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Abstracts

Table of Contents

A possible new role of Indian Ocean in causing the recent global warming hiatus

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Recent studies have documented a slowdown in the warming rate, apparently termed as 'hiatus', in annual mean global surface temperature. In the recent decade (2002−2012), sea surface temperature (SST) over the tropical Pacific Ocean (PO) has shown cooling trend despite a continued rise in SST over the tropical Indian Ocean (IO). Strong cooling in PO is attributed to this hiatus in global warming. In this study, the role of the IO warming on imposing the Pacific cooling is investigated. IO and the PO are strongly coupled through El Niño on interannual timescales. IO basin wide warming is triggered during the onset phase of El Niño in the eastern PO. In the recent decade, enhanced convection over IO (due to warmer SST) generates anomalous cyclonic circulations on either side of equator over the tropical IO and anomalous easterlies along the western PO through the atmospheric response (similar to Matsuno-Gill model). Anomalous easterlies in the equatorial PO force Ekman divergence and produce upwelling Kelvin waves. Enhanced upwelling along the equator cools the tropical Pacific and this cooling eventually leads to the hiatus in global warming.

Southern border zones of OMZ and SNM in the central Arabian Sea

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The canonical understanding of open-ocean OMZs and SNMs is based on Winkler's iodometric titration of dissolved O_2. The new, almost decade-old era is based on the STOX electrode and also optodes, with a greatly lowered limit of detection (LOD) by the former. In the OMZ off southern Peru and northern Chile, STOX discovered NO_2^-, mostly from NO_3^- reduction, appearing only at ~0.05 µM O_2 (the new border of the SNM) rather than the canonical ~0.5 µM O_2. The newly defined SNM is considered to be functionally anoxic and to exclude resident metazoan zooplankton.

During 6 visits in 1994/95 along 64˚E, T-S relations between ~100 and 450 m depth moved similarly south of the principal O_2 gradients while the OMZ and SNM moved southward by ~1˚ of latitude. The location of the OMZ border zone was determined by hydrography, but not by a shifted balance between O_2 supply and consumption.

“Oxic holes in the SNM”: Of 650 NO_2^- measurements in the SNM from 1960-2004 between ~200 and ~500 m depth, 154 (23.7%) ranged from zero to 0.05 µM NO_2^-. They suggest that some O_2 was still present and so, they may not have been functionally anoxic for resident zooplankton.

Annual and seasonal variability of net heat budget in the northern Indian Ocean

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Air-sea interactions determine exchanges of heat, moisture, momentum, and other properties between the ocean and the atmosphere, which in turn play a prominent role in a number of oceanic and atmospheric phenomena on different scales, and impact the Indian Monsoon, regional climate variability, and the biogeochemistry of the Indian Ocean. Both radiative and turbulent fluxes have significant impact on SST anomalies. Indeed, during northern hemisphere winter, the anomalies of latent heat flux and radiative shortwave (SW), fluxes, both in phase with the ocean entrainment, lead to a strong SST response. The oceanic heat storage also depends, among others, on the surface net heat flux. There is a need for consistent and accurate fluxes with high spatial and temporal resolutions at regional scale. We have derived such fluxes, primarily from satellite observations that give a regional view; they have been evaluated using the various buoy arrays in the region. Moreover, the shortwave radiative fluxes are derived spectrally, allowing to estimate the photosynthetically active component that is crucial for oceanic biogeochemistry. Results from this activity will be presented.

Testing the fidelity of Nd isotopes as a paleocirculation tracer in the southeast Indian-Southern Ocean

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In the modern open ocean, neodymium (Nd) isotope values of seawater are often explained by advective mixing of end member water masses; as such, Nd is recognized as a ‘quasi-conservative’ tracer. Implicit in this ‘quasi-conservative’ behavior is the assumption that no significant source of Nd exists along the water mass flowpath. This is the basic principle behind using Nd isotopes archived in marine sediments as a tracer of past ocean circulation. Over the past years, several studies of Nd sources, sinks, and biogeochemical cycling challenged this conventional wisdom and proposed additional sources of Nd, such as, i) exchange with

particulates that modifies seawater Nd isotope ratios, or ii) addition of pore water Nd influenced by reactions with sediment. To successfully use Nd isotopes as a water mass tracer proxy, it is essential to understand these limitations.

The National Science Foundation has recently funded a project which will allow us to collect samples that constitute the different components of modern Nd cycle (e.g., filtered seawater, water column particulates, pore waters and concurrent down hole sediment samples) during a cruise in the Southeast Indian-Southern Ocean (SEISO). The SEISO cruise track will (i) cover major water masses of Southern Ocean origin (Antarctic Mode Water, Antarctic Intermediate Water, Upper and Lower Circumpolar Deep Water), (ii) extensively transit over the southeast Indian Ridge, and (iii) sample the region just north of the Subantarctic Front, where Subantarctic Mode Water is forming today. Seawater and pore water Nd isotopes and Rare Earth Elements will be analyzed, thereby allowing characterization of the Southern Ocean water masses, the effects on seawater Nd isotopes from potentially reactive ridge rocks, and the influence of pore water Nd flux on bottom water Nd isotopes. Besides improving the understanding of Nd cycling, data from this project will be of interest to a wide range of climate scientists as well as biogeochemical modelers, chemical and biological oceanographers, and polar scientists.

