Biogeosciences
Discussions

Interactive comment on "Challenges in modelling spatiotemporally varying phytoplankton blooms in the Northwestern Arabian Sea and Gulf of Oman" by S. Sedigh Marvasti et al.

S. Sedigh Marvasti et al.

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I would like to express our appreciation to Referee #1 for the comments. I believe that the comments will improve clarity of the manuscript, especially as regards the global coupled models. Below, I respond to every single one of the comments, providing more elaboration or changing the manuscript if applicable.

1) The analyses are very qualitative and in many instances, the authors jump to conclusions without sufficient support.

Response: We have revised the manuscript to clarify both the motivation for our study and provide quantification for the reasoning behind our conclusions.

2) A large part of what is shown regarding the data analysis has already been published elsewhere and these papers are not referenced here (Gaube et al., 2014), The anti-correlation between satellite Chla and SSH was already reported by Gaube et al. Gaube et al, 2014, JGR, looked at Regional variations in the influence of mesoscale eddies on near-surface chlorophyll and the cross-correlation between SLA and Chl at the global scale, including the Arabian Sea where they find a negative correlation.

Response: Thank you very much for mentioning this reference. It was definitely our mistake not to see this paper. This paper will be highlighted in the literature review and references. However, we note that Gaube et al. show only the overall correlation while we examine the correlation between SSH and Chl as it varies over the course of the year in the Arabian Sea. Additionally, we show that this variation in the correlation also holds for backscatter and CDOM (which supports the idea that it is driven by nutrients and not by photo-adaptation). Moreover, as discussed in our paper, based on the numerical results the diffusive flux of nutrient mirrors the chlorophyll. It also shows that for the few cases where the bloom is clearly associated with eddy passage diffusive flux is actually larger and positive at the center of the cyclone and negative in other parts of the region. Please see section 4.2.2 and Fig. 13. This mechanism is not one of the ones on which Gaube focusses. We will add the following text to the manuscript

Gaube et al. (2014) provide a global overview of how eddies influence chlorophyll blooms. They find that the effect of mesoscale eddies on the chlorophyll bloom varies both temporally and spatially. They identify four particular mechanisms that can be distinguished by linking sea surface anomalies to chlorophyll, namely eddy stirring, trapping, eddy intensification, and Ekman pumping. The eddy stirring mechanism involves advection of high and low chlorophyll signals around an eddy, resulting in a low which is offset from the center of an anticyclone and a high which is offset from the center of a cyclone. Trapping of chlorophyll involves eddies retaining the properties that they had when shed from a boundary current, which would generally imply low values in anticyclones and high values in cyclones. Eddy intensification, by contrast, would

be expected to produce the same picture, as cyclones would see rising nutriclines in the center but anticyclones would see deepening nutriclines. Finally, Ekman pumping would be expected to produce negative anomalies in cyclones with a positive "halo" and positive anomalies in anticyclones with a negative "halo" (Gaube, Fig.2). Although Gaube et al. find a negative correlation between chlorophyll and SSH in the Arabian Sea, they do not analyse which of these mechanisms is involved in this region. We also will add the following paragraph to the discussion The bloom associated with eddies E1 and E2 do not fit with any of the mechanisms studied in Gaube et al. (2014). We first consider the mechanism of trapping. Eddy E1 is generated in the ocean interior, not as a result of coastal upwelling. As shown in Fig. 13 of the paper, the nutrient supply rate ranges between 5 and 8 mmol/m2/month in the eddy. The concentrations in this eddy are only 0.01 μM or only about 5 mmol/m2 over the top 50 m. It cannot be the case that the nutrients in the eddy can last for several months as a result of "trapping", there must be a continuous supply. Although eddy E2 shows a horizontal advection signal in November (with a positive ring around the edge in Fig. 11a), the signal in December has the opposite sign. Eddy intensification is an unlikely mechanism for explaining the blooms, as dSSH/dt is relatively small (particularly if we track the minimum SSH associated with E1 in Fig. 11c or E2 in Fig. 11d) Finally, Ekman pumping signatures in Gaube et al. (2014) have the opposite sign as what is seen in E1 and E2. We will also contrast the results here with Resplandy et al. The focus in Resplandy is on the productivity driven by horizontal and vertical advection in summer and mostly vertical advection in winter. This would appear to us to contradict our finding of a primary diffusive source of nutrient in winter although it is consistent the finding of advective source of nutrients in summer.

