Radiant heating rates and surface biology during the Arabian Sea Monsoon Experiment

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Abstract
Radiometric observations are carried out to estimate the net shortwave solar radiation in the upper ocean during the Arabian Sea Monsoon Experiment Phase II (ARMEX-II). Radiant heating rates in the Arabian Sea Warm Pool (ASWP) region from \textit{in situ} radiometric measurements are presented for the first time. The estimated shortwave fluxes (300–700 nm) from the observed data are 101, 62, 40 and 29 W m\textsuperscript{-2} at 10, 20, 30 and 40 m depths respectively. About 5\% of the surface light reaches below 50 m. Heating of the water column by penetrating solar radiation is substantial and estimated to be 0.18, 0.11, 0.08 and 0.07 \textdegree C day\textsuperscript{-1} in the upper 10, 20, 30 and 40 m respectively. Simultaneous observations from space-based sensors (SeaWiFS and IRS-P4 Ocean Colour Monitor) show an increase in solar absorption in regions with enhanced concentration of biologically active constituents.

Keywords: ARMEX, Arabian Sea Warm Pool, radiant heating rate, chlorophyll

1. Introduction

Study of evolution of the Arabian Sea Warm Pool (ASWP) prior to the onset of the southwest (summer) monsoon is one of the key objectives of the Arabian Sea Monsoon Experiment (ARMEX). It is expected to eventually lead to a better understanding of monsoon variability. The role of shortwave radiant heating in conjunction with biologically active constituents in the thermodynamics of the ASWP has been studied for the first time during ARMEX Phase II (ARMEX-II). The chlorophyll-\textalpha (Chl-\textalpha ) pigments in phytoplankton lead to strong optical attenuation (Smith and Baker 1978, Morel 1988). Therefore they can play a significant role in the upper ocean heat budget (Godfrey and Lindstrom 1989). An effort has been made to understand the relationship between the sub-surface temperature of the ASWP, radiant heating rate due to shortwave flux and Chl-\textalpha concentration over this domain. This paper demonstrates significant changes in the upper ocean heating rates and possible relationship with optically active bio-constituents using observations from cruise 190 of the research ship ORV \textit{Sagar Kanya} (SK190) and Chl-\textalpha concentration from remote sensing satellites (SeaWiFS and OCM).

2. Data and methods

Data from the SK190 cruise of ARMEX-II, conducted in the southeastern Arabian Sea (figure 1) from 14 March to 10 April 2003, are used to study the evolution of the pre-monsoon warm pool. \textit{In situ} measurements of upper-ocean optical, physical, biological and meteorological parameters were made from ORV \textit{Sagar Kanya} during this cruise. The optical profiles were used to estimate the radiant heating rates in terms of net penetrating radiation over the 300–700 nm wavelength domain. During SK190, optical measurements could be made only from 14 to 23 March 2003 because of a telemetry problem between the profiler and deck unit. However, the spatial
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Figure 1. Locations (squares) for bio-optical measurements taken during ARMEX-II (14–23 March 2003).

Table 1. Station locations of concurrent bio-optical and physical measurement locations during SK190 (cf figure 1).

<table>
<thead>
<tr>
<th>St. Position no (°E/°N)</th>
<th>Date</th>
<th>St. Position no (°E/°N)</th>
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<tbody>
<tr>
<td>01 74.00/12.66</td>
<td>14 March</td>
<td>09 72.66/08.28</td>
<td>18 March</td>
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<td>02 72.70/12.07</td>
<td>15 March</td>
<td>10 72.66/08.28</td>
<td>18 March</td>
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<tr>
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<td>15 March</td>
<td>11 74.45/09.19</td>
<td>19 March</td>
</tr>
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coverage of sampling during this short period is good (figure 1, table 1) and the data can be treated as representative of the ASWP waters.