Physical forcing of air-sea carbon flux in the Bay of Bengal from the Bay of Bengal ocean acidification mooring (15°N, 90°E)

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The Bay of Bengal Ocean Acidification (BOBOA) moored buoy site was established at 15°N, 90°E on 23 November 2013. It is providing the first continuous measurements of surface water and air CO_2 concentrations and pH along with physical measurements (which include near surface temperature and salinity, wind speed, precipitation, current speed, etc.) in the northern Indian Ocean. The Bay of Bengal is of interest because it is subject to strong ocean-atmosphere interactions. The air-sea flux of CO_2 is likely to be influenced by severe tropical storms and by large intraseasonal, seasonal and interannual variations in wind, surface heat and fresh water fluxes. Yet there are relatively few discrete carbon flux and pH measurements to quantify these impacts in the region. The BOBOA time series reveals strong seasonal variations in air-sea CO_2 flux with outgassing of CO_2 to the atmosphere occurring predominantly during the spring intermonsoon and early southwest monsoon time periods (April through June) and ingassing occurring predominantly during the northeast monsoon (November-February). Seasonal changes in pH and its variability are also observed. However, significant interannual, intraseasonal and high frequency variability is also apparent in both time series measurements. The influence of physical forcing on this variability is examined using the physical measurements from the mooring.

Forcing of mesoscale eddy kinetic energy variability in the southern subtropical Indian Ocean from remotely sensed altimeter and scatterometer data

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A region of elevated mesoscale eddy activity spans the southern subtropical Indian Ocean (SSIO) between Madagascar and Australia. The year-to-year changes in eddy activity, as represented by the interannual variability of eddy kinetic energy (EKE), have consequences for the overturning circulation and heat transport between the Southern Hemisphere tropics and mid-latitudes. An analysis of satellite altimeter and scatterometer data focuses specifically on EKE associated with the SLA field high-passed for zonal wavelengths less than 6° longitude (mesoscale EKE). Comparisons of mesoscale EKE with surface winds and vorticity gradients suggest that there are two distinct mechanisms controlling the interannual variability of mesoscale eddy levels in the SSIO region. The first mechanism involves oceanic planetary waves forced by surface winds in the western tropical Pacific, which propagate southwestward through Indonesia; these waves affect the sea level, current strength, and thus eddy activity in the eastern SSIO near the Australian coast. The second mechanism involves surface vorticity gradient variance within the SSIO, likely forced by surface wind or current shear, which predominantly controls mesoscale EKE variability in the central SSIO. The identification of these mechanisms using remotely sensed data presents opportunities for short-term (6-12 month) predictability of eddy activity levels in the SSIO, and assessment of model simulations of eddy activity in the region.

CDOM optical properties in the central/western Arabian Sea: Late-monsoon patterns from field and ocean color satellite observations

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Chromophoric dissolved organic matter (CDOM) absorption properties were examined along two transects in the central and western Arabian Sea during late South West Monsoon (SWM) (24 Aug to 9 Sept 2007). Surface CDOM absorption coefficient a_g375 was low in the eastern and central part of the basin (0.101 ± 0.005 m-1) and was elevated (0.202 ± 0.189 m-1) along the western transect showing an increasing trend westwards. Correspondingly, surface spectral slope

S (µm-1) was high in the central and eastern basin (22.01 ± 1.19 µm-1) and lower (17.87 ± 2.22 µm-1) along the western transect. These patterns of a_g375 and S suggest strong association to upwelling areas off the Arabian Peninsula (high a_g375 and low S) and its subsequent photooxidation (low a_g375 and high S) as these upwelled waters are advected offshore into the central Arabian Sea. MODIS SST reveals the widespread upwelling region off the Arabian peninsula while ocean color imagery (surface chlorophyll and CDM or CDOM plus nonalgal absorption) reveal the transition from oligotrophic to high biomass high CDM regime between May to Aug/Sept period of the SWM especially in the western and central Arabian Sea. Sectional views of CDOM optical properties show a_g375 and S to be relatively uniform with depth in the upwelling region (western transect) while a_g375 was greater and S lower in surface waters in comparison to subsurface waters (> 30 m) in the central basin. This pattern strongly suggests biological contribution to CDOM in the overlying productive waters linked to the offshore exported upwelled waters during the SWM period.

