GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 15, 10.1029/2002GL015340, 2002

Spring Warming of the Eastern Arabian Sea and Bay of Bengal from Buoy Data

Debasis Sengupta, Pallav Kumar Ray, and G. S. Bhat
Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, India

Received 17 April 2002; accepted 6 June 2002; published 7 August 2002.

[1] Observations from moored buoys during spring of 1998–2000 suggest that the warming of the mixed layer (~20 m deep) of the north Indian Ocean warm pool is a response to net surface heat flux Q_{net} (~100 W m^{-2}) minus penetrative solar radiation Q_{pen} (~45 W m^{-2}). A residual cooling due to vertical mixing and advection is indirectly estimated to be about 25 W m^{-2}. The rate of warming due to typical values of Q_{net} minus Q_{pen} is not very sensitive to the depth of the mixed layer if it lies between 10 m and 30 m. *INDEX TERMS:* 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; 9340 Information Related to Geographic Region: Indian Ocean; 4572 Oceanography: Physical: Upper ocean processes; 4504 Oceanography: Physical: Air/sea interactions (0312)

1. Introduction

[2] The seasonal cycle of Indian Ocean sea surface temperature (SST) is important for the onset and subsequent evolution of the south Asian summer monsoon [*Webster et al.*, 1998]. Several studies have shown that there is a significant positive correlation between SST in the Indian Ocean spring warm pool and Indian monsoon rainfall. In particular, the quasi-biennial variability of the summer monsoon seems to be influenced by Indian Ocean SST in the previous winter and spring seasons [*Li et al.*, 2001] rather than by tropical Pacific SST. *Loschnigg and Webster* [2000] have pointed out that in spring the sky is clear and winds are light over the north Indian Ocean, giving a net surface heat input of 75–100 W m^{-2}. The SST in this region warms by 3–4°C in this season, giving rise to April-May SST's that are among the warmest in the world. Until recently there have been no studies of the spring warming of the Indian Ocean using in-situ observations. Year-long surface and subsurface observations in the north central Arabian Sea at 61.5°E, 15.5°N in 1994–95 [*Weller et al.*, 2002] show a net surface heat flux of about 100 W m^{-2} in spring, with SST rising by 4°C from mid-February to May. The daily maximum mixed layer depth shallows to less than 20 m in April from about 100 m in early February as the upper ocean is stabilized due to buoyancy flux. *Weller et al.* [2002] suggests that upper ocean processes in spring are primarily one-dimensional, with the warming being a response to surface heat flux minus penetrative shortwave radiation flux. Here we present the first calculations of the mixed layer thermodynamics of the Indian Ocean warm pool [*Vinayachandran and Shetye*, 1990] in spring based on moored buoy observations from 1998–2000 in the eastern Arabian Sea and central Bay of Bengal.

[3] In 1997–1998, the Department of Ocean Development, New Delhi, installed several moored buoys in the Bay of Bengal and Arabian Sea for routine monitoring of the near surface ocean and atmosphere. The seasonal evolution of daily SST from one buoy in the eastern Arabian Sea (AS; 69.3°E, 15.3°N; February 1998 to December 2000), and one in the central Bay of Bengal (BoB; 87°E, 13°N; September 1997 to September 1998) are shown in Figure 1a. The spring warming of SST between February and late May or early June (just prior to the onset of the summer monsoon) is about 4°C in 1998 and 1999, and 2.5°C in 2000. The abrupt termination of spring warming at AS in early June 1998 and late May 1999 is due to the passage of tropical cyclones 03A and 02A (Climate Diagnostics Bulletin of India, India Meteorological Department, New Delhi) close to the buoy; the spring warming at BoB is terminated in May 1998 by a depression that subsequently developed into tropical cyclone 01B. Figures 1b and 1c show the 1998–2000 average SST field for 1–15 May and the average magnitude of the spring warming, from the microwave sensor (TMI) on the Tropical Rainfall Measuring Mission satellite. The mean bias of 3-day mean 0.25° gridded TMI SST relative to buoy SST is about −0.2°C in the north Indian Ocean [*Senan et al.*, 2001]. The data and the method of heat flux estimation are discussed in section 2. Our results are presented in section 3, followed by a discussion in section 4.

