236 At a depth of about 100 m, the discrepancy between the WOA13 data and the model is more
 237 pronounced. At a depth of 500 m the WOA13 and modeled nitrates are very similar, which is
 238 obviously due to the small influence of the seasonal ecosystem dynamics upon the distribution of
 239 nitrates at such depths. The maximum deviations in surface nitrate field between the model and
 240 WOA13 data occur during the bloom periods (winter and summer) in both simulations (INDJ and
 241 INDB), while this deviation is minimal in spring. In general, the modeled annual surface
 242 concentration of dissolved nitrate is slightly higher than in WOA13.

243 *Sea surface chlorophyll-a concentration.* Verification of the biogeochemical module
 244 HAMOCC was also made based on the ocean surface chlorophyll-a concentration (Fig. 3). The
 245 calculated surface phytoplankton concentration (in carbon units) was converted into the chlorophyll-
 246 a concentration (in mg/m³) using the constant C:Chl ratio equal to 60 gC / gChl used in HAMOCC
 247 (Ilyina et al., 2013).

248



249

250 **Figure 3.** Comparison of the simulated (INDJ) and observed (SeaWiFS) surface chlorophyll-a concentration.
 251 The fields are time-averaged seasonally (DJF, JJAS) for the period 1997–2005.

252

253 It is clear that the modeled chlorophyll-a concentration is overestimated in comparison with
 254 the SeaWiFS satellite data. Still, according to SeaWiFS, the model captures the main patterns in the
 255 spatial distribution of chlorophyll-a concentration in the surface layer during the periods of maximum

256 phytoplankton development (bloom in JJAS, Fig. 3). To the north of 5°N, both the model and the
257 satellite data show the seasonal dynamics of chlorophyll-a. The model produces lower chlorophyll-a
258 concentrations in the Arabian Sea under the predominant NE wind regime during the winter monsoon,
259 compared to SeaWiFS data. By contrast, SW winds during the summer monsoon induce upwelling
260 of nutrients from deeper layers and stimulate primary production. In the model, the enhanced
261 chlorophyll-a concentrations occur during winter along the eastern boundary of the Bay of Bengal
262 while reduced production is indicated there during summer. While these changes are in accordance
263 with the changing wind regime, the satellite data show higher concentrations also during summer.
264 The most plausible explanation for this is a persistently high supply of riverine nutrients around the
265 year. Another difference between the model and satellite data is the presence of increased chlorophyll-
266 a concentration zone stretching along the equator in the model results, especially during the winter
267 period. It is not present in satellite data. We think that the cause is the overestimated upwelling in the
268 equatorial region and, thus, the enhanced supply of nutrients to the surface. The overestimation or
269 underestimation of ocean productivity along the equatorial divergence zone is a common problem of
270 many ocean general circulation models (e.g., Steinacher et al., 2010).

271 A comparison of the time-series of the HAMOCC surface chlorophyll-a concentration with
272 satellite data was also carried out (Fig. 4).

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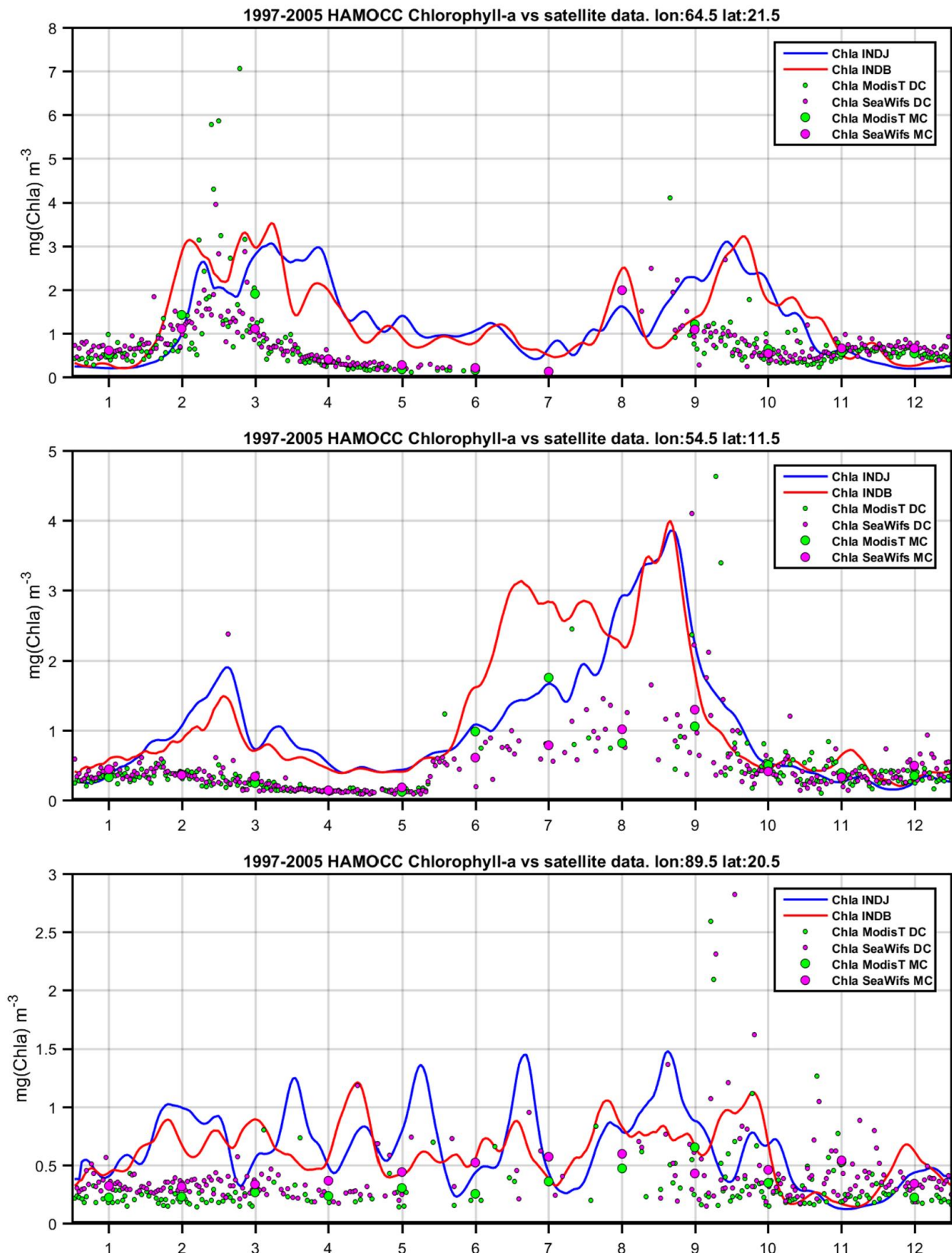


Figure 4. Comparison of the simulated (INDJ and INDB) and observed (SeaWiFS, MODIS Terra) time-series of surface chlorophyll-a concentration in the Arabian Sea (a), Somali upwelling area (b), and the Bay of Bengal (c).

3.1.2 Vertical distributions

Vertical distribution of water temperature, salinity and nutrients. We have also analyzed the spatially-averaged vertical profiles of water temperature, salinity and dissolved nitrate and