3a) Regarding why the model fails are reproducing the observations is not particularly interesting and not convincing either. In particular, I was not at all convinced that interannual variability of the bloom was driven by eddy activity.

When we examined the region of interest in the observations, we found that whether or

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not a bloom was found in the Gulf of Oman depended almost entirely on whether there was a cyclone or anticyclone there. The reviewer considers Fig. 5 and 6 convincing evidence of this in a statistical sense but will add two additional figures.

The first of these (Fig. 2, below) shows sea surface chlorophyll and height during the months of November. The relationship between blooms and SSHA is clear and striking. Note particularly the difference between 1998 and 2001, when the location of high and low chlorophyll regions relative to the Ras al Hadd is opposite, and this difference is captured by the SSHA.

Additionally shown in Fig. 3 (below), low-resolution models (Core and coupled Topaz) provide an almost uniform seasonal coefficient of variation (mean C.o.Vs are 0.1 and 0.09, respectively), while both data and eddy resolving CM2.6 models show higher interannual variability and seasonal changes (mean C.o.Vs are 0.14 and 0.2, respectively).. Together with the Fig. 2, this statistical analysis suggests that eddies are indeed necessary to explain the variability. We will make this clearer in the revision.

3b) The conclusions regarding the inability of the model to reproduce interannual variability are not convincing and do not bring sufficient insight - Fig 7 does show interannual variability in the data and also in all models - but the bloom amplitudes are so different that it is difficult to conclude anything on the ability of the model to reproduce the interannual variations since they do a bad job at reproducing the seasonal variations already.

Response:

There is increasing interest in using global models to project ecological changes and to understand interannual variability, and it is so important to identify regions where the models are not going to work and the reasons why they might break down. Accordingly, as indicated in the title of the current paper, we are trying to highlight the challenges in modeling phytoplankton blooms using cutting-edge earth system models in the northwestern Arabian Sea and Gulf of Oman. That these models are less sophisticated than

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regional models (such as Resplandy et al.) is to be expected as they have not been tuned for this specific region.

As the Fig. 7 (in the paper) was plotted using relatively low-resolution CM2.6 (miniBling) model, the figure is replotted and the associated paragraphs in the paper are revised, as follows: ….. The maximum values that can be considered as a winter bloom in the whole region are mostly seen around February (Piontkovski et al., 2011), with values of 0.32–0.38, 0.48–0.62, 1.2–2, 0.5-0.75 mg/m3 for chlorophyll and 31, 66, 80–140, 30-40mgC/m3 for biomass in CORE-TOPAZ, Coupled-TOPAZ, CM2.6 (miniBLING), and satellite data, respectively. A summer bloom is also pronounced in September as a second maximum in the yearly cycle over the whole region, with peak magnitudes of about 0.52, 0.66, 0.6–0.8, 0,2-1.2mg/m3 for chlorophyll and 33, 59, 50, 20-50mgC/m3 for biomass, in CORE-TOPAZ, Coupled-TOPAZ, CM2.6, and satellite data, respectively. Both chlorophyll a and carbon biomass show minimal values of 0.2mg/m3, and 20–25mgC/m3, respectively, in a yearly cycle over the whole region.

3c) Another important contribution comes from the variability of the mixed-layer depth, which is not addressed here (Keerthi et al., 2015,Climate Dynamics). - It is not because the main source is vertical mixing that vertical mixing is too strong during winter. The question is how the mixed-layer depth compared with observations.

