SHRINKING SNOWCAPS & RISING PRODUCTIVITY: RESPONSE OF THE ARABIAN SEA ECOSYSTEM TO RECENT CLIMATE CHANGE

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ACKNOWLEDGEMENTS

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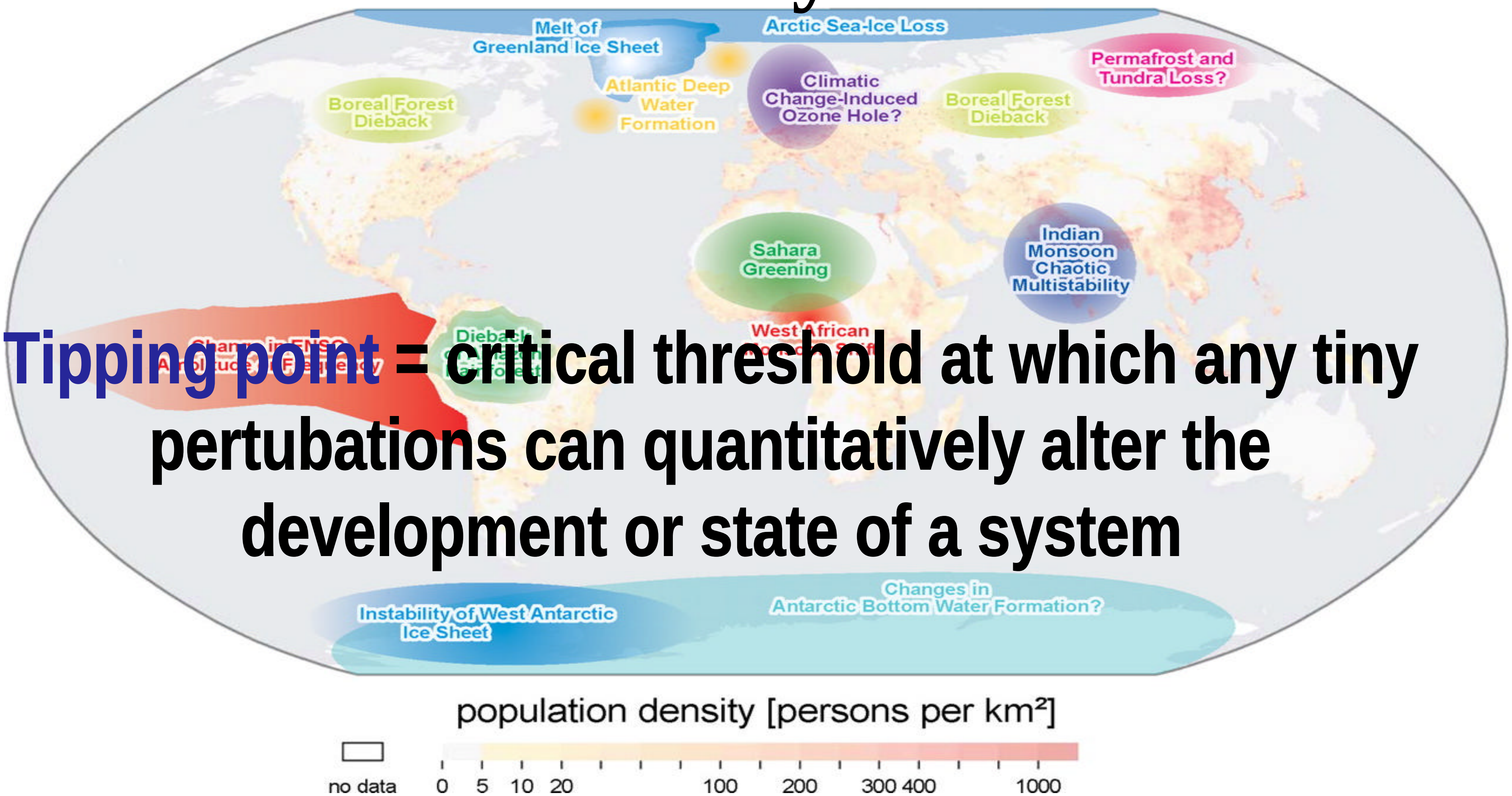
Why should we care about the Arabian Sea?

Tipping elements in the Earth's climate system



Tipping point = critical threshold at which any tiny pertubations can quantitatively alter the development or state of a system

Tipping element = changes within the political horizon, significant population impact, policy relevant

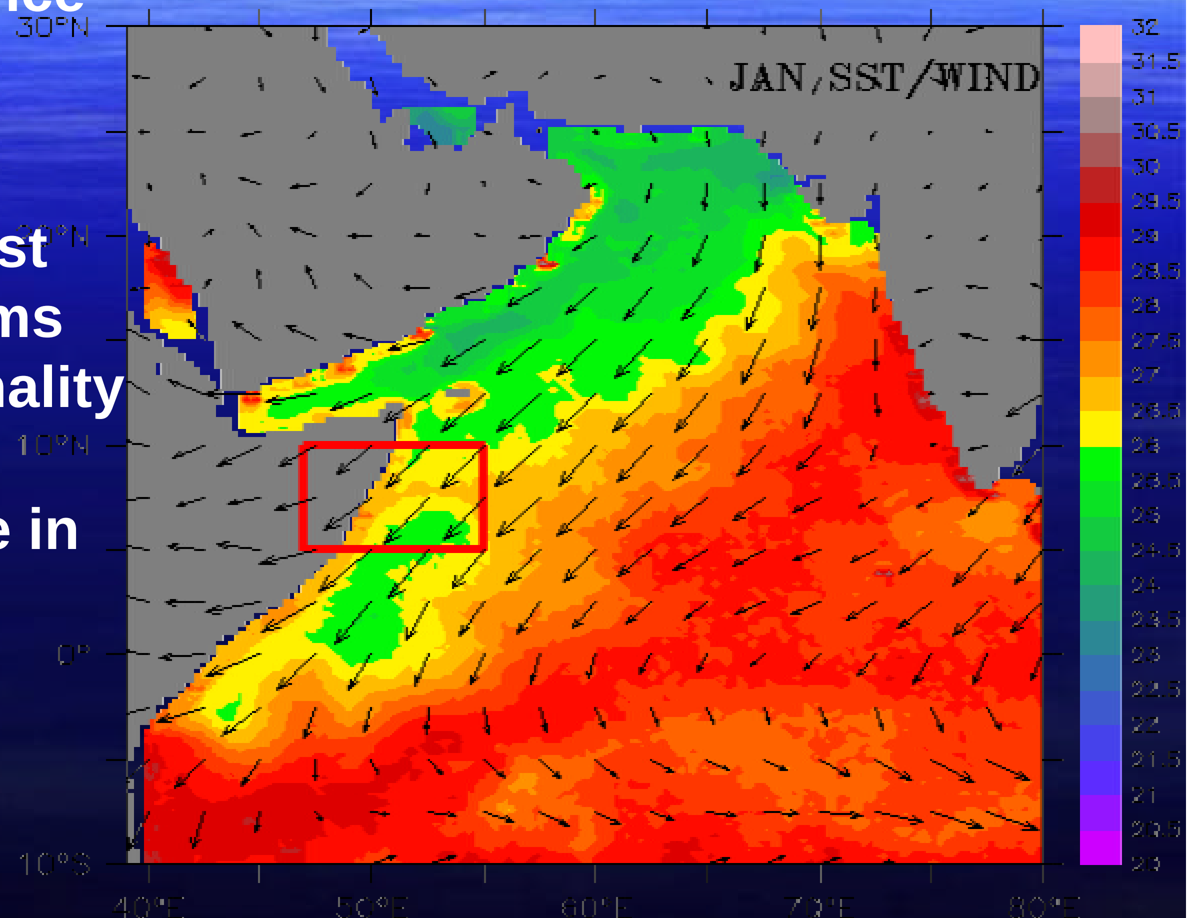
Lenton et al. 2008. PNAS. 155:1786-1793

ARABIAN SEA - A UNIQUE ECOSYSTEM

Comes under the influence of seasonally reversing monsoon winds

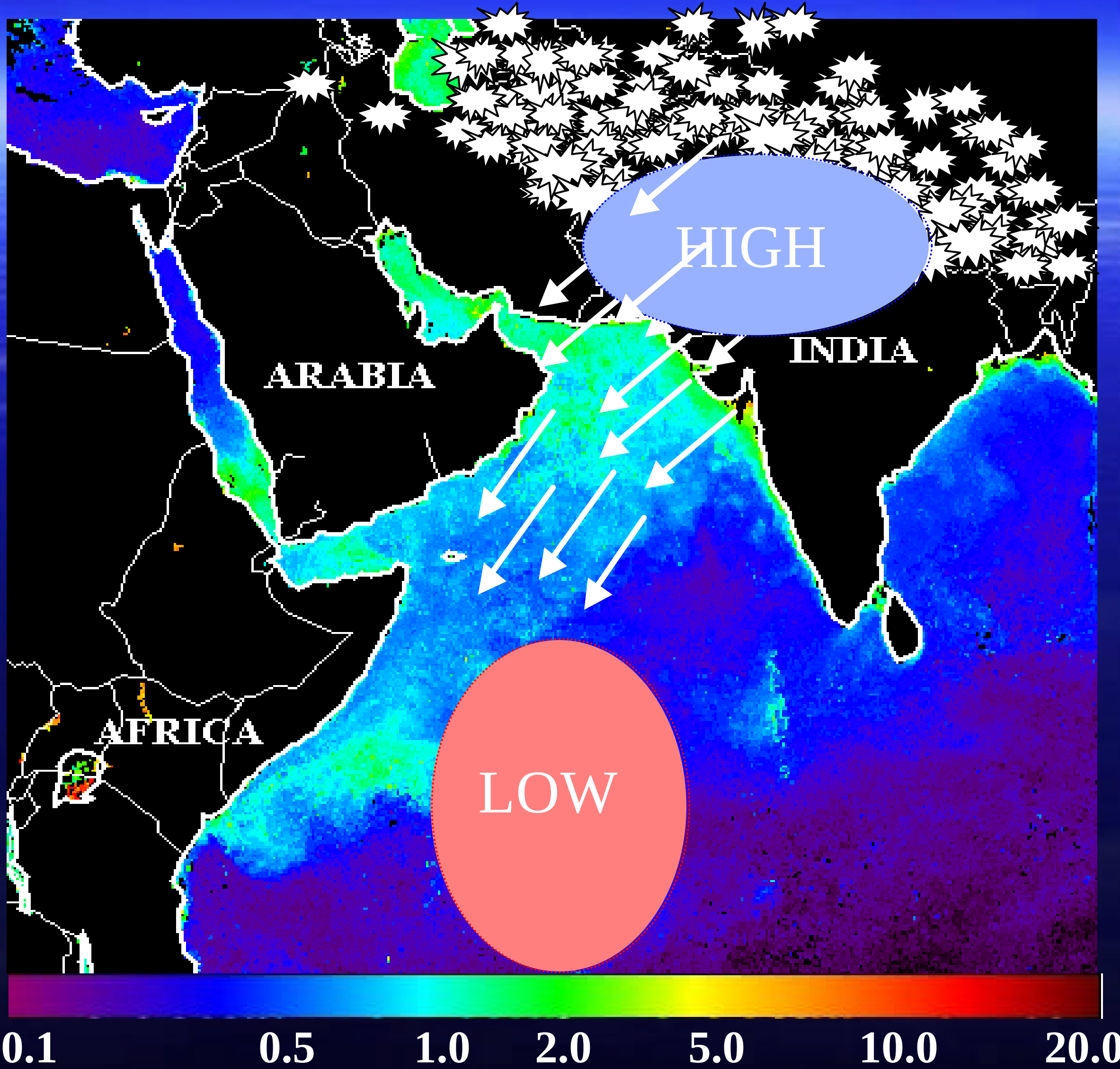
Winds drive one the most energetic current systems and the greatest seasonality in phytoplankton productivity observable in all oceans

Development and intensity regulated by thermal gradient between land and sea

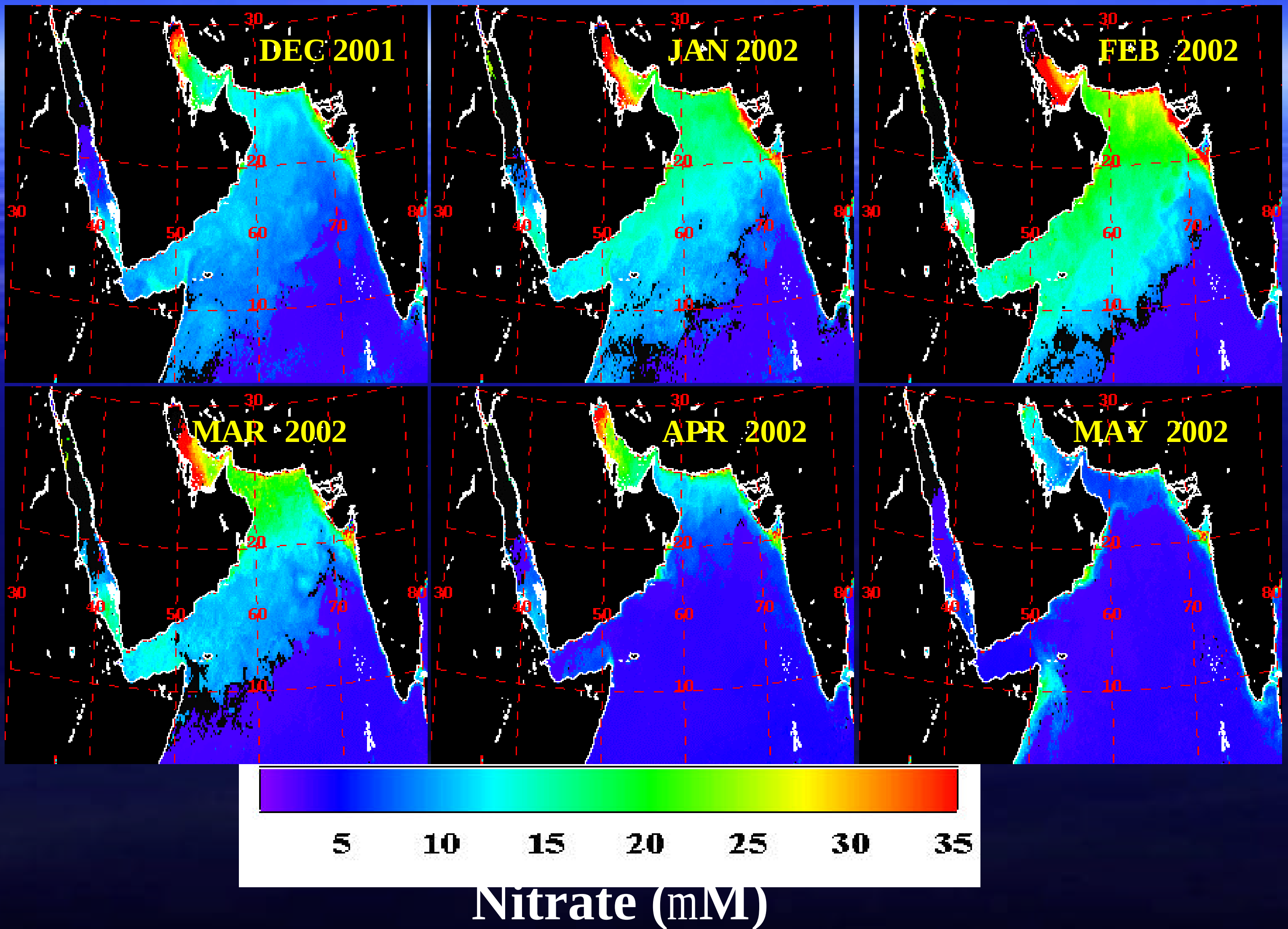


Between 1992-1996, the US spent ~$50M on the Arabian Sea JGOFS

WINTER MONSOON

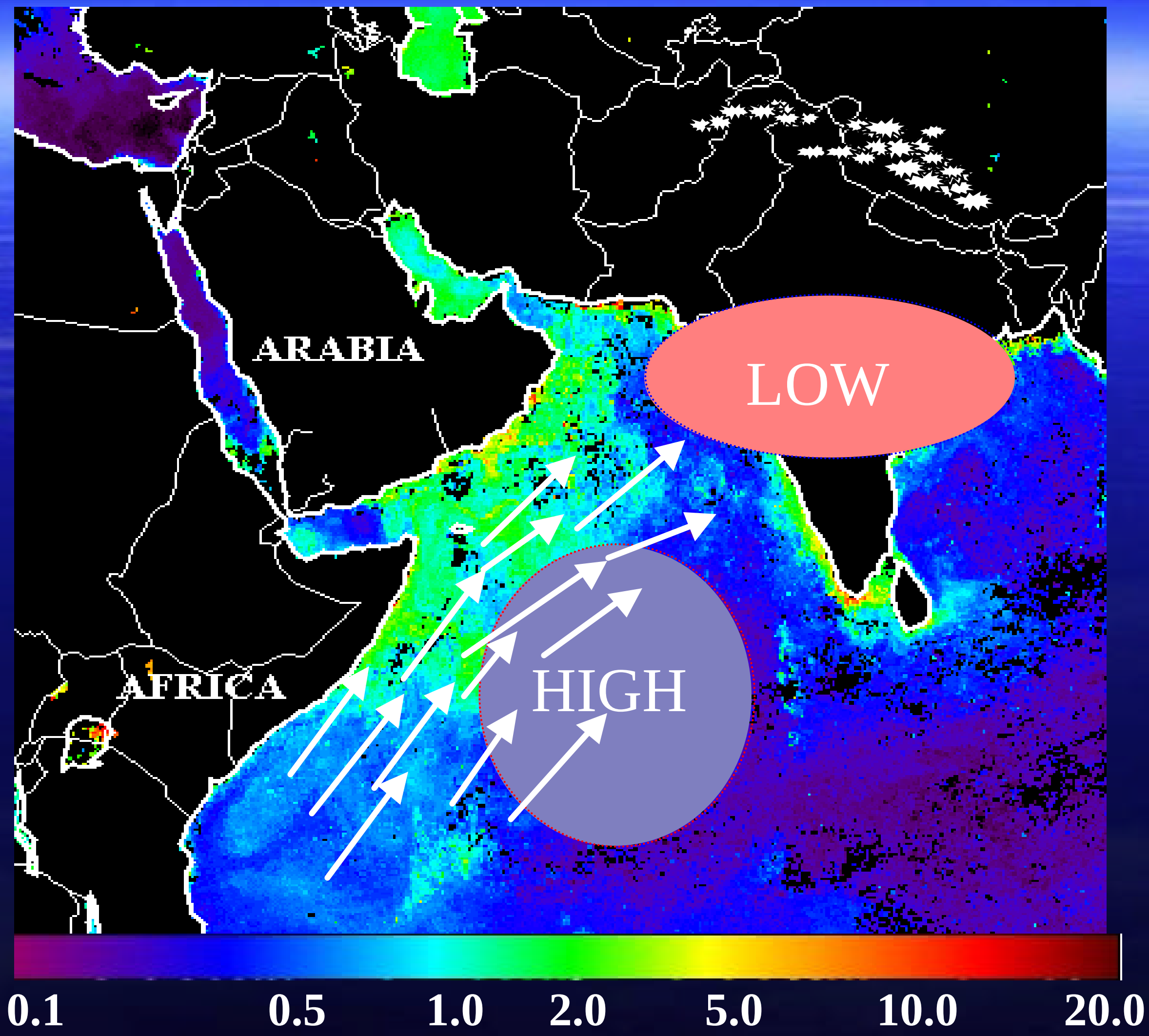


Schematic showing snow cover extent and wind direction superimposed on an ocean color chlorophyll image for the northeast monsoon season (Nov-Feb).