2. Data and Heat Flux Estimation

[4] Windspeed (U), SST and air temperature (T_a) are from the 3-hourly buoy observations. The buoy measures U and T_a at a height of 3.2 m and SST at a depth of 2.2 m; windspeed is extrapolated to 10 m height using a power law [*Panofsky and Dutton*, 1984]. The buoys have no radiation or humidity sensors. The relative humidity at the buoy locations is taken from the Comprehensive Ocean Atmosphere Data Set [COADS; *da Silva et al.*, 1994] climatology. In April and May 1998, the north Indian Ocean was anomalously warm by over 1°C [Figure 1; *Yu and Reinecker*, 2000; *Senan et al.*, 2001]. Therefore the relative humidity in spring is taken to be 5% lower than the COADS values, in keeping with our observations during the Indian Ocean Experiment (INDOEX) as well as the interannual monthly estimates of the Hamburg Ocean-Atmosphere Parameters and fluxes from Satellite data [*Grassl et al.*, 2000]. The sensible heat flux Q_{sen} and latent heat flux Q_{lat} are estimated from bulk formulas using daily buoy wind, SST and T_a, with a constant exchange coefficient of 0.0013;

0094-8276/02/2002GL015340$05.00

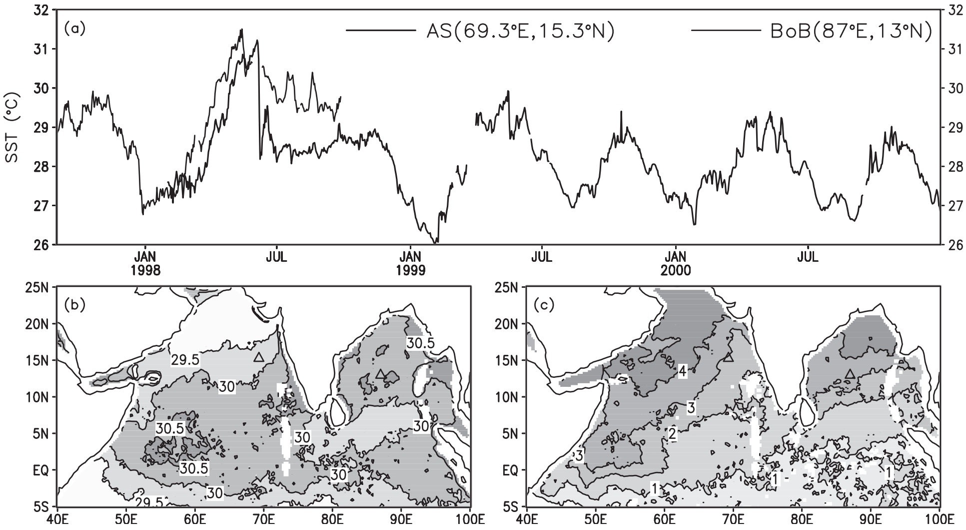

Figure 1. (a) Evolution of daily buoy SST (2.2 m) from the two buoys. (b) 1–15 May 1998–2000 mean SST and (c) mean SST warming between 1–5 February and 10–15 May 1998–2000 from TMI. Buoy positions are marked with triangles.

the magnitude of the latent heat flux is increased by 28 W m^{-2} when windspeed is below 3 m s^{-1}, following *Bradley et al.* [1993].