Response: This is a good point and one which we have added to the revision. Comparison of the high resolution model to the measured values in WOA09 and the Argo mixed layer dataset (see Fig. 5 below which we will add to the revision), verifies that in the winter time the modeled mixed layer depth is considerably deeper than that of summer. Both the model and observations shows same trend of seasonal mixed layer variations. As shown in the Figure the model prediction is deeper than the measured values in WOA09.

There are two possible ways for the eddies to modulate mixing of nutrient from below. The first is that they could modulate the near surface stratification, so that in warm

anticyclones we would expect the mixed layer to be shallower. We would then expect a negative correlation between MLD and SSH, and a positive correlation between MLD and nutrients. The second is that the eddies could modulate the depth of the pycnocline, bringing nutrients closer to the surface and more accessible to mixing. It is not clear that this would necessarily produce strong correlations between mixed layer depth and SSH, because the pycnocline is closer to the surface in cyclones, but in anticyclones the density constrast between warm surface waters and the colder pycnocline is larger.

The model does not clearly show either of these possible mechanisms. Mixed layer depth shows a weak positive correlation with SSHA for almost all months during year 197 (Fig 6 below), consistent with the pycnocline being a bit shallower. However while the mixed layer depth cross-correlation with chlorophyll a and nutrients (PO4) is positive in JFM, it is negative during SON. As shown in Fig. 7 (below), comparison of mixed layer depth (MLD) and sea surface height anomaly (SSHA) during the winter shows very deep mixed layers, relative to the measured values from WOA09 (see Fig. 1). However, in the northern regions the MLD seems to be too deep in winter. There is no consistent relationship between the mixed layer depth and the eddies, with deep mixed layers sometimes appearing in the centers of both cyclonic and anticyclonic eddies (see for example the upper right hand corner of Fig 6b below). This observation again justifies the hypothesis of having too deep MLD in the northern part of the region to let mesoscale eddies modulate chlorophyll blooms. If we look during the time period where we have eddies E1 and E2 (Nov-Dec. year 197, Fig 6c,d below) we see shallower mixed layers associated with both eddies.

3d) Moreover, the authors do not clearly show that eddies are supplying nutrients to the euphoric layer but this was shown with another eddy resolving model of the Arabian Sea by Resplandy et al (2011, JGR).

Response: The mechanism in Resplandy et al., (2011) is actually different than ours. The argue that the advective term dominates nutrient supply in the winter and that eddy

driven advection a dominant term in that supply. However, the clearest signatures of vertical advection are found at the boundaries of eddies, not in the interior as appears to be seen in the observations. (As Resplandy et al., do not correlate their chl with SSH it is not clear whether they also miss this phenomenon). This point will be made in the revision.

3e) It should also be noted that the NEM bloom is very likely driven by convective supply of nutrients - but possibly also by reduced grazing during convection (Marra et al. 1995).

Response: Our model does of course parameterize grazing, and does so based on a global synthesis of data (see discussion below). We will, however, include the reference by Marra and add the caveat that the model does not include temporal imbalances between phytoplankton and zooplankton, which Marra suggests are important in this area.

4) Regarding the analysis: - the scale at which the study is performed (a rather small box in the WAS) is not suited to address the question of interannual variability (Fig. 2).

Response: To examine the effect of region size on the interannual variability of the model, eight different regions with different sizes are used to calculate coefficient of variation of the chlorophyll results in the satellite data. The region bigger than the study region in this study (56–66E, 15–26N: thick line in Fig. 8 below) are plotted with solid lines and the regions smaller than the study region are dashed lines. Fig. 8 (below) shows that for smaller regions (i.e. south, north, eddy E1, and E2), the interannual variability is considerably higher due to comparable size of the regions to the mesoscale structure. For bigger regions, however the interannual variations asymptote and the size effect odes not significantly change the results and diagnostics. In addition, many studies have used regions of similar size to ours, in Resplandy et al. (2011) the region is (40–80E, 3–27N), in Al-Azri et al 2010 and 2013: (53–63E, 18o–28oN), in Gomes 2008: (55–75E, 5–28N), in Sarma 2013: (50–65E, 15–30N), in

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Piontkovski 2012: (50–63E, 15–27N).

