Warming of the Eurasian Landmass Is Making the Arabian Sea More Productive

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The recent trend of declining winter and spring snow cover over Eurasia is causing a land-ocean thermal gradient that is particularly favorable to stronger southwest (summer) monsoon winds. Since 1997, sea surface winds have been strengthening over the western Arabian Sea. This escalation in the intensity of summer monsoon winds, accompanied by enhanced upwelling and an increase of more than 350% in average summertime phytoplankton biomass along the coast and over 300% offshore, raises the possibility that the current warming trend of the Eurasian landmass is making the Arabian Sea more productive.

From 1994 to 1996, the multinational Joint Global Ocean Flux Study (JGOFS) expeditions to the Arabian Sea helped unravel several linkages between physical forcing and carbon cycling in the northern Arabian Sea, but these were mostly on seasonal and shorter time scales (7, 11, 12). Here we present results of rapid and profound interannual changes being experienced by the Arabian Sea and, furthermore, evidence that ascribes these changes to the warming trend and the declining wintertime snow cover over the Eurasian landmass.

In 1997, the tropical Indian Ocean experienced a dipole mode (IOD) event: a pattern of zonal (east-west) variability across the ocean, with anomalously low sea surface temperatures (SSTs) off Sumatra, high temperatures in the western Indian Ocean, and accompanying wind and precipitation anomalies (13, 14). This was also the year of one of the strongest El Niño events in recent history (15). Although uncertainty exists as to whether the dipole structure was triggered remotely by the El Niño event in the tropical Pacific or generated locally (16), SSTs along the entire western and central parts of the Arabian Sea were warmer than normal (17–19). Our analysis of a 7-year record of satellite ocean color data (20) from 1997, encompassing the period of the IOD event, revealed that concentrations of chlorophyll a in the coastal region of the western Arabian Sea (47°N to 55°E, 5° to 10°N) (fig. S1) were lower than normal during the summer upwelling season of 1997 (Fig. 1A). Although satellite chlorophyll data are not available for

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Fig. 1. Annual trends of (A) satellite-derived chlorophyll a data; (B) Reynolds blended (R&S, 1° × 1°) SSTs; and TMI (0.25° × 0.25°)–derived SSTs; and (C) wind stress curl values derived from NCEP-NCAR reanalysis data (open histograms) and TMI-derived wind speed for the region off the coast of Somalia (5° to 10°N and 47° to 55°E) in the western Arabian Sea. Positive wind stress curl values and lower SST values indicate upwelling, whereas negative wind stress curl values indicate downwelling. M, March; J, June; S, September; D, December.

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the entire summer monsoon period of 1997 because of the premature demise of the ADEOS-1 satellite (20), the low chlorophyll a concentrations are explainable given that sea surface wind stress in May and June, the primary driver of upwelling during the summer monsoon in the western Arabian Sea, was much weaker than normal (21). The timing of the onset and the intensities of sea surface winds are both critical to the development of the Findlater Jet, which in turn is responsible for coastal divergent upwelling off the Somali coast and offshore Ekman forced upwelling off the Omani continental shelf (3, 4). Coincident with the IOD event of 1997, sea surface winds (21) picked up only by June, almost a month later than in a normal year, followed by a peak in July that was short-lived. The impact on upwelling of the early collapse of the monsoon winds in the coastal region is clearly visible in the higher-than-normal SSTs (22) in June and July (Fig. 1B), an indicator of weaker upwelling that year.

In the time series record of chlorophyll a, however, the most conspicuous observation was the consistent year-by-year increase in phytoplankton biomass over the 7-year period (Fig. 1A). By the summer of 2003, chlorophyll a concentrations were >350% higher than those observed in the summer of 1997. The increase in chlorophyll a was accompanied by a year-by-year decline in summertime SSTs and cyclonic wind stress curl values (Fig. 1C) (23), both indicators of a progressive intensification of upwelling along the coast of Somalia resulting from a progressive strengthening of sea surface winds over the 7-year period (Fig. 1C). Upwelling off Somalia is also associated with the development of the Somali Current gyres, such as in the Great Whirl, where the vorticity balance forces an uplift of the thermocline to the left of the offshore flows (24, 25).