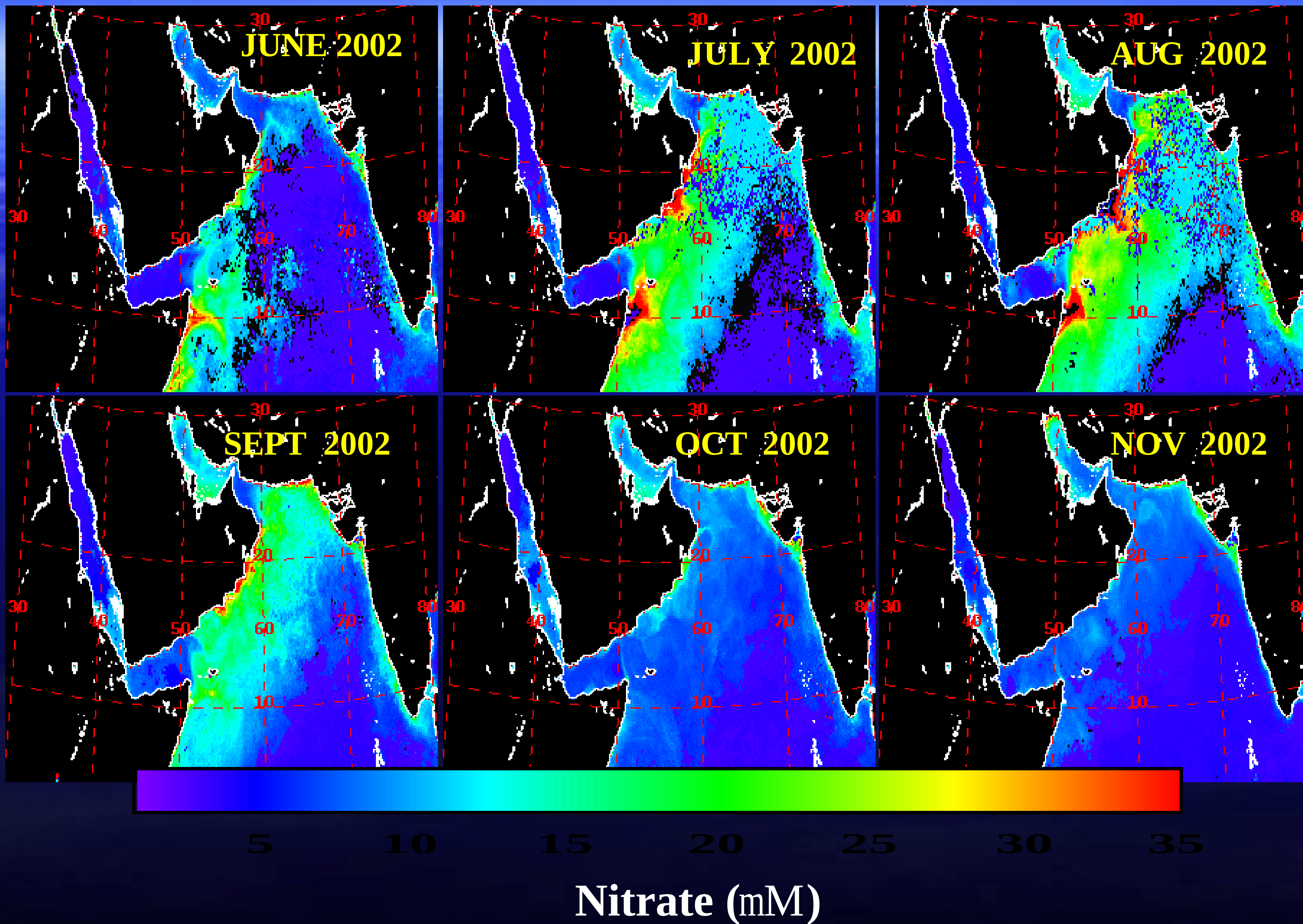


NITRATE INPUTS IN THE ARABIAN SEA DUE TO WINTER CONVECTIVE MIXING DURING NORTHEAST MONSOON

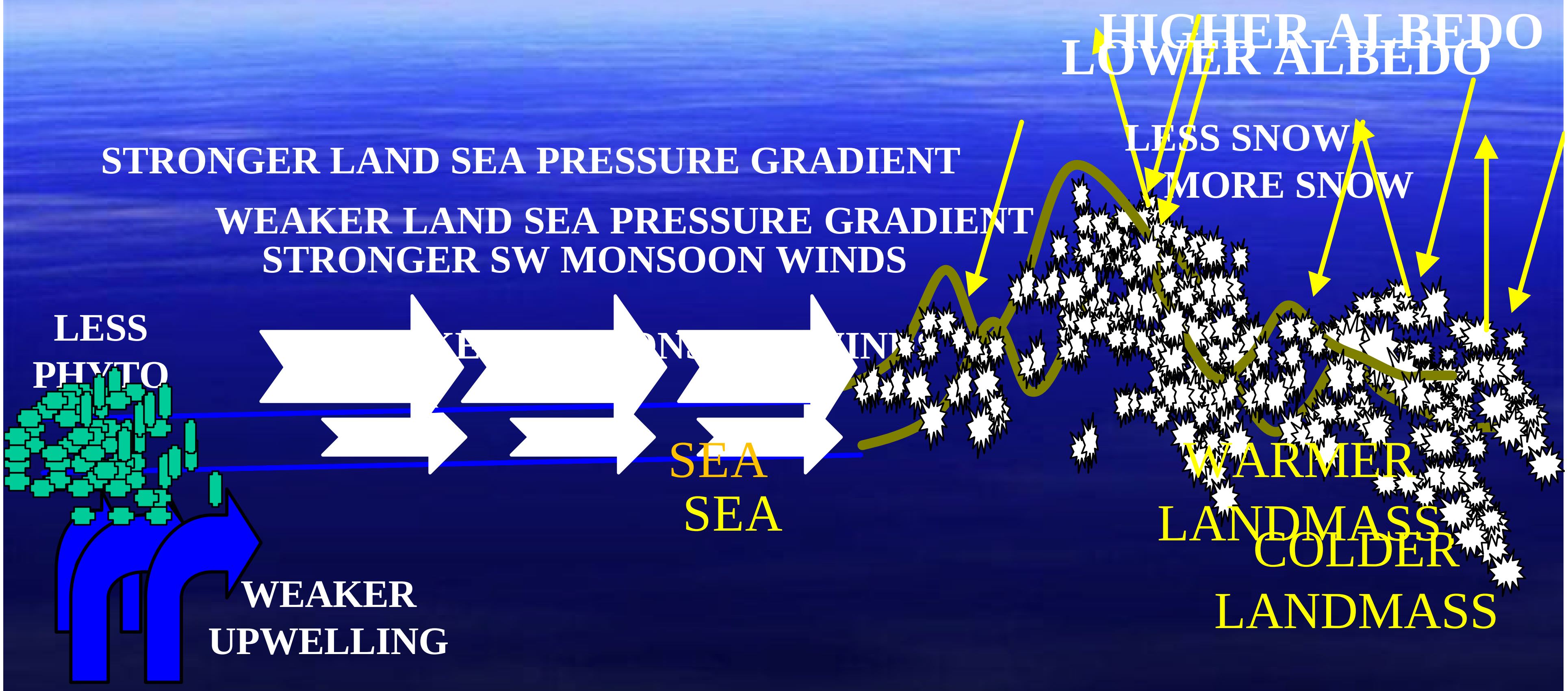
SUMMER MONSOON



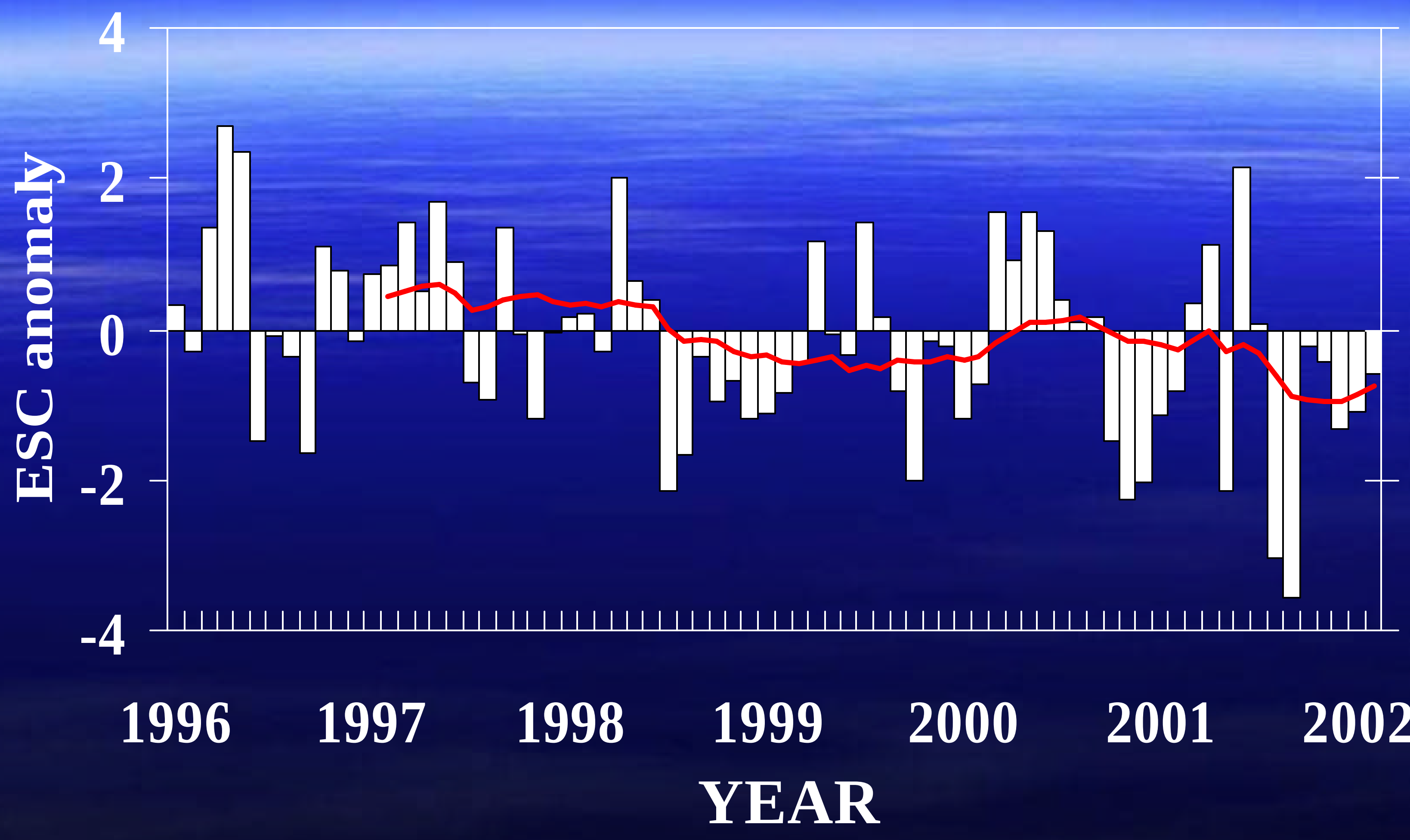
Schematic showing the reversal in wind direction during the southwest monsoon (Jun-Sept), superimposed on satellite derived chlorophyll fields



NITRATE INPUT DUE TO UPWELLING DURING THE SOUTHWEST MONSOON

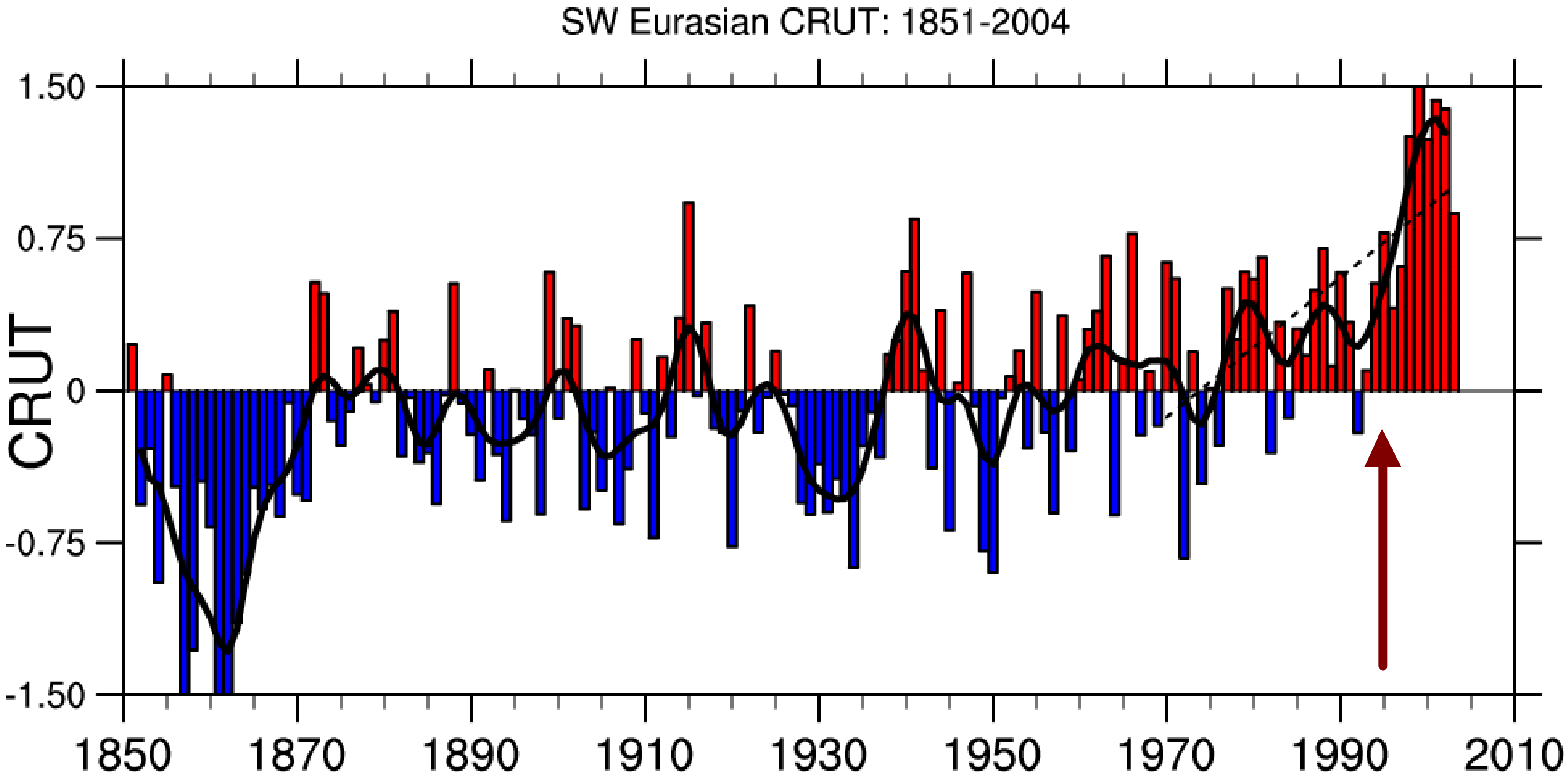


Schematic showing the SW Monsoon response of the Arabian Sea to snow cover over the Himalayan-Tibetan Plateau



Anomalies (departures from monthly means for period between 1996-2002) of Eurasian Snow Cover (x10^6 km^2). Trend line shown in bold is 14 point moving average.

SW Eurasian-Land Warming

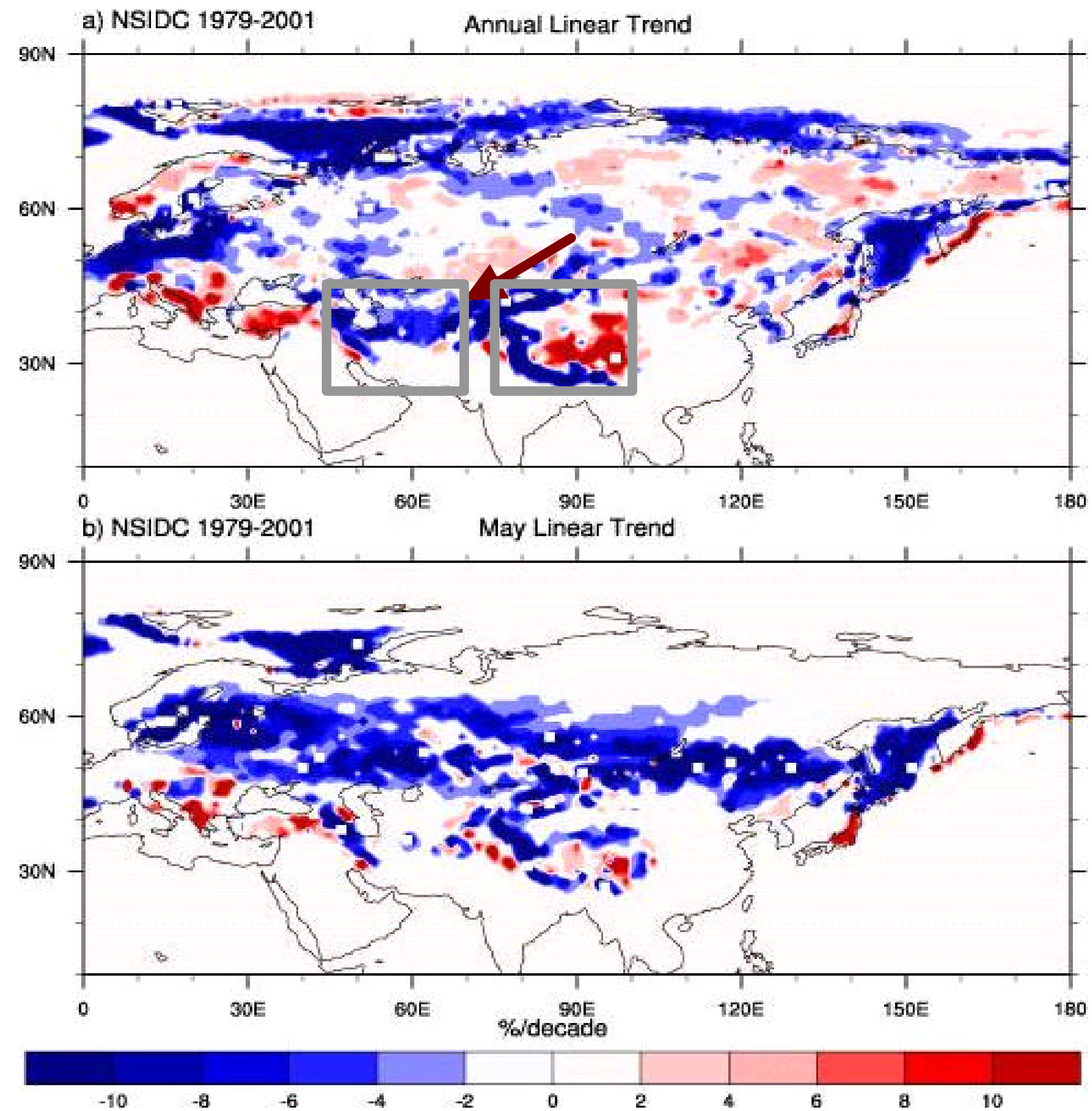


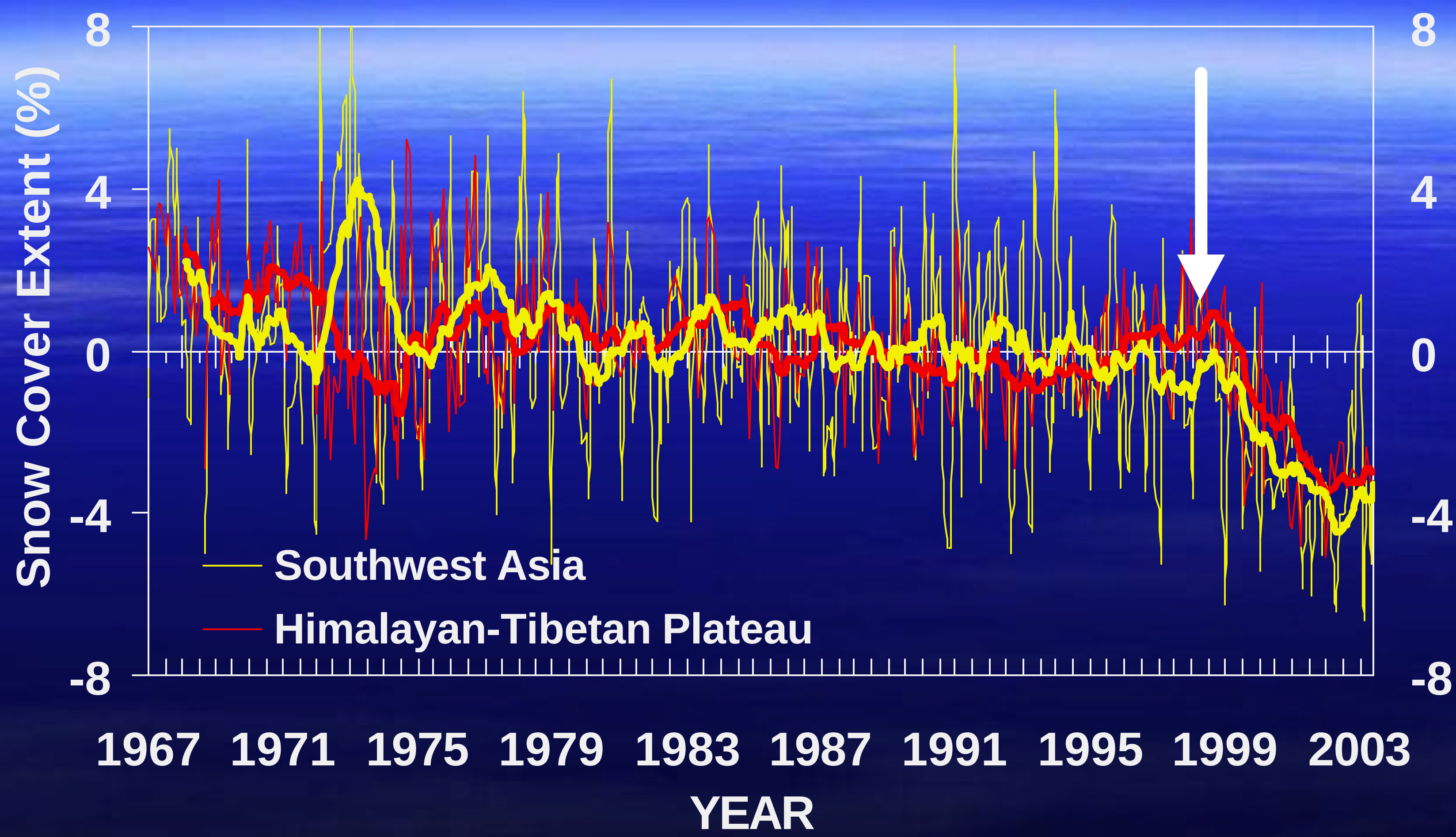
Warming of SW Eurasia mirrors the global-land signal, but recent warming anomalies are >50% larger than global temperature trends.

