A **K**orea-**U**S in**D**ian **O**cean **S**cientific (KUDOS) Research Program

on the

Physical, Biogeochemical and Ecological Dynamics of the Seychelles-Chagos Thermocline Ridge

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Table of Contents

Preface

This document is the outgrowth of a workshop held at Seoul National University over 29 November – 1 December 2017 attended by 30 Korean and U.S. scientists with shared interests in Indian Ocean research (https://kiost-noaa-lab.wixsite.com/kudos). The workshop was motivated by the successful maiden voyage to the Indian Ocean in July 2017 of the new Korean global class research vessel *Isabu*, operated by the Korean Institute of Ocean Science and Technology (KIOST), on which U.S. participants from the U.S. National Oceanic and Atmospheric Administration (NOAA) successfully recovered and deployed three moored buoys of the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA). The goals of the workshop were threefold:

1. To review the status of Indian Ocean research programs with relevance to Korean and U.S. interests in the Second International Indian Ocean Expedition (IIOE-2);

2. To identify new opportunities for collaborative research among investigators in Korea, the U.S., and elsewhere over the next 5-years, taking advantage of ongoing and planned Indian Ocean research initiatives; and

3. Establish a network of Korean, U.S. and international investigators to advance a research agenda of mutual interest within the framework of IIOE-2.

With regard to the second objective, workshop participants identified the Seychelles-Chagos Thermocline Ridge (SCTR) region for a coordinated research focus over the 5-year period 2018-2022. As described in this scientific plan and implementation strategy, the SCTR presents many compelling research problems of mutual interest to Korean and U.S. investigators that are at the forefront of ocean science. Many of these problems are interdisciplinary in scope and cut across multiple themes of the IIOE-2 science plan. They are tractable with existing technologies, offer the potential for major breakthroughs in our understanding, and are of great societal relevance. Moreover, a Korean-U.S. focus on the SCTR will provide a unique complement to other national IIOE-2 contributions.

The authors would like to thank KIOST and NOAA for supporting the workshop. We also thank Seoul National University for hosting the workshop at Hoam Faculty House.

Abstract

The Seychelles-Chagos Thermocline Ridge (SCTR) is a feature unique to the Indian Ocean – it is a consequence of the meridional asymmetry in the Indian Ocean circulation that arises as a result of geometry of the Indian Ocean and its strong monsoon forcing. The SCTR strongly influences atmospheric convection in both the Indian and Pacific Oceans via initiation of the Madden-Julian Oscillation (MJO) and it is also an important foraging ground for tuna. Yet, in large part because of its remote location, the current understanding of the physical dynamics of the SCTR remains rudimentary at best, while knowledge of the biogeochemical and ecological dynamics is even less developed. Moreover, sea level has been falling and the thermocline shoaling in the SCTR region in association with a trend towards rising SSTs in the Indian Ocean since the 1960s. These trends are likely due to changes in atmospheric circulation in response to anthropogenic greenhouse gas forcing. How future global warming may affect the SCTR and its impacts on patterns of weather variability in the Indian Ocean region and over East Asia, North America, and other parts of the globe, is poorly known if at all. Likewise, how marine biogeochemistry, carbon cycling, ocean acidification, ecosystems and fisheries will change in the SCTR under continued anthropogenic greenhouse gas forcing is highly uncertain.

This document describes a science plan and implementation strategy for studying the SCTR that is structured around five themes, each of which presents significant opportunities for profound advances in our ability to understand and predict dynamical variability in the region, its far field impacts, and its effects on biogeochemical processes and ecosystem function in the Indian Ocean. The five themes are: 1) ocean-atmosphere interactions; 2) ocean circulation; 3) biogeochemical and carbon cycles; 4) climate variability, change and extreme events; and 5) ecosystems and fisheries. We introduce each theme, followed by a short list of high level scientific questions and an outline of observational and modeling implementation strategies for how to address them.