[5] Climatological monthly mean estimates of net shortwave radiation at the buoy locations from the 1984–1989 Earth Radiation Budget Experiment [ERBE; *Li et al.*, 1993], and satellite daily outgoing longwave radiation (OLR) data on a 2.5° grid [*Liebmann and Smith*, 1996] are used to estimate daily net shortwave radiation Q_{sw} in the same manner as in *Sengupta et al.* [2001]. This follows the prescription of *Shinoda et al.* [1998] for obtaining the daily Q_{sw} from daily OLR, modified to account for the seasonal march of the sun. Daily net longwave radiation Q_{lw} is calculated from the daily SST, T_a and OLR following *Shinoda et al.* [1998]. The daily net surface heat flux Q_{net} is given by $Q_{net} = Q_{sen} + Q_{lat} + Q_{sw} + Q_{lw}$, with the convention that heat flux is positive into the ocean.

[6] Mixed layer depth H (level at which temperature is 0.3°C lower than SST) is estimated from the climatological temperature data of *Levitus and Boyer* [1994] to be about 20 m in March to May at AS and BoB. Records of 3-hourly subsurface temperature at 15 levels (5 m interval in the upper 60 m) to a depth of 125 m are available from a thermistor chain on the AS buoy from February to May 1998; there is no subsurface salinity data. Figure 2 shows seven day running mean temperature at different depths from the surface (i.e. 2.2 m) to 50 m at AS. The upper ocean is progressively stabilized due to surface heat input under low winds [*Weller et al.*, 2002]. The mixed layer depth H_{tc} is estimated from the SST minus 0.3°C criterion applied to seven-day running mean temperatures. H_{tc} is about 45 m in the first half of March, shallowing to 15 m in early May, and subsequently deepening to 20 m. There is no subsurface temperature data at BoB in spring, or at AS in other years.

[7] Penetrative shortwave radiation flux at the base of the mixed layer Q_{pen} is estimated following *Paulson and Simpson* [1977], $Q_{pen} = Q_{sw}(1-R)e^{z/\zeta}$ where R = 0.58, ζ = 23 m for clear water, which gives a Q_{pen} that is about 18% (27%) of Q_{sw} for a mixed layer depth of 20 m (10 m). The assumption of optically clear water is reasonable in the Arabian Sea in spring [*Dickey et al.*, 1998], where the upper 30 or 40 m of the water column is devoid of nutrients and low in chlorophyll [*Madhupratap et al.*, 2001].

3. Spring Warming of SST at the Buoy Locations

[8] Figure 3 illustrates the variation of Q_{sw}, Q_{lat} and Q_{net} at AS from 1 March to 31 May 1998 and 1999. The major differences between the two seasons are in May, with cloudier skies and stronger surface winds in 1999. The March April May (MAM) mean windspeed is 5.4 m s^{-1} in 1998, and 6.0 m s^{-1} in 1999. The MAM 1998 and 1999 mean values of fluxes in W m^{-2} are: Q_{lat} −132 and −124 (note that relative humidity is 5% lower in 1998); Q_{lw} + Q_{sen} −44 and −41; Q_{sw} 278 and 257; Q_{pen} (with H = 20 m)

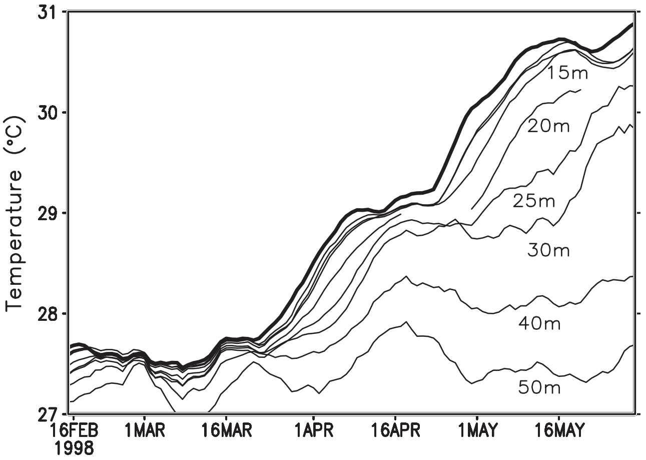

Figure 2. 7-day running mean temperature at different levels at AS, 1998. Thick line is buoy SST (2.2 m), 2nd and 3rd lines from top are at 5 m and 10 m depth; there are data gaps at 20 m during April and May.