NSIDC SNOW COVER TRENDS

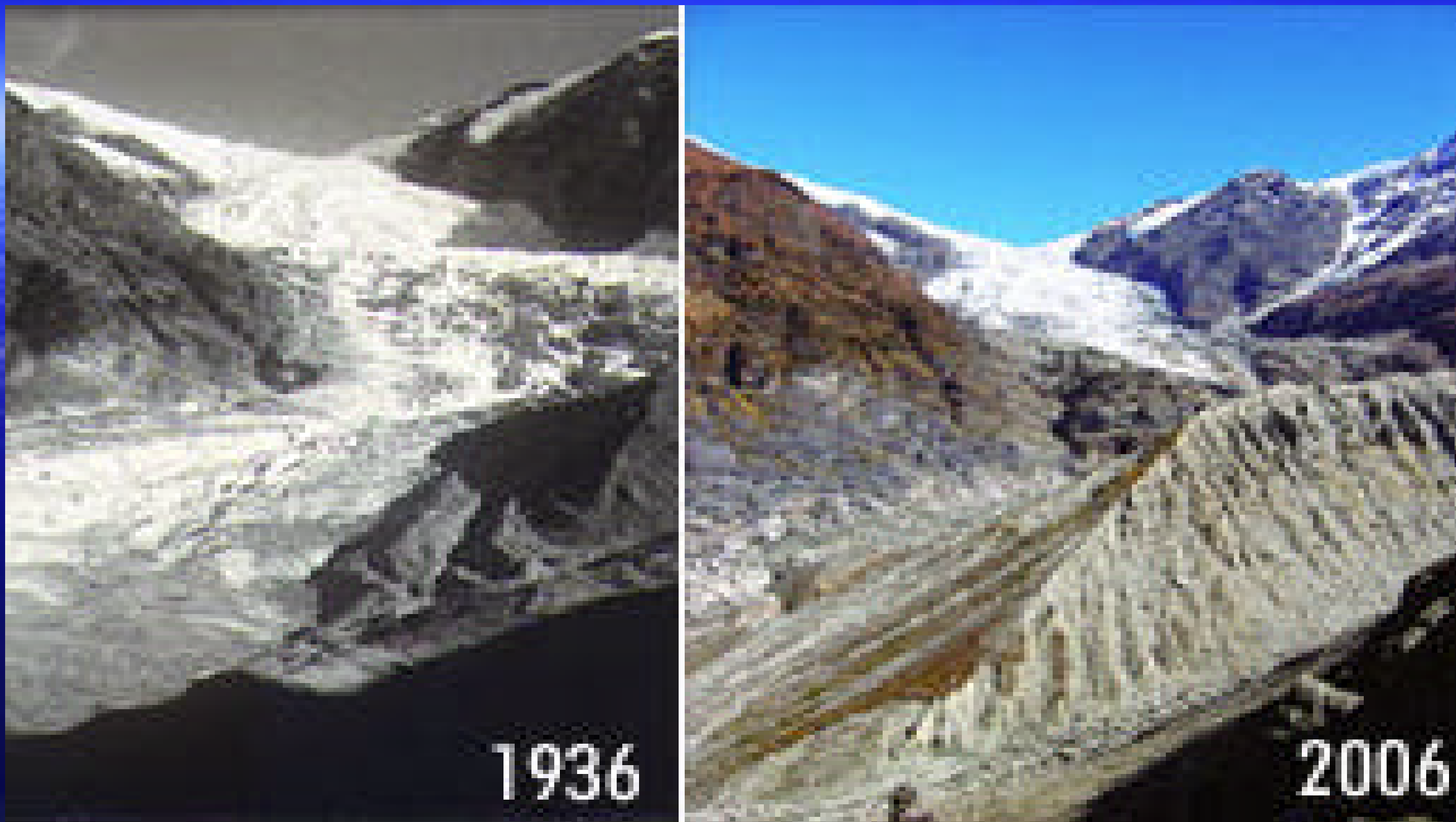
Annual snow cover trends suggest a marked decrease in snow accumulation north of the Arabian Sea.

May snow cover trends are largely negative all over Eurasia reflecting an earlier and stronger spring melt-off.

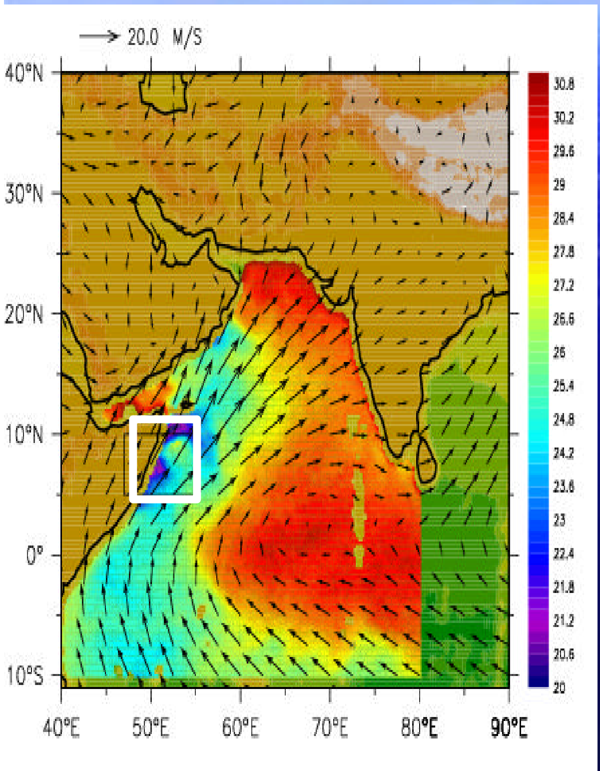


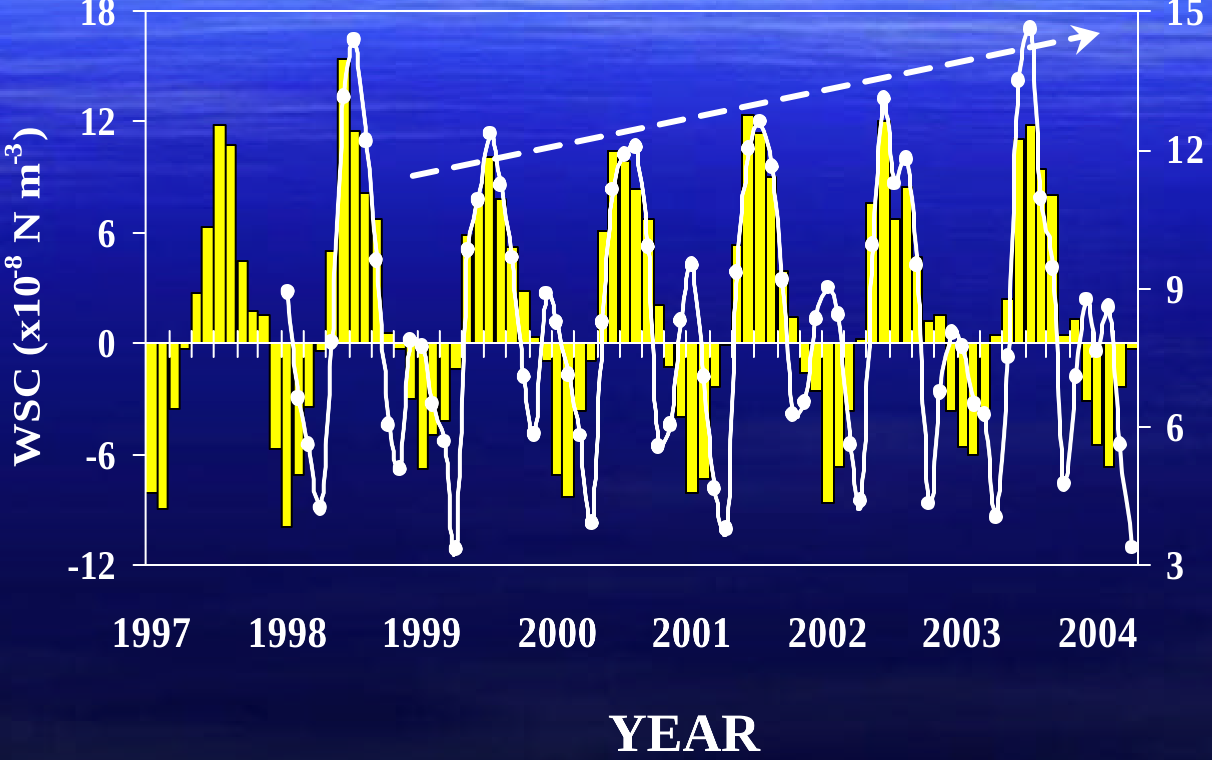


Trend line showing anomalies (departures from monthly means) of snow cover extent over Southwest Asia and Himalayas-Tibetan Plateau between 1967 and 2003.



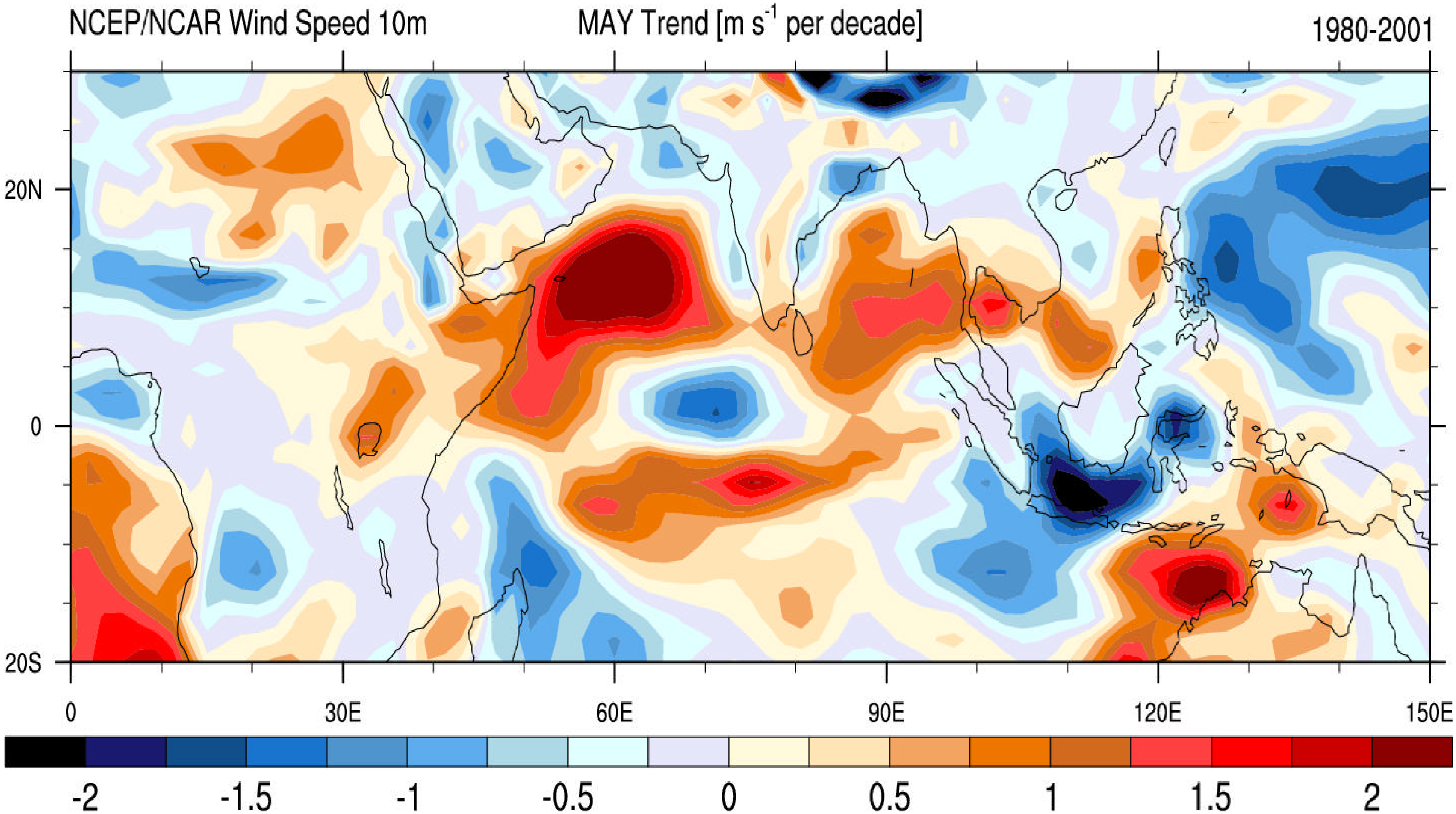
70 years of global warming: Photograph of the Pindari glacier in the Himalayas taken on October 7, 1936, by then Deputy Conservator of Forests F W Champion. 70 years later at the exact spot, his grandson James Champion photographed the same glacier. (Source Sunday Indian Express, 29th Dec. 2006).

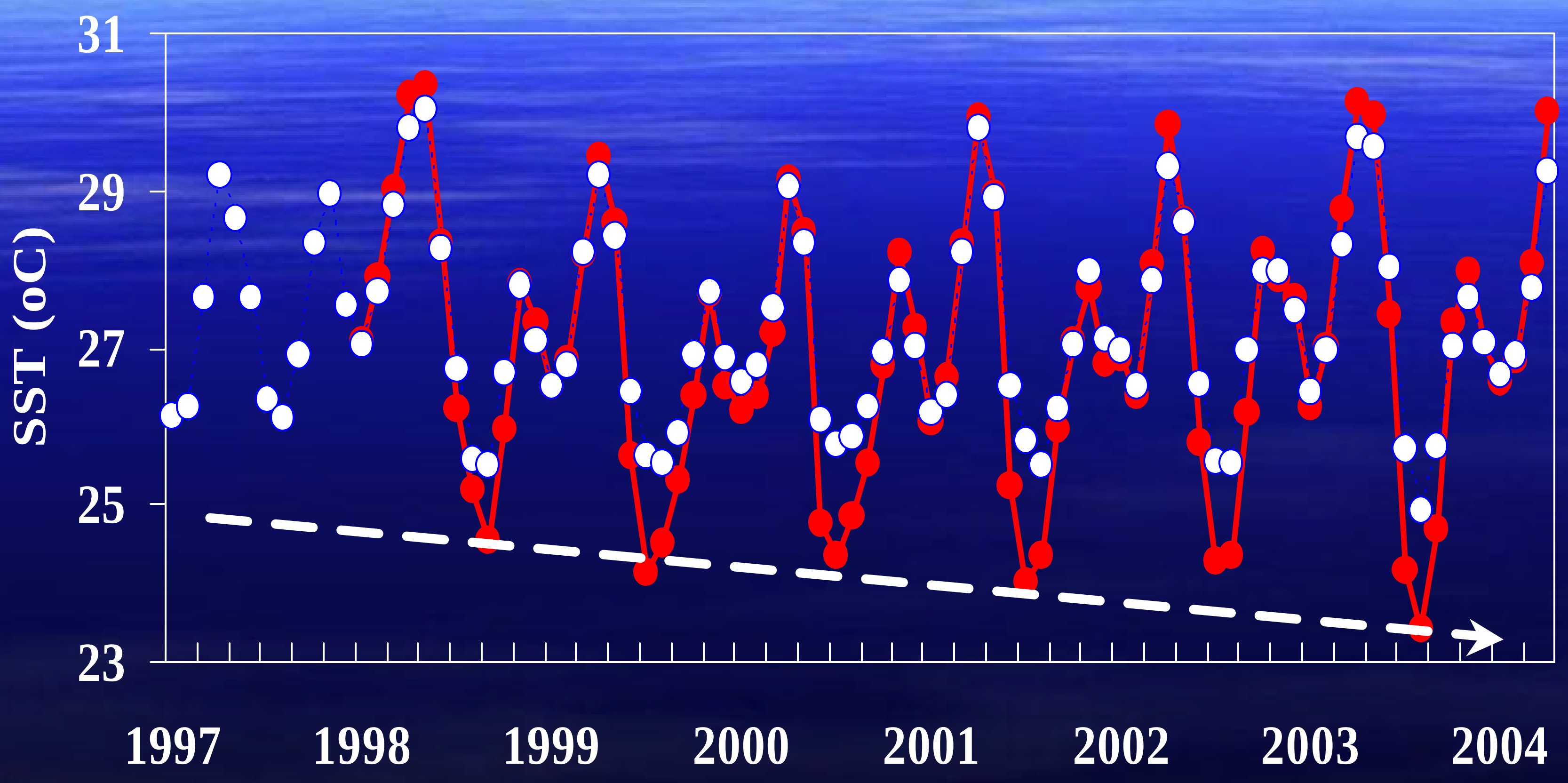




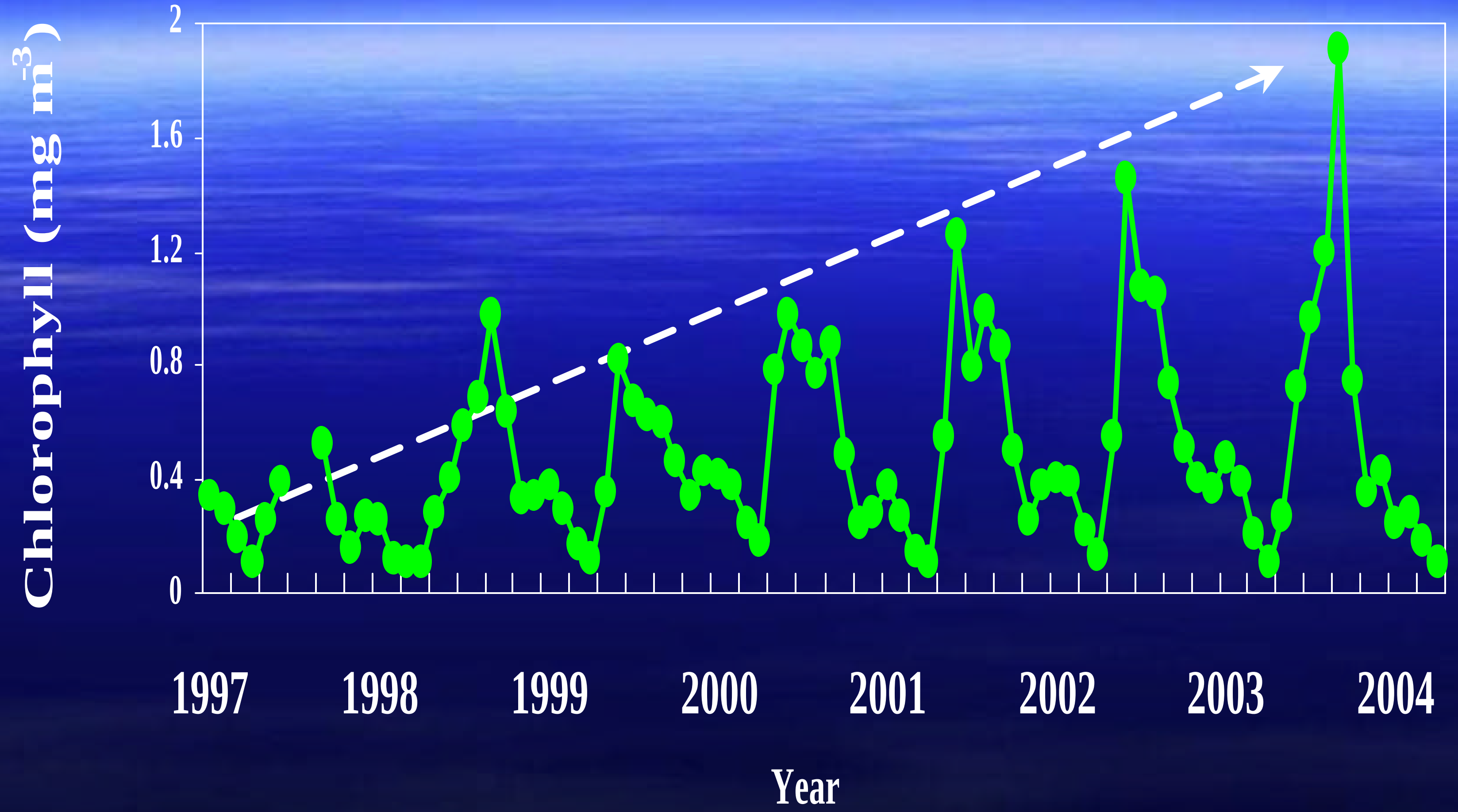
Left Panel - TMI derived SST in the Arabian Sea showing upwelling and offshore advection of cooler upwelled waters during the SW monsoon (July) of 2003. Arrows indicate wind vectors for the same month. Right panel – Interannual variability of Wind Speed and Wind Stress Curl.