2.1. Optical data in the 400–700 nm range

Optical radiometer/profilers, the SPMR (SeaWiFS Profiler Multi-channel Radiometer, or the profiler) and the SMSR (SeaWiFS Multi-channel Surface Reference, or the surface unit) deployed in the present experiment were designed and developed by Satlantic Inc., Canada. The profiler measures the upwelling radiance, \( L_u(z, \lambda) \), and the downwelling irradiance, \( E_d(z, \lambda) \), at seven discrete wavelengths (centred approximately at 412, 443, 490, 510, 555, 670 and 780 nm). The surface unit measures the downwelling irradiance, \( E_d(0^\circ, \lambda) \), just above the sea surface at these wavelengths. The nominal half-power bandwidth for each channel is 10 nm except for the last two (20 nm). Typical saturation of the radiance and irradiance signals are 20 \( \mu \)W cm\(^{-2}\) nm\(^{-1}\) sr\(^{-1}\) and 300 \( \mu \)W cm\(^{-2}\) nm\(^{-1}\), respectively. The detectors, made of Si-photodiodes, have spectrally corrected cosine response (for irradiance sensors) with noise equivalent irradiance (NEI) \( \sim 5 \times 10^{-5} \) W cm\(^{-2}\) nm\(^{-1}\) and noise equivalent radiance (NER) \( \sim 1 \times 10^{-6} \) W cm\(^{-2}\) nm\(^{-1}\) sr\(^{-1}\). The system data rate in free-fall mode is nearly 10 Hz with an optimized profiler speed of 0.4–0.7 m s\(^{-1}\) where it collects approximately 10–12 samples per metre depending on the free-fall speed of the profiler. Both systems are equipped with internal tilt and roll sensors for data quality checking during the casts. Optical data from individual profiles were excluded when the profiler tilt was greater than 5°. This reduces the uncertainty that could arise from the wave action and multiple reflections in the near surface waters. The radiometer units were deployed away from the vessel to avoid ship-induced perturbations and self-shadowing in the light field (Mueller and Austin 1993).

2.2. Shortwave flux correction for 300–400 nm

The climatological mean (from the Earth Radiation Budget Experiment, ERBE) incident shortwave radiation at the surface during March is 250–280 W m\(^{-2}\). The solar radiation incident at the surface lies in the wavelength range 300–3000 nm. For a clear sky tropical region, the net shortwave flux (over 300–3000 nm) reaching the Earth’s surface is about twice the radiative flux in the 300–700 nm range (Baker and Frouin 1987). The solar radiation in the wavelength range 300–700 nm, however, is important in the upper ocean heat balance because it penetrates into the sub-surface layers.

The total net shortwave flux at different layers beneath the surface must include the irradiances from 300 to 700 nm. Although the contribution of radiation in the wavelength range greater than 700 nm is negligibly small below the first few centimetres from the sea surface, the contribution from the 300 to 400 nm wavelength range is significant (figure 2). Since the Satlantic radiometer has only seven discrete bands in the 300–400 nm range, we performed a statistical analysis using hyper-spectral data (LI-COR, LI-1800) over the Arabian Sea (centred at 16°23’N/71°22’E) from a comparison in April 1997 to obtain the relationship between the 300–400 nm flux in relation to the total 300–700 nm flux. LI-COR is a portable spectro-radiometer, which measures hemispheric spectral irradiance (with cosine response) from 300 nm to 900 nm at 1 nm wavelength intervals. After examining each
Figure 2. Sample LI-COR (a) downwelling, (b) upwelling and (c) surface irradiance spectra taken during April 1997. The fractional irradiance over 300–400 nm (especially underwater) contributes significantly to the net shortwave (400–700 nm) irradiance. Panel (d) renders a typical Satlantic profile showing changes in the downward irradiance spectrum with depth, on 18 March 2003 around 1300 hrs LST. Correction for the shadowed region is applied to all Satlantic profiles in this study. Note the rapid attenuation of energy in wavelengths greater than 600 nm below 10 metre depth (panels (a) and (d)).

profile (eight profiles at depths 02, 05, 10, 20, 30 and 40 m) it was clear that the irradiance values beyond 700 nm are negligible below the sea surface due to a strong attenuation of longer wavelengths. The per cent contributions of irradiances over the 300–400 nm range (per cent fractional flux) are estimated as a function of depth based on linear regressions within the photic zone. Equations (1.1), (1.2) and (1.3) are used effectively to compute the per cent contribution of the downwelling irradiance profile, $\Delta \bar{E}_d(z)$, the upwelling irradiance profile, $\Delta \bar{E}_u(z)$, and the surface downwelling irradiance, $\Delta \bar{E}_s(0^+)$, respectively:

$\Delta \bar{E}_d(z) = (0.1695z + 14.535) \int_{400}^{700} E_d(z, \lambda) \, d\lambda$  \hspace{1cm} (1.1)