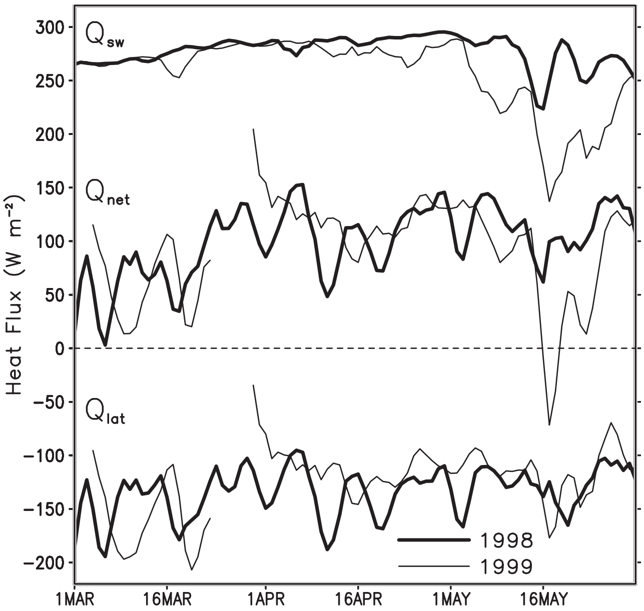

Figure 3. 3-day running mean net shortwave radiation (Q_{sw}), latent heat flux (Q_{lat}) and net surface heat flux (Q_{net}) at AS in 1998 and 1999.

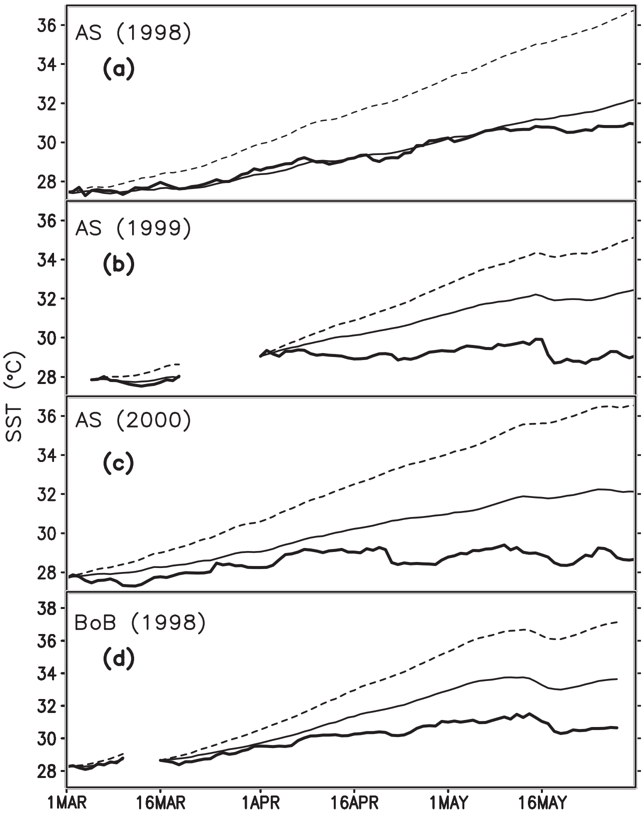

Figure 4. Observed SST (thick), predicted SST due to Q_{eff} with H = 20 m (thin), and predicted SST due to Q_{net} (dashed), i.e. without accounting for penetrative solar radiation. The SST range on the y-axis is 10°C for AS and 12°C for BoB.