WIND SPEED TRENDS (1980-2007)
NCEP/NCAR

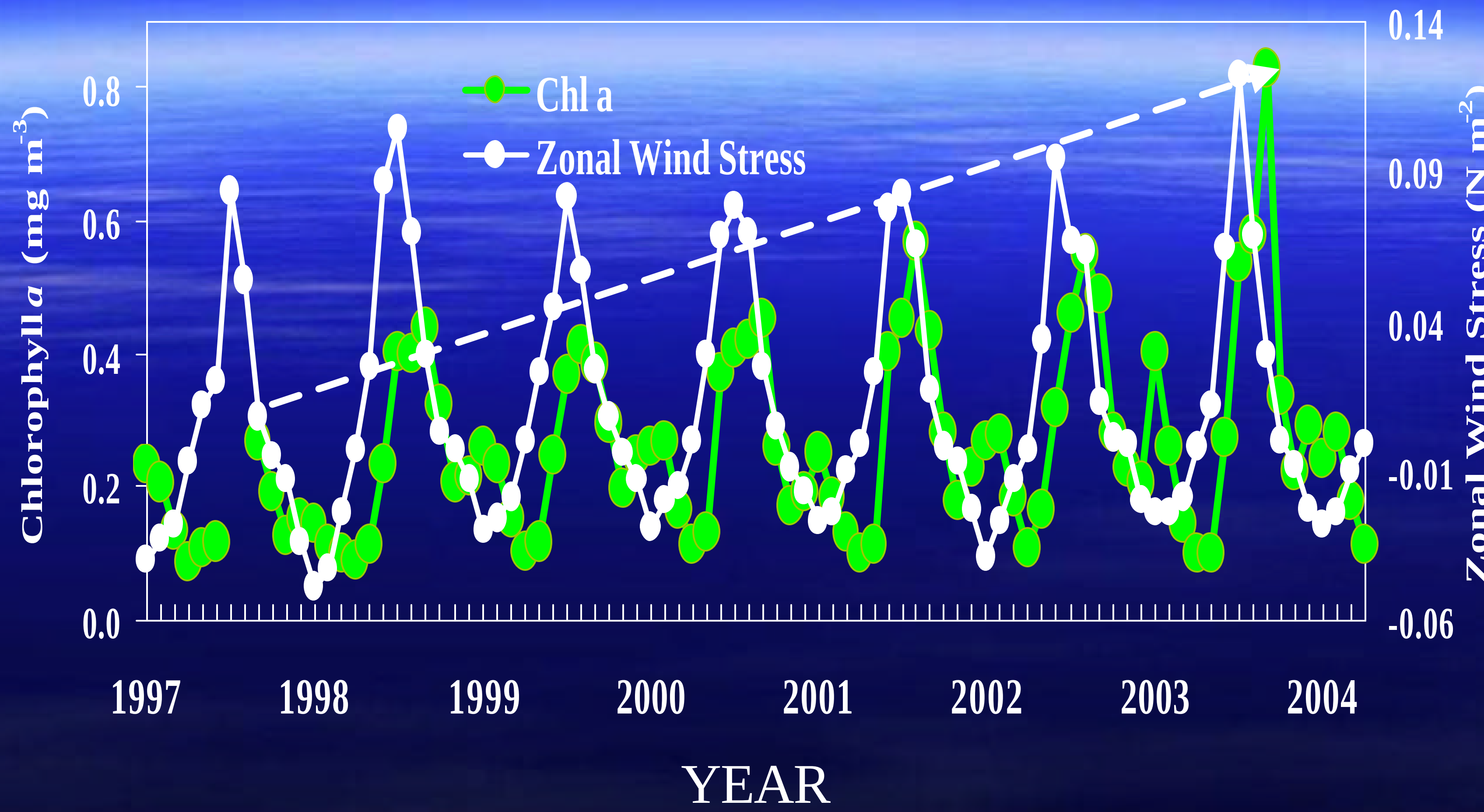




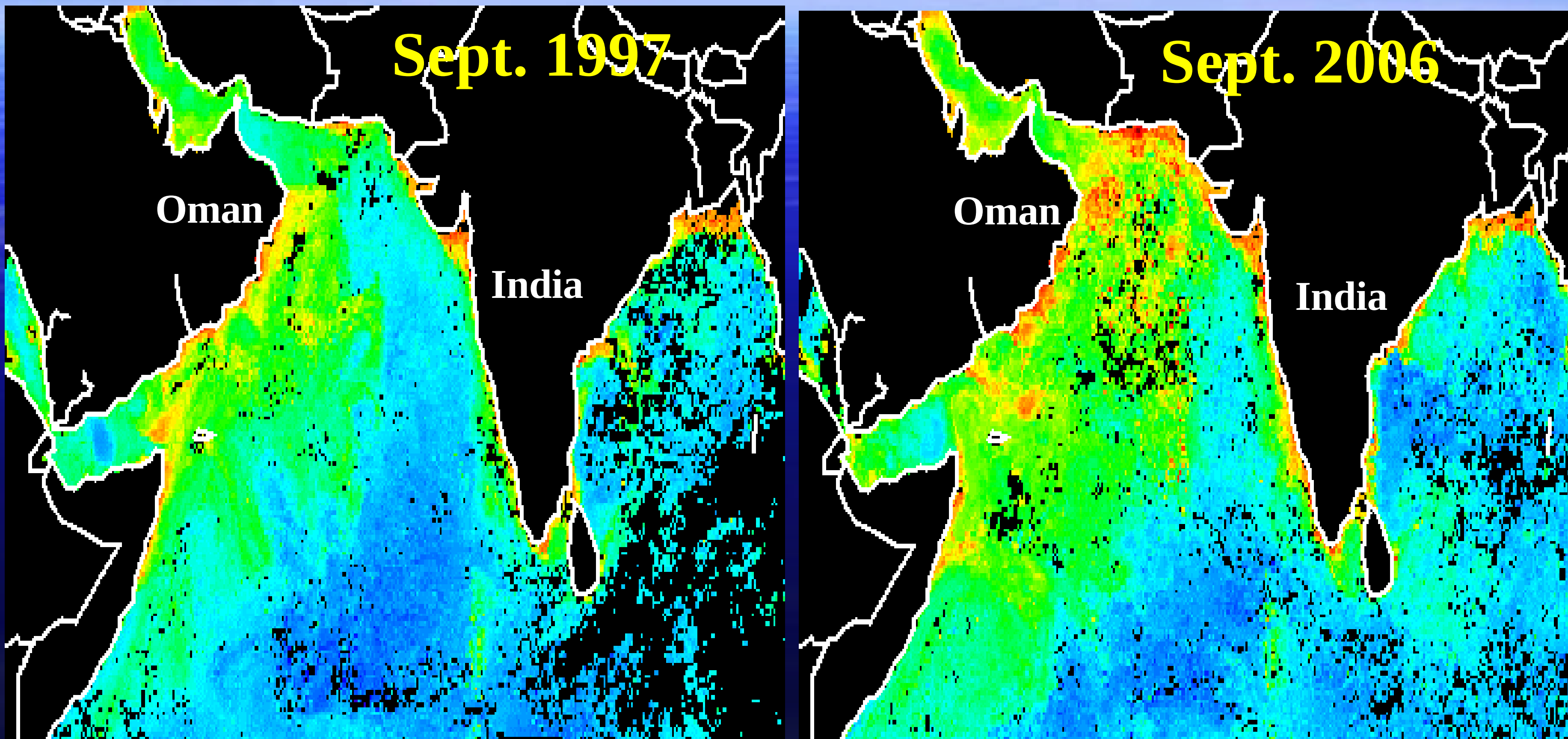
Interannual variability in SST along the coast of Somalia



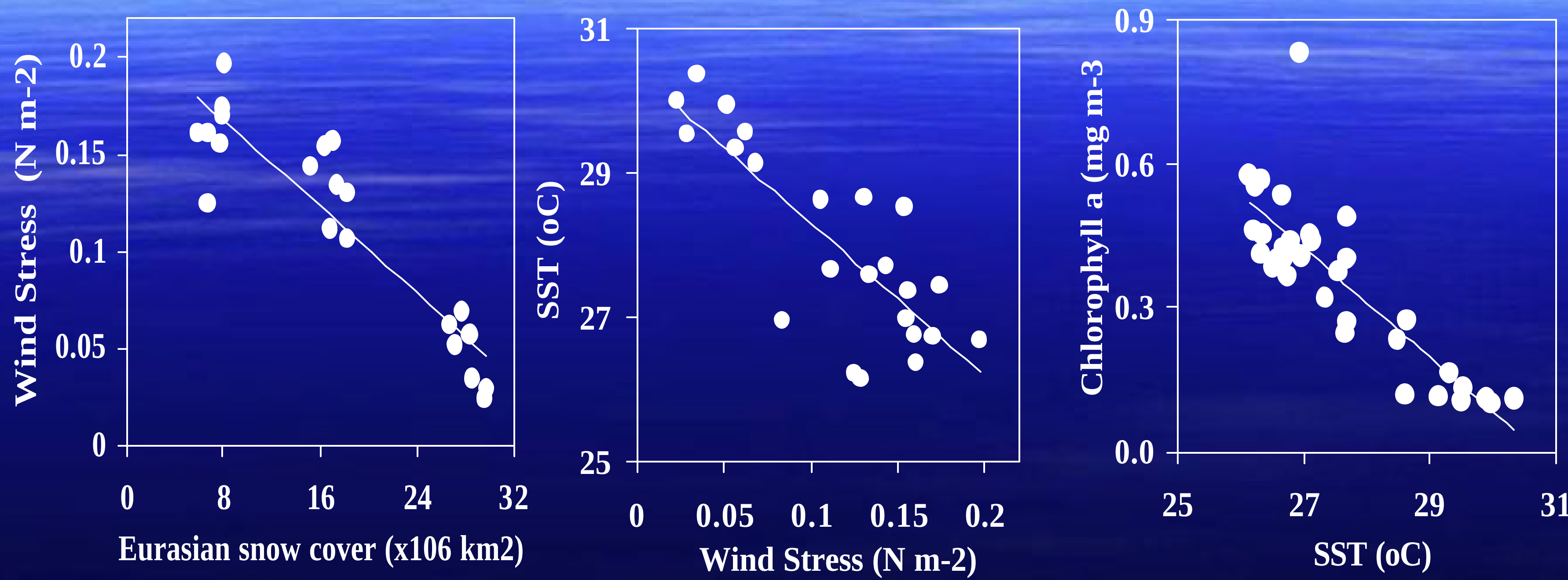
Interannual changes in chlorophyll along coast of Somalia since 1997



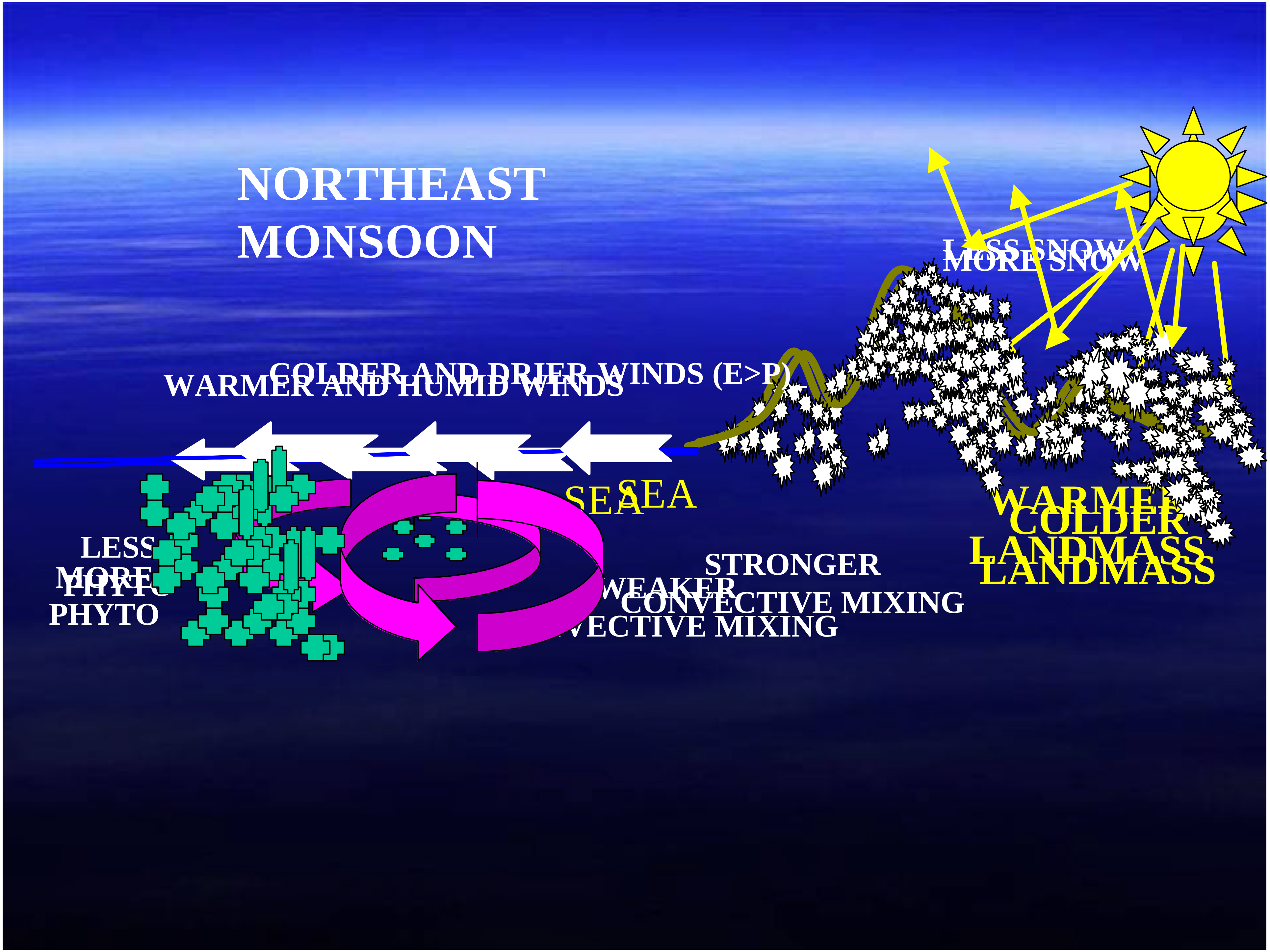
Annual trends of satellite derived chlorophyll *a* and zonal wind stress in the offshore western Arabian Sea.

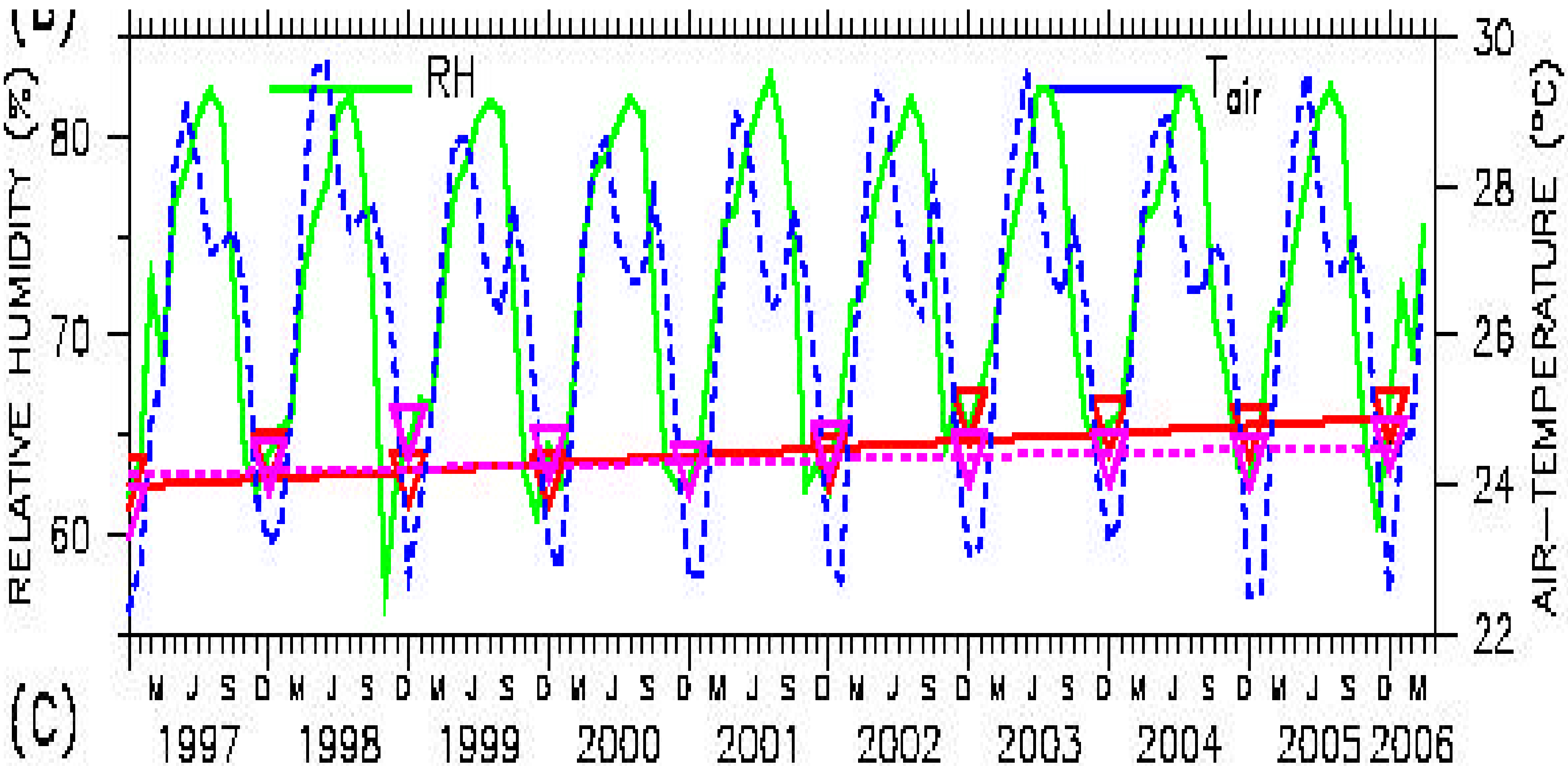


SeaWiFS derived chlorophyll fields during the peak southwest monsoon growth season of 1997 and 2006

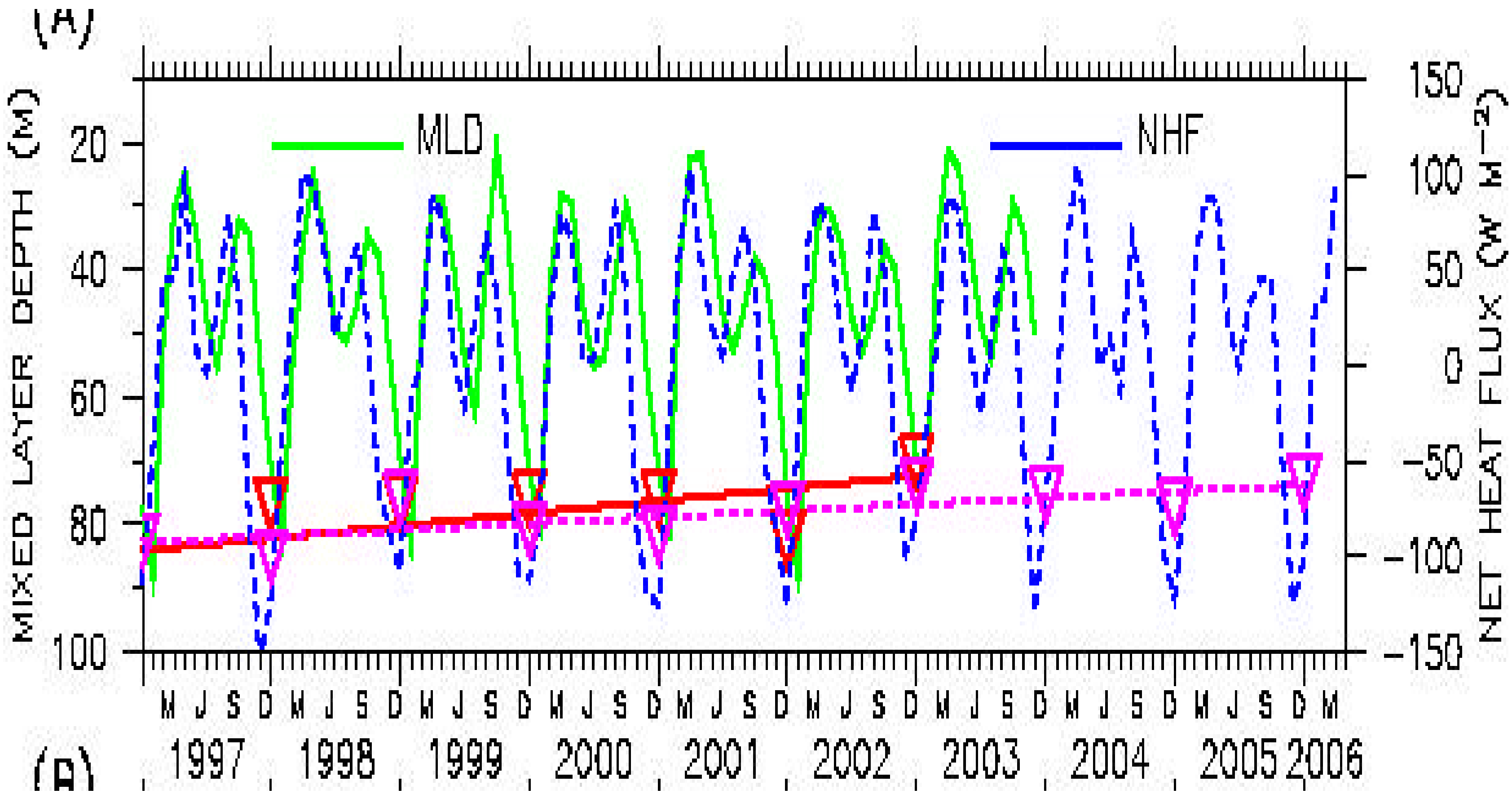


Scatter plots showing the impact of the decline in Eurasian snow on phytoplankton in the Arabian Sea