5) The correlations between Chla and SSHA are convincing (5 and 6) but not Fig 4

Response: We will replace Fig. 4 (in the paper) with Fig. 2 (below) showing chl and SSH fields during the winter in different years, illustrating how on a small scale (which is the scale that many biological oceanographers focus on) different locations will have a bloom or not depending on whether there is a cyclonic eddy there. As shown in Fig. 2 below, there is a very clear relationship during the month of November, particularly in years 1998, 2001, 2002, 2004 and 2005. By contrast, in February (Fig. 9 below) the relationships are less clear, with blooms seen in both cyclones and anticyclones.

6) Fig. 8 is clearly not sufficient to explain what drives the bloom in the model.

Response: The two terms in Fig. 8 are the two terms in the model that affect growth rate (see response to 8 below). Because biomass in the miniBLING model is a function of growth rate also, it is in fact sufficient to understand what drives the growth in the model. We will make this clearer in the final revision.

7) What about grazing?

Response: We will add the following paragraph Grazing is highly parameterized in our global models. This is because these models were designed to reproduce the effect of grazing on size structure and biomass across ecosystems rather than trying to explicitly simulate zooplankton and introducing sensitivity to poorly known parameters (such as handling efficiency or grazing half-saturation). Instead, the grazing formulation was fit to ∼40 field sites to produce a size structure that transitions realistically between being dominated by small phytoplankton at low levels of growth and large phytoplankton in nutrient and light-replete conditions. The resulting parameterization produces biomass that is a function of growth rate. The model also reproduces the scaling in particle size seen across ecosystems by Kostadinov et al. The fact that such a model is so different than Resplandy et al. is another reason to evaluate it in the open literature.

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8) Fig 9. over what level ? for what nutrient ?

Response: Thank you very much for this comment. Figure 9 in the paper is averaged flux values over the upper 50 meter calculated for phosphate (PO4).

For more clarity the caption of Figure 9 is revised as follows:

Figure 9: PO4 Advection, diffusion and tendency flux from the CM2.6 model over the whole region averaged over top 50 m (56–66E, 15–26N).

9) The authors seem to have missed recent literature that have examined their hypothesis in much more details than what they are doing: - Gaube et al, 2014, JGR, looked at Regional variations in the influence of mesoscale eddies on near-surface chlorophyll and the cross-correlation between SLA and Chl at the global scale, including the Arabian Sea where they find a negative correlation

Resplandy et al. , 2011, JGR, Looked at the contribution of eddies to the nutrient budget in the AS using a 1/12âŬę model are highlighted the important role of eddies in supplying nutrients to the euphoric layer during both the NEM and SWM blooms .

- Levy et al. , 2014, GRL, examined how mesoscale variability could affect the interannual variability of the bloom in the NA and their conclusion suggests that the variability is shared between internal (eddy) and external (atmosphere) forcings.

Response: Thank you again for these references. It was our mistake to miss these three papers, which do indeed bring up some of the key physics. We have revised the manuscript to include these references and to better address summer and winter blooms, mesoscale eddy activity and mechanisms. Gaube et al (2014) has been discussed in item 2.

On Resplandy et al (2011) and Levy et al. (2014):

These papers are a relevant paper to our work. Both papers indicted that the spatial variability associated with mesoscale eddies produces spatial variability in the bloom

and that another source of variability is found to be restratification at these structures. Advection from coastal region is identified as the mechanism providing nutrients in summer, while vertical velocities associated with mesoscale structure are increasing nutrient supply. However, we believe to some extent our paper contradicts this paper due to the following reasons:

First, Resplandy et al (2011) do not really focus on structures at the eddy scale, they are more concerned with the net impact of eddies. One could easily read this paper as an observational oceanographer and miss the tight coupling we see in Fig. 7 below. We make this point in the revised manuscript.