282 phosphorus concentration for the northern part of the Indian Ocean (IO) and for the Arabian Sea
 283 (ASF) and the Bay of Bengal (BBF) regions (Fig. 5).
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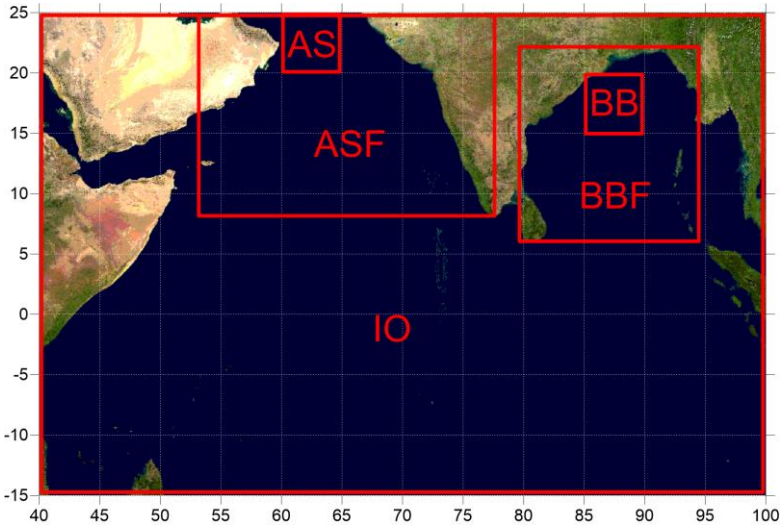
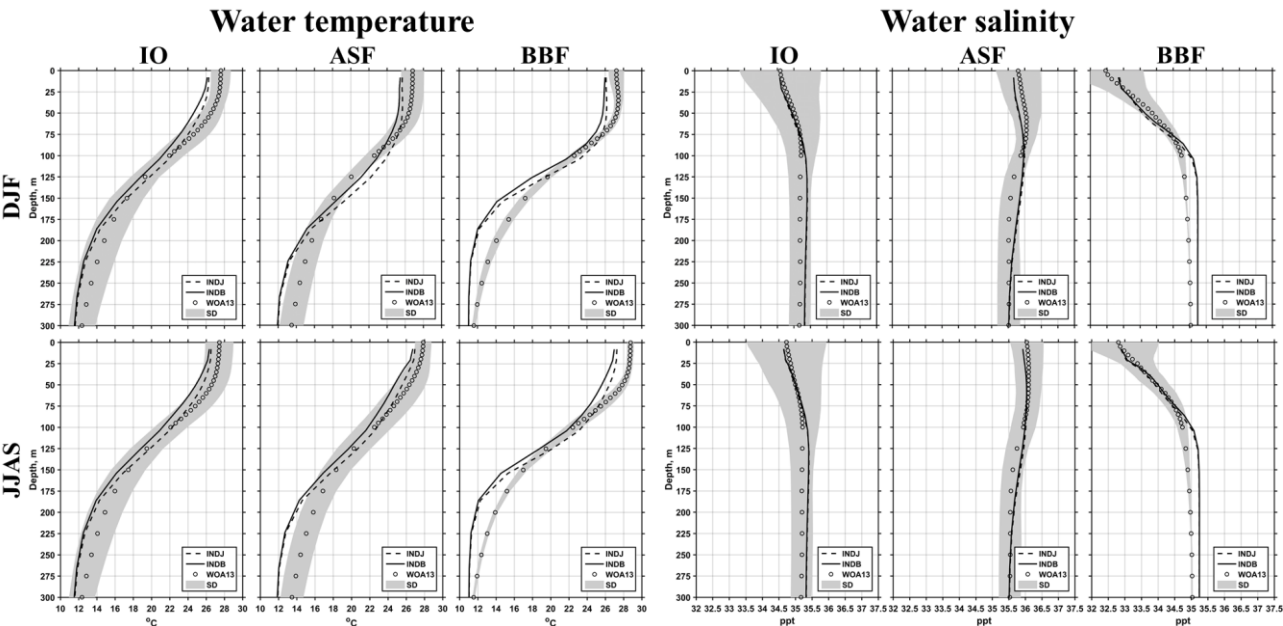


Figure 5. Spatially-averaged areas in the model domain.

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 286
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 288 As seen from Fig. 6, the simulated vertical distribution of temperature and salinity is in
 289 relatively good agreement with WOA13 data. The modeled values are generally within the standard
 290 deviation range of the corresponding WOA13 data. The results are close to the climatic in the Arabian
 291 Sea and in the Bay of Bengal but they are out of the standard deviation range there in most cases.
 292 Still, it should be noted that the standard deviation of WOA13 data is very small in these areas due to
 293 the scarcity of observations. The same is true for the vertical distribution of nutrients (Fig. 7).
 294



295
 296 **Figure 6.** Vertical profiles of water temperature and salinity time-averaged seasonally (DJF, JJAS) for the
 297 period 1975–2004. INDJ and INDB designate the model runs; WOA13 designates the climatic data from the
 298 World Ocean Atlas 2013; SD designates the standard deviation of the WOA13 data.
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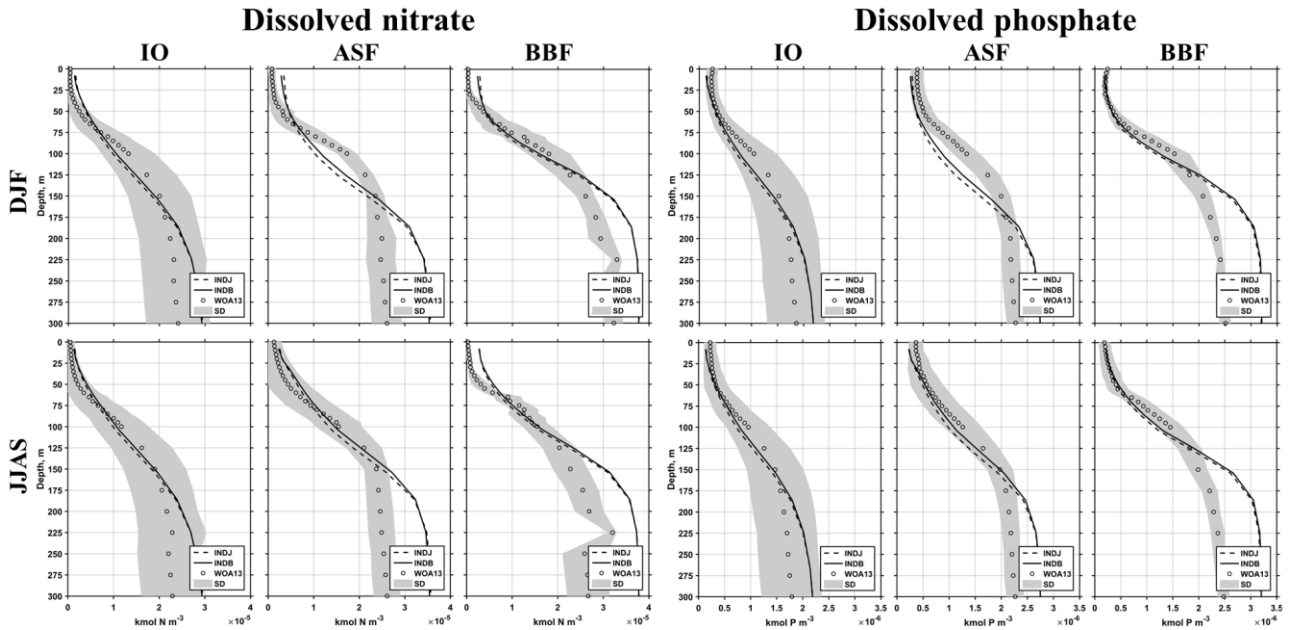


Figure 7. Vertical profiles of dissolved nitrate and phosphate time-averaged seasonally (DJF, JJAS) for the period 1975–2004. INDJ and INDB designate the model runs; WOA13 designates the climatic data from the World Ocean Atlas 2013; SD designates the standard deviation of the WOA13 data.

3.1.3 Impact of the marine biogeochemistry feedback

Impact of the feedback on the water temperature and salinity. We have also compared the results of two model runs (INDJ and INDB) between each other in order to investigate the impact of the chlorophyll-dependent light attenuation parameterization (Gröger et al., 2013) upon the main oceanic variables. The vertical distribution of temperature, salinity, dissolved nitrate and phosphate for different regions of the model domain was already presented in Fig. 6–7 for both experiments. Figure 8 shows the spatial distribution of the climatological (1975–2004) values of the SST difference between the two model runs (INDB-INDJ), as well as the difference in SST standard deviation for both experiments. In winter (DJF) the feedback between the ocean and the atmosphere through the marine ecosystem leads to the colder SST, with differences reaching up to 1° C in the northern part of the Arabian Sea. The exceptions are the areas near the southwestern coast of India, the northwestern coast of Indonesia and the eastern part of the Andaman Sea. But the SST increase in these areas is insignificant and does not exceed 0.1° C. In summer (JJAS) the difference in SST between the two runs is even more pronounced, especially in the northern part of the Arabian Sea and along the eastern coast of India. SST in the INDB experiment is also characterized by stronger variability, the standard deviation of temperature fluctuations being higher by approximately 0.3° C compared to INDJ.