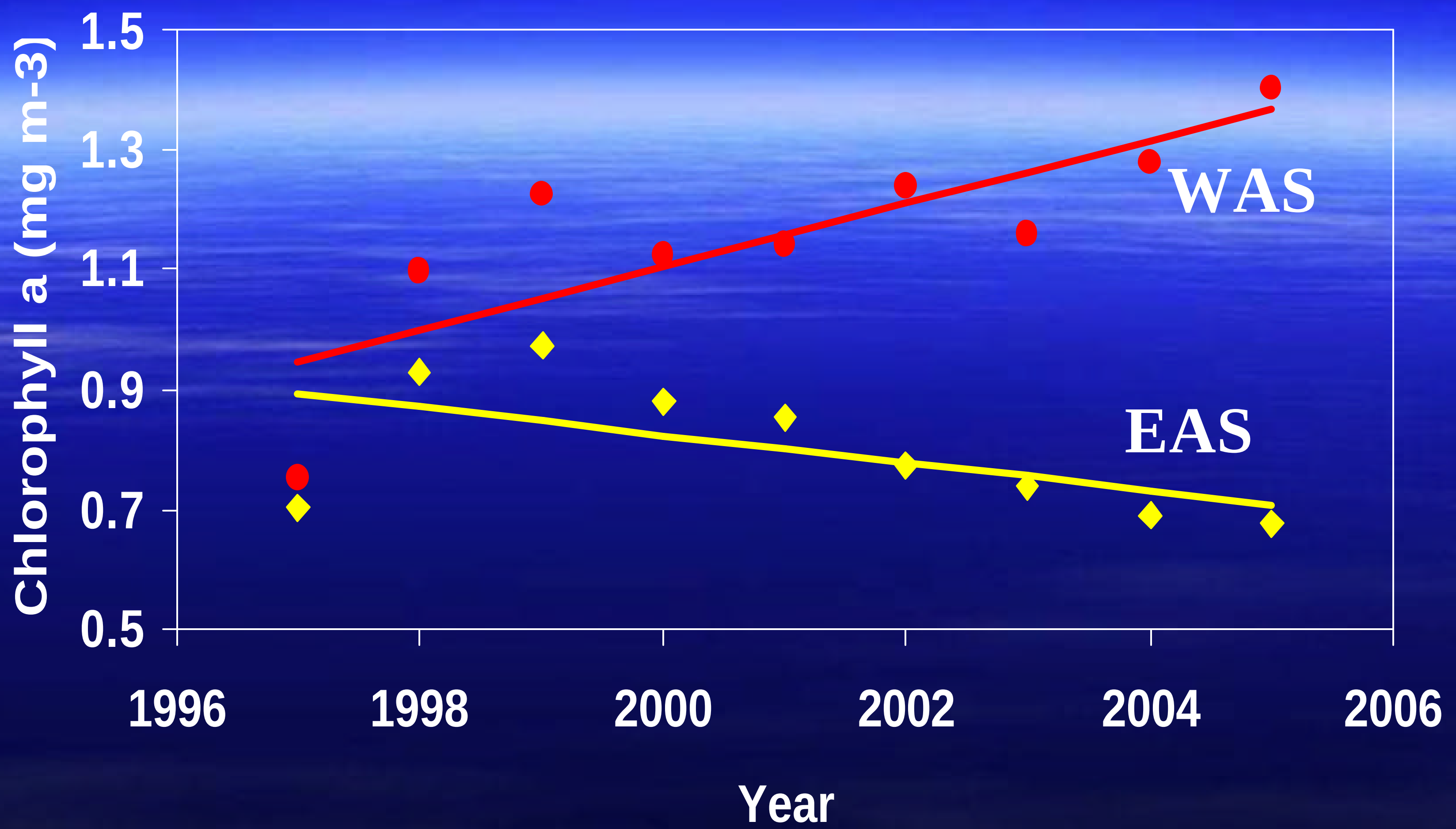

NORTHEAST
MONSOON
LESS SNOW
MORE SNOW
COLDER AND DRIER WINDS (E>P)
WARMER AND HUMID WINDS
SEA
SEA
WARMER
COLDER
LANDMASS
LANDMASS
LESS
MORE
PHYTO
STRONGER
CONVECTIVE MIXING
WEAKER



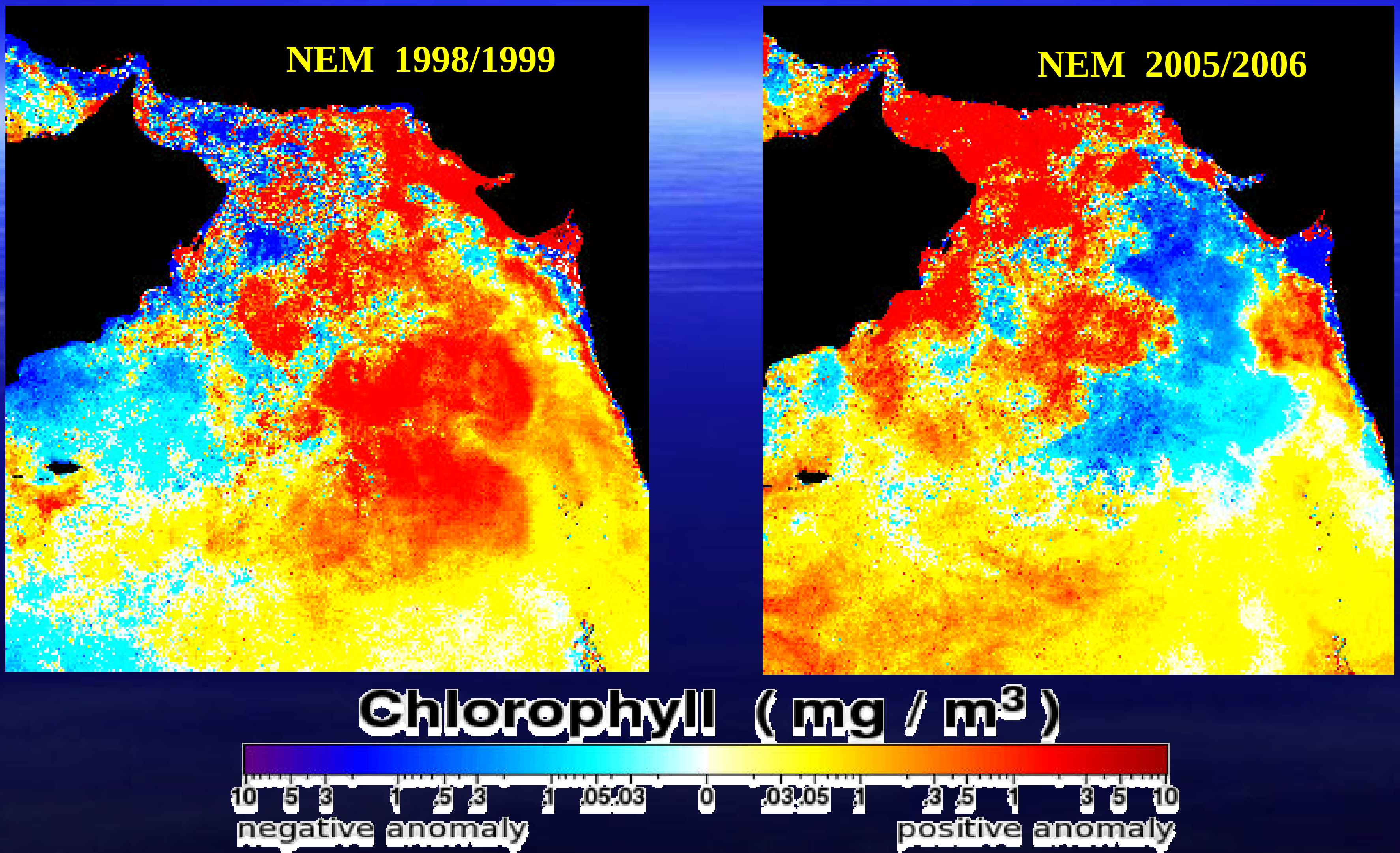
Air-temperature and Relative humidity for the northern Arabian Sea (60°E-70°E, 14°N-25°N).



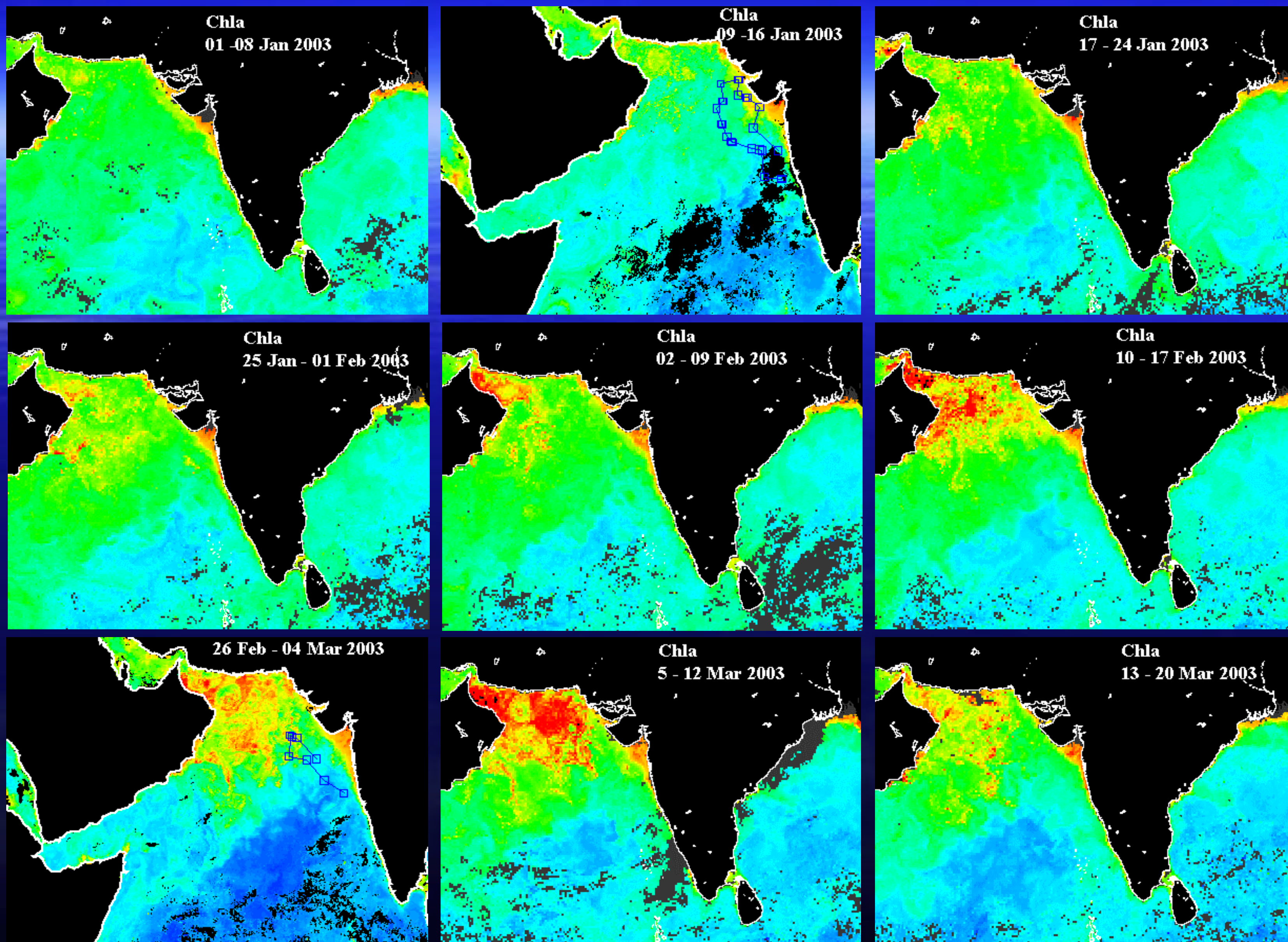
Annual trends of net heat flux (NCEP-NCAR) (60-70°E, 14°N-25°N) and Mixed Layer Depth (XBT, JEDAC, USA)



Winter mean SeaWiFS Chl *a* averaged over the Eastern Arabian Sea (EAS, 66°E-70°E, 15°N-24°N) and in the western Arabian Sea (WAS, 55°E-62°E, 17.5°N-22.5°N).

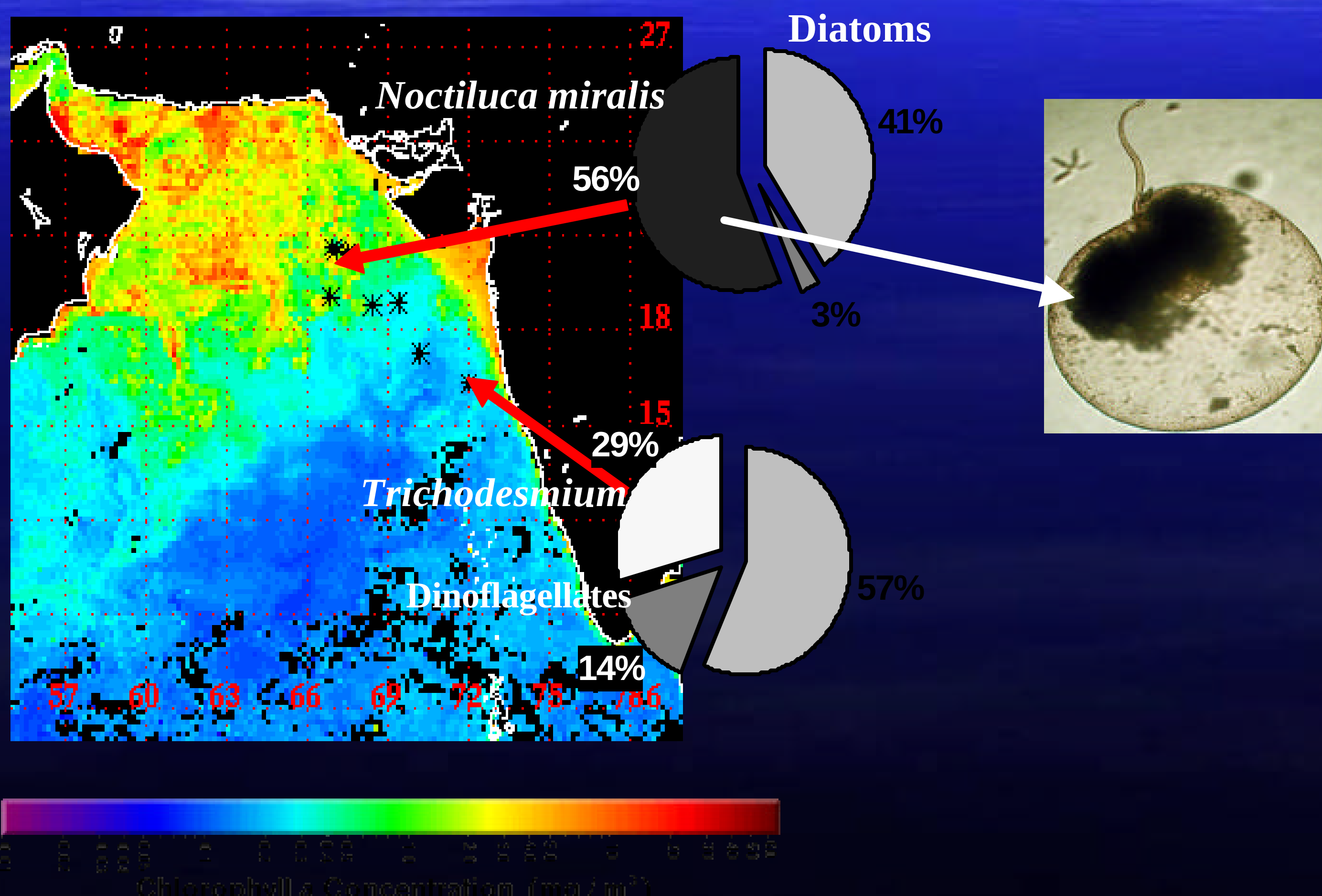


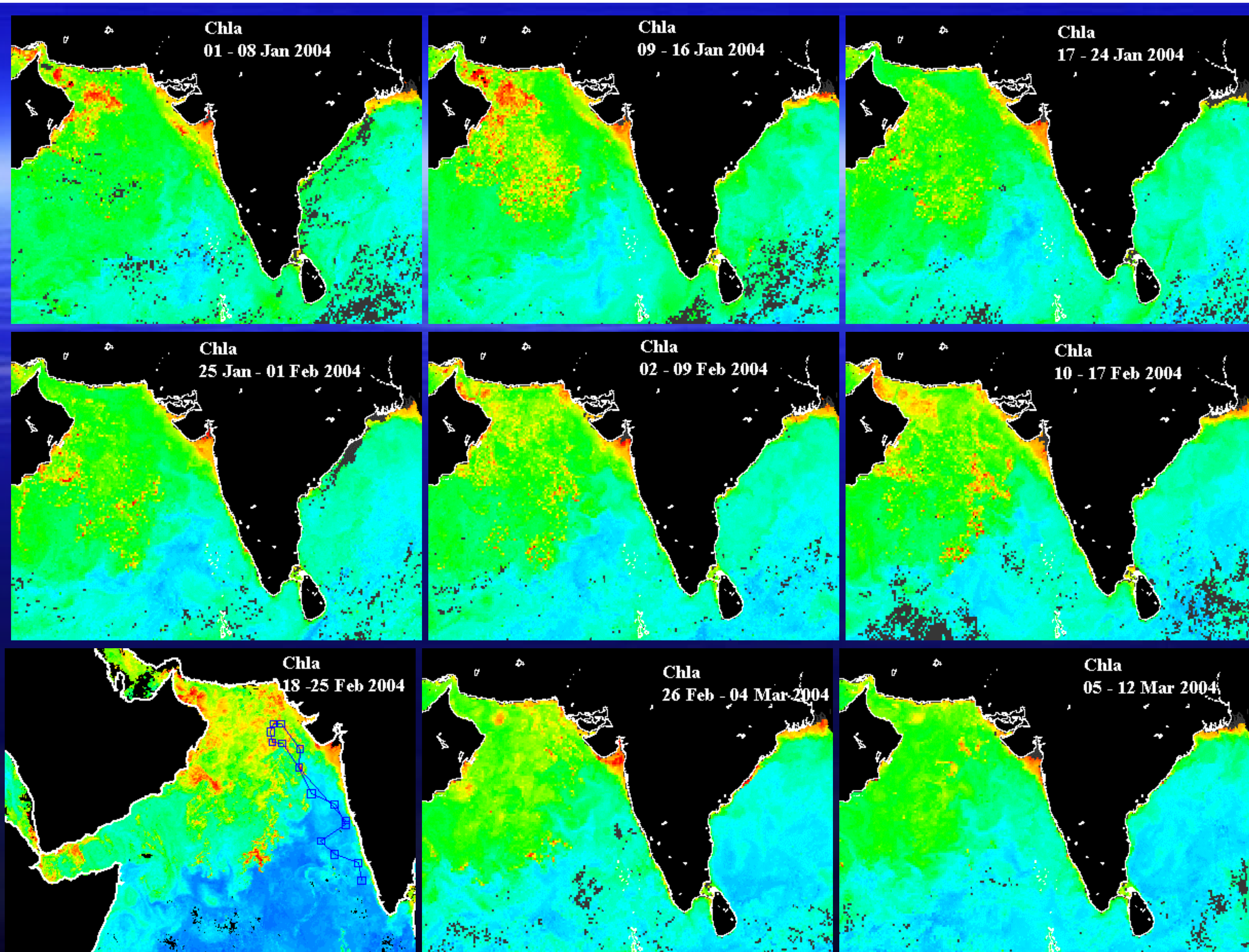
SeaWiFs derived chlorophyll anomaly plots for the winter monsoons of (A) Nov 2002 to Feb 2003 and (B) Nov 2005 to Feb 2006.