$\Delta \bar{E}_u(z) = (0.4373z + 25.401) \int_{400}^{700} E_u(z, \lambda) \, d\lambda$ \hspace{1cm} (1.2)

$\Delta \bar{E}_s(0^+) = (9.11) \int_{400}^{700} E_s(0^+, \lambda) \, d\lambda.$ \hspace{1cm} (1.3)

So, the directional shortwave flux over 300–700 nm can be calculated as

$\bar{E}_N(z) = \int_{300}^{700} E_N(z, \lambda) \, d\lambda \equiv \int_{400}^{700} E_d(z, \lambda) \, d\lambda + [0.01 \Delta \bar{E}_N(z)].$ \hspace{1cm} (2)

$E_N$ may be substituted by $E_u$ (i.e., $z = 0^+$), $E_d$ or $E_s$ profiles from the Satlantic observations. The Satlantic measured
upwelling radiances, $L_d(z, \lambda)$, were multiplied by a Q-factor
($= \frac{Q \lambda}{Q} \approx 4.5$) to obtain the upwelling irradiance profiles (Morel
and Gentili 1991, 1993). All integrations were performed using the
MATLAB\textsuperscript{\textregistered} trapezoidal scheme. Prior to integration,
all SPMR/SMSR irradiance spectra were interpolated to 1 nm
wavelength using cubic splines (de Boor 1978).

2.3. Ancillary measurements

The profiler also carried ancillary sensors—a WetSTAR
fluorometer that measures the Chl-\(a\) fluorescence, a thermistor
to measure the water temperature, and a Viatran pressure
transducer to estimate the pressure converted depth. A
significant underestimation of the Chl-\(a\) concentration
measured by the WetSTAR fluorometer has been found
(Raman 2003). Nevertheless, the relative accuracies of
concentrations are adequate for the purpose of this study.
To overcome the absolute accuracies, all Chl-\(a\) data were
normalized to the cruise maximum.

3. Results

Radiant heating of the upper ocean due to the absorption of
sunlight by seawater and biogenous matter can be determined
from the net irradiance spectrum (Ivanoff 1977, Morel 1988,
Seigel \textit{et al} 1995), which is defined as

$$E_n(z, \lambda) = E_d(z, \lambda) - E_a(z, \lambda), \quad (3)$$

where $E_n$, $E_d$ and $E_a$, respectively, are the net irradiance,
downwelling (measured) and upwelling (estimated)
irradiances. The apparent changes in the net irradiance
below the surface water is observed as rapid attenuation
occurs in wavelengths greater than 600 nm. Below a depth
of 10 m, the contribution of longer (red) wavelengths to the
net irradiance is negligible (less than 5\%). Thus the total net
irradiance at greater depths can be attributed to the blue–green
regions of the solar spectrum (with a peak at $\sim 490$ nm).
The surface flux and net solar radiation flux at each depth from the
Satlantic data are calculated by integrating the net irradiance
over the wavelength range 400–700 nm as

$$E_n(z)_{400}^{700} = \int_{400}^{700} E_n(z, \lambda) \, d\lambda. \quad (4)$$

The net penetrating solar flux from the net irradiance spectrum over 300–700 nm, $E_n(z)$, was then corrected using equation (2). The transmission function, $T_c(z)$, for penetrating solar radiation within the upper ocean, which gives the amount of energy available at any depth for a given surface energy, is the total net solar flux normalized by the total incident flux at the surface

$$T_c(z) = \frac{E_n(z)}{E_n(0^+)}. \quad (5)$$

Figure 3 represents the SK190 cruise mean transmission function. ($T_c(z)$), which follows an ideal near-exponential decay of the net flux with depth (Jerlov 1976). More than 50% of the surface flux is absorbed within the top 5 m. Thus, if the incident flux and the transmission function are known, the net solar flux profile can be retrieved from equation (5).

$$\frac{\partial T_z}{\partial t}_{\text{rad}} = \frac{\bar{E}_n(0^+) - \bar{E}_n(z)}{\rho_w C_p z}, \quad (6)$$

where, $\rho_w$ is typical seawater density ($\sim 1025$ kg m$^{-3}$) and
$C_p$ is the specific heat of seawater at constant pressure (4100 J kg$^{-1}$ K$^{-1}$). The net flux just beneath the surface layer can be approximately obtained from the net incident surface flux as $\bar{E}_n(0^+) = (1 - \alpha) \bar{E}_s(0^+)$, where the sea surface albedo ($\alpha$) is 0.06 (Payne 1972).

