Physical processes that impact biological activity in the Indian Ocean at climatological and intraseasonal time scales

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Overview

Climatological processes

Shallow overturning cells
- Cross-Equatorial Cell (CEC)
- Subtropical Cell (STC)

Arabian Sea
- Upwelling and mixed-layer processes

Bay of Bengal
- Subsurface phytoplankton maximum

Intraseasonal processes

MJOs
- Thermocline ridge (5–10°S)
Overview
SeaWiFS annual chlorophyll composite (1999)

- Central and northern AS
- Western Bay
- Somali and Oman
- Sri Lanka
- Java/Sumatra
- South Indian Ocean band

Vinayachandran (2006; priv. comm.)
The wind field in the Indian Ocean is very different from that in the other oceans, accounting the unique properties of Indian Ocean circulation and its phytoplankton distributions.

There are no easterly winds (trades) on the equator, so that there is no equatorial upwelling. Instead, there are reversing cross-equatorial winds.

There are seasonally reversing monsoon winds in the Arabian Sea, the Bay of Bengal, and extending to 10°S, with a stronger (weaker) clockwise circulation during the summer (winter).

South of 10°S, the Southeast Trades are relatively steady.
Thermocline response

**January**

During the NEM, the mixed-layer in the central and northern Arabian Sea thickens to ~100 m.

**July**

During the SWM, upwelling favorable winds lift the thermocline off Somalia and Oman, on the Indian coast, and around Sri Lanka.

There is a **thermocline ridge in a band from 5–10°S**. It is driven by Ekman pumping associated with the northward weakening of the Southeast Trades, and is **stronger in northern summer** when the Trades are stronger.
Climatological processes

Shallow overturning cells
The CEC carries nutrients from the southern hemisphere to the upwelling regions in the northern hemisphere. Similarly, the STC supplies nutrients for the upwelling band from 5–10°S.

C.I. = 1 Sv

Garternicht and Schott (1997) from global GCM (Semtner)
Upwelling, subduction, and inflow/outflow regions for IO overturning cells

- Somali/Omani upwelling
- Indian upwelling
- Sumatra/Java upwelling
- 5-10°S upwelling
- Indonesian throughflow
- Subduction
- Agulhas Current
- Southern Ocean
Climatological processes
Arabian Sea
Chlorophyll from SeaWiFs

SWM (Jul): Upwelling, filaments, mixing and entrainment; nutrient replete, high production, eutrophic.

NEM (Jan): Wind and buoyancy-driven mixing; nutrient replete, high production, but light limited.

Intermonsoon (May, Oct): Stratified conditions, low nutrients, near oligotrophic.
The physical component is a 4½-layer model of the Indian Ocean. Layer 1 represents the oceanic mixed layer, and its physics are based on the Kraus-Turner (1967) parameterization. The biological component is an NPZD model included in each layer of the physical model, which allows for advection within layers and transport across them.
Under climatological forcing, there are unrealistically large detrainment blooms at the end of the monsoon seasons when the mixed layer thins rapidly. There are weak entrainment blooms at the beginning of the monsoons when the mixed layer begins to thicken and nutrients are entrained into the mixed layer. During the monsoons, the mixed layer is so thick that phytoplankton growth is light limited.
Under forcing by actual winds (1994) and with the diurnal cycle, there are a number of detrainment and entrainment blooms, so that phytoplankton growth is spread more realistically throughout both monsoons.
When compared with (US JGOFS Arabian Sea Process Study) data elsewhere in the basin, the model’s response was initially not good. Many model/data discrepancies were traceable to the solution’s mixed-layer thickness being too thick (purple curve).