Second, because regional models are very tightly constrained, they do not have the problems that global models do. Regional models sponge the boundaries, hiding key physics not represented in global models. It should be noted that the global models are being used for projection, and it is so important to identify the reasons that models are not going to work. This point is also made in the revised manuscript.

Third, the papers argue that the advection of nutrients by eddies is most important. We point out that in our model, the only two eddies that actually look like what we see in the satellite observations involve enhanced mixing from below. This is a different result from Levy et al. and Resplandy et al. Moreover it is not clear whether these papers get the seasonal correlation with SSH or not. We note this in the revised manuscript.

10) The introduction discusses red tides with no relation with the content of the paper.

Response: Fair point. The red tides in the introduction are to emphasizing that this phenomenon is important in the Gulf of Oman and nearby regions such as Persian Gulf. We recognize that just chlorophyll is not equivalent to red tide, but the first step in understanding that is: Are the nutrients flux going to change? Where do we expect the nutrient flux to change and what are the bloom dynamics? A significant point of this paper is that we can't use the global climate models to answer this question. We have rewritten the introduction to make this clearer, moving this paragraph to the start

of the paper. The general structure of the introduction is now 1. There is a lot of interest in red tides and harmful algal blooms in the Northeast Arabian Sea. 2. We want to understand whether anthropogenic climate change or variability could drive such changes in chlorophyll and productivity. (Goes et al.) 3. Large-scale climate models represent a key methodology for exploring such questions. . . 4. But only if they get the physics and biology that drive variability in nutrient supply in this region.

11) The diagnostics are performed over a region, which is too small

Response: The region size effect on the results is studied in the response to comment 4. Actually, for management purposes the region is not too small. We just used the results of a global mode in a smaller region that includes Northwestern Arabian Sea and Gulf of Oman. Please see answer of the comment 4 for examples with relatively similar region sizes, and for our quantification of the stability of the coefficient of variation.