Changes in ventilation in the subtropical south Indian Ocean on time scales of decades*

**Online only*

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We used an eddy resolving model to quantify effects on tracer ages - for southern hemisphere subtropical gyres - of the spatial dependence of internal ocean tracer variability due to stirring from eddies (~2 years in the subtropics) and biases from non-stationarity of the atmospheric transient when there is mixing. For the subtropical South Indian Ocean, we examine two time scales using tracer data from the I5 section along 32°S between 26 and 27.2 $\sigma\theta$. 1) For the years 2002 versus 1987, most or 64% of the boxes show an age decrease of at least 2 to 10 years, while 76% show a decrease that is greater than zero. Based on age decreases of at least 2 years in most of the boxes, we infer increased ventilation. Also, there is mostly decreasing apparent oxygen utilization (AOU) in the lower thermocline across the section, with exceptions being above 26.5 $\sigma\theta$ in the east and west parts of the section. 2) For the years 2009 versus 1987, 35% of boxes have ages decreasing. However, when considering an error of 2 years then ages are decreasing ages for only 9% of the boxes. The South Indian age differences are least in the west and particularly in the lower thermocline, where AOUs are also increasing. Note that the AOU differences are considerably more positive between the 2009 and 1987, as compared with between the 2002 and 1987. Thus, in the South Indian there is real increased ventilation between 1987 and 2002, also in the other two southern subtropical gyres. However, there appears to be no trend of increased ventilation between 1987 and 2009. These results are consistent with increased Agulhas leakage and regional changes in the Southern Angular Mode. It is important to note that ventilation changes are specific to the years of the cruises, and also are likely embedded in longer timescale climate trends.

Modulation of the Ganges-Brahmaputra river plume by the Indian Ocean Dipole and eddies inferred from satellite observations

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The Bay of Bengal (BoB) receives large amounts of freshwater from the Ganga-Brahmaputra river during the summer monsoon. The resulting upper-ocean freshening influences seasonal rainfall, cyclones, and biological productivity. Ocean currents play a prominent role in the BoB sea surface salinity (SSS) space-time variations, in particular the western boundary current known as the East Indian Coastal Current (EICC). Sparse in-situ observations suggest that the EICC transports these freshwaters southward after the monsoon as a ~200-km wide, 2000-km long "river in the sea" along the East Indian coast. Circulation changes associated with the Indian Ocean Dipole (IOD) and offshore meandering of freshwater due to mesoscale eddies can strongly influence the transport of freshwater within the BoB. SSS from the Soil Moisture Active Passive (SMAP) satellite along with altimetry data, including sea surface height (SSH) and currents, provide unprecedented views of this peculiar "river in the sea" feature from intraseasonal to interannual timescales. The good correspondence in the synergistic use of SSS and altimetry, two independent datasets, shows that SMAP SSS well captures mesoscale features such as eddies. In addition, SMAP SSS agree well with in-situ measurements, capturing the strong cross-shore SSS contrasts (~10-pss) measured along ship transects. Our results further show that remote forcing associated with the negative IOD in the fall of 2016 caused a stronger EICC and "river in the sea" that extended approximately 800 km further south than that in 2015. Moreover, mesoscale eddies induced meandering of this plume, exporting freshwater away from the coast.

Nutrient supply controls particulate elemental concentrations and ratios in the Indian Ocean

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Recent work has revealed extensive variation in the elemental stoichiometry of particulate organic matter across ocean regions with important implications for ocean biogeochemistry. However, there are three competing hypotheses for elemental variability including i) temperature via the 'translation-compensation', ii) the nutrient supply, and iii) an allometric diversity based hypothesis. In the central Indian Ocean, there is a unique temperature and nutrient supply relationship that enable us to test how C:N:P in controlled. The Indian Southern Subtropical Gyre (SIO Gyre) had low nutrient supply but colder water and the equatorial and Bay of Bengal regions were hot and had elevated nutrient supply. Throughout, the phytoplankton community was dominated by *Prochlorococcus*. POC concentrations had a daily periodicity leading to an oscillation in C:N and C:P with a peak in these ratios near sunset. On regional scales, POM concentrations were lowest in SIO Gyre, highest north of 10°S through the equatorial upwelling region and lower in the Bay of Bengal. Ratios were highest in the gyre (C:N:P 166:21:1), and were closer to Redfield values near the equator (128:18:1), and the Bay of Bengal (122:17:1). As *Prochlorococcus* dominated the biomass and temperature related to C:P in the opposite direction as predicted, we found that variation in elemental ratios is principally linked to nutrient supply rates. Particulate labile Fe:C ratios were characteristic of a Fe stressed system south of the equator but elevated in the north. We propose a model, where Fe limitation and reduced N-fixation in SIO Gyre results in lower C:P ratios compared to the North Atlantic and Pacific gyres. Thus, our data suggests that a combination of macro- and micro-nutrient supply drives POM ratios in the IO and across gyre systems.