This year-by-year increase in chlorophyll a concentrations was not confined to the coast alone but was also observed over a wider area of the western (52° to 57°E, 5°S to 10°N) Arabian Sea (Fig. 2A). Outside the region of coastal upwelling, chlorophyll a concentrations in the summer of 2003 attained values that were >300% higher than those observed in the summer of 1997. This increase in chlorophyll a was also accompanied by an intensification of sea surface winds, in particular of the zonal (east-to-west) component (Fig. 2A). It is clear from the offshore observations that the influence of southwest monsoon winds on phytoplankton in the Arabian Sea is not through their impact on coastal upwelling alone but also via the ability of zonal winds to laterally advect newly upwelled nutrient-rich waters to regions away from the upwelling zone. When colder waters are advected offshore, they cause a reduction in the latent heat flux to the atmosphere and an increase in the net heat input into the oceans. Increased heat flux into the ocean stabilizes the water column, causing the mixed layer to shoal (26). Thus, although sea surface winds showed a progressive year-by-year increase after 1997, mixed layer depths during the summer monsoon shallowed progressively over the 7-year period (Fig. 2B). Increased water column stability during the summer monsoon associated with a shallower mixed layer is particularly crucial for retaining phytoplankton in the euphotic layer, especially when overcast skies and insufficient light can limit phytoplankton photosynthesis and growth (10, 11).

The summer monsoon winds are a coupled atmosphere-land-ocean phenomenon, whose strength is significantly correlated with tropical SSTs and Eurasian snow cover anomalies on a year-to-year basis (27, 28). The intensification of the winds across the Arabian Sea during the southwest monsoon is largely governed by the land-sea thermal gradient that develops over the Arabian Sea in late spring and early summer. Therefore, the extent of winter and spring snow cover over the Eurasian landmass and the latent heat released by the sea during spring have a major impact on this land-sea thermal gradient (29). In general, positive snow anomalies in winter and spring can give rise to colder ground temperatures in the subsequent summer, because a substantial fraction of the available solar energy during spring and early summer goes toward melting the snow and evaporating water from the wet soil rather than toward heating the ground (30). Excessive snowfall in the early part of winter also tends to reduce solar radiation heating in winter by increasing the surface albedo, resulting in persistently colder temperatures over the land (31). Conversely, reduced snow cover over Eurasia strengthens the spring and summer land-sea thermal contrast and is considered to be responsible for the stronger southwest monsoon winds and positive rainfall anomalies over the subcontinent (32, 33).

Analysis of snow cover data (34) for the period beginning in 1997 revealed a progressive decline of winter and spring snow cover over the Eurasian landmass (Fig. 2C), which is consistent with the mid-latitude continental warming trend reported in the Northern Hemisphere (33). Since 1979, the decline in snow cover has been particularly pronounced over northern Eurasia poleward of 70°N, over Western Europe, to the northeast of Russia, over southwest Asia, and over the northern Indian Himalayan Tibetan Plateau region (fig. S2). Of greatest relevance to the strength of the

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**Fig. 2.** Annual trends of (A) satellite-derived chlorophyll a data (CHL) and zonal wind stress and (B) mixed layer depth (MLD) and Reynolds SSTs from the region (52° to 57°E, 5°S to 10°N) in the western Arabian Sea. (C) Anomalies (departures from monthly means for the period between 1996 and 2002) of Eurasian snow cover (ESC). The trend line shown in bold is a 14-point moving average.
southwest monsoon winds are the latter two regions, on account of their proximity to the Arabian Sea. A plot of Eurasian snow cover extent versus wind stress data (Fig. 3A) and wind stress versus SST (Fig. 3B) for the period from late spring to midsummer (May–July) suggests that the year-by-year decline in winter and spring snow cover over Eurasia is creating conditions that are conducive to stronger winds and lower summertime SSTs across the western Arabian Sea. By regressing SST against satellite-derived chlorophyll a concentrations over this region for the summer season (Fig. 3C), we conclude that the escalating strengths of sea surface winds is largely responsible for the increase in phytoplankton biomass in the western Arabian Sea over the past 7 years. The fact that disparate satellite-derived and observational data sets of SSTs and winds come together to fit into a physically consistent scenario gives us a great deal of confidence in our results.