1. Introduction

The Seychelles-Chagos Thermocline Ridge (SCTR, Vialard et al., 2009) is characterized by a relatively shallow thermocline and thin mixed layer (~30m) across the south tropical Indian Ocean in the latitude band 5-15°S (Fig. 1). The ridge is set up by wind stress curl patterns and it undergoes significant variations on seasonal and interannual time scales due to both local and remote forcing (Fig. 2; Xie et al, 2002; Hermes and Reason, 2008; Yokoi et al., 2008; McPhaden and Nagura, 2014; Nyadjro et al, 2017). It marks the southernmost latitudes of monsoon-driven circulation in the Indian Ocean, to the south of which a steadier trade wind regime prevails (Fig. 2). The Intertropical Convergence Zone is located over the SCTR during boreal winter; as the year progresses the convergence zone and associated rainfall migrates northwards to the Indian subcontinent where it is the source of precipitation during the summer monsoon.

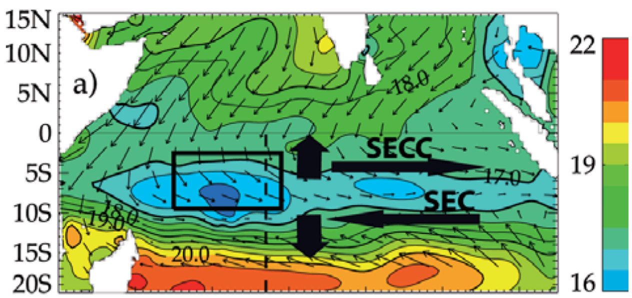

Figure 1. Climatological surface winds and 0–300 m average ocean temperature in Jan–Feb. The thick black arrows indicate the surface flow induced by wind that promotes upwelling and leads to the SCTR formation. The arrows marked SEC and SECC indicate the south equatorial current and south equatorial countercurrent. From Vialard et al (2009).

The SCTR is a region of significant upwelling, which affects sea surface temperature (SST), ocean-atmosphere coupling, biogeochemistry, and fisheries (Fig. 3). Unlike in the easterly trade wind-forced Pacific and Atlantic Oceans, upwelling centers in the monsoon-dominated Indian Ocean are found in off-equatorial regions because the mean winds along the equator are westerly (Schott et al, 2009; Wang and McPhaden, 2017). The SCTR is the most geographically extensive and persistent of these upwelling regions, which also include the Somali coast, the Sri Lankan Dome, and the coastal zone off Sumatra and Java.

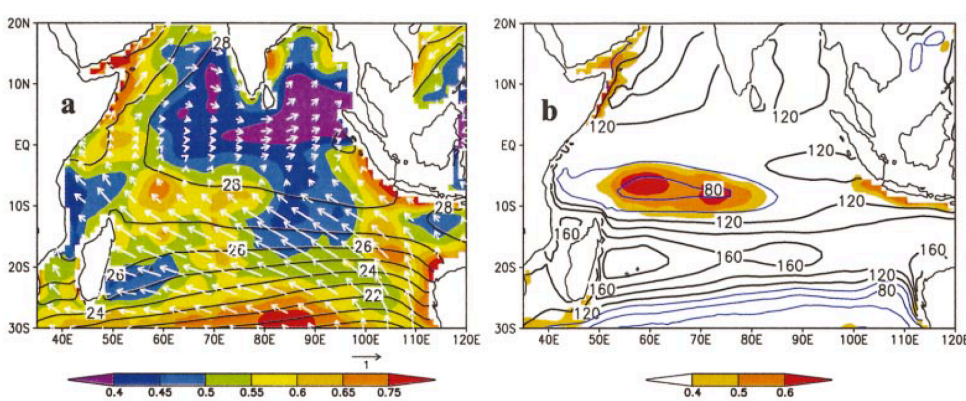

Figure 2. Annual mean distributions of (a) wind stress (vectors in N m^{-2}), SST (contours in

°C) and its interannual rms variance (color shading); and (b) the 20°C isothermal depth (contours in m) and its correlation with local SST anomalies (color shading). From Xie et al (2002).

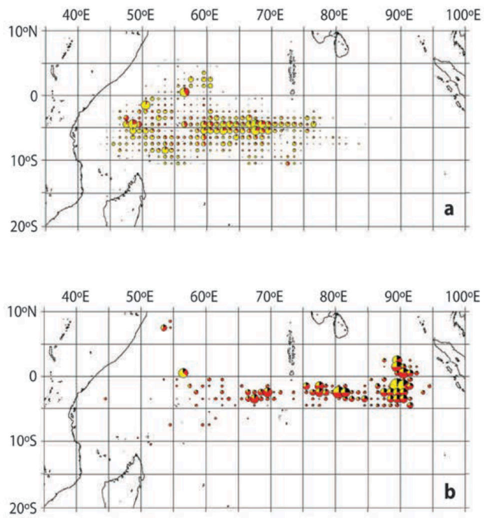

Figure 3: Tuna catch in the Indian Ocean during (a) in normal years compared to (b) the 1997/1998 IOD event. From Robinson et al. (2010). ©Inter-Research 2010.