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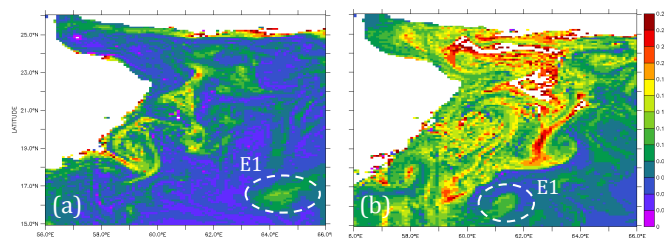
Fig. 1. (a), (b) : CM2.6 (miniBLING) Po4 on 9 November and 28 December of year 197.(56–66E, 15–26N).
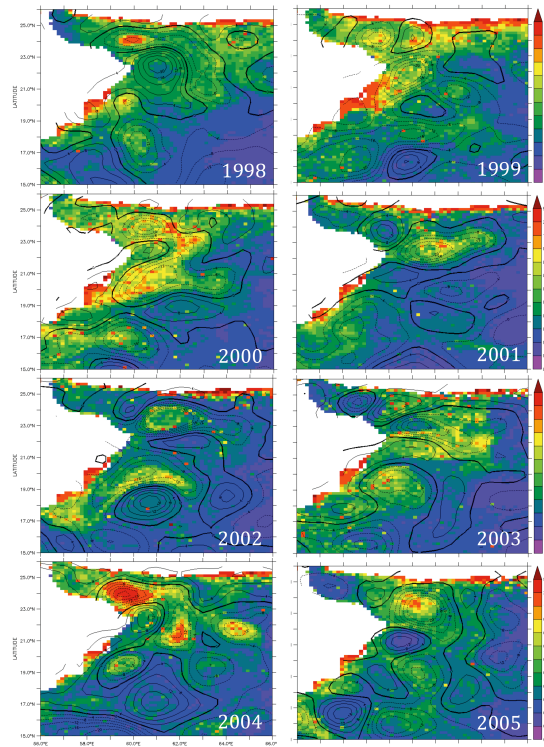
Fig. 2. Chlorophyll-a in mg/m3 (colors) and sea surface height anomaly (SSHA, contours) in meter in Gulf of Oman in November.
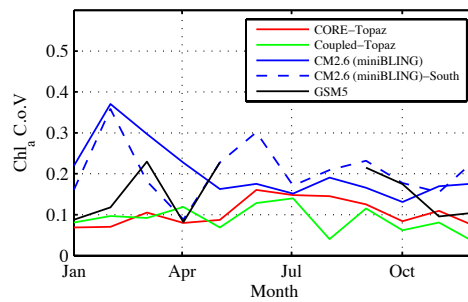
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Fig. 3. Average monthly coefficient of variation of Chlorophyll a in satellite data between 1998 and 2005 and GFDL models (eight characteristics years) within (56–66E, 15–26N) and within the south region (56–
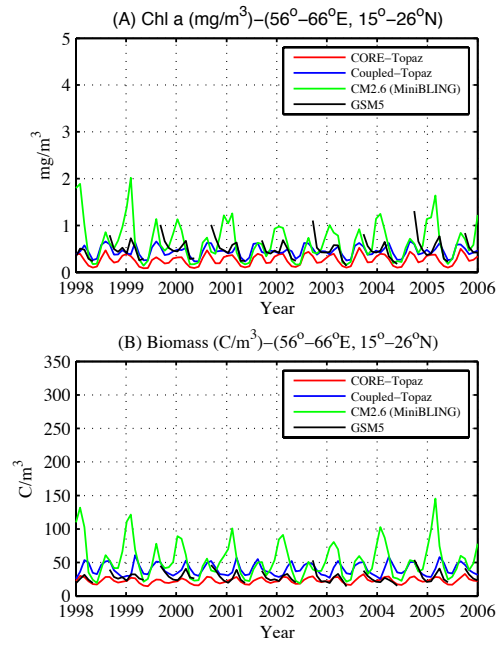
Fig. 4. Monthly variation of organic matter in satellite data between 1998 and 2005 and GFDL models (8 characteristic years) within 56–66E, 15–26N: (a) chlorophyll from GFDL models and GSM5 algorithm; (b) c
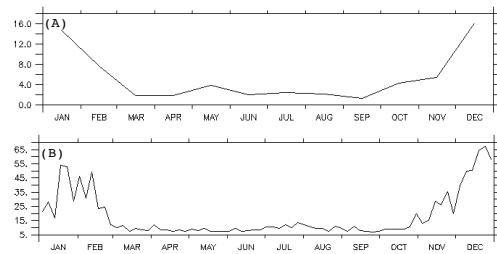
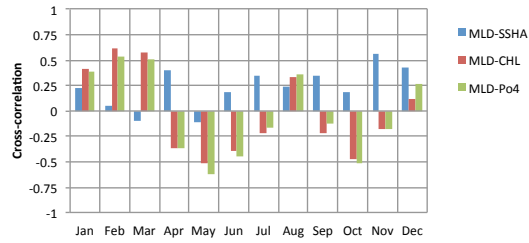**Fig. 5.** Seasonal mixed layer depth in meter: (A) WOA09; (B) CM2.6. model (56-66E, 15–26N).