Our findings raise the intriguing possibility that the western as well as the central regions of the Arabian Sea could witness more widespread blooms of phytoplankton if the mid-latitude continental warming trend and the decline in winter snow cover over the Northern Hemisphere continue. Although our findings have an immediate and important bearing on regional fisheries, the implications of a more productive Arabian Sea go far beyond that; for example, to our planet’s climate. The Arabian Sea hosts a distinct, basin-wide oxygen minimum zone between 150 and 1000 m (35–37), whose presence has a substantial impact on marine elemental cycles, in particular those linked to the production of climatically relevant trace gases (37). The changing productivity of the Arabian Sea could thus have far-reaching consequences for the oxygen minimum zone, whose existence is regulated by a balance between the ventilation of intermediate depths and oxygen consumption during the oxidation of organic matter produced in the euphotic column (36, 37).

Fig. 3. Scatter plots of (A) resultant wind stress and Eurasian snow cover for May to July; (B) SSTs and resultant wind stress for May to July; and (C) satellite-derived chlorophyll a data and SSTs for May to September. Oceanographic data are for the region (52° to 57°E, 5°S to 10°N), and Eurasian snow cover is from the Northern Hemisphere EASE grid. Linear least-squares fits to scatter plots yielded $r^2$ values of 0.84, 0.66, and 0.70 ($P < 0.01$) for (A), (B), and (C), respectively.

References and Notes
3. F. Schott, Prog. Oceanogr. 12, 357 (1983).
20. Chlorophyll a data from November 1996 to June 1997 are reprocessed (V4.1). Level 3–binned, ADEOS-1, Ocean Color Temperature Sensor (OCTS) monthly data obtained from the Earth Observation Center, National Space Development Agency (NASA) of Japan. For the period from September 1997 to April 2004, we used reprocessed Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (V4.1) Level 2 Global Area Coverage, monthly images from the Disturbed Active Archive Center of the Goddard Space Flight Center, NASA, USA. These monthly binned products have been corrected for atmospheric light scattering and for sun angles differing from the nadir. In addition, the influence of clouds has been substantially reduced. To account for sensor degradation over time, the instrument is calibrated using internal lamps, solar diffuser observations, and lunar images, as well as vicarious methods.
21. The wind data used in this study come from two sources: the Tropical Rainfall Measurement Mission Imager (TMI) derived monthly SSTs on a 0.25° × 0.25° grid) and the monthly mean surface wind stresses ($u^*$, $v^*$) from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCPE-NCAR) reanalysis product, calculated according to E. Kalnay et al. (38).
22. Monthly mean SSTs were obtained from two sources: the optimally interpolated ($1° × 1°$ grid) Reynolds reanalysis product, which is a blend of Advanced High Resolution Radiometer and Comprehensive Ocean-Atmosphere Data Set observations [see (39)]; and TMI, available from January 1998 onward. These data are processed by the Remote Sensing Systems algorithm and mapped to a 0.25° × 0.25° grid.
23. The curl of the wind stress is calculated as $\partial v/\partial x - \partial u/\partial y$, where $\tau$ and $\sigma$ are the zonal and meridional wind stress, respectively.
26. The mixed layer depth was taken as the depth at which the temperature declined to 1°C below SST, using Expandable Bathymthermograph (XBT) data optimally interpolated to a 5° × 2° longitude-latitude grid from the Joint Environmental Data Analysis Center (40).
34. Snow cover extents from 1979 onward were obtained from the National Snow and Ice Data Center's CD-ROM of Northern Hemisphere EASE-Grid weekly snow cover and from ice extent data sets of R. L. Armstrong and M. J. Brodzik (available at http://nsidc.org/data/snow.html).
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