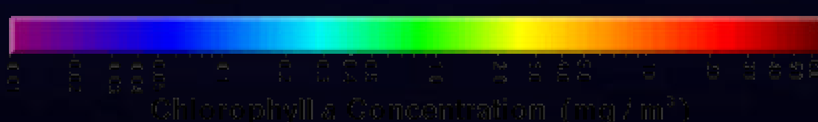
PHYTOPLANKTON BLOOM OF 2003

PHYTOPLANKTON TAXA ASSOCIATED WITH THE BLOOM OF 2003

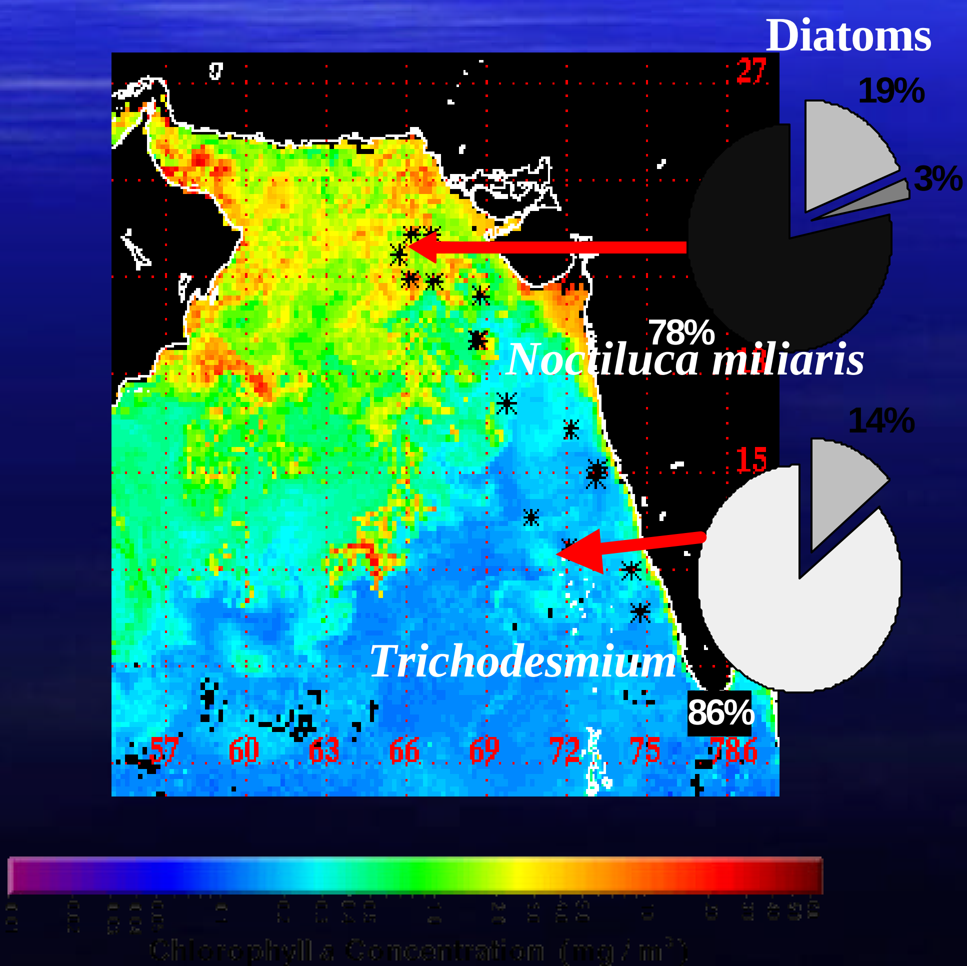


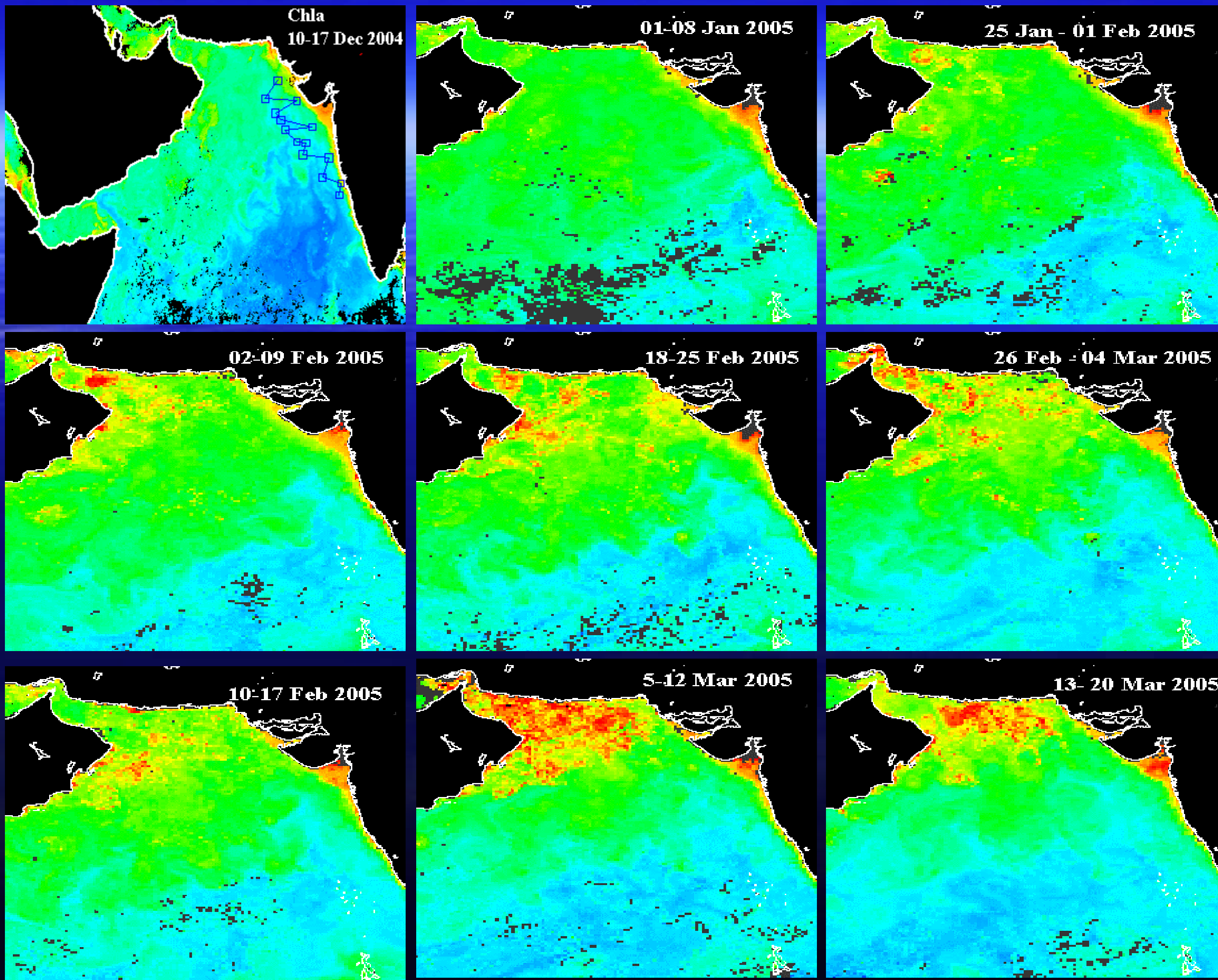


PHYTOPLANKTON BLOOM OF 2004



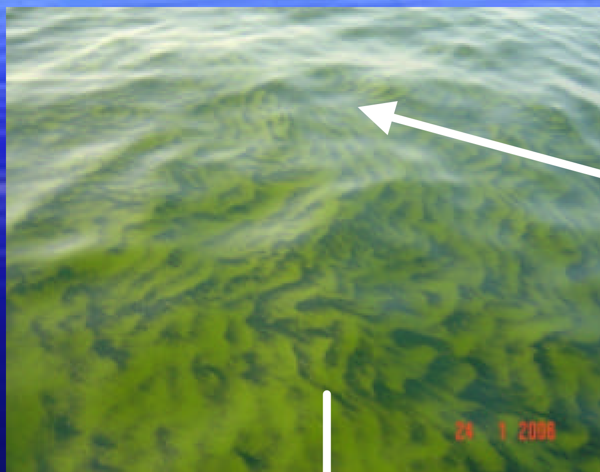
PHYTOPLANKTON TAXA ASSOCIATED WITH THE BLOOM OF 2004



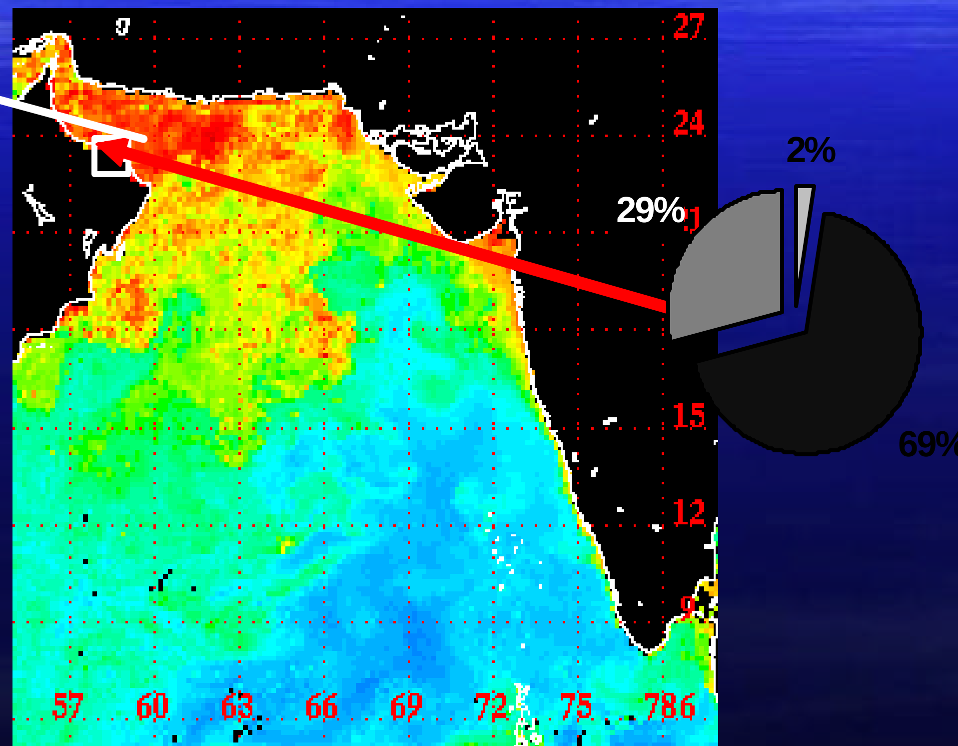


PHYTOPLANKTON BLOOM OF 2005

NOCTILUCA MILIARIS BLOOM IN THE GULF OF OMAN, 24TH JAN 2006



Pedinomonas noctilucae



Dinoflagellate, which thrives in (cold) <22^{o}C, nutrient rich and oxygen poor waters

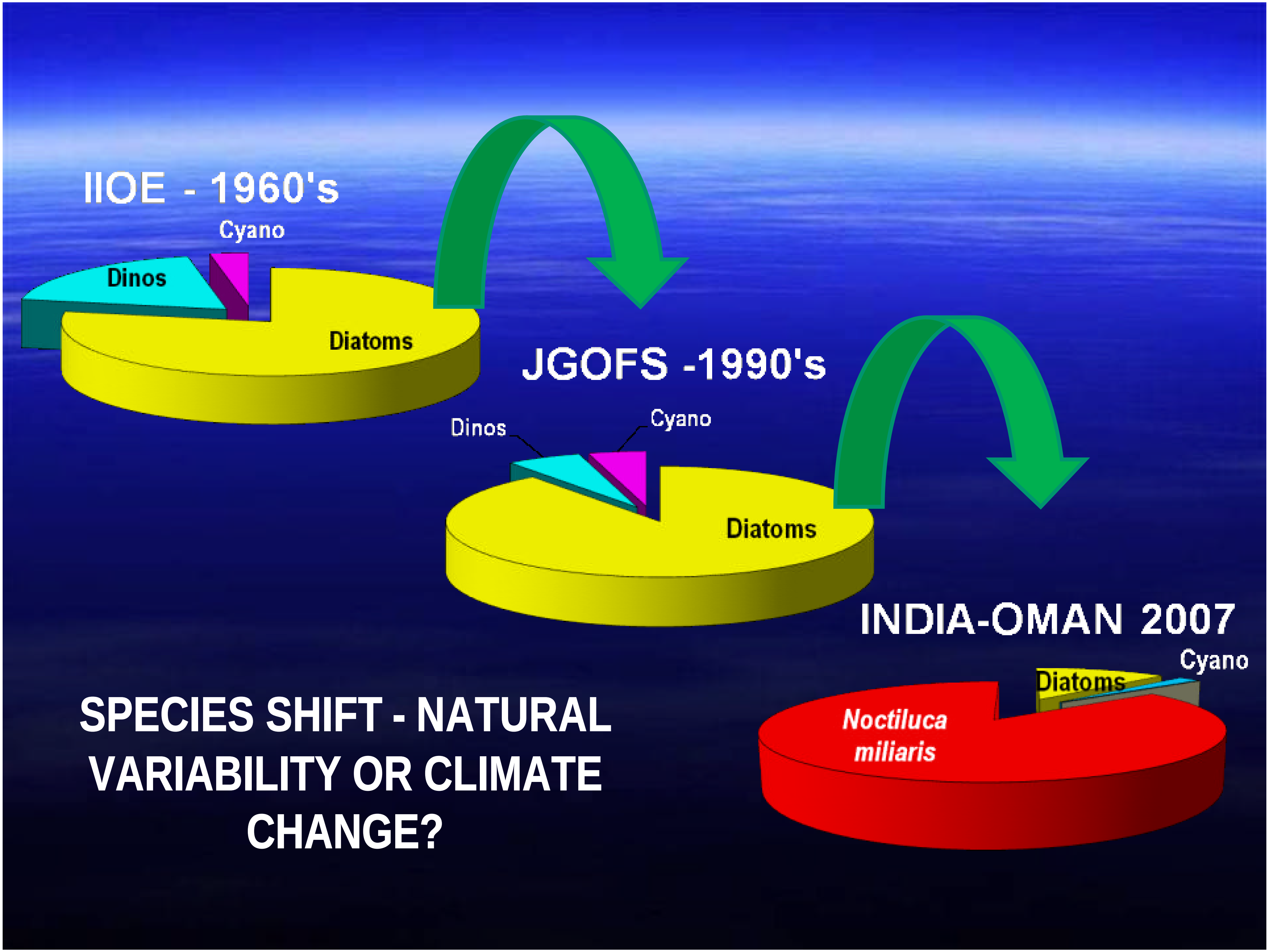
CHARACTERISTICS OF ARABIAN SEA *NOCTILUCA MILIARIS* BLOOMS

***Noctiluca* is a heterotrophic dinoflagellate containing a green endosymbiont "*Pedinomonas noctilucae*"**

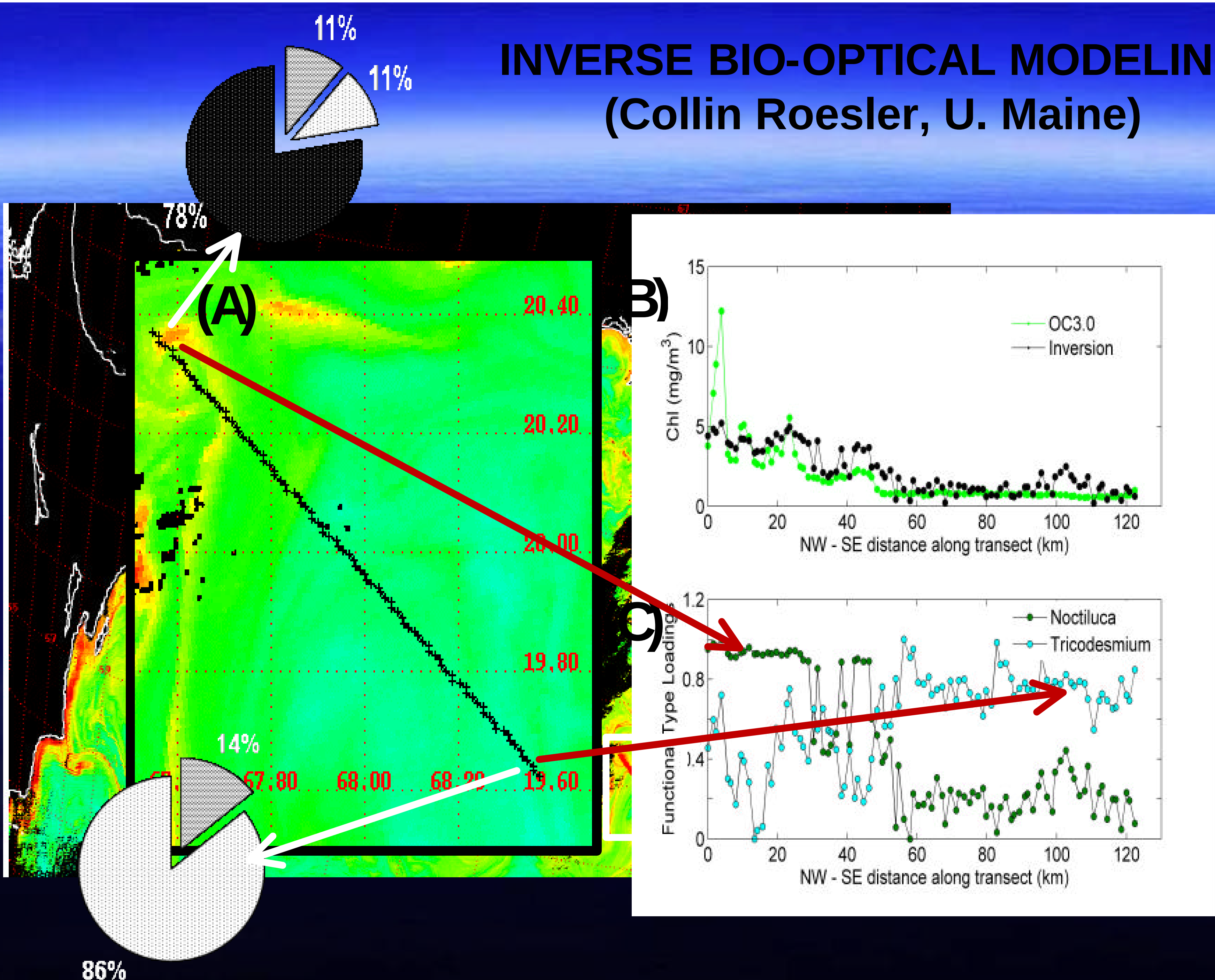
It occurs in (cold) <22^{o}C, nutrient rich and oxygen poor waters

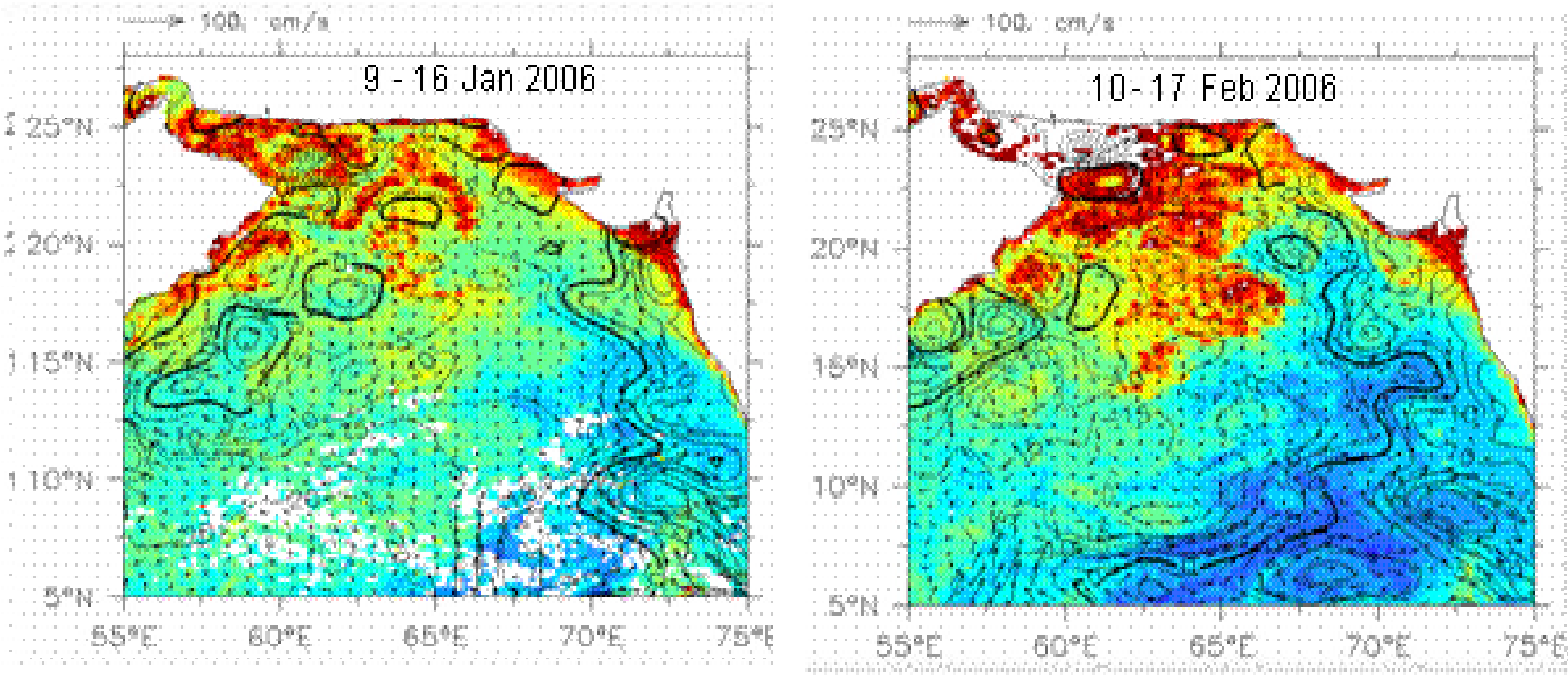
Its appearance in bloom proportions during the NEM is unprecedented as no reports of blooms of this organism during Int. Arabian Sea JGOFS 1992 to 1996 or from Int. Indian Ocean Expeditions of the 1960's.

***Noctiluca* appears to have replaced diatoms as the major bloom forming phytoplankton of the NEM.**


IIOE - 1960's
Cyano
Dinos
Diatoms
JGOFS -1990's
Dinos
Cyano
Diatoms
INDIA-OMAN 2007
Cyano
Diatoms
Noctiluca miliaris
SPECIES SHIFT - NATURAL VARIABILITY OR CLIMATE CHANGE?