Organic matter and bacterial metabolic rates variations in the coastal Bay of Bengal: Influence of river discharge flow

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The Bay of Bengal (BoB) receives a significant amount of terrestrial organic matter from various rivers resulting in the higher total organic matter in the mixed layer (150±20 μM) compared to other regions of Indian Ocean (90±10 μM). It is hypothesized that terrestrial organic matter may be modified significantly in the surface waters of BoB leading to increase in pCO_2 levels and flux to the atmosphere. In order to test this hypothesis, the organic matter nature, sources and bacterial metabolic rates (respiration and production) were measured along the coastal BoB, during peak river discharge period (southwest monsoon). The stable isotopic composition of organic carbon and nitrogen revealed that allochthonous (75%, dominantly C3 plants) and autochthonous (60-70%, dominantly marine planktons) sources are mainly contributed to organic matter pool in the southwest (SW) and northwest (NW) coastal BoB respectively. Lower suspended load in the NW compared to SW region creates a conducive environment for phytoplankton growth leading to higher contribution of autochthonous in the former region.

Bacterial respiration rates varied from 12.1 to 156 μg CL-1d-1. Relatively higher respiration rates were observed in the SW (~ 60 μg CL-1d-1) than NW region (~52 μg CL-1d-1) associating with dominant allochthonous organic matter suggesting that allochthonous organic matter enhances bacterial respiration rates than hitherto hypothesized. Higher bacterial respiration rates in the SW region were associated with the high bacterial abundance which was advected from the Godavari estuary along with discharge. An enhanced abundance of mesohaline bacteria could able to utilize allochthonous organic matter resulting in enhanced pCO_2 levels in the SW (>500 μatm) compared to NW region (< 250 μatm). The bacterial respiration rates contributed up to ~59% of the pCO_2 level in the coastal BoB. This study suggested that source of organic matter and bacterial community determine their metabolic activity having significant control on pCO_2 levels and flux of CO_2 to the atmosphere in the BoB.

A new mode of salinity variability in the tropical Indian Ocean and its regional impacts

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Salinity is an important physical property which controls the upper ocean processes and thus can modulate the ocean circulation and air-sea coupled processes directly and indirectly. Most of the previous studies over the tropical Indian Ocean were mainly focused on quantifying the salinity variability associated with the Indian Ocean Dipole (IOD). Several salinity indices were put forward in view of their role on air sea interaction. The present study identifies a new mode of surface and subsurface salinity variability in the South Central Tropical Indian Ocean (SCTIO) region with strong support to air sea coupling. The mode is sustained without any IOD forcing suggesting the existence of an internal dynamics of the north Indian Ocean possibly different from the one associated with IOD. The driving mechanisms of the surface and subsurface salinity variability are further explored by analyzing the sea surface temperature, sea surface height, precipitation etc. Argo salinity profiles during 2005 to 2015 have been used for the analysis. The long-term salinity variability is also studied using ocean reanalysis products for the period of 1958 to 2015. The analysis highlights the role of Rossby waves in driving subsurface salinity variability. The regional impact of this variability is also addressed by examining the lead-lag correlation with different oceanic and atmospheric variables and indices. The correlation of the of first principal component of salinity anomalies with the other indices addressing the prominent modes of variability such as subsurface dipole index (SDI), equatorial wind index (EQWIN), El Nino index (Nino3.4) and Dipole Mode Index (DMI) are also estimated. The highest correlation (0.78) is observed with SDI. The observed significant correlation with different monsoon proxies paves the way for predicting the extreme ISMR events.

High-resolution simulations for the Bay of Bengal: Sensitivity to river input and wind forcing

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We present a multiscale validation and sensitivity study of a set of high-resolution (~9km) simulations for the Bay of Bengal (BoB) region using the Regional Ocean Modeling System (ROMS). We compare and analyze four main simulations of fifteen-year duration each. They utilize different climatological monthly surface wind forcing (weaker COADS or stronger QuikSCAT) and different buoyancy inputs (river inflow with seasonally varying estuarine salinity or with zero salinity). We first complete a statistical validation to establish the model's overall capability and specific sensitivity in reproducing basin-scale annual and seasonal variabilities. The basin-scale (large-to-mesoscale) performance is quantified in terms of biases, correlations, skills, and root-mean-square-differences (RMSD) against satellite and in situ monthly climatologies. The skill in reproducing the seasonal variability for sea surface temperature (SST), sea surface salinity (SSS), sea surface height (SSH), mixed layer depth (MLD) and depth of the 23°C isotherm (D23) is found to be heterogeneous in space, when compared to the overall annual skill. The skills for SST and SSS were high in all the simulations. Stronger winds and fresher river inflow increased the MLD skill by almost 10% individually. Stronger winds (added freshness) have a significant negative (minimal) impact on the SSH skill.

We then analyze the sensitivity to wind and buoyancy forcing in terms of the ability to capture the: (i) surface circulation including the boundary currents and monsoonal circulation; (ii) vertical structure of temperature, salinity and stratification; (iii) freshwater plume dispersion; and (iv) coastal upwelling along the western boundary during late spring/summer. We find that the major effects of winds and river inputs are limited to the upper 50 m of the water column in a domain-average sense, with deeper and stronger influence in the northern BoB. Stronger QuikSCAT wind induced enhanced mixing lowers (enhances) the upper ocean temperature (salinity), weakens the near-surface stratification, and reduces both surface spreading and volume occupation of the freshwater plume. Moreover, stronger winds enhance eddy activity, strengthen springtime Western Boundary Current (WBC) and enhance coastal upwelling during spring and summer along the east coast of India. Increasing the coastal buoyancy (fresher river input) reduces the overall salinity at the surface by ~0.4 psu towards climatology and increases the near-surface stratification in the northern BoB; however, significantly underestimates the SSS near the river mouths where the estuarine salinity river input simulates more realistic SSS. The lower salinity simulation prefers an eddy-dominant springtime WBC, and enhances the freshness, strength, and southward extent of the autumn East India Coastal Current (EICC) core with plume water inhibition by about 10% over the domain.