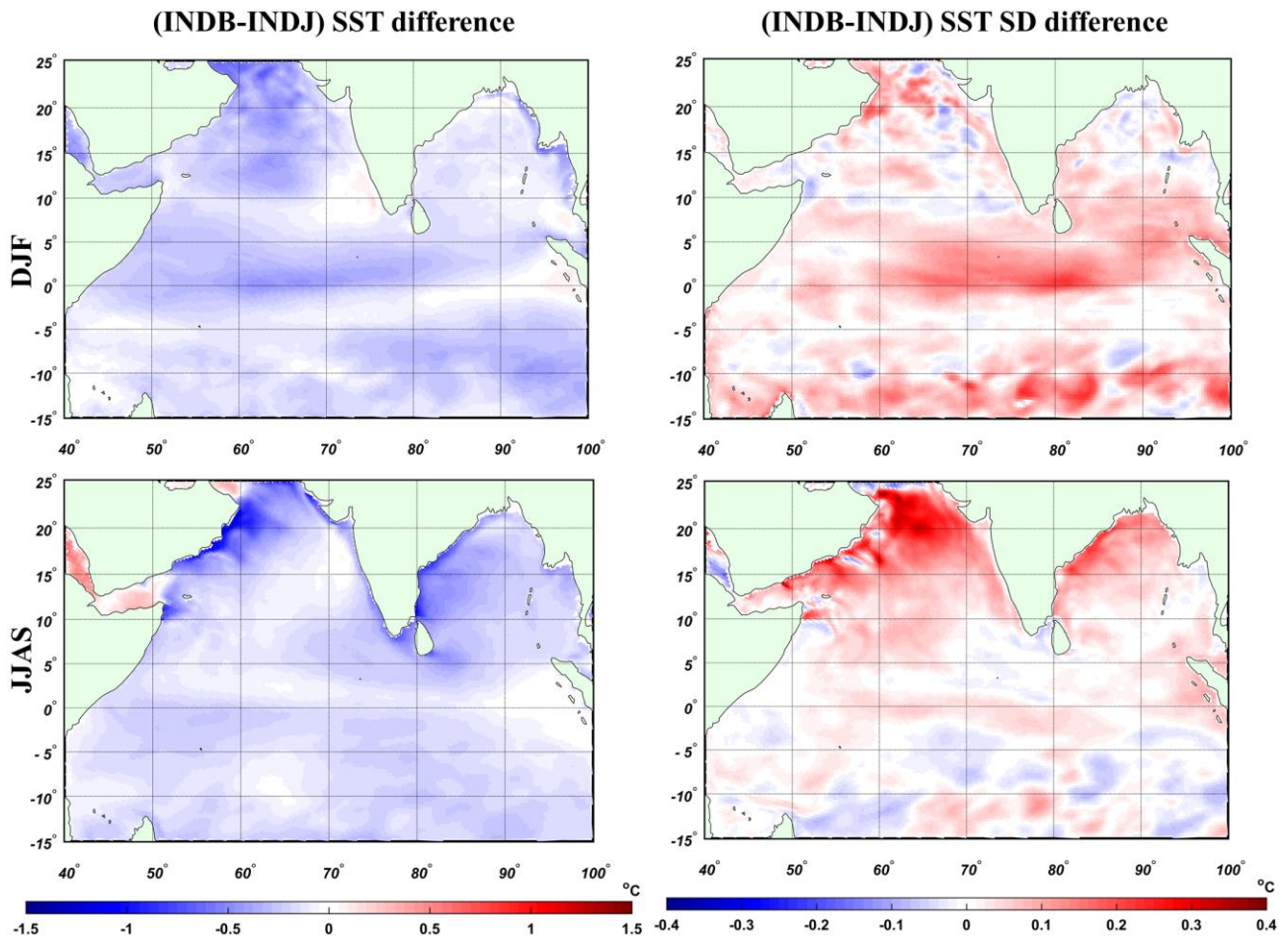


Figure 8. Spatial distribution of the difference between model runs (INDB-INDJ) for SST (left column) and SST standard deviation (std., right column). SST and its std. deviation are time-averaged seasonally (DJF, JJAS) for the period 1975–2004.

When averaging over the annual period (not shown), SST in the INDB run is also slightly lower and its deviation is higher than in INDJ. Summing up, we can say that the INDB run demonstrated the largest changes in SST occurred in summer during the active phytoplankton bloom.

Figure 9 shows the spatial distribution of the SSS difference (INDB-INDJ) and the SSS standard deviation difference for the same period (1975–2004). Our results show that in all seasonal climatic averages the SSS difference between INDB and INDJ experiments is not strongly pronounced and does not generally exceed 0.2‰. The most significant changes in SSS occurs in the Bay of Bengal. Figure 9 also shows that standard deviation in the two simulations remained virtually unchanged, with the exception of the northern part of the Bay of Bengal where the INDB run showed larger seasonal deviations relative to the INDJ experiment.

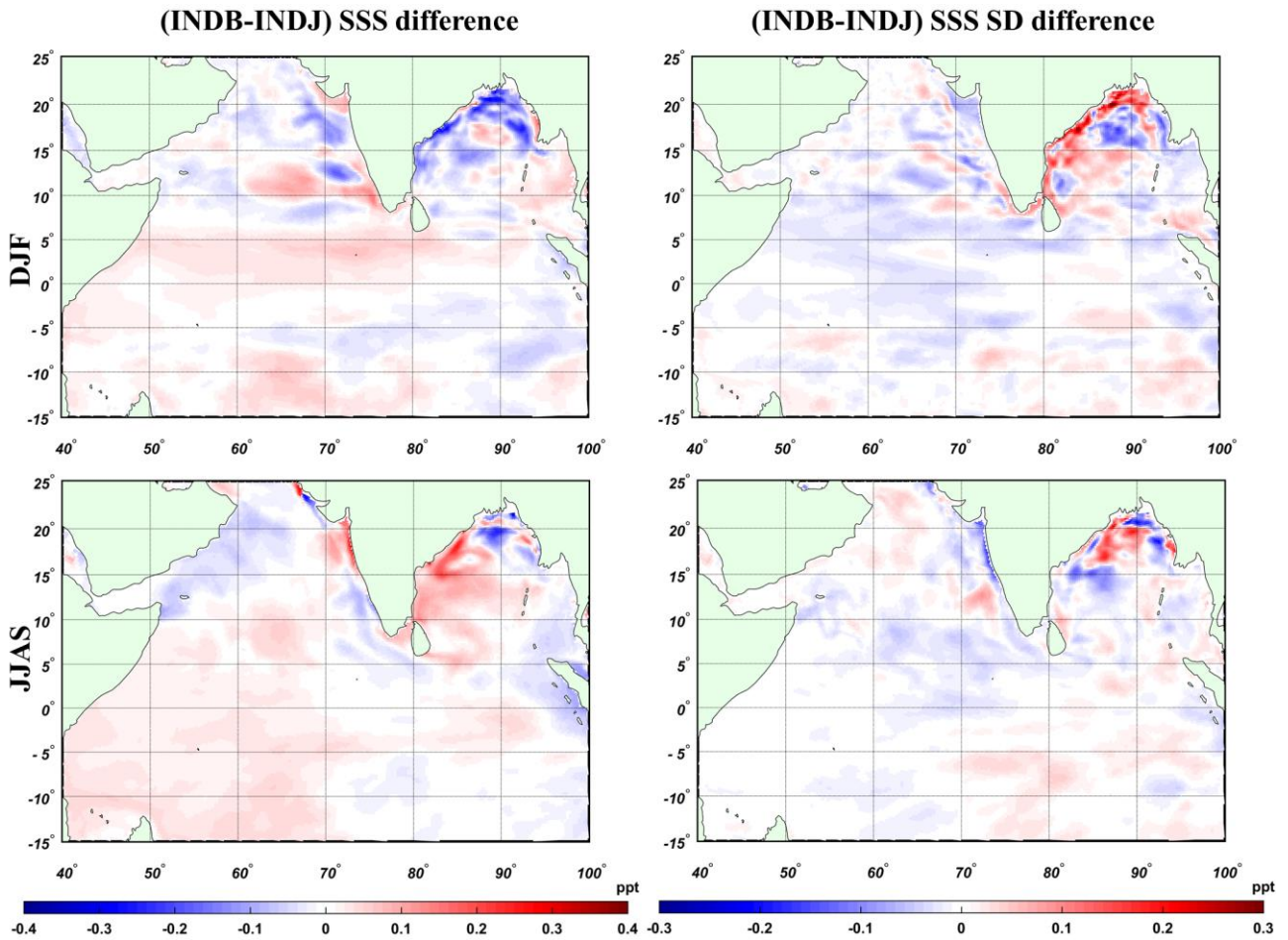


Figure 9. Spatial distribution of the difference between model runs (INDB-INDJ) for SSS (left column) and SSS standard deviation (std., right column). SSS and its std. deviation are time-averaged seasonally (DJF, JJAS) for the period 1975–2004.

Impact of the feedback on the primary production and dissolved nitrate is shown in Fig. 10 where the differences in depth-integrated modeled phytoplankton primary production (PP) and surface concentration of dissolved nitrate (NO_3) are presented. It can be seen that the PP is higher in the INDB experiment during phytoplankton bloom periods (DJF and JJAS). The surface concentration of dissolved nitrates is lower in the INDB than in the INDJ experiment throughout the year and agrees well with the increased PP since nutrients are consumed more intensively in the surface layer.