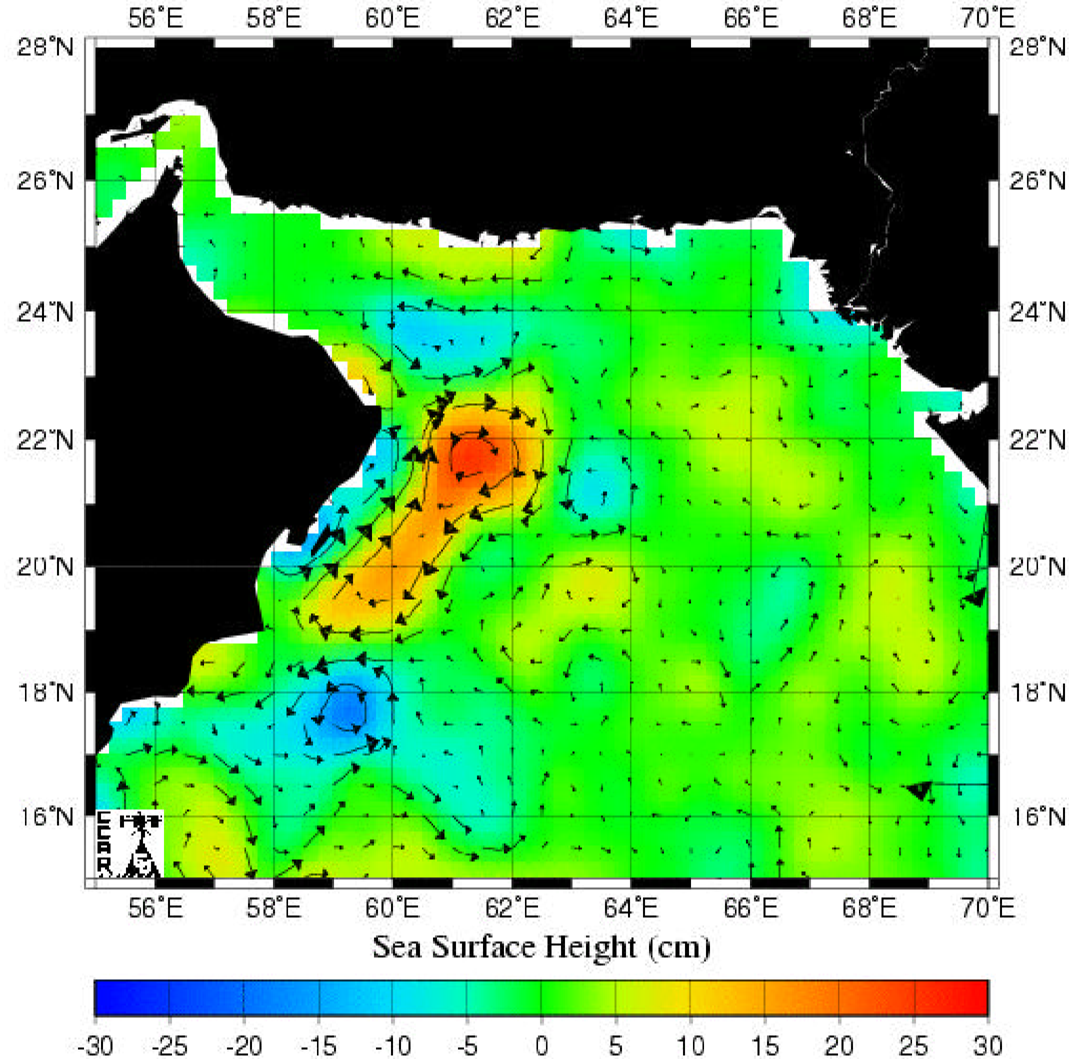
INVERSE BIO-OPTICAL MODELING
(Collin Roesler, U. Maine)

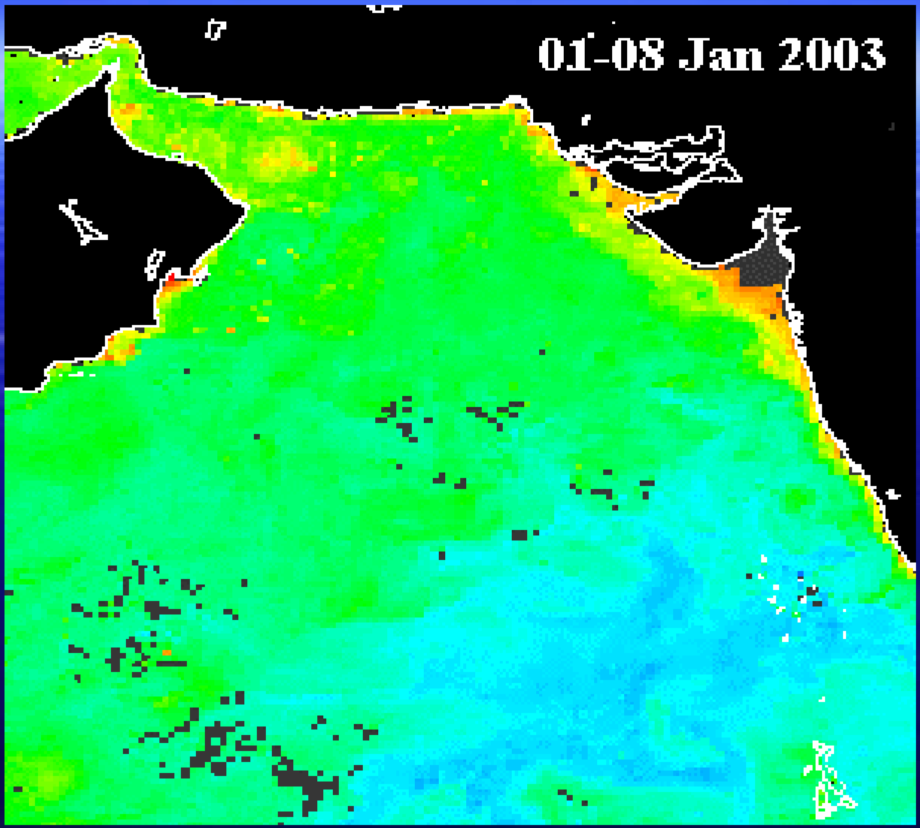




Weekly SeaWiFS and MODIS/Aqua Level-3 merged Chl *a* images with Sea Surface Height anomalies and geostrophic velocity vectors from TOPEX/POSEIDON and ERS-2

Historical Mesoscale Altimetry - Jul 20, 2002





Evolution of phytoplankton bloom during the NE monsoon of 2003

1. **The emergence of *N. miliaris* blooms is tied to eddy activity in the western Arabian Sea**

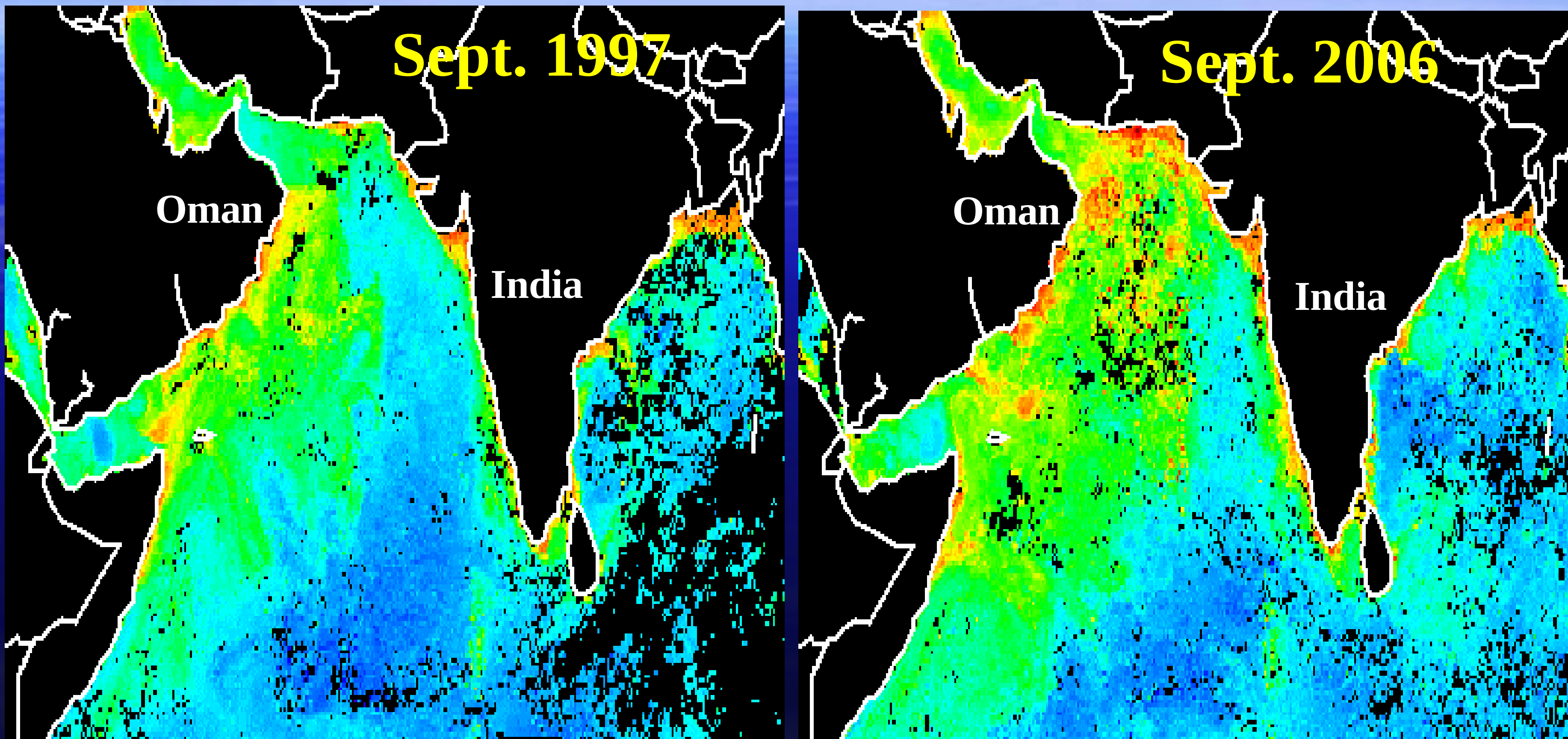
2. **The cold core cyclonic eddy located at the mouth of the population Gulf of Oman acts as a natural incubator for the seed population of *N. miliaris***

3. **The dispersal of the seed population from the Gulf of Oman is regulated by eddy activity.**

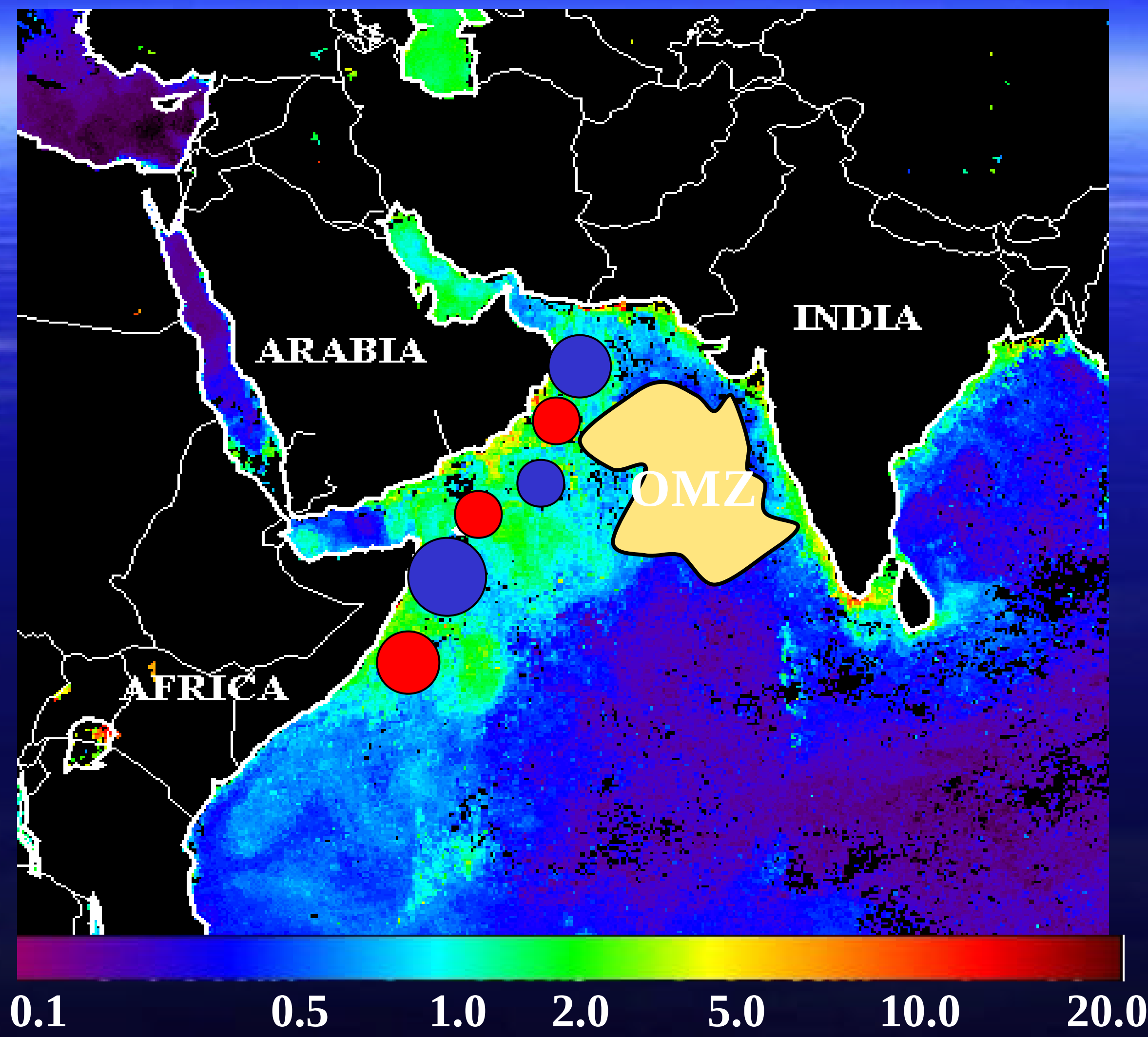
Gomes et al. (2008) Deep-Sea Research

What are the long-term impact of this possible change in phytoplankton biodiversity and biological productivity on:

- Carbon delivery to deeper layers of the Arabian Sea
- Bacterial processes
- Denitrification rates
- The Oxygen Minimum Zone and
- Coastal Fisheries?



SeaWiFS derived chlorophyll fields during the peak southwest monsoon growth season of 1997 and 2006



What is the biogeochemical significance of eddies in the Arabian Sea?

FISH MORTALITY OMAN – NOV 2005

FISH MORTALITY, MALDIVES – SEPT 2007

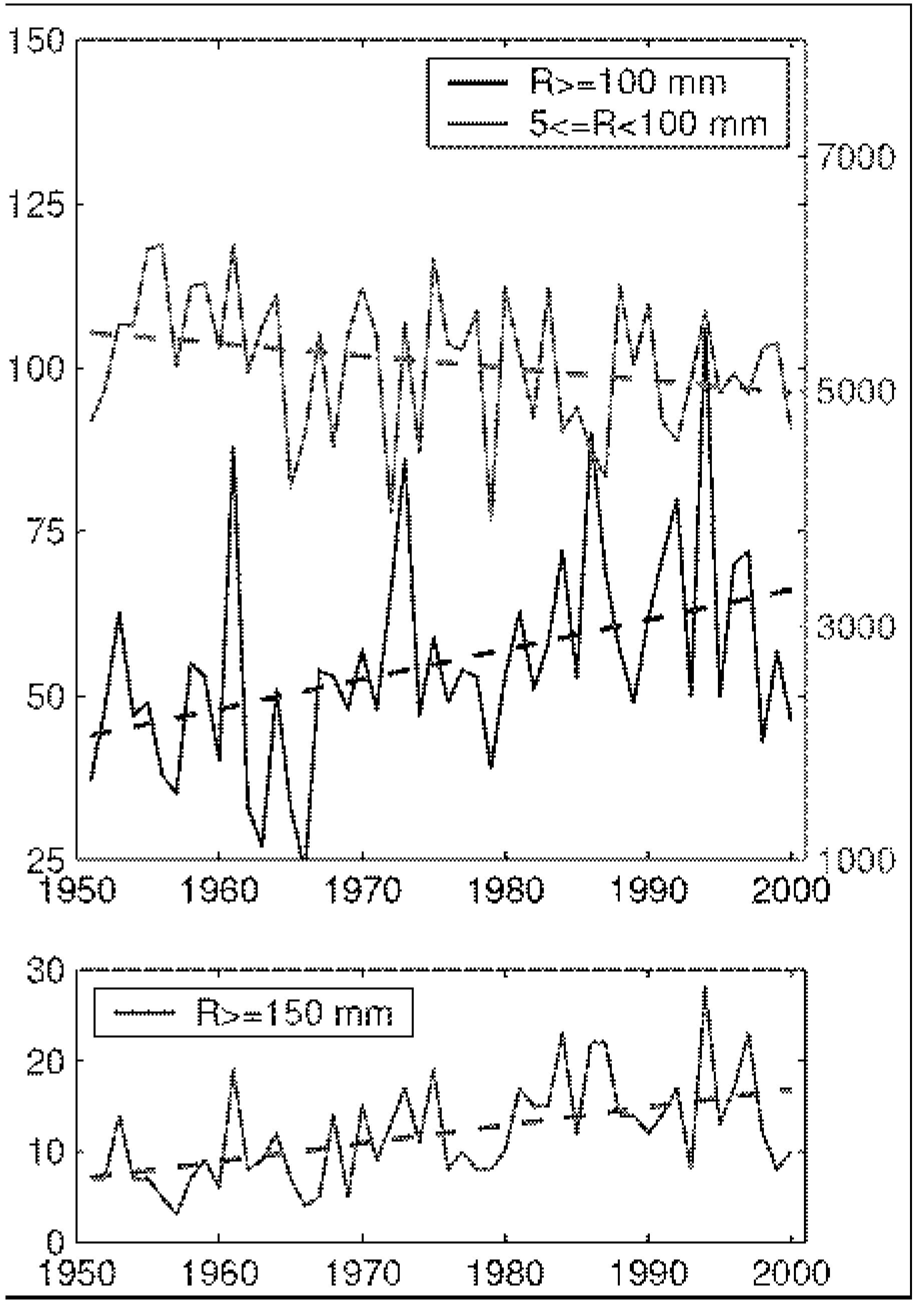
Global warming and Rainfall in India

Increasing Trend of Extreme Rain Events Over India in a Warming Environment

B. N. Goswami,[1*] V. Venugopal,[2] D. Sengupta,[2] M. S. Madhusoodanan,[2] Prince K. Xavier[2]

Against a backdrop of rising global surface temperature, the stability of the Indian monsoon rainfall over the past century has been a puzzle. By using a daily rainfall data set, we show (i) significant rising trends in the frequency and the magnitude of extreme rain events and (ii) a significant decreasing trend in the frequency of moderate events over central India during the monsoon seasons from 1951 to 2000. The seasonal mean rainfall does not show a significant trend, because the contribution from increasing heavy events is offset by decreasing moderate events. A substantial increase in hazards related to heavy rain is expected over central India in the future.