Our discrete observations during the entire cruise span almost equally from morning till evening (figure 4). Hence the cruise mean net penetrating flux counts for the diurnal cycle of the intensity of the solar energy. The mean day time incident flux at the ocean surface during SK190, ($E_s(0^+)$), was 308.5 W m$^{-2}$. Table 2 summarizes the cruise mean transmission function at different depths and radiant heating rate of different layers in the upper ocean in the ASWP region. The unprecedented radiant heating rates for the ASWP domain, computed from the \textit{in situ} observations, are comparable to those found by Seigel \textit{et al} (1995) in the western Pacific warm pool.

Time variation of the surface Chl-\(a\) and temperature is shown in figure 5. During the study period, a deep chlorophyll maximum (DCM) was found at around 60–80 m depth which is shallower than the summer monsoon (June–September).
mixed layer depth (MLD) in the Arabian Sea (Prasad 2004). The deepening of the MLD after the warm pool event is due to the strong wind-driven vertical mixing. There was no significant change in the Chl-a concentration during this short observation except for stations 3 and 12–14, where the DCM was found at shallower depths. There was a significant fall in SST by 0.9°C (figure 5) between stations 1 and 2 accompanied by cooling down to ~100 m depth, associated with an increase in the Chl-a concentration. There was also a corresponding decrease in the MLD (estimated approximately from the temperature profile) from station 1 to station 2. The cooling and the increase in the Chl-a is probably because the ship moved into a region with an increased Chl-a concentration and a different thermal structure (see below). The OCM snapshot on 15 March reveals an eddy and traces of high chlorophyll concentration at its periphery (figure 6). This picture coincides with the in situ surface chlorophyll high on 15 March at station 3 as the Chl-a concentration in OCM
images are around 0.5–0.7 µg l⁻¹, which is higher than normal in open ocean (case 1) waters. Hence cooling and enhanced Chl-a concentration may be attributed to the eddy-induced vertical upwelling and injection of subsurface nutrients near station 3. An increase in the chlorophyll concentration is responsible for a reduction in the transmission of net solar radiation to depth (figure 5). The increase in the upper layer of the Chl-a concentration resulted in a decrease in the penetrative radiation at stations 2–4, which allows ~10% of the surface energy down below the MLD (~30 m) (table 2). Figure 7 shows the time evolution of the spatially averaged (70°–77°E/6°–14°N) satellite derived Chl-a concentration and light attenuation coefficients at 490 nm (K490) around the study area from November 2002 to July 2003. A clear increasing trend in the surface chlorophyll and light attenuation are seen from March until May 2003. Although in situ measurements were obtained for a short period, the results are significant, showing the possible coupling between the upper layer biological and physical processes and most importantly a baseline for the ASWP heating rates.

4. Discussion and conclusion

This experiment was targeted to the understanding of the upper layer thermodynamics of the Arabian Sea Warm Pool and to quantify with the aid of novel optical instruments the radiant heating rates during the pre-onset of the southwest monsoon. About 14% of the total incident shortwave flux penetrates into the mixed layer (30 m), which eventually results in a heating rate of 0.08 °C day⁻¹ in the 20–30 m water slab. The warming rate in the surface 10 m is about 0.18 °C day⁻¹. In addition to this, satellite ocean colour data are quite useful for understanding the bio-physical coupling over large dynamic areas. Since remotely-sensed ocean colour information is not just a surface manifestation (the pigment concentration retrieved by means of remote ocean colour sensors is a value representative of the upper few metres of the water column i.e., the first attenuation depth), they can be treated as important components of upper ocean dynamics. This work also suggests that biogenic matter can have a significant influence on the absorption of sunlight (in 300–700 nm wavelength domains) as a function of depth in the upper ocean. The trapped solar energy eventually enhances radiant heating rates within the upper layers of the ASWP developing a shallow MLD before the onset of summer monsoon period (transition), when the impact of the wind-induced mixing is minimum. So the enhanced chlorophyll concentration could increase the heating rates until May although inter-annual variability cannot be ruled out.

The present study demonstrates the importance of solar penetration and warm pool thermodynamics based on a small dataset collected during ARMEX-II. Nevertheless, further field observations of subsurface solar radiation together with optical and biological measurements are needed to understand the interrelationship between radiant heating and phytoplankton.
Acknowledgments

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