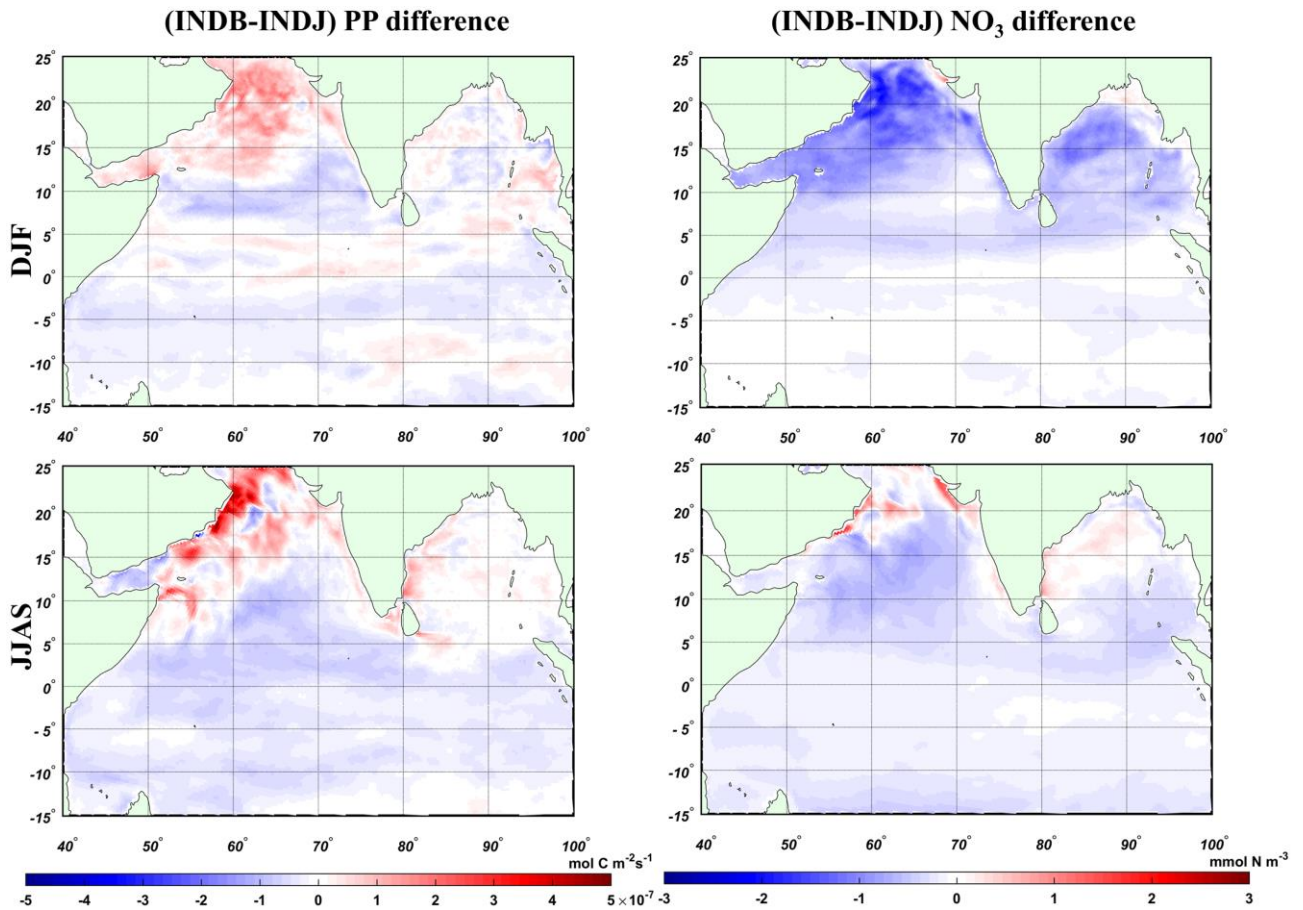


Figure 10. Spatial distribution of the difference between model runs (INDB-INDJ) for PP (left column) and NO₃ (right column). PP and NO₃ are time-averaged seasonally (DJF, JJAS) for the period 1975–2004.

Impact of the feedback on water temperature in ocean upper layers. In order to compare the simulated water temperature in the ocean upper layers (up to 100 m depth), we chose two regions with the largest SST difference between the two model experiments (designated in Fig. 3 as AS: 60–65° E, 20–25° N and BB: 85–90°E, 15–20° N). Figure 11 shows the vertical profiles of water temperature (T), short-wave radiation (SW) and phytoplankton concentration (Phyt.) for the two model experiments considered. These vertical profiles of corresponding variables are spatially-averaged over the regions AS, BB and IO and temporally-averaged over DJF and JJAS for the period 1975–2004. We note significant cooling of subsurface layers in the INDB results. For all the considered regions and the averaging periods, the amount of short-wave radiation penetrating into subsurface layers in the feedback-based experiment (INDB) is less than that in the experiment with classical light attenuation parameterization (INDJ). This is especially noticeable during the phytoplankton bloom period in the Arabian Sea in summer (JJAS).

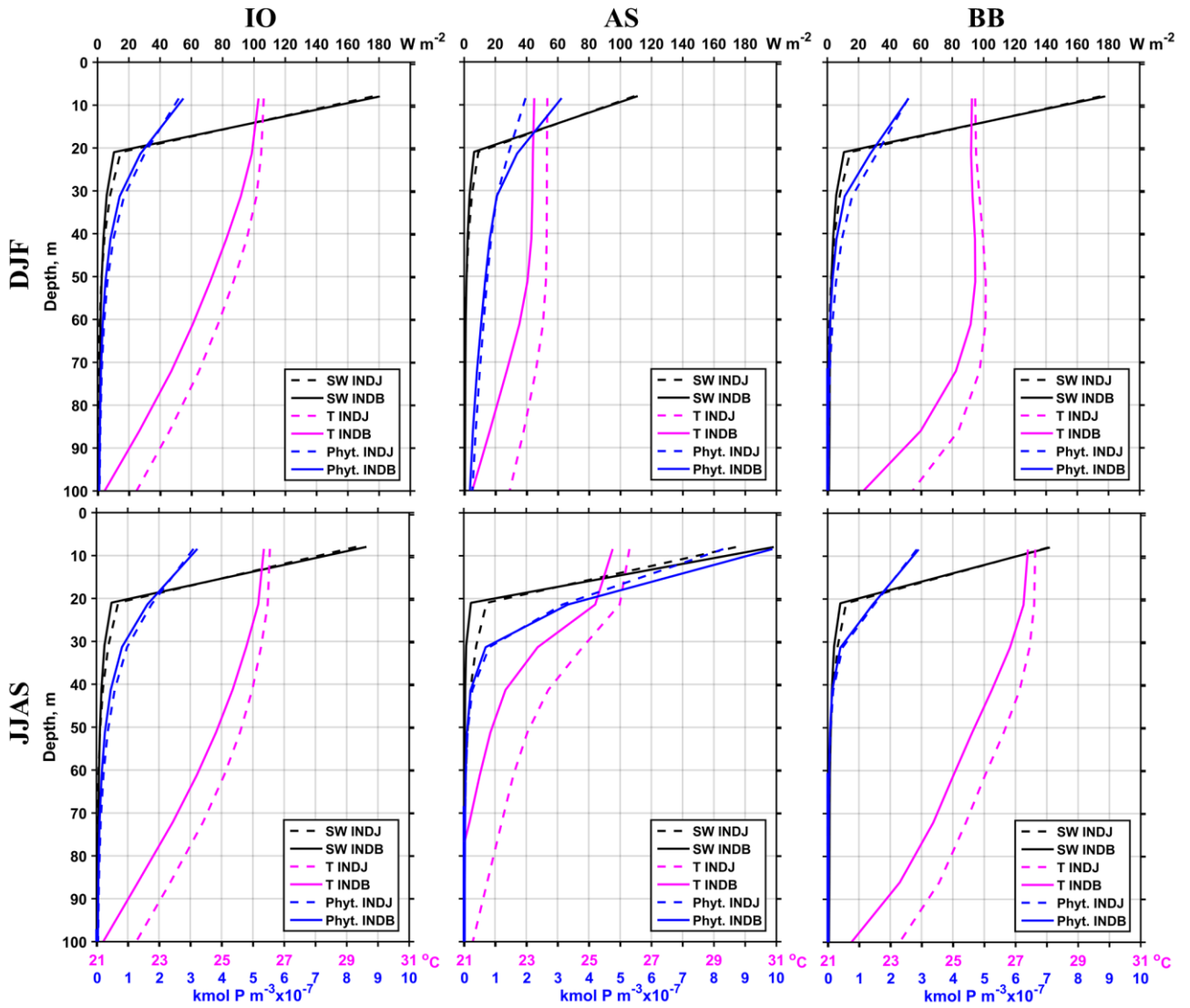


Figure 11. Vertical profiles of short-wave radiation (SW), water temperature (T) and phytoplankton concentration (Phyt.) in INDJ (without ocean-atmosphere feedback through the marine ecosystem) and INDB (with the feedback) experiments.