Diurnal convection–wind coupling in the Bay of Bengal

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Satellite observations of infrared brightness temperature and rainfall have shown offshore propagation of diurnal rainfall signals in some coastal areas of the tropics, suggesting that diurnal rainfall is coupled to land–sea breeze circulations. Here we utilize satellite observations of surface winds and rainfall to show the offshore co-propagation of land breeze and diurnal rainfall signals for 300–400 km from the east coast of India into the Bay of Bengal. The wind observations are from the 2003 QuikSCAT–SeaWinds "tandem mission" and from 17 years of the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI); the rainfall observations are from the TRMM 3B42 product and from TMI. The surface wind convergence maximum leads the rainfall maximum by 1–2 h in the western part of the bay, implying that the land breeze forces the diurnal cycle of rainfall. The phase speed of the offshore propagation is approximately 18 m s−1, consistent with a deep hydrostatic gravity wave forced by diurnal heating over India. Comparisons with a cloud system-resolving atmospheric model and the ERA-Interim reanalysis indicate that the models realistically simulate the surface land breeze, but greatly underestimate the amplitude of the rainfall diurnal cycle. The satellite observations presented in this study therefore provide a benchmark for model representation of this important atmosphere–ocean–land surface interaction.

The distribution of *Prochlorococcus* ecotypes reveals patterns of nutrient limitation in the Indian Ocean

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One of the world's most understudied regions is the Eastern Indian Ocean. However, the unique biogeochemical characteristics of this system make it an excellent region to use *Prochlorococcus*, a highly abundant and well-characterized cyanobacterium, to test hypotheses on the relationship between nutrient limitation, temperature, and microbial community composition. We examine *Prochlorococcus* communities across environmental gradients in the Indian Ocean using Illumina sequencing of the rpoC1 gene to determine how ecotype distributions may predict nutrient limitation. Sampling was performed in April, 2016 on the IO9 GO-SHIP cruise, which crossed three biomes: The Southern Indian Ocean subtropical gyre

(SIO), the equatorial upwelling region (EqIO), and the Bay of Bengal (BoB). The EqIO has high temperature, low Fe, and intermediate N and P. Therefore, we hypothesized that the high nutrient low chlorophyll (HNLC) *Prochlorococcus* ecotype would be numerically dominant. We also hypothesized that the high light II (HLII) ecotype would dominate in the BoB and SIO due to its tolerance for high temperatures and low nutrient concentrations, respectively. Contrary to our hypotheses, HLII *Prochlorococcus* was the dominant ecotype across the Eastern Indian Ocean. This result suggests that *Prochlorococcus* may be more macronutrient- than micronutrient-stressed and that Fe-limitation may be a less important driver of community composition in this region. Additionally, principal coordinates analysis of the HLII ecotype reveals three regionally-distinct communities, indicating that microdiverse partitioning plays an important role in microbial community assembly in the Eastern Indian Ocean. This work demonstrates that significant changes in ocean biogeochemistry can result in niche partitioning at fine taxonomic scales.

Subseasonal to seasonal variation of thermodynamics and hydrodynamics in the north Indian Ocean as related to the summer monsoon

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We found that the Southwest (Summer) Monsoon onsets, as observed by the Advanced Scatterometer (ASCAT) in the two embayments of the North Indian Ocean are preceded by a surge of sea surface temperature (SST) measured by Tropical Rain Measuring Mission (TRMM) microwave imager (TMI) above the deep convection threshold, and the changes occur earlier in the Bay of Bengal than in Arabian Sea. The surface shortwave radiation, which is the major surface thermal forcing, derived from the Moderate-Resolution Imaging Spectroradiometer (MODIS), is strong through the entire pre-monsoon season in both embayments. The SST surges are found to coincide with a shallowing of the ocean mix-layer exhibited by an ocean general circulation model, and corresponds to the freshening of the surface as observed by the salinity sensor, Aquarius. The onset of summer monsoon is marked by rain episodes, revealed by TRMM, with clear mesoscale signatures on top of the seasonal reversal of salinity advection. The rain episodes also have clear correspondence with the intraseasonal variation of surface shortwave radiation; both are related to cloud cover. Radiation and hydrologic forcing are found to be closely related in the intraseaonal scales.