Upwelling in the SCTR, which represents the ascending branch of the subtropical circulation cell in the southern hemisphere, is balanced primarily by meridionally divergent flow in the surface layer (Lee, 2004; Fig. 4). Horizontal flow circulates cyclonically around the ridge axis, with the westward South Equatorial Current (SEC) to the south and the eastward South Equatorial Countercurrent (SECC) to the north (Fig. 1). The SEC and westward flowing ITF in the SCTR region are the conduit for interbasin exchanges that link the Pacific Ocean to the Atlantic Ocean through the Indonesian Seas and the Agulhas Current.

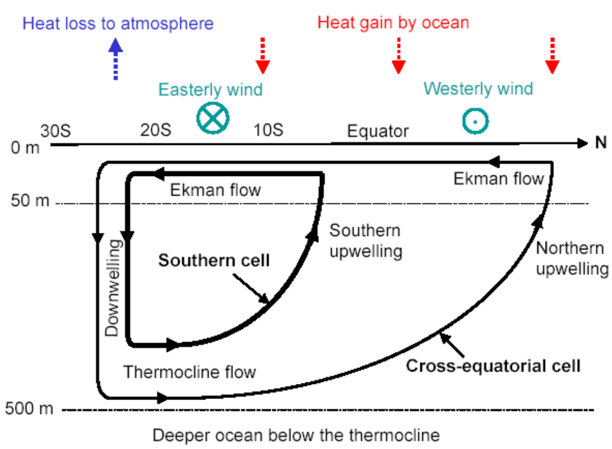

Figure 4. Conceptual illustration of the time-mean meridional overturning circulation of the upper Indian Ocean that consists of a southern and a cross-equatorial cell. The time-mean zonal wind and surface heat flux are also shown schematically. This flow is believed to partially supply the cross-equatorial thermocline flow. From Lee (2004)

SST variations are relatively strong in the SCTR on intraseasonal to interannual time scales (Figs. 2 and 5), because the shallow mixed layer is sensitive to changes in air-sea heat fluxes, upwelling, vertical mixing, and horizontal advection (Vialard et al, 2008; Foltz et al., 2010). Pronounced SST variations on intraseasonal time scales are a response to forcing from the MJO (Madden and Julian 1972), which is spawned in this region. Those variations feedback to the atmosphere to help organize the MJO convective variations. On interannual time scales, large SST variations are associated with the Indian Ocean Dipole (IOD; Webster et al., 1999; Saji et al., 1999) and El Nino Southern Oscillation (ENSO). These year-to-year SST variations affect the frequency of tropical storms in the southwestern Indian Ocean (Xie et al., 2002), Indian summer monsoon rainfall (Izumo et al., 2008), and the climate of East Asia (Yamagata et al, 2004). For Korea in particular, a positive IOD is associated with a hot and dry summer and opposite conditions are more likely to occur during a negative IOD. The IOD also profoundly affects the tuna fishery in the Indian Ocean, which is well developed in the SCTR region during normal years (Fig. 3). However, during the positive IOD event of 1997/1998 when upwelling weakened in the SCTR and increased dramatically off the coast of Java and Sumatra, tuna migrated eastward, presumably in search of more favorable foraging grounds (Fig. 3, Robinson et al., 2010).