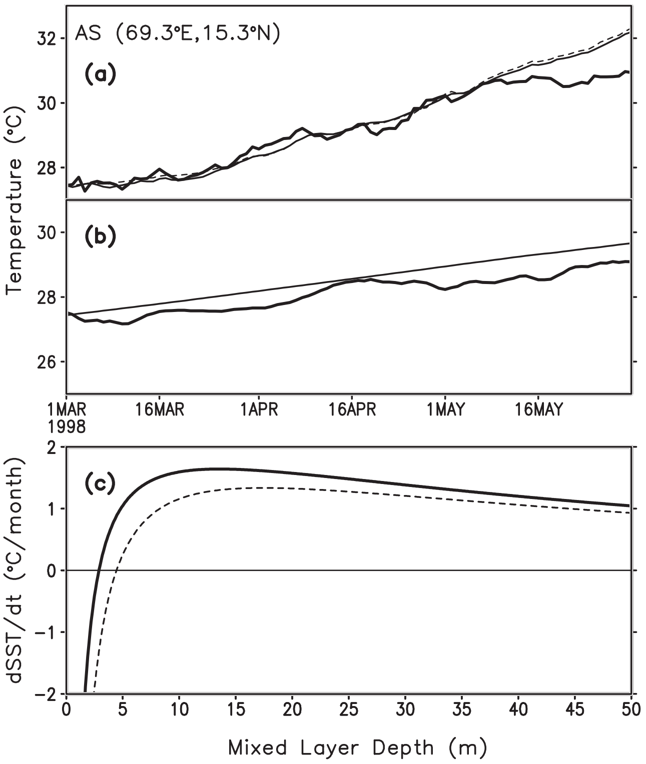

Figure 5. (a) Observed SST at AS in 1998 (bold), predicted SST due to Q_{eff} with H = 20 m (thin), and predicted SST due to Q_{eff} with H_{tc} from subsurface data (dashed). (b) 5-day running mean observed warming of the 20–50 m layer (bold) and estimated warming (thin) of this layer due to penetrative solar radiation. (c) SST change per month (°C) as a function of MLD for Q_{sw} = 270 W m^{-2}, Q_{net} = 100 W m^{-2} (bold), and Q_{sw} = 260 W m^{-2}, Q_{net} = 90 W m^{-2} (dashed).

49 and 45; Q_{net} 102 and 92. Our estimates of MAM mean Q_{net} and Q_{pen} at all buoy locations and seasons is about 100 W m^{-2} and 47 W m^{-2}. The mean effective heat flux Q_{eff} available to warm the mixed layer is therefore 53 W m^{-2}. Note that since Q_{sw} is large and the mixed layer is shallow, our estimates of Q_{pen} are much larger than those in the west Pacific warm pool, where solar penetration is 5–25 W m^{-2} [*Lewis et al.*, 1990; *Siegel et al.*, 1995].

[9] We examine the heat balance of the thermally mixed layer $\rho C_p H\,(dSST/dt) = Q_{eff} = Q_{net} - Q_{pen}$, where ρ is the density and C_p the specific heat of seawater. Figure 4a shows the MAM 1998 warming at AS estimated by integrating the above equation in time, together with the observed SST. The predicted SST due to Q_{net} is also shown in order to illustrate the effect of solar penetration. Neglect of Q_{pen} would increase the predicted SST by 4.5°C over the season. Predicted SST due to Q_{eff} differs substantially from observed SST in May 1998, showing an excess warming of 1.3°C. This corresponds to an excess heat gain of 40 W m^{-2} during this month for a mixed layer depth of 20 m. The difference between the slopes of the predicted and observed SST curves is large in the second and third weeks of May, pointing to the possible importance of advection or vertical mixing on subseasonal scales. The predicted SST evolution due to Q_{eff} and Q_{net} as well as the

observed SST at AS and BoB in other spring seasons is shown in Figures 4b–4d. The MAM mean prediction overestimates warming by 2.7°C.