Goswami et al., Science Dec. 2006



Low & Moderate events

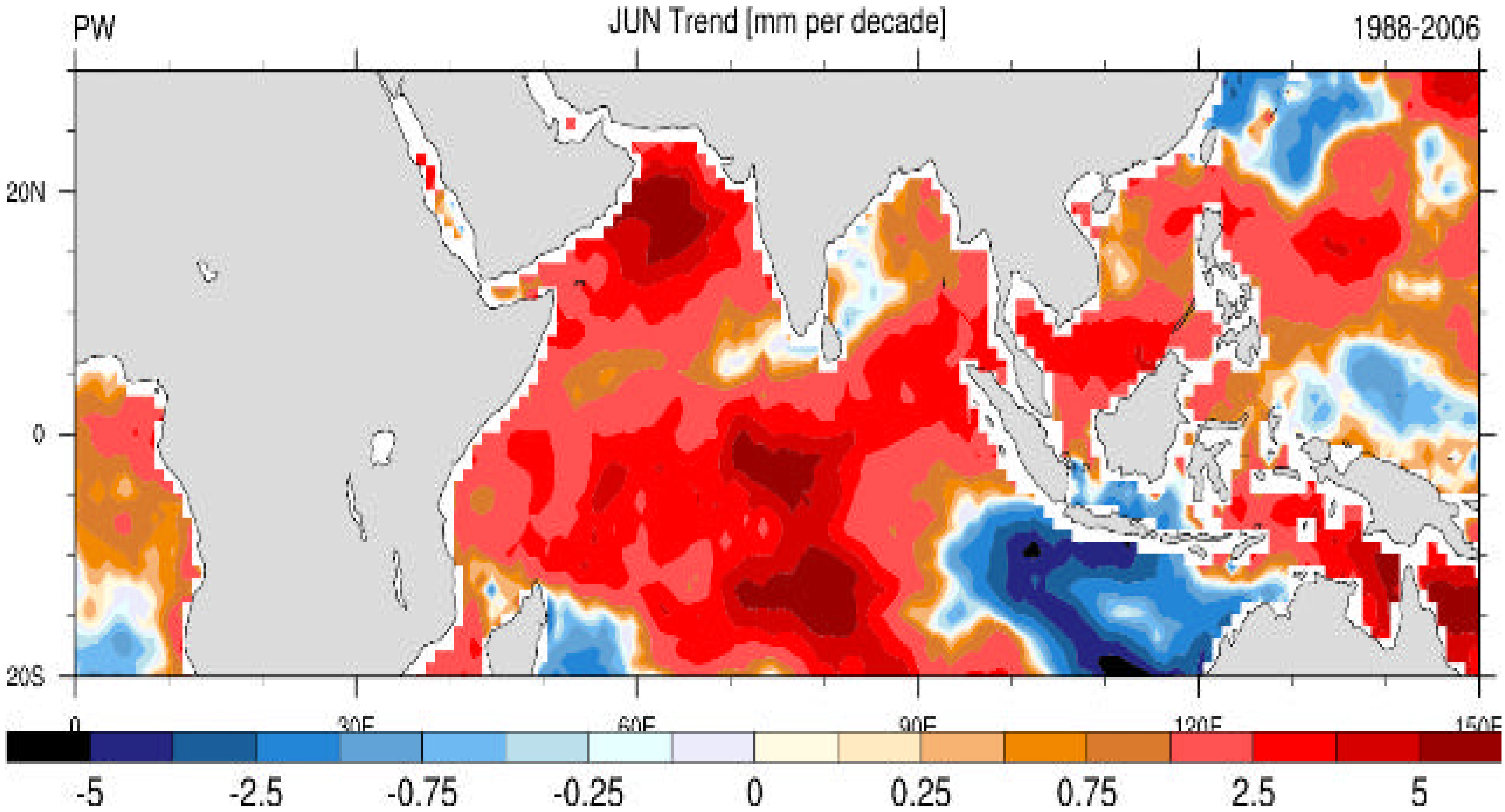
Heavy events (>10cm)

V. Heavy events (>15cm)

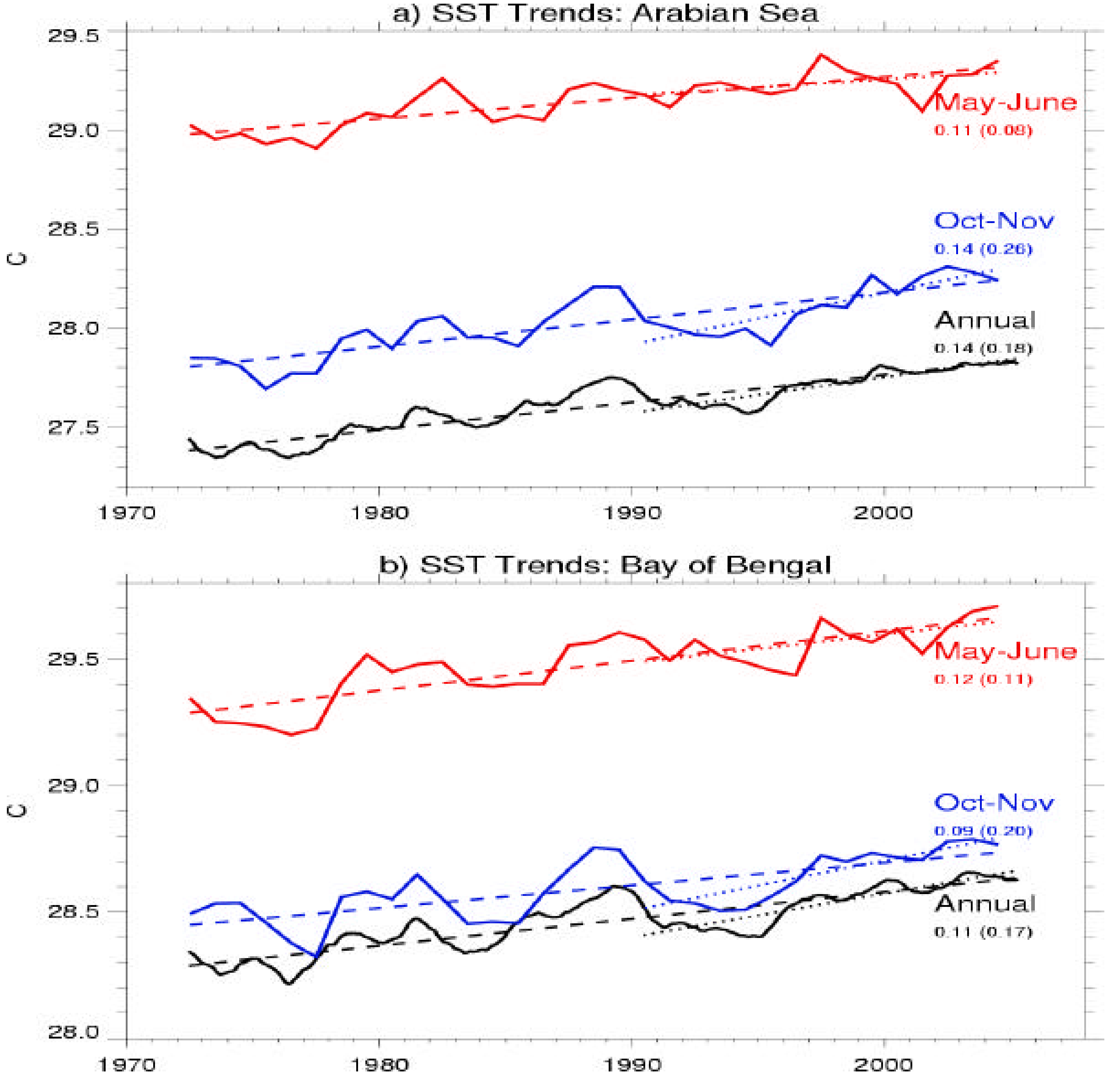
Goswami et al., Science Dec. 2006

Monsoon floods cause widespread damage, affecting millions in India 2005 and 2006

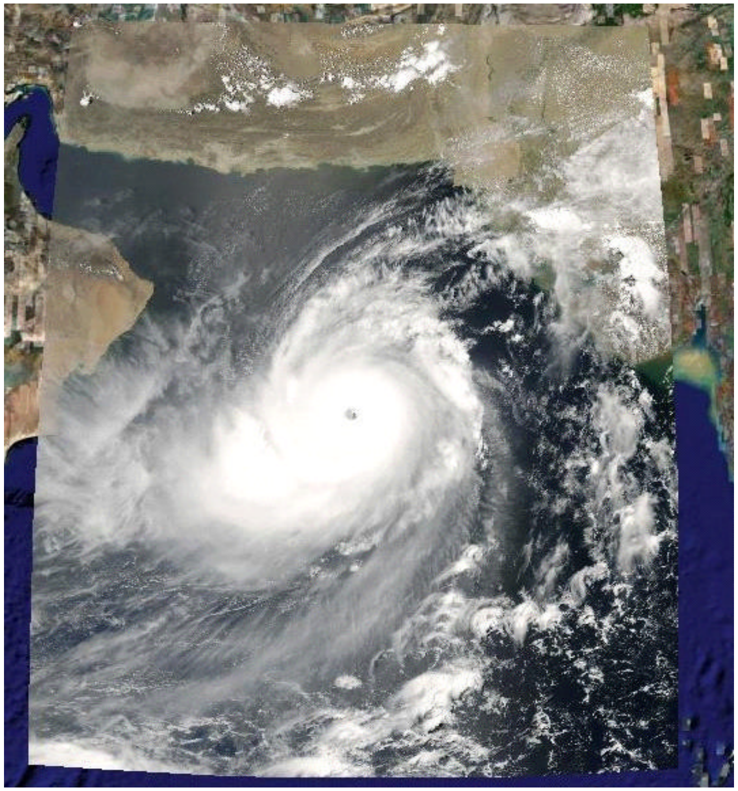
PRECIPITABLE WATER TRENDS (June 1988-2006, mm decade^{-1})

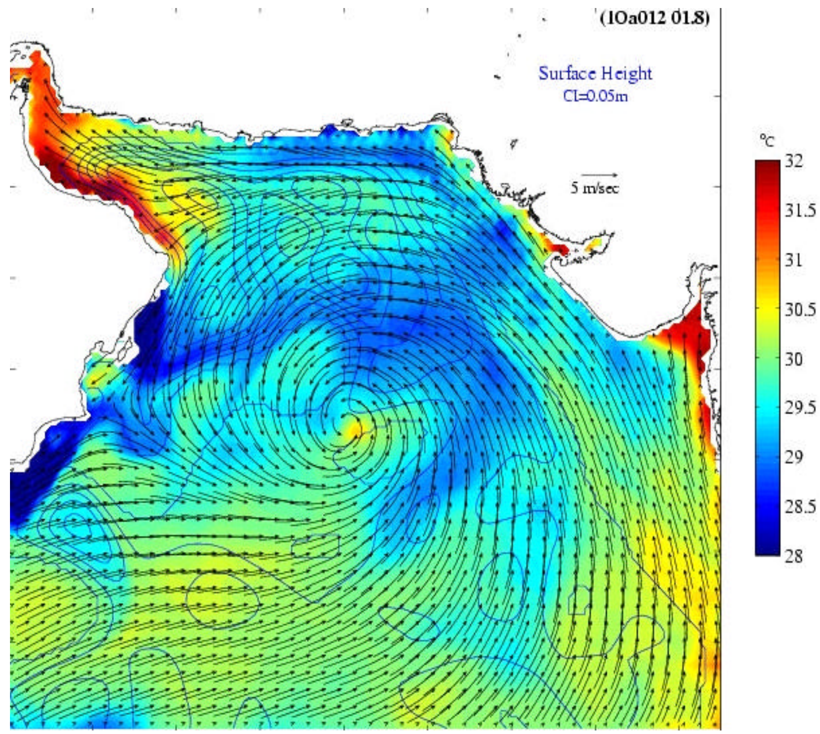


SST TRENDS (1970-2006)



Qualitative comparison of the NCOM model SST, SSH, and atmospheric model winds (vectors) to satellite imagery on Jun 4, 2007 when cyclone GONU struck Oman



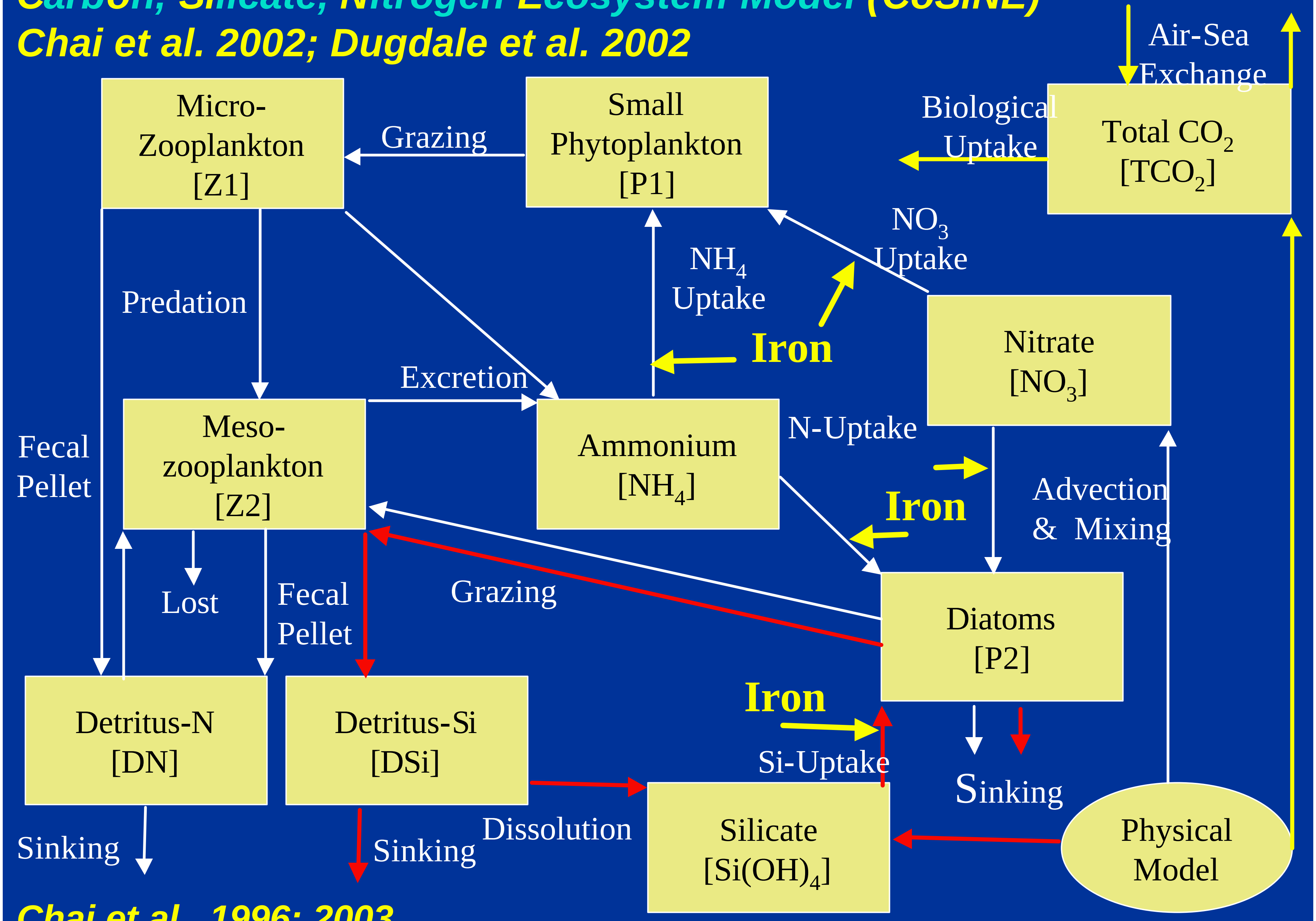


INDIAN OCEAN CIRCULATION MODEL

- **1/8-degree NCOM (Navy Coastal Ocean Model)**
- **30S to 30N, 30.5 to 121.5E**
- **Mercator grid (~13km), 40 Levels s/z**
- **Boundary and initial conditions from Global NCOM**
- **0.5-degree NOGAPS Atmospheric forcing**
- **MODAS: Full 3D Temperature and Salinity relaxation**
- **Initial simulation for 2007**

Carbon, Silicate, Nitrogen Ecosystem Model (CoSiNE)

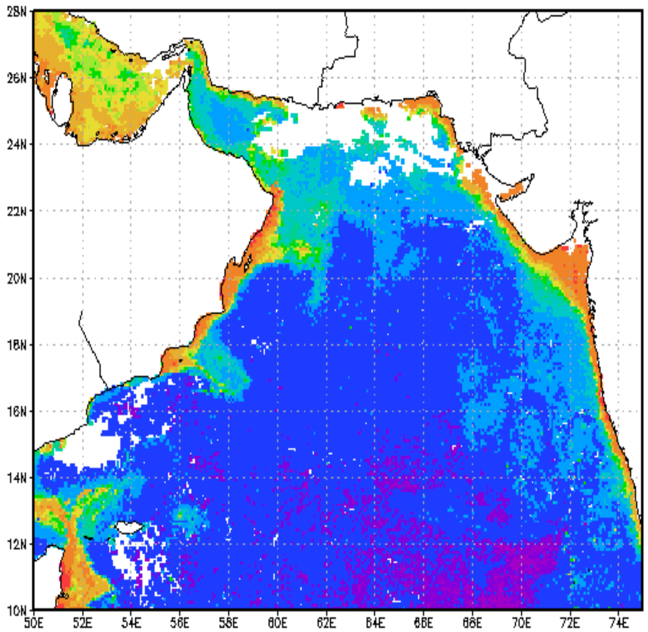
Chai et al. 2002; Dugdale et al. 2002



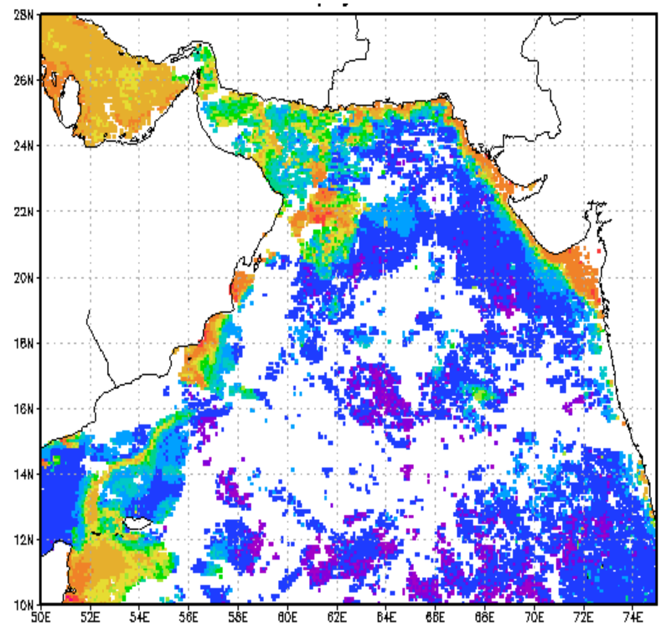
Chai et al., 1996; 2003

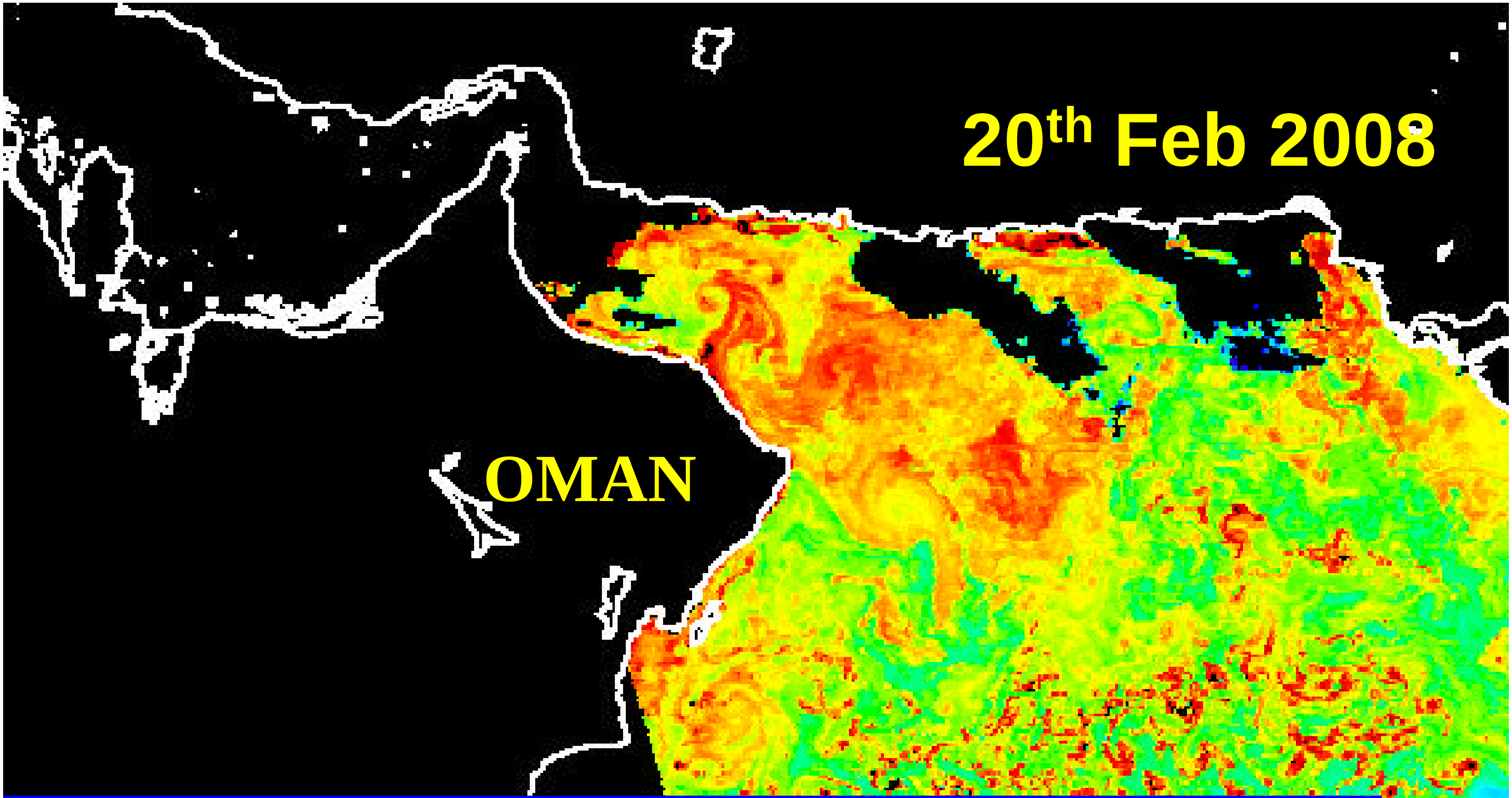
Qualitative comparison of the coupled physical-biological (NCOM-COSINE) modeled chlorophyll with SeaWiFS chlorophyll fields

Model - Jun 4, 2007



SeaWiFS -Jun 4, 2007





"Nothing in the sea falls haphazard; if we cannot predict, it is because we do not know the cause, or how the cause works..."

Henry Bryant Bigelow