During summer (JJAS) the difference in short-wave radiation between the two runs reaches 7-10 W/m^2 in the Arabian Sea at the depth of 20 m. It is reasonable to assume that this difference would be much larger at the moments of peak phytoplankton bloom when no time-averaging is made.

Thermocline dynamics. The thermocline dynamics are among the most important factors mediating the temporal and spatial shape of phytoplankton blooms and its feedback on climate. On the one hand, it acts as a barrier for the vertical exchange between nutrient-depleted surface waters and nutrient-enriched waters from deeper layers and can limit biological productivity. On the other hand, a strong thermocline can effectively reduce the local mixed layer depth and allow phytoplankton to persist longer within the euphotic layer thereby increasing the growth rate of marine algae. Moreover, the thermocline has a temperature mediating effect, with a shallower thermocline allowing the surface layer to faster adapt to atmospheric temperatures (e.g., Gröger et al., 2015). The inclusion of phytoplankton into the radiative heat transfer equation alters the vertical distribution of heat absorption and thus influences the thermocline dynamics. In the following, we test the effect of the biogeochemical feedback upon the model physics by comparing thermocline dynamics between the two runs with and without coupling (Fig. 12). Where feasible a comparison

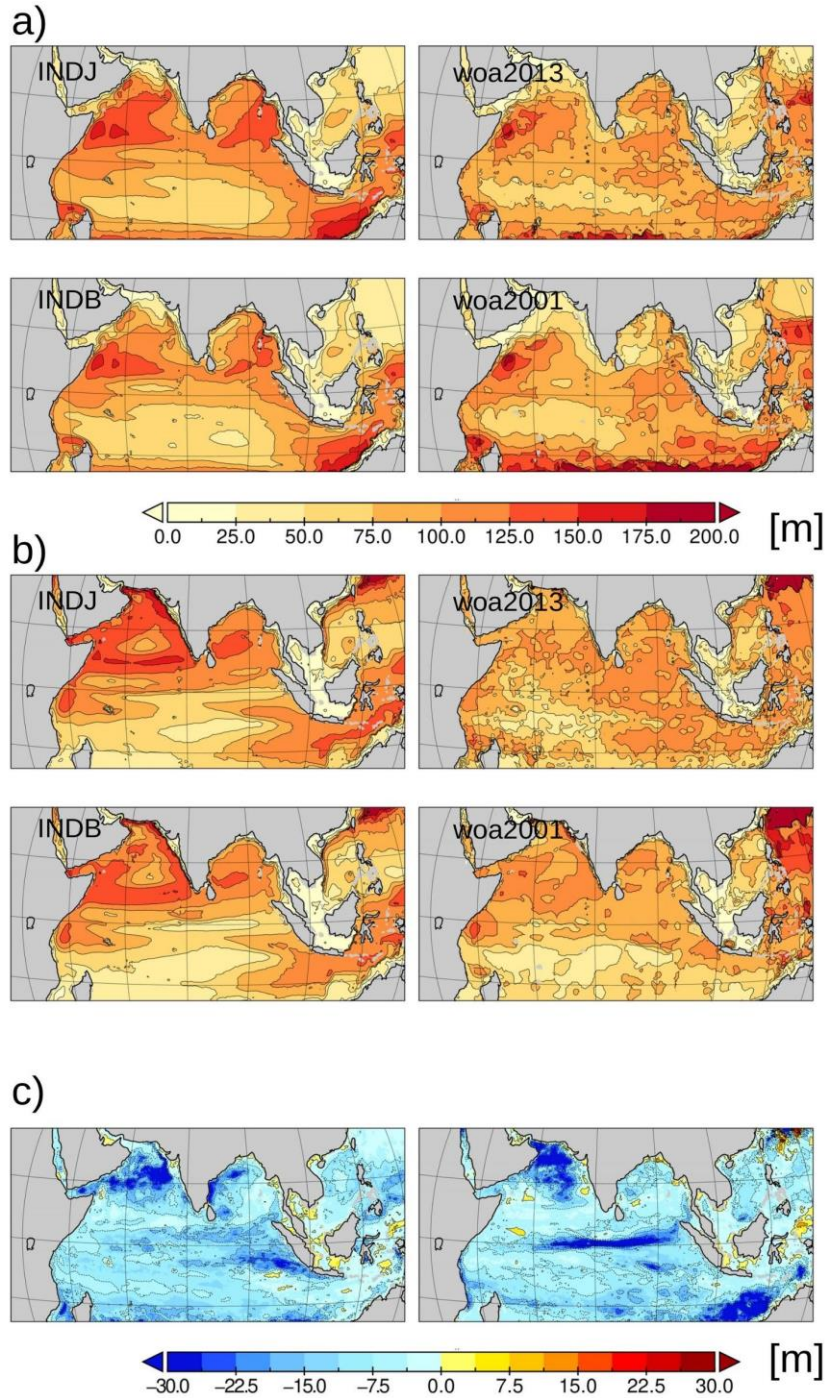


Figure 12. a) Comparison of simulated summer (JJAS) thermocline depth with thermocline depth derived from WOA data sets. b) same as (a) but for winter thermocline (DJF). c) The difference in thermocline depth between the two runs (INDB-INDJ) for JJAS (left) and DJF (right).

with WOA 2001 and WOA 2013 data is discussed. Data generally tend to be sparse in open ocean regions with less dense measuring campaigns like the Indian Ocean. Therefore, caution should be applied when interpreting thermocline dynamics derived from sparse gridded data sets like WOA. This is indicated by the irregular isolines displayed in the WOA data sets. We, therefore, do not provide a quantitative validation here but rather discuss the processes underlying the spatial pattern.

Both model simulations and WOA data show distinct gradients in thermocline depth. During the summer monsoon (Fig. 12a) the thermocline shoals to values below 25 m along the northern coast of the Arabian Sea and along the Indian coast where moisture carrying SW monsoon winds cause a positive P-E flux and maintain a vigorous runoff (Ramesh and Krishnan, 2005). Off the Somalian

403 coast and further offshore, the strong SW monsoonal winds lead to a deepening of the thermocline in
404 wide areas of the open ocean. In the model runs the extension of this area is larger than in WOA data
405 sets. In the Bay of Bengal, the model simulates a clear east-west gradient with a deeper thermocline
406 in the east compared to the west. Such a pattern is also observed to some extent, at least in the WOA
407 2001. To the south of the equator the thermocline shoals in an extended zonal band to values well
408 below 50 m. This is likewise seen in the two WOA data sets though this is less pronounced there.
409 During the winter monsoon, the very shallow thermocline in the coastal Arabian Sea strongly deepens
410 in response to changed monsoon (Fig. 12b). This seasonal change is more pronounced in the model
411 simulations but is still significant in the WOA data sets. This indicates that the seasonal variability is
412 well represented in the model near the coasts.

413 The simulated thermocline depth is almost everywhere shallower when including the
414 biogeochemical feedback (Fig. 12c) in both summer and winter. However, the spatial structure (Fig.
415 12a and 12b) is very similar, indicating that physical processes play a dominant role whereas the
416 vertical structure is controlled by biophysical processes in heat uptake. The explicit use of
417 phytoplankton in the radiated heat transfer (INDB experiment) leads to more heat absorption in the
418 upper layers and less heat absorption in lower layers. As a result, the thermocline shifts upward
419 compared to the Jerlov type absorption (INDJ experiment) which follows a simple exponential curve
420 with a constant exponent.

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422 **3.2 Atmosphere**

423 Here we study the regional distribution of some key atmospheric fields over the South Asia
424 CORDEX region and validate them for winter (DJF) and summer (JJAS) over the 1975-2004 period.
425 In section 3.2.1 we focus on the regional distribution of 2-meter air temperature (T2M) biases relative
426 to the ERA5 reanalysis. Also, temperature differences between the INDB and INDJ experiments are
427 analysed. This allows us to gain insight into temperature changes that occur in response to the ocean
428 biogeochemical feedback. In section 3.2.2 the same procedure is followed but taking into
429 consideration the precipitation instead.