Observational studies have documented concentrated tuna fishing activities at precise locations where surface phytoplankton blooms had been observed in satellite observations 2-3 weeks previously (Fonteneau et al. 2008), invoking a strong connection between the food webs that respond to SCTR blooms and the prey required by large tuna. Studies of apex predator distributions, particularly in context of spawning and recruitment, demonstrate that oceanic convergence zones are critical to their concentrated appearance (Bakun et al., 1998; Polovina et al., 2001). In contrast, biogeochemical modeling results indicate that both phytoplankton biomass and carbon export from the euphotic zone change little in response to seasonal and interannual variability of the SCTR thermocline depth (Resplandy et al., 2009). These contrasting scenarios define a paradox in the current understanding of ecological dynamics in the SCTR upwelling region. It is also unknown to what extent iron may be a limiting micronutrient for primary production in the SCTR region, though independent modeling studies and remote sensing-based analyses both suggest it may be (Wiggert et al, 2006; Behrenfeld et al., 2009). Finally, there is a high degree of uncertainty in whether the Indian Ocean is a net source or sink of carbon to the atmosphere because the variability in pCO_2 fluxes across air-sea interface is poorly constrained by existing observations, particularly in active upwelling zones like the SCTR.

Sea level has been falling (Han et al., 2010) and the thermocline shoaling (Alory et al., 2007) in the SCTR region in association with a trend towards rising SSTs in the Indian Ocean since the 1960s. These trends are likely due to changes in atmospheric circulation in response to anthropogenic greenhouse gas forcing (Dong and Zhou, 2014). How future global warming may affect the SCTR and its impacts on patterns of weather variability in the Indian Ocean region and over East Asia, North America, and other parts of the globe, is poorly known if at all.

Variability originating in the SCTR is of profound societal relevance. Ocean-atmosphere interactions in this region across a broad range of time scales from synoptic to interannual and longer affect the Indian, East Asian, African and Australian monsoons, which collectively support the agricultural production of one third of the world's population. The MJO affects the formation of severe meteorological events (cyclones, typhoons, and hurricanes) in all three tropical oceans, with enormous consequent impacts on people and property in the path of these storms. The SCTR also affects regional biogeochemistry and fisheries. Recent yellowfin tuna stock assessments indicate that this fishery is subject to overfishing driven by unsustainable catches combined with relatively low recruitment levels estimated by models (IOTC, 2017). Yet, these assessments are based on fisheries models that are not informed by an understanding of the food web dynamics of the SCTR. Studies focused on the dynamics of the SCTR will provide understanding that is needed to better predict tropical storms, monsoon rainfall, the MJO and the IOD and their far field impacts. Biogeochemical and ecological studies will provide the information that is needed to determine the connection between the marine food web and availability of tuna forage in the SCTR which will, in turn, improve fishery management practices. Collectively, these studies will provide greater insight into how the SCTR influences weather, climate, marine ecosystems, fisheries and ultimately human populations around and beyond the Indian Ocean rim.

2. Scientific Themes

2.1 Ocean-Atmosphere Interactions

Background

The ocean and the atmosphere interact across a wide range of time and space scales in the Indian Ocean with certain regions, like the SCTR, where these interactions are particularly vigorous. These interactions give rise to monsoonal circulation patterns that are modulated on interannual time scales by the IOD and ENSO, on decadal time scales by low frequency processes, and by global warming. Also, embedded in the monsoon system are higher frequency intraseasonal oscillations that lead to pronounced SST variations in the SCTR (Fig. 5) and that generate active/break periods in rainfall. Understanding the multi-time and space scale interactions that generate the unique circulation features of the Indian Ocean and overlying atmosphere therefore require a better understanding of the fluxes of heat, moisture and momentum across the air-sea interface. Determining the aeolian sources of iron (Fig. 6), the spatio-temporal variations of iron deposition in the ocean, the bioavailability of dust-derived iron, and identifying any boundary sources (e.g., the Mascarene Plateau) contributing to lateral advection of dissolved iron into the SCTR, are all crucial for understanding planktonic species assemblage and primary production in this region and the overall role in ecosystem dynamics. Similarly, pCO_2 fluxes across the air-sea interface are a critical component of the carbon cycle. However, these fluxes, and how they vary in space and time, are poorly constrained by existing measurements. The research strategy for understanding ocean-atmosphere interactions in the SCTR should involve coordinated interdisciplinary studies that focus on the following fundamental questions to advance the integrated understanding of the physical, biogeochemical, and ecological dynamics of the region.