Phytoplankton biogeography, primary productivity and nitrogen uptake in the ultra-oligotrophic Indian Ocean

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Biogeochemical data from the central Indian Ocean is currently limited, but it is known that there are stark geographical gradients in the physical and chemical conditions that may lead to unique biogeochemical regimes. As participants on the IO9N GO-SHIP cruise, a transect from 28ºS to 18ºN in the Indian Ocean completed in spring of 2016, samples for nutrient uptake and phytoplankton cell counts were obtained at approximately every other degree of latitude. Stable isotopically labeled ^{13}C-bicarbonate was used to measure primary productivity and ^{15}N labeled nitrate, ammonium, and urea to measure uptake of nitrogen compounds in near surface waters (~20 m). Nitrate and phosphate concentrations were below detection limits throughout the surface 50 m, while ammonium was undetectable at all stations and depths measured. Below ~50 m, nitrate and phosphate concentrations steadily increased from south to north, to a maximum of 31 and 2.2 µM respectively, with their supply ratio (N:P) always below 15. Absolute uptake rates of all N compounds were less than 1.5 nmol N L^{-1} h^{-1} south of 15ºS, and steadily increased until highest observed values were reached between 1.5-6.5ºN; 1.8, 5.2, and 5.1 nmol N L^{-1} h^{-1} for nitrate, ammonium, and urea respectively. In the Bay of Bengal (10- 18ºN), uptake rates were not variable, with a mean of 0.86, 3.2, and 3.1 nmol N L^{-1} h^{-1} for nitrate, ammonium, and urea respectively. Ammonium and urea uptake rates were consistently 3-5 times higher than concurrent nitrate uptake rates, with a mean observed f-ratio of 0.23 for the entire transect. Rates of primary production followed the same general trend of nitrogen uptake, with a maximum of 77.8 nmol C L^{-1} h^{-1}. Cell counts by flow cytometry indicate that at all stations and depths, heterotrophic bacteria dominated in both numerical abundance and biomass. *Prochlorococcus* was the dominant phytoplankton group, but with increasing contributions of *Synechococcus* and small eukaryotes from south to north. This data represents the first reported direct measurements of primary production, nitrogen uptake, and phytoplankton abundance in the eastern central Indian Ocean, a large but relatively understudied region of the global ocean.

Regulation of phytoplankton biomass and productivity in the Arabian Sea: A review

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Phytoplankton in the Arabian Sea have adequate light and nutrients throughout the seasons. Nutrients are never limiting, surface irradiance shows little seasonal variability; and vertical

mixing never exceeds the critical depth. Phytoplankton biomass varies with the monsoons, but moderately: the phytoplankton appear never to reach their growth potential in terms of biomass. The "dilution hypothesis," originally proposed in Marra and Barber (2005, Progr. In Oceanography), suggests that mixing dilutes grazers and phytoplankton alike, but that phytoplankton growth then exceeds grazing until an equilibrium between growth and grazing is re-established. The dilution hypothesis explains (1) the moderate biomass variability over the seasons, (2) the high rates of primary production relative to observed changes in phytoplankton biomass, (3) the secondary role of nutrients, and (4) the importance of the mixed layer depth variability to seasonal dynamics. The Arabian Sea is an ideal place to study the interplay among mixing, growth, and grazing in the plankton.

Cooling and salinification of the Red Sea Eastern Boundary Current due to wintertime westward mountain-gap wind jets

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The Red Sea Overflow Water (RSOW) is one of the most saline water masses of the global oceans. It is formed in the northern Red Sea as part of the Red Sea Overturning Circulation. The RSOW is exported to the Indian Ocean and affects both adjacent and remote areas at intermediate depths. Its salty signal has been found as far as the southern tip of Africa and also off western Australia, and may even contribute to the Indo-Atlantic water exchange through Agulhas eddies, possibly being a component of the global overturning circulation. It is believed that maximum RSOW production occurs during the boreal winter as a result of intense evaporation and surface cooling, especially under extreme meteorological conditions. One of these conditions is the onset of the wintertime mountain-gap wind jets along the northern Red Sea eastern boundary. According to model simulations, this region is dominated by a surface poleward Eastern Boundary Current (EBC) that becomes cooler and saltier as it moves northward due to strong air-sea fluxes. In the present work, we investigate the effects of the wintertime mountain-gap wind jets on the EBC through analysis of in situ observations from a heavily instrumented WHOI air-sea interaction mooring deployed between 2008-2010, the Satellite Sea Surface Temperature from the Multi-scale Ultra-high Resolution (MUR) product, and 1/12 HYCOM Reanalysis outputs. We show that during westward wind jet events the eastern boundary becomes cooler and saltier (denser) than usual, the mixed layer deepens and the EBC signature disappears from SST images. Analyses of terms in the mixed-layer temperature equation during these events indicate that the cooling is dominated by both heat loss and entrainment

Comparative behavior & distribution of iron in the Western Indian Ocean and Eastern Tropical South Pacific: A GEOTRACES Synthesis

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Results of the Japanese GEOTRACES section highlights the Importance of the Arabian Sea OMZ and Hydrothermal inputs of iron into the basin. There are intriguing similarities with the Eastern Tropical South Pacific GEOTRACES Section, suggesting common processes. My group participated in both cruises, and I have carried out two independent surveys of iron cycling in both basins as well. Here a synthesis is presented to highlight key processes. It is accompanied by modelling efforts by Tim De Vries and Al Tagliabue that enables and assessment of hydrothermal sources of iron to the Southern Ocean from the Indian Ocean. A key common feature is the deep iron plume underneath each OMZ within deep oxygenated waters. It is unclear how these deep iron plumes arise.