CONCLUSION: Relatively simple biogeochemical models can capture the first-order biological variability in the Arabian Sea, but solutions are very sensitive to how well the models represent the physical state, particularly mixed-layer thickness and vertical-exchange processes.
Climatological processes
Bay of Bengal
Southwest monsoon

SeaWiFS images for 1997–2002

Vinayachandran et al. (2004; GRL)

This monthly climatology from SeaWiFS clearly shows that there is a biological response south of India during the SWM. As shown in the next slide, different physical processes account cause the bloom in different locations.
Southwest monsoon

IRS-P4 OCM image during July, 1999

Ekman Pumping

Advection by SMC

Coastal Upwelling
Northeast monsoon

There is also usually a bloom in the western Bay during the NEM. In the above sequence, the only exception was during 1997 when there was a bloom in the eastern Bay, likely a consequence of the ongoing IOD event.
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Evolution of the 1996 bloom

The model is able to reproduce the bloom at the right time and right place.
An essential part of the bloom dynamics is the presence of a prior subsurface (layer 3) phytoplankton maximum. As a result, the initial surface bloom is caused largely by the entrainment of subsurface phytoplankton into the mixed layer (layer 1).
Prior to an increase in the wind, the mixed layer of the Bay is thin. Thus, there is sufficient light at subsurface levels (layer 3) to allow a subsurface bloom to develop, where nutrients are also available. When the winds strengthen, both nutrients and chlorophyll are entrained (or upwelled) into layer 1.
Intraseasonal processes

MJOs
Madden-Julian oscillations (MJOs) are eastward-propagating, convective disturbances, typically with periods of 40–60 days.

Their impacts on rainfall, oceanic surface fluxes, and SST are well documented.


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Mixed-layer thickness (NH summer)

Model-derived, mixed-layer-thickness anomalies associated with MJO forcing.

Positive anomalies indicate a thicker mixed layer, and thus regions that might be expected to have enhanced nutrients and hence to higher phytoplankton concentrations. This relationship holds at some, but not all, locations.
Intraseasonal processes

Thermocline ridge
Thermocline ridge

The thermocline rises close to the surface in a band from 5º–10ºS in the western and central IO in response to Ekman suction associated with the Southeast Trades.

The model shown at the left illustrates the thermocline ridge and its seasonal variability.

Because the thermocline is so shallow, strengthened intraseasonal winds can cause thermocline variables to be entrained into the surface mixed layer.

McCreary, Kundu, and Molinari (1993)
The figure shows band-passed (30–90 day) SST anomalies averaged from 5–10°S, the latitude band of the thermocline ridge.

There are zonally elongated SST anomalies that are strongest during winter, and westward-propagating anomalies (Rossby waves) during summer and fall.
Wintertime cooling events

A particular cool event studied by Harrison and Vecchi (2001) & Duvel et al. (2004)
Observed (left panel) and modeled (right panel) chlorophyll (mg/m³) concentrations during September, 1998. Units are mg/m³. In the model, there is a band of high concentration from 10–12°S.
Chl and sea-level variability during 1998

Observed and modeled chlorophyll (top) and sea level (bottom) during summer and fall, 1998.

In both the model and observations, chlorophyll variations are associated with westward-propagating disturbances.
During a phase of high chlorophyll, there is upwelling, the mixed-layer thickens, and the subsurface, chlorophyll maximum is entrained to the surface.
Shallow overturning cells: The CEC provides the water that upwells in the northern IO. The STC does so for the 5–10ºS band.

Arabian Sea: In the central Arabian Sea (away from upwelling regions), blooms are driven by mixed-layer entrainment and detrainment events. There, the response of an NPZD model is very sensitive to mixed-layer thickness, indicating that the precise simulation of the physical state is critical for the realistic simulation of biological activity.

Bay of Bengal: In the southern Bay and south of Sri Lanka, summertime blooms are driven by upwelling and advection. In the western Bay, wintertime blooms are driven in part by entrainment of subsurface phytoplankton into the surface mixed layer.

MJOs: The strength of phytoplankton blooms is linked to the life cycle of MJOs, and some blooms appear to be driven by MJO-induced changes in mixed-layer thickness.

Thermocline ridge (5–10ºS): During the summer, some surface blooms are associated with the passage of Rossby waves, which shallow the thermocline and allow subsurface phytoplankton to be entrained into the surface layer.
Structure

Subsurface flow crosses the equator only near the western boundary due to PV conservation.

Near-surface water crosses the equator in the interior ocean. Surface flow, however, crosses only near the eastern boundary due to summertime equatorial roll.

Cross-equatorial flow

Cross-equatorial flow is driven by the antisymmetric component of the zonal wind.

Such a wind has no Ekman pumping, and hence its Sverdrup transport is equal the Ekman transport.