430

431 **3.2.1 Air surface temperature**

432 In both seasons the mean surface temperature in ERA5 is clearly influenced by topography
433 (Figs. 13a, 13d). The lowest values are reached on highly-elevated terrain - especially in winter. The
434 lowest temperatures are attained in world highest mountain ranges: the Himalaya, Pamir, Hindu Kush
435 and the Tibetan Plateau. The highest summer temperatures are reached along with the Indo river
436 depression and the Arabian Peninsula. In experiment INDJ the winter daily mean temperatures are
437 simulated quite well and biases are relatively small (Fig. 13b and 13e), T2M is underestimated over
438 most of the model domain, except for its northern and northwestern areas where positive biases can
439 reach up to 5 °C. The negative biases are mostly below 2 °C, except for Tibet and Himalaya, where
440 simulated T2M more than 4°C colder than ERA5 can be found. The largest errors are found in
441 depressed and/or highly-elevated regions and their values may be dependent on factors such as the
442 limited amount of meteorological stations in topographic highs and lows used for the assimilation in
443 the region and the different representation of the orography in both REMO and ERA5. JJAS T2M
444 biases are generally lower than in winter, with a similar dependence on orography. They become
445 positive over most of the Indian subcontinent with maximum values over the northern Indo river basin
446 where mean temperatures are up to 4 °C above ERA5. Over the ocean a positive bias develops in the
447 region where the monsoon winds are stronger. In general, the largest T2M biases are located in
448 regions where larger temperatures are obtained, pointing to a role of the simulated nocturnal boundary

layer and/or radiative fluxes. Just like for the SST, the biogeochemical feedback leads to a colder surface air temperature over most of the ocean. In DJF the cooling is stronger over the Arabian Sea and the equatorial strip, reinforcing the weak negative biases already present in INDJ. Over the land the feedback slightly improves the cold bias in northwestern and southern India but leads to a cooling in the central part. The ocean cooling induced by the feedback is also present in JJAS, with stronger values near the western coast of the Arabian Sea and the Bay of Bengal, downstream of the Monsoon winds.

3.2.2 Monsoon precipitation

The monsoon season in Southern Asia is shaped by different processes which change the atmospheric circulation due to the summer strengthening of the ocean-land temperature contrast. The spatial structure of the observed monsoon precipitation is characterized by two regions of strong rainfall over land (Fig. 14a). The first is located windward, over the western coast of India, Myanmar and the southern side of the Himalayas. The second region which covers Bangladesh, central India and the eastern coast of the Indian peninsula is the area of maximum monsoon precipitation over the land. The precipitation is weaker over the northwest of India and Pakistan (Kumar et al., 2013). The complex orography and physical mechanisms involved make the simulation of the monsoon precipitation a difficult task both for global and regional models (Lucas-Picher et al., 2011). However, stand-alone simulations with REMO have shown to be able to reproduce spatial monsoon precipitation patterns rather well, although a better quantitative agreement is desirable (Kumar et al., 2014). For instance, the precipitation over south and central India is overestimated, while the precipitation over the Indo-Ganges plain is strongly underestimated. Over the ocean a wet bias is usually found over the Bay of Bengal and the southern Indian Ocean.

As shown in previous versions of the model (Kumar et al., 2014), ROM is able to improve the performance of REMO, simulating a more realistic precipitation. The coupling reduces the magnitude of the biases, especially in the regions where REMO has the strongest biases, near the eastern coasts of the Arabian Sea and the Bay of Bengal (Fig. 14b). It should be noted that in both INDJ and INDB experiments ROM is forced by MPI-ESM and the results are influenced by the biases of the driving ESM (e.g., Cabos et al., 2020).

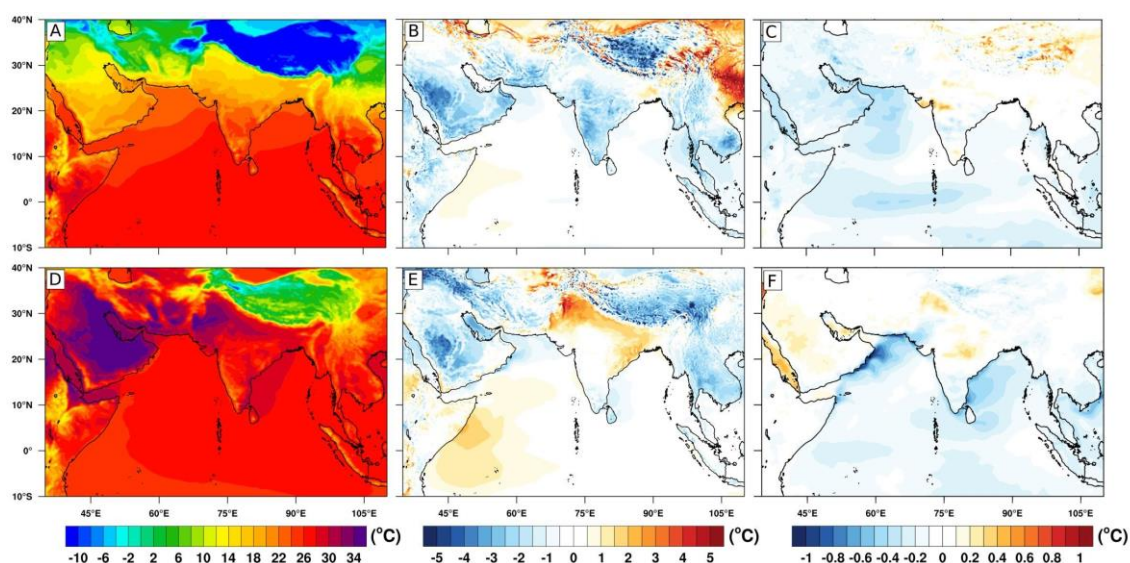
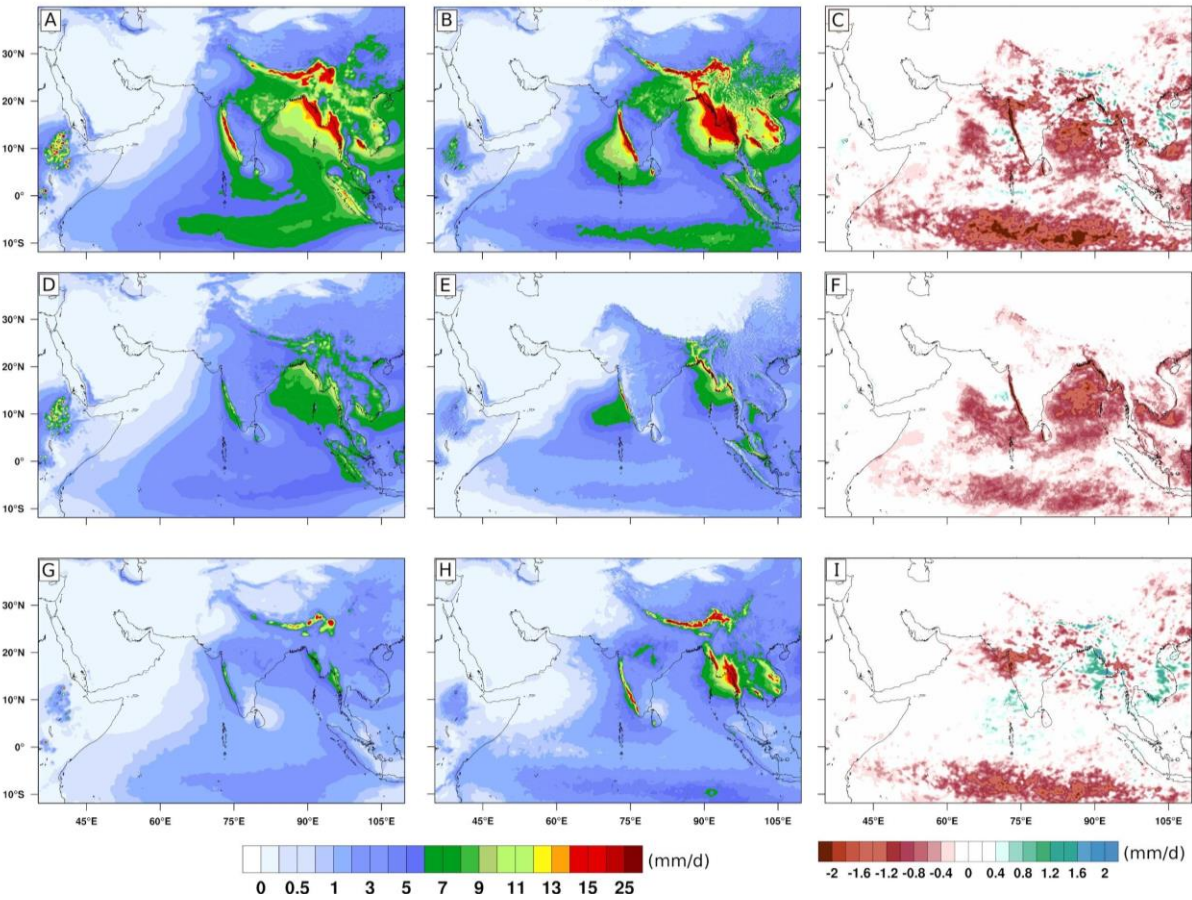


Figure 13. DJF (upper row) and JJAS (lower row) a) and d) 2 meter temperature ERA5 climatology b) and e) bias for the experiment INDJ; c) and f) INDB-INDJ difference.