4. Discussion

[10] Solar penetration can have some very interesting effects on SST evolution. Figure 5a shows that the estimated warming due to Q_{eff} at AS in 1998 is nearly the same whether the mixed layer depth (MLD) is taken to be equal to H (= 20 m) or H_{tc}, which can differ substantially from 20 m. Solar penetration compensates for the expected larger warming of a shallower mixed layer under the action of large positive Q_{net}. The estimated Q_{pen} at AS in spring 1998 (49 W m^{-2} at 20 m) gives predicted warming of the 20–50 m layer (see *Weller et al.* [2002]) of 2.3°C in MAM compared to the observed warming of 1.7°C (Figure 5b), lending support to our estimates of Q_{pen}. For heat fluxes typical of spring in the Indian Ocean warm pool, the rate of warming of SST is not very sensitive to MLD if it lies between 10 m and 30 m (Figure 5c). For very shallow MLD, SST can cool substantially because Q_{pen} is larger than Q_{net}, making Q_{eff} negative. *Sengupta and Ravichandran* [2001] speculate that solar penetration in the presence of a very shallow salinity controlled mixed layer is responsible for the absence of SST warming in the post monsoon north Bay of Bengal in 1998 although Q_{net} is about 80 W m^{-2}. A weaker form of this result has been reported from the west Pacific warm pool [*Anderson et al.*, 1996] where the rate of SST warming under positive Q_{net} can decrease with decreasing MLD.

[11] Although our calculations are subject to substantial uncertainty, they show that the magnitude of spring warming of SST is much smaller than expected mainly due to large solar penetration. Abrupt cooling and intraseasonal episodes of smaller than predicted dSST/dt (Figure 4) are due to vertical mixing and/or advection; the residual MAM cooling of the mixed layer is about −27 W m^{-2}. The contribution from upwelling due to local wind stress curl calculated from reanalysis winds is small (about −3 W m^{-2}). The effects of solar penetration, vertical mixing and advection on the Arabian Sea warm pool SST and subsurface temperature will be studied using more comprehensive data from ships and moorings [*ARMEX Science Plan*, 2001].

[12] **Acknowledgments.** This work was supported by the Department of Ocean Development, New Delhi. We thank the National Institute of Ocean Technology, Chennai for buoy data and Frank Wentz of Remote Sensing Systems, CA, USA for making the TMI data available on their site ftp://ftp.ssmi.com.

References

Anderson, S. P., R. A. Weller, and R. Lukas, Surface buoyancy forcing and the mixed layer of the western Pacific warm pool: Observations and 1D model results, *J. Climate*, *9*, 3056–3085, 1996.

ARMEX Science Plan, Arabian Sea Monsoon Experiment (ARMEX), Indian Climate Research Programme, August 2001, 72 pp. (available at http://caos.iisc.ernet.in).

Bradley, E. F., J. S. Godfrey, P. A. Coppin, and J. A. Butt, Observations of net heat flux into the surface mixed layer of the western equatorial Pacific Ocean, *J. Geophys. Res.*, *98*(C12), 22,521–22,532, 1993.

da Silva, A., C. Young, and S. Levitus, Atlas of surface marine data, Volume 1 and 2, NOAA, Department of Commerce, U.S., Washington D.C., 1994.

Dickey, T., J. Marra, D. E. Sigurdson, R. A. Weller, C. S. Kinkade, S. E. Zedler, J. D. Wiggert, and C. Langdon, Seasonal variability of bio-optical and physical properties in the Arabian Sea: October 1994-October 1995, *Deep Sea Res., Part II*, *45*, 2001–2025, 1998.

Grassl, H., V. Jost, J. Schulz, M. R. Ramesh Kumar, P. Bauer, P. Schluessel, The Hamburg ocean-atmosphere parameters and fluxes from satellite data (HOAPS): A climatological atlas of satellite-derived air-sea interaction parameters over the world oceans, Report No. 312, Max-Planck Institute for Meteorology, Hamburg, Germany, 130 pp., 2000.

Levitus, S., and T. Boyer, World Ocean Atlas, vol. 4, *Temperature*, NOAA Atlas NESDIS 4, U.S. Department of Commerce, Washington, D.C., 117 pp., 1994.

