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Linking Seacolor to Near-Surface Ocean Dynamics in the Indian Ocean

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1. Summary

The large variability of the oceanic response to the two Indian monsoons results in a large diversity of phytoplankton seasonal cycles in the Indian Ocean (Fig. 1). Here we propose a comprehensive description of these seasonal cycles in terms of the characteristics of the summer and winter blooms (timing, duration, intensity, mechanism). This description is based on the analysis of a climatological year constructed from SeaWifs data. The interpretation in terms of physical forcings is guided by physical parameters derived from an Ocean General Circulation Model (OGCM). Our analysis takes into account the non-synopticity of the blooms at the scale of a few hundred kilometers. It confirms processes that have previously been described locally and provides a thorough image of their regional extension.

2. Data

Seawifs : Level 3 weekly 9x9 km SeaWiFS Sea Surface Chlorophyll (SCHL)
A climatology is constructed from 8 years (Nov 1997- Nov 2005) of data:
- Interpolation in space and time is performed over missing data
- Low-pass space (81 x 81 km) and time (40 days) filtering
- Degradation of the initial spatial resolution of the data to 0.5°x0.5°

Model
-Global 0.5° OGCM (OPA) forced with ERS1-2 wind stress and of CMAP precipitation flux
-Heat and evaporation are diagnosed through bulk formulae
-Years 1993 to 2000 of the model run are used to construct a climatology

3. Method

-Definition of two semesters: "summer" (15 May-15 Nov) and "winter" (15 Nov-15 May).
-Identification of the SCHL maximum within each semester (time t_{max}, stars on Fig. 1).
-Identification of the preceding SCHL minimum (time t_{min}, circles on Fig. 1).
-The bloom period is defined as the period that extends from t_{min} to t_{max} (thick lines on Fig. 1).
-The Cumulated Biomass Increase (CBI) is defined as the integral of the increase in SCHL during the bloom period.
-Velocities (U, V, W) from the OGCM are averaged during the bloom period.
-Identification of the maximum Mixed-Layer Depth (MLD) from the OGCM during the bloom period.

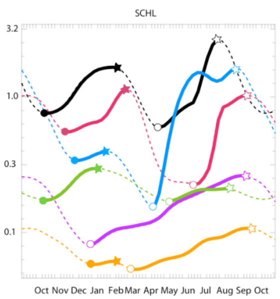

Fig. 1: Examples of SCHL seasonal cycles in the Indian Ocean. The maximum summer (resp. winter) SCHL value during the summer semester is marked with an open (resp. filled) star. The preceding summer (resp. winter) minimum SCHL value is marked with an open (resp. filled) circle. The periods of the summer and winter blooms are marked with thick contours: they are defined as extending from the SCHL minimum until the SCHL maximum. Note that there is no winter bloom in the purple seasonal cycle. Note also the large variability in the phase and amplitude of the blooms.

4. Variability of the SCHL seasonal cycle

- The seasonal cycle of SCHL is described by six parameters: the time of the SCHL maximum (t_{max}, Fig. 2c and 2d), the time of the SCHL minimum (t_{min}, Fig. 2a and 2b) and the CBI (Fig. 3a and 3b), in winter and in summer.
- Most areas are characterized by a bi-modal seasonal cycle except: southwest of India, the southern Oman coast and the subtropical gyre in the southern hemisphere, which follow a single-mode seasonal cycle (Fig. 2e and 2f).
- The timing of the summer and winter blooms show large variability: from March to June for the summer bloom onset (Fig. 2a) and from September to November for the winter bloom onset (Fig. 2b).
- The bloom period is longer in summer (3-4 months) than in winter (2-3 months, Fig. 2e and 2f). The regions with a single-mode seasonal cycle are characterized by a much longer bloom period (5-6 months).

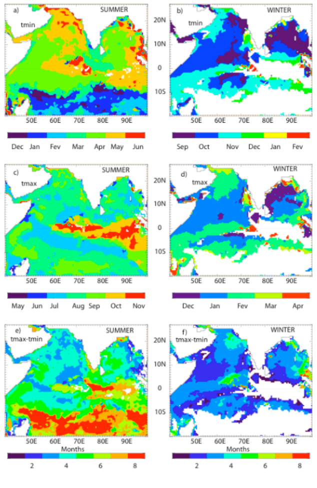

Fig. 2: Time of bloom onset (t_{min}), time of bloom maximum (t_{max}) and bloom duration (t_{max} - t_{min}) for the summer blooms (a, c, and e) and for the winter blooms (b, d and f). t_{min} and t_{max} are defined as in Fig. 1 (starts and circles).