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Besides the total precipitation, in Fig. 14.d-e we show the convective (thereafter APRC) and in 14.g-h the large scale (thereafter APRL) component of the precipitation. We can see that in INDJ the main contribution to the biases over the ocean near the eastern coast of the Arabian Sea comes from APRC, while over the coastal land the main contributor is APRL. The opposite is true for the eastern coast of the Bay of Bengal, especially in Myanmar where the main contributor over the ocean and the coastal regions is APRL, with a lesser contribution from APRC. To the south of the equator, between 10° S and the equator, both components give a contribution of similar magnitude, albeit the large scale is stronger. Here, both components show a similar displacement of the region of maximum precipitation to the south, and while the magnitude of the convective precipitation is lower than in ERA5, the large scale component is stronger and more zonal than the ERA5 large scale precipitation.



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Figure 14. JJAS precipitation for ERA5 (left column), INDJ experiment (middle column), and the differences between INDB and INDJ (right column) for total precipitation (upper panels); convective precipitation (middle panels), and large scale precipitation (lower panels).

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In the INDB experiment the activation of the biogeochemical feedback leads to a drying over most of the ocean, especially over the Bay of Bengal, central and north-eastern Arabian Sea and the strip south of the equator. A clear reduction in precipitation can also be found inland, along the western Indian coast. As seen in Fig. 14.F and 14.I, the contribution of convective and large scale components to these differences varies along the regions.

We can see that APRC gives the main contribution to the total effect (in terms of precipitation) of marine biochemistry feedback over the Bay of Bengal, the central part of the Arabian Sea and the

507 coastal regions of western India. APRL gives the main contribution to the drying in the northern-
508 central India, while in the region of Myanmar it causes a wetting, thus offsetting the impact on APRC.
509 To the south of the equator, between 10° S and 0°, the impact is similar on both components of the
510 precipitation.

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512 **4. Discussion**

513 The effect of the feedback on the water temperature decline in the upper layers can be
514 explained as follows. In the INDB experiment, during the phytoplankton bloom period, there exists
515 more phytoplankton in the upper ocean layers than that considered according to Jerlov's climatic
516 annual-mean estimates (INDJ experiment). An increase in the amount of phytoplankton in INDB in
517 the upper layers leads to an increase of the light attenuation coefficient there, thus a smaller amount
518 of short-wave radiation penetrates into the underlying layers (this can be seen from Fig. 11). As a
519 result, the subsurface layers get colder. The thermocline shifts upward compared to the Jerlov type
520 absorption (INDJ experiment) where a simple exponential curve of light attenuation is implemented.
521 Despite the shallower thermocline in INDB, this run shows overall cooler SSTs than INDJ (Fig. 8).
522 This is somewhat counter-intuitive as a lower mixed-layer depth should reduce the mixing with cooler
523 waters from depth leading to overall higher SSTs in run INDB. However, the different solutions of
524 the radiative equation used in INDB and INDJ will also affect the total absorbed radiation which
525 makes it difficult to link the direct effect of changed thermocline depth to the difference in SSTs.
526 Given the widespread cooling of SSTs in INDB (Fig. 8) however, it is likely that the parameterization
527 of absorption in INDB leads to a general decrease in total absorption compared to the Jerlov solution.
528 Also, it may be assumed that during the vertical mixing process the cold water may enter the upper
529 ocean layers, thus the upper-mixed layer temperature declines, and so does SST, although for SST
530 this effect is less pronounced because it can be more influenced by other ocean-atmosphere heat
531 fluxes. Thus, during the period of active heating of the upper ocean layers the heat in the INDB
532 experiment is redistributed differently than in the INDJ and, as a result, a significant cooling of the
533 subsurface layers occurs. At the same time, the spatial pattern of SST cooling is not homogeneous
534 (see Fig. 8) that can be explained by other heat fluxes, which, in contrast to short-wave radiation, are
535 absorbed by the upper 1-meter layer of the ocean almost completely. In future studies we are planning
536 to analyze this mechanism in detail and to evaluate the impact of advection.

537 Thus, the main impact of including the biogeochemical coupling in the Indian Ocean is a
538 shallower thermocline with cascading effects on model physics like altered SST which further
539 translates into altered atmosphere dynamics. Likewise, due to the temporarily varying chlorophyll-a
540 concentrations in the surface layer and subsequent variable heat absorption, SSTs are by far more
541 variable in run INDB than in run INDJ.

542 The higher phytoplankton primary production in INDB (Fig. 10) is most likely the effect of
543 the lowered mixed-layer depth which allows phytoplankton to prevail longer in the euphotic layer.
544 This effect is more pronounced to the north of 10° N where the thermocline is relatively deep (and a
545 reduction of the mixed-layer depth is most effective). In regions where the thermocline is generally
546 shallower (to the south of 10° N) this effect is of minor importance as light is less limiting there.

547 During JJAS, the simulated wind in INDJ is slightly weaker than in ERA5 in the Arabian Sea
548 but stronger in the Bay of Bengal (compare Fig. 15.a and 15.c).

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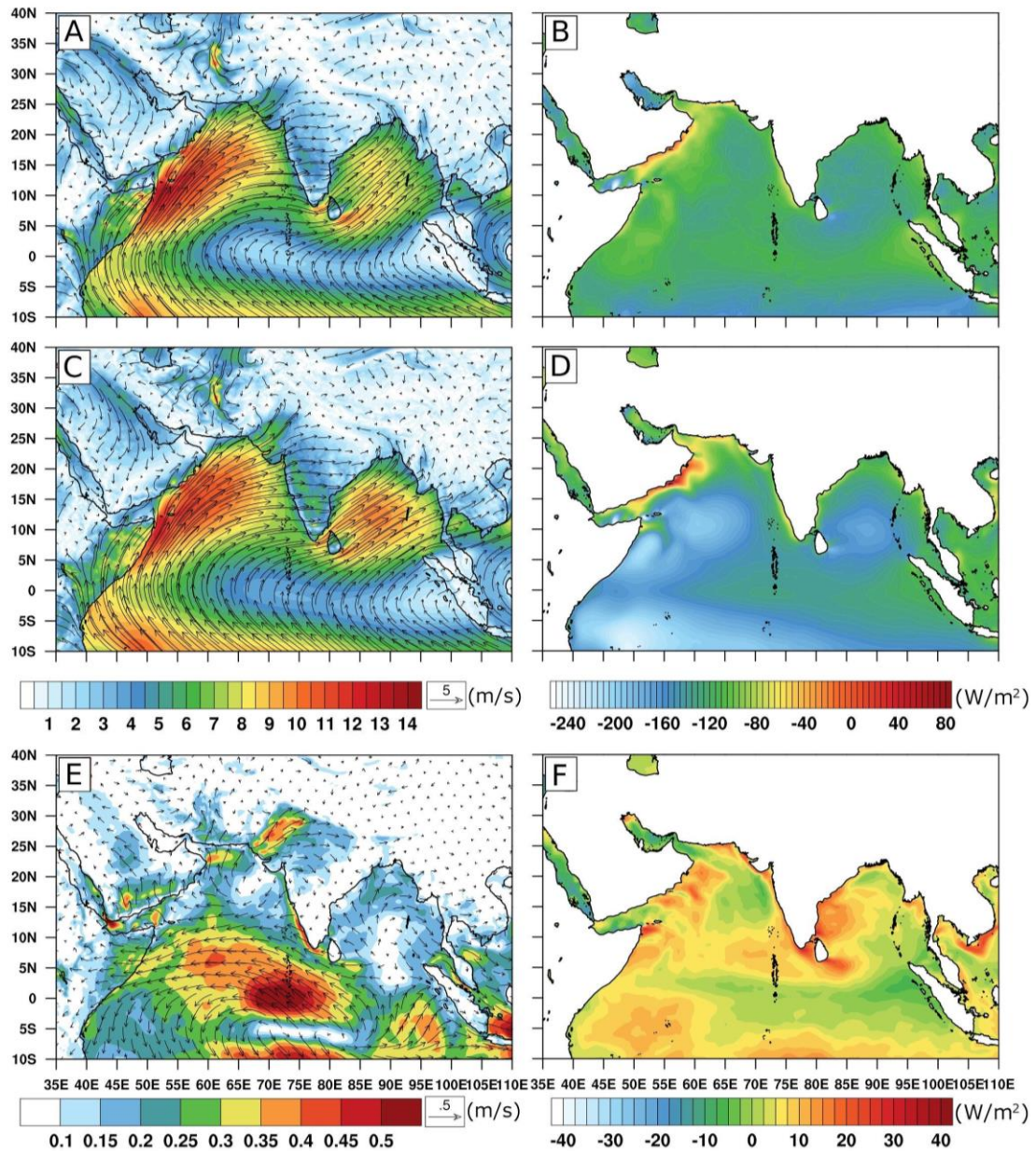
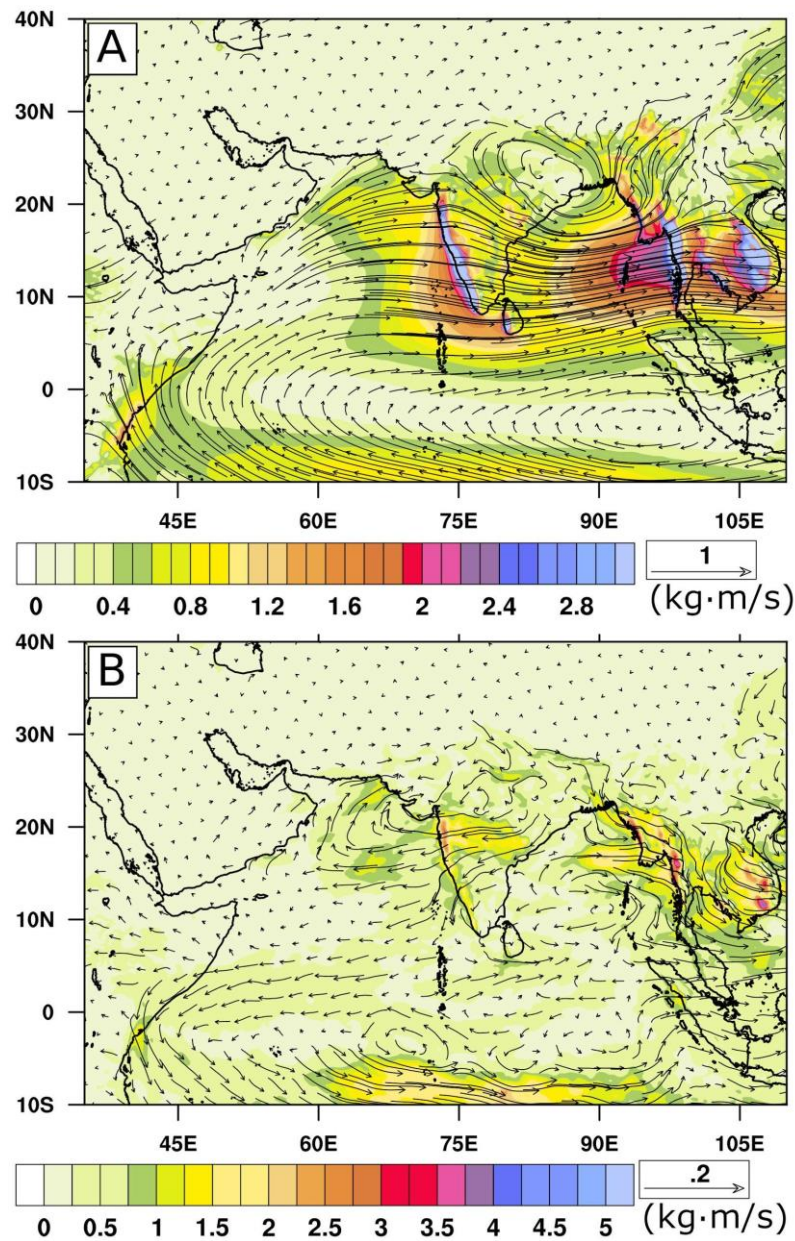