Lewis, M. R., M. E. Carr, G. C. Feldman, W. Esaias, and C. McLain, Satellite estimates of the influence of penetrating solar radiation on the heat budget of the equatorial Pacific Ocean, *Nature*, *347*, 543–545, 1990.

Li, T., Y. Zhang, C. P. Chang, and B. Wang, On the relationship between Indian Ocean sea surface temperature and Asian summer monsoon, *Geophys. Res. Lett.*, *28*, 2843–2846, 2001.

Li, Z., and H. G. Leighton, Global climatologies of solar radiation budgets at the surface and in the atmosphere from 5 years of ERBE data, *J. Geophys. Res.*, *98*(D3), 4919–4930, 1993.

Liebmann, B., and C. A. Smith, Description of a complete (interpolated) outgoing longwave radiation dataset, *Bull. Am. Meteor. Soc.*, *77*, 1275–1277, 1996.

Loschnigg, J., and P. J. Webster, A coupled ocean-atmosphere system of modulation for the Indian Ocean, *J. Climate*, *13*, 3342–3360, 2000.

Madhupratap, M., K. N. V. Nair, T. C. Gopalkrishnan, P. Haridas, K. K. C. Nair, and P. Venugopal, Arabian Sea oceanography and fisheries of the west coast of India, *Current Sci.*, *81*, 355–361, 2001.

Panofsky, H. A., and J. A. Dutton, Atmospheric Turbulence, John Wiley and Sons, New York, 397 pp., 1984.

Paulson, C. A., and J. J. Simpson, Irradiance measurements in the upper ocean, *J. Phys. Oceanogr.*, *7*, 952–956, 1977.

Senan, R., D. S. Anitha, and D. Sengupta, Validation of SST and wind speed from TRMM using north Indian Ocean moored buoy observations, CAOS Report 2001AS1, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, 30 pp., 2001. (available at http://caos.iisc.ernet.in/hpg/students/retish.html).

Sengupta, D., B. N. Goswami, and R. Senan, Coherent intraseasonal oscillations of ocean and atmosphere during the Asian summer monsoon, *Geophys. Res. Lett.*, *28*, 4127–4130, 2001.

Sengupta, D., and M. Ravichandran, Oscillations of Bay of Bengal sea surface temperature during the 1998 summer monsoon, *Geophys. Res. Lett.*, *28*, 2033–2036, 2001.

Shinoda, T., H. H. Hendon, and J. Glick, Intraseasonal variability of surface fluxes and sea surface temperature in the tropical western Pacific and Indian Ocean, *J. Climate*, *11*, 1685–1702, 1998.

Siegel, D. A., J. Ohlmann, L. Washburn, R. R. Bidigare, C. T. Nosse, E. Fields, and Y. Zhou, Solar radiation, phytoplankton pigments and radiant heating of the Equatorial Pacific, *J. Geophys. Res.*, *100*, 4885–4891, 1995.

Vinayachandran, P. N., and S. R. Shetye, The warm pool in the Indian Ocean, *Proc. Ind. Acad. Sci. (Earth Planet. Sci.)*, *100*, 165–175, 1990.

Webster, P. J., T. N. Palmer, V. O. Magana, J. Shukla, R. A. Tomas, T. M. Yanai, and A. Yasunari, Monsoons: Processes, predictability and the prospects for prediction, *J. Geophys. Res.*, *103*, 14,451–14,510, 1998.

Weller, R. A., A. S. Fischer, D. L. Rudnick, C. C. Erikson, T. D. Dickey, J. Marra, C. Fox, and R. Leben, Moored observations of upper ocean response to the monsoon in the Arabian Sea during 1994–1995, *Deep Sea Res.*, (to appear), 2002.

Yu, L., and M. Reinecker, Indian Ocean warming of 1997–1998, *J. Geophys. Res.*, *105*, 16,923–16,939, 2000.

D. Sengupta, P. K. Ray, and G. S. Bhat, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, 560012, India. (dsen@caos.iisc.ernet.in; pallav@caos.iisc.ernet.in; bhat@caos.iisc.ernet.in)