Circulation and carbon budget in the Kerguelen Plateau region

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The Kerguelen Plateau (KP) region in the Indian Ocean sector of the Southern Ocean is well known for (1) its complex ocean circulation, and (2) its elevated chlorophyll concentration associated with phytoplankton activity. Given the important role of phytoplankton blooms in carbon sequestration, this region is a fundamental component of the Southern Ocean carbon cycle. Previous studies showed that natural fertilization is at the base of the KP bloom, but the mechanisms that supply iron into the euphotic layer and the physical-biological impact on the KP carbon cycle are not fully understood.

A series of modeling studies are used to investigate the two components that make the KP region unique. First, the circulation in the KP area is investigated using two very high-resolution ocean models (1/20 deg and 1/80 deg resolution), that resolve length scales from 4 km down to approximately 1km, thus resolving the scales at the meso- and submesoscales. By using a simple model for the evolution of iron concentration, applied to a set of Lagrangian particles released into the meso- and the submesoscale-resolving models, it is found that the vertical flux of iron to the base of the mixed layer is enhanced by a factor of 2 in the submesoscale case.

Furthermore, a 1/3 deg physical-biogeochemical state estimate is used to analyze the footprint of the KP bloom on the carbon budget. The KP bloom is one of the largest productive area in the

Southern Ocean, and results indicate a large variability in the ocean carbon uptake, driven by both the ocean circulation and the large seasonal variability of the biological activity.

Coordinated multi-platform autonomous observations in the northern Arabian Sea interior

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Arabian Sea High Salinity water occupies the interior of the Northern Arabian Sea from the surface to 100-150 m depth. This water mass is created by complex stirring and mixing of the high-salinity waters of the Red Sea and the Persian Gulf with relatively fresh waters originating in the Bay of Bengal. The resulting thermohaline structure is characterized by numerous fronts in the horizontal, and multiple interleaved layers in the vertical. Salinity stratification of the upper ocean inhibit entrainment of cool thermocline water into the mixed layer and thus allow faster warming of the surface ocean in spring; this, in turn, has a pronounced local climate effect and may control the onset of the Summer Monsoon. Frontal stirring, interleaving, and subduction are known to be patchy and intermittent phenomena associated with a range of instabilities on scales from 1 to 100 km. Analysis of the historic Argo profiling float observations allowed us to identify the “hot spots” for these processes in the Northern Arabian Sea. Sporadic float observations, however, provide little information on the 3-dimensional synoptic structure of the frontal zone and the associated subduction features.

To remedy this gap of knowledge, the ONR NASCar DRI team organized a focused multi-platform observational study intended to characterize the scales and structure of the upper-ocean fronts and interleaving layers in the Northern Arabian Sea. A cluster of autonomous instruments (ALAMO and APEX profiling floats, Seagliders, and surface drifters) was deployed on 4 March 2017 along the 1,300-km line crossing the interior Arabian Sea from northwest to southeast. For the next 50 days, the Seagliders navigated in a coordinated formation around the target ALAMO floats, mapping the evolution of the fine-scale horizontal and vertical thermohaline structures in the interior of the basin.

Indian Ocean overturning, diapycnal mixing, and heat/freshwater budgets

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The Indian Ocean's role in the global overturning circulation is to upwell abyssal waters to deep and thermocline waters, and also to export thermocline waters from the Indian and Pacific into the Atlantic Ocean. Three different aspects of this role are examined using a combination of hydrographic observations, Argo profiles, and high-resolution models: (1) transports, structure and variability of the overturning volume, heat and freshwater transport, (2) distribution of diapycnal diffusivity and diapycnal mixing in the deep Indian Ocean, and (3) pathways of export of Indian Deep Water to the Southern Ocean. Important to the global biogeochemical balances, the IDW, along with Pacific Deep Water, is a carbon and nutrient rich water mass, which, when it upwells to the surface in the Southern Ocean, outgases CO_2 to the atmosphere and provides nutrients to the global thermocline.