Figure 15. JJAS wind (left column) and latent heat (right column) for ERA5 (upper panels); INDJ experiment (middle panels), and (INDB-INDJ) difference (lower panels).

In the latter, stronger winds lead to stronger latent heat fluxes, while the opposite is true for the Arabian Sea where the weaker wind is associated with a stronger latent heat (Fig 15.b and Fig 15.d). This points to a different nature of the relationship between wind speed and latent heat in both regions that, nevertheless, lead to stronger heat flux in both regions. The monsoon winds bring drier air into the Arabian Sea because it flows over colder water all the way from the equatorial region. Although the cold bias here leads also to a decrease of surface humidity, as the SST bias is lower, the surface humidity bias is lower. The resulting increase of the sea-air humidity difference overcomes the decrease of the wind, thus giving a stronger latent heat flux. This is not true for the western coast where most of the air comes from land (Wu et al., 2007). In the Bay of Bengal the increase in latent heat is mainly associated with the simulated winds which are stronger than in ERA5. In the INDB experiment the biogeochemical feedback causes a further cooling over the basin (Fig. 8) and this cooling causes a further drying over most of the domain, especially over the land in regions that are downstream of the monsoon winds. The drying is related to changes both in convection activity and

567 moisture transport. Figure 16.a shows the horizontal transport of cloud water for the INDJ experiment.
 568 This figure shows the contribution of the large-scale circulation to the monsoon rain. The Arabian
 569 Sea winds are charged with moisture in their path to the Indian subcontinent and Sri Lanka,
 570 contributing to the large scale precipitation in the eastern part of the basin and the coastal regions
 571 (Fig. 14.h). The wind, which loses moisture over the land, is again recharged in his way over the Bay
 572 of Bengal, contributing to the strong precipitation in the eastern part of the Bay of Bengal, Myanmar
 573 and southeastern Asia. It is noteworthy the recirculation of cloud water in northeastern India due to
 574 the presence of the Himalayan range which influences the amount of precipitation there. The marine
 575 biochemistry feedback affects the precipitation over the Arabian Sea and the Bay of Bengal in
 576 different ways. From one side, it reduces the transport of humidity across the equator towards the
 577 eastern part of the basin, reducing the large scale precipitation there and in the adjacent coastal
 578 regions, reinforcing the effect of the colder water on the convective precipitation. In the Bay of Bengal
 579 the feedback reinforces the transport of humidity, increasing the large scale precipitation, contouring
 580 the decrease of convective precipitation due to the SST cooling (Fig 16.b).
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582 **Figure 16.** JJAS horizontal transport of cloud water in INDJ (a) and INDB-INDJ difference (b)
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5. Conclusions

A regional Earth System Model based on the ROM model (Sein et al., 2015) has been implemented for the CORDEX South Asia region. We use the model to investigate the effect of one of the marine biogeochemical feedbacks, which affects the attenuation of the short-wave radiation in the water, upon the regional climate. To this end we carry out two model runs for the period 1920–2005 with CMIP5 historical forcing. The runs differ in various parameterizations of the attenuation of short-wave radiation into the ocean.

Our simulations capture the main fundamental features of the intra-annual dynamics of the marine ecosystem in this region. This is a good result for a global biogeochemical model that works with only one type of phytoplankton. Some overestimation of the chlorophyll-a surface concentration compared to satellite data is acceptable due to the known uncertainties in the estimates of the C:Chla ratio which is set constant in the model.

In the experiment where the feedback is activated the average SST is lower over most of the domain than in the simulation without the feedback. The greatest deviations (more than 1 °C) in SST between the two runs occur in the summer period during the phytoplankton bloom. During the period of active heating of the upper layers (spring and summer) the short-wave radiation calculated by the simulation with the feedback activated is more strongly absorbed in the upper ocean layers, a significant cooling of subsurface layers occurs (up to 1-1.5 °C) and the thermocline shifts upward compared to the Jerlov type absorption. In other words, the explicit taking into account the phytoplankton concentration while calculating the short-wave radiation attenuation leads to a cooling of the subsurface layers. At the same time, the spatial pattern of SST cooling is not homogeneous that can be explained by other heat fluxes, which, in contrast to short-wave radiation, are absorbed by the upper 1-meter layer of the ocean almost completely. The phytoplankton primary production and its deviation in the feedback-based simulation turned out to be higher, especially during periods of winter and summer phytoplankton blooms. The feedback-based simulation also showed the lower surface concentration of dissolved nitrates almost the whole year since the primary production was higher and more nutrients were consumed by phytoplankton.

Both simulations reproduce adequately the precipitation climatology for all seasons. In particular, the spatial pattern of the monsoon precipitation is well simulated, albeit with some systematic wet biases which are stronger over the eastern parts of the Arabian Sea and the Bay of Bengal and the adjacent coastal regions. We found that the marine biogeochemistry feedback also affects the amount of precipitation in the model, leading to a drying over most of the basin in the monsoon season. The associated SST cooling leads in general to a reduction of the precipitation but affects in different ways the two components of the precipitation. In the Arabian Sea the reduction of the transport of humidity across the equator leads to a reduction of the large scale precipitation in the eastern part of the basin, reinforcing reduction of the convective precipitation. In the Bay of Bengal the feedback increases the large scale precipitation, contouring the decrease of convective precipitation due to the SST cooling.

Thus, the main impacts of including the biogeochemical coupling in the Indian Ocean include the enhanced phytoplankton primary production, a shallower thermocline and decreased SST, with cascading effects upon the model ocean physics which further translates into altered atmosphere dynamics.

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635 https://swiftbrowser.dkrz.de/tcl_s/SSG22k1U4mIXVr
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