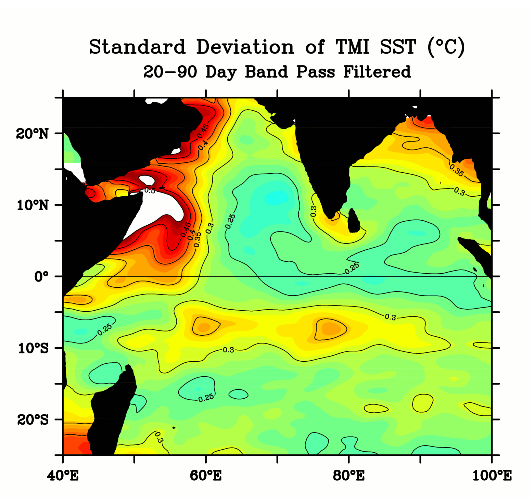

Figure 5. Standard deviation of SST in the 20-90 day period band based on TRMM Microwave Imager (TMI) SSTs. Variability in the SCTR region is related to the Madden-Julian Oscillation whereas in the Arabian Sea, variability is related to ocean eddies in the Somali Current.

Scientific Questions

Key questions related to physical oceanography and climate include:

- ***What is role of the air-sea heat flux in generating SST variability in the SCTR region relative to other mixed layer processes, such as vertical mixing and horizontal advection, and how do these fluxes vary across time scales? How do fresh water fluxes due to rainfall variations affect upper ocean stratification, barrier layer formation and the mixed layer heat balance? What is the impact of SST variations on the overlying atmosphere and does the feedback between the ocean and atmosphere in this region influence coupled modes of variability in the basin?***

- ***What is the relative importance of local versus remote wind stress forcing on the three-dimensional circulation of SCTR and how does this forcing vary on intraseasonal, seasonal, interannual, and longer time scales?***

Key questions related to carbon and micro-nutrient fluxes across the air-sea interface include:

- ***What are the aeolian sources of iron, and the spatio-temporal variations of iron deposition in the SCTR region? What is the bioavailability of aeolian iron? How do these sources compare with oceanic sources of iron? Is primary production in the SCTR iron-limited? What is the ecosystem response to iron stress?***

- ***How does the pCO_2 flux change in space and time over the SCTR region? What processes control these fluxes? How do these fluxes compare with those in other parts of the Indian Ocean, e.g. in the Bay of Bengal and Arabian Sea?***

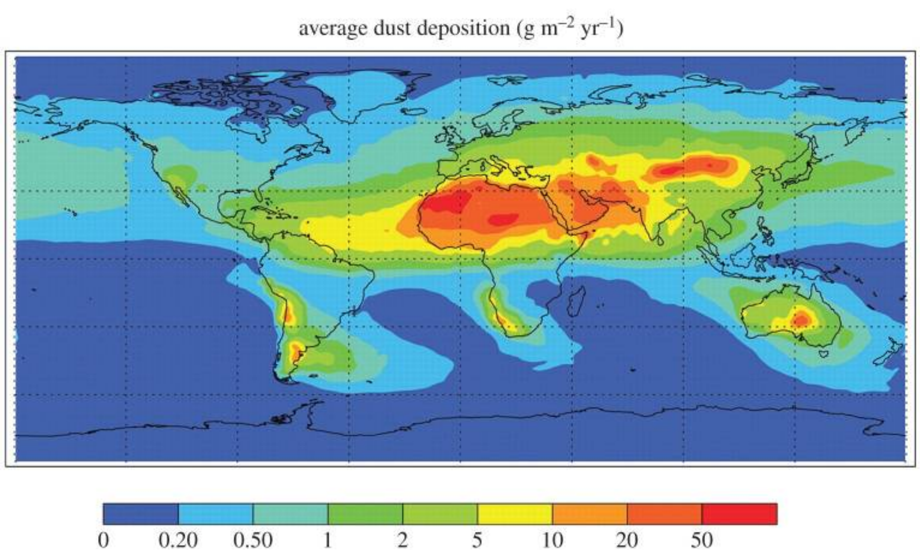

Figure 6. Modelled dust fluxes to the oceans and land surface. From Jickells et.al. (2005).

Implementation Strategies

Addressing scientific questions in the SCTR will benefit from a variety of satellite measurements, including those for SST, sea surface height and salinity, winds, ocean color, aerosol optical depth, and rainfall. Complementing these satellite data are measurements from the Indian Ocean Observing System (IndOOS) for temperature, salinity, velocity, air-sea fluxes of heat, fresh water and momentum, surface air pressure