(1) The GO-SHIP I5 sections at 30°S in 2002-2003 and 2009 were used to diagnose the Indian Ocean overturning circulation and its changes. Vertical structure of the overturn changed, associated with a large increase in southward heat transport. Diagnosed net evaporation also more than doubled in the Indian Ocean. These increased heat and freshwater exports coincided with Indian Ocean warming, a shift in the Indian's shallow gyre overturning transport to lower densities, and an increase in southward Agulhas Current transport from 75 Sv in 2002 to 92 Sv in 2009. The Indian's deep overturn weakened from about 11 Sv in 2002 to 7 Sv in 2009. (Hernandez-Guerra and Talley, Progress in Oceanography, 2016)

(2) We use the fine scale parameterization for diapycnal diffusivity with WOCE CTD/LADCP profiles to map dissipation, diffusivity, and diapycnal mixing of heat, salt and buoyancy relative to topography, isoneutral surfaces that span the water column, and monsoon phase (northern Indian). Largest deep diapycnal mixing is found in the most energetic regions: downstream of Kerguelen Plateau, in the Agulhas, in the complex of western boundary currents along Madagascar, Somalia and the Arabian Sea, and along the eastern boundary (throughflow, Australian coast and Andaman Sea). Regions of high deep diffusivity but low diapycnal mixing include the Central Indian and West Australia Basins where the deep waters have low stratification. Regions of lowest mixing and lowest diffusivity, top to bottom, are the Bay of Bengal and central Arabian Sea. Upper ocean diffusivities are much lower than in the deep ocean, and match published estimates from Argo profiles (Whalen et al., GRL 2012).

(3) High resolution models show the export pathways of Indian Deep Water to the Southern Ocean, importantly along the western boundary as part of the Agulhas, equally importantly along the eastern boundary and then eastward along Australia's southern coast (a 'deep eastern

boundary current'), and more diffusely along the Southwest Indian Ridge. Hydrographic observations at 30°S (GO-SHIP I5) reflect these pathways.

An Indian deep water pathway along the southern coast of Australia

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Indian Deep Water (IDW) is an important source of carbon and nutrient-rich deep water that upwells in the Southern Ocean. However, until recently the exact pathways that carry IDW from the Indian Ocean into the Antarctic Circumpolar Current (ACC) were not well characterized. New work has identified two dominant pathways of deep upwelling water exiting the Indian Ocean along its western and eastern boundaries. While a current has been identified in observations at 115°E by its eastward transport and low oxygen content, characteristic of IDW, the role of this flow as an important upwelling pathway has not been appreciated and its physical cause has not been shown. Here we characterize the eastern IDW pathway and investigate its underlying dynamics with a combination of hydrographic observations and Lagrangian experiments in an eddy-permitting model. We find an eastward flow extending between 1500 m and 4000 m along the Australian continental slope, reaching the ACC southwest of Australia. We hypothesize that an eddy thickness flux mechanism that has been shown to drive an eastern deep water pathway in the Atlantic may also operate in the Indian, driven by eddy transport around the southwest tip of Australia.

INDO-US collaborative Project ASIRI-OMM

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Air-sea interactions in the Northern Indian Ocean- Regional Initiative (ASIRI) Ocean Mixing and Monsoons (OMM). Indian and United States institutions collaborating on establishing a legacy of ocean observations, models, human and technological capacity for improved cyclone and intraseasonal monsoon forecasts.

- Training and capacity building
- A multi-faceted approach for multi-scale processes
- Multi-scale ocean modeling
- Observational tools

Seasonal cycle and annual reversal of the Somali Current in an eddy-resolving global ocean model

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The dynamics of the Somali Current are studied using an atmospheric reanalysis forced strongly eddying global ocean model. With the help of the numerical model, we examine the controlling dynamics of the Somali Current at various latitude. We find that the Somali Current system consists of three distinct different dynamical regimes that become active leading up to the onset of the southwest monsoon. The northern regime (roughly north of 6°N – 10°N) is the first to reverse from southward to northward during early boreal spring due to the arrival of a downwelling Rossby wave that propagated across the Arabian Sea from the tip of India. The flow in the southern regime (near the equator south of 2°N) which also reverses earlier than the local wind, is largely affected by the northward flowing Eastern Africa Coastal Current. The reversal of the flow in the central regime (between 2°N and 6°N) matches most closely to the timing of the wind reversal, but is also affected by the advection of northward momentum from the south.

Central Indian Ocean Mode and Indian summer monsoon

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A Central Indian Ocean (CIO) mode is found to play a critical role in driving the heavy precipitation during the Indian summer monsoon (ISM). It is typically denoted with a combination of intraseasonal sea surface temperature (SST) anomalies and intraseasonal wind anomalies over the central Indian Ocean, and it preserves the mechanistic links among various dynamic and thermodynamic fields. Like a T-junction, it controls the propagation direction of the intraseasonal variabilities (ISVs) originating in the western Indian Ocean. During the ISM, the CIO mode creates an environment favorable for the northward-propagating mesoscale variabilities. Besides the intraseasonal variabilities, the CIO mode also has pronounced seasonal and interannual variabilities. The CIO mode is active during boreal summer, but suppressed during boreal winter. The seasonality is mainly attributable to the barotropic instability which is caused by the large meridional shear of zonal winds. The identification of the CIO mode deepens our understanding of the coupled monsoon system and brightens the prospects for better simulation and prediction of monsoonal precipitation in the affected countries. However, evidence shows that modern ocean-atmosphere coupled models

are likely to lack the ability to capture the CIO mode, which requires more diagnosis and significant model improvement in the future.