Fig. 6. Mixed layer depth (MLD) cross-correlation with sea surface height anomaly (SSHA), surface chlorophyll a, and surface phosphate (Po4) for year 197 of the CM2.6 (miniBLING) models (60–64E, 17–24N).
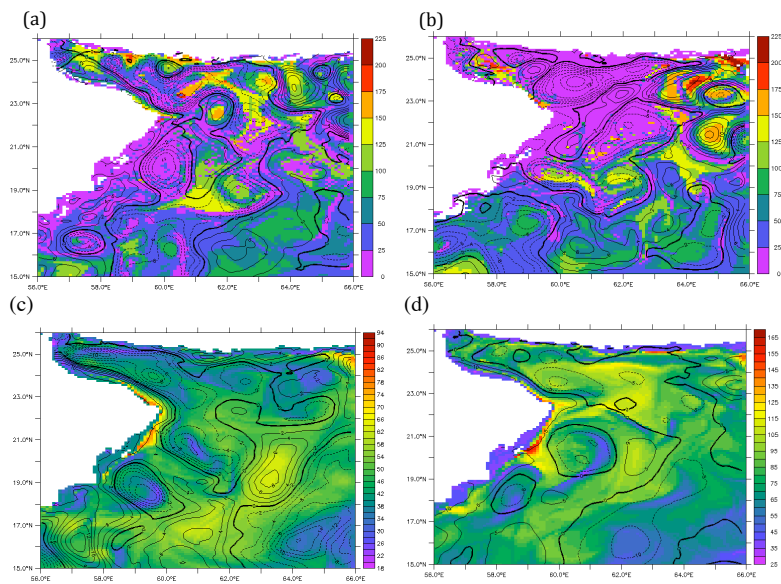
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Fig. 7. CM2.6 (miniBLING) mixed layer depth (MLD) and sea surface height anomaly (SSHA) in: (a) January, (b) February; and i (c) November, (d) December of year 197.
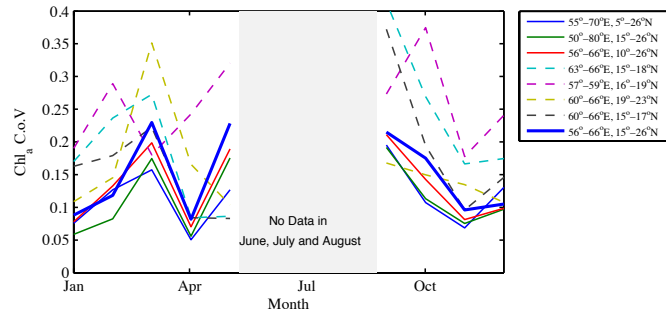
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Fig. 8. Average monthly coefficient of variation of Chlorophyll a in satellite data between 1998 and 2005 within different regions.
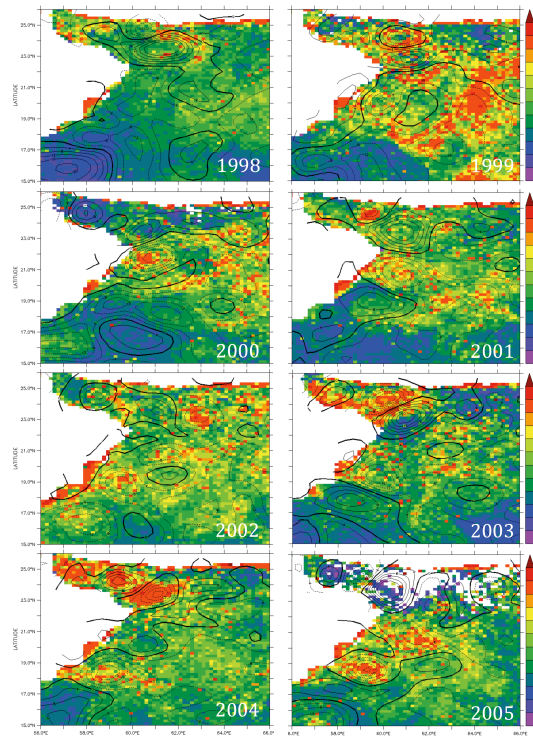
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Fig. 9. Chlorophyll-a in mg/m3 (colors) and sea surface height anomaly (SSHA, contours) in meter in Gulf of Oman in February.

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