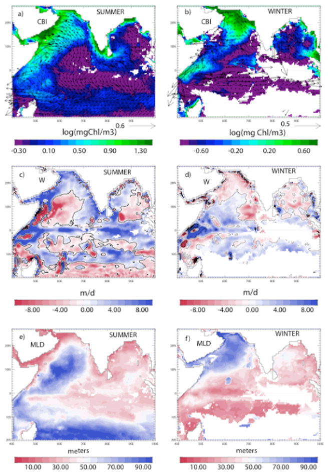

Fig. 3: Cumulated Biomass Increase (CBI), mean currents (U,V), mean vertical velocity at 50 m (W) and maximum Mixed-Layer Depth (MLD) during the summer and winter bloom periods defined on Fig. 1. SCHL data are from an 8-year climatology constructed from SeaWiFS data, and physical parameters are from a 7 year-climatology constructed from OGCM results.

6. Conclusions

Taking into account the variation in the timing of the winter and summer blooms in the Indian Ocean has allowed us to derive regional maps of the extension of these blooms and to relate them to the northeast and to the southwest monsoons. This analysis has highlighted the important role of horizontal advection in setting the boundaries of the regions.

5. Regional analysis in relation with the physics

Fig. 4 highlights the regions where the CBI is large during summer and winter. We will now discuss these regions one by one.

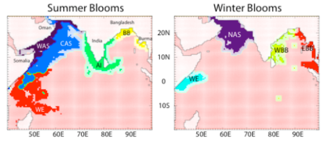

Fig. 4: Regionalization of summer and winter blooms defined from CBI contours (Fig. 3a and 3b).

Summer blooms

WAS (West Arabian Sea):
- Higher CBI off Oman and Pakistan, lower off Somalia (Fig. 3a).
- The bloom is driven by upwelling (Fig. 3b).
- The bloom starts off Somalia in early March, and in late March off Oman (Fig. 2a), and does not reach the coast of Pakistan until late May. This northward propagation of the bloom onset is in agreement with the onset of upwelling (not shown).

CAS (Central Arabian Sea):
- High CBI away from the direct influence of the upwelling (Fig. 3a).
- Due to horizontal advection from the coastal areas (Fig. 3a). This is consistent with the bloom beginning in the CAS approximately one month after the WAS (Fig. 2a).
- Local nutrient supply by entrainment (Fig. 3e).
- In the north, local nutrient supply by upwelling (Fig. 3c).

AI (Around India):
- Earliest and longer bloom in summer (Fig. 2a and 2e).
- The bloom is driven by upwelling (Fig. 3c).
- Time shift of two months between the onset of the bloom at the coast and its onset 100-200 km from the coast (Fig. 2a).
- This time shift is explained by the off-shore propagation of the upwelling.
- Compared to the WAS, the AI bloom does not propagate in the interior. Rather, it is advected along the coast by the West Indian Coast Current and around the Indian peninsula by the Southwest Monsoon Current (Fig. 3a).
- In the Bay of Bengal, the area of high CBI exceeds the extent of the upwelling: advection from the south, by flow out of the SMC around Sri Lanka (Fig. 3a). The signature of this horizontal advection can be seen in the timing of the bloom onset (Fig. 2a).

BB (Bangladesh-Burma):
- Large rivers outflow during the SWM rains.

WE (West Equatorial):
- The bloom is driven by upwelling (Fig. 3c).
- The southern end of the region coincides with the South Equatorial Current, which is partly deflected to the North. The positive W are associated with the SEC (Fig. 3a), and located on its northern side. Upwelling is therefore intimately associated with horizontal advection in this region.

Winter blooms

NAS (North Arabian Sea):
- The bloom is driven by the entrainment of the ML (Fig. 3f).
- The CBI is more intense (Fig. 3b) and the bloom lasts longer (Fig. 2f) in the east than in the west.
- Transport by the West Indian Coast Current (Fig. 3a).

WE (West Equatorial):
- The bloom is driven by upwelling (Fig. 3d).
- Southward advection by the Somalia Current (Fig. 3a). The time shift in the bloom timing north and south of the equator is indicative of this advection (Fig. 2b).

WBB (West Bay of Bengal):
- The bloom is driven by local upwelling (Fig. 3d).

EBB (East Bay of Bengal):
-The bloom is more intense than in the WBB (Fig. 3b) and lasts longer (Fig. 2f).
-The bloom is driven by local upwelling (Fig. 3d).