Equatorial rolls

Equatorial rolls are very shallow \((z > -100m)\), equatorially trapped (\(|y|<5^\circ|\) circulations driven by cross-equatorial meridional winds. They play a secondary role in the CEC dynamics.
Summary

• Satellite observations of rainfall and Chlorophyll (Chl) indicate that the MJO has systematic and significant influence on ocean surface Chl concentrations over a number of regions of the Indian and Pacific Oceans. This finding holds for both summer and winter.

• Satellite observations of surface wind and solar variations, as well as model-derived ocean surface mixed-layer depths, indicate that wind-induced vertical mixing (of nutrients) may be responsible for the Chl changes occurring in a number, but not all, of the regions examined.

Implications

• The results above, coupled with the indication that the MJO is predictable with lead times as great as 2-3 weeks (e.g., Waliser et al. 2003, 2004, 2005), imply that large-scale changes in ocean Chl might also be predictable with similar lead times which is likely to be a valuable asset to the ocean fishing industry. In addition, given the influence Chl has on solar attenuation there may be some modest indirect influence on the local SST.

Future Work

• Examine historical fish-catch data to determine if the influence of the MJO on Chl extends to an impact on fish abundance. Tried to do some of this but data is very limited.

• Use bio-physical ocean models along with satellite-derived MJO forcing and validation data to determine the mechanisms responsible for the MJO-Chl relationship including their regional dependencies.
Summary

- Large intraseasonal variability in SST over the tropical South Indian Ocean where the ITCZ and thermocline dome are observed.
- Associated with organized convective and wind anomalies
- Lower frequencies than on the equator (MJO), suggestive of an oceanic feedback.
Hood et al. 2003:

Although the model results were much improved through adjustment of both biological and physical parameters, improving MLD variability was a key step.

Most of the remaining biogeochemical discrepancies are related to problems with the physics.

Correct representation of spatial, physical variability and eddy effects is crucial.

Corollary

Implementing a more complicated biogeochemical model will not dramatically improve our solution.
Grand Conclusion:

Relatively simple biogeochemical models can capture the 1st order variability, but they are very sensitive to how physical models represent physical reality, and especially vertical exchange processes, i.e., mixing/entrainment, diapycnal exchange, upwelling, eddy perturbations, etc.

The upside: Biogeochemical models provide a powerful means of discerning subtle problems in physical models, especially those related to vertical exchange.

The downside: Do physical simulations have to be “perfect” in order to model biogeochemical cycles in the Ocean? For simulation, maybe yes. For climate prediction, hopefully not.
Conclusions

- There are phytoplankton blooms in the western Bay of Bengal (NEM) and around Sri Lanka (SWM).
- Physical processes driven by wind events play a crucial role in the generation of blooms as well as distribution of chlorophyll.
- It is possible to simulate (qualitatively) these blooms using a coupled physical-biological model.
- Subsurface maximum enriches surface chl in regions of thin mixed layers (where light penetrates below the mixed layer).
There is also an increase in chlorophyll in the western Bay during the NEM. As shown in the next slide, this phenomenon typically repeats each year.
CEC in JAMSTEC model

Equatorial roll

![Graph showing Equatorial roll in the JAMSTEC model](image)
A composite of 11 wintertime events when SST anomalies exceeded 1.5 sigma. A phase change of 45° is equivalent to 7–10 days.
Ekman transport appears to be involved off the equator. But, what dynamics are involved near the equator?
Ekman flow = Sverdrup flow at equator

Consider forcing by $\tau^x$ that is antisymmetric about the equator

$$\tau^x = X(x)Y(y) = \tau_0 X(x) y / L$$

The Sverdrup transport is

$$V = -\frac{1}{\beta} \partial \tau^x / \partial y = -\frac{\tau_0 X}{\beta L}$$

but $V$ can be rewritten

$$V = -\frac{\tau_0 X}{\beta L} \frac{y}{y} = -\frac{1}{\beta} \frac{\tau^x}{y} = -\frac{\tau^x}{f}$$

Thus, for this wind the Sverdrup and Ekman transports are equal. It follows that the concept of Ekman flow can be extended to the equator, since $\tau^x$ tends to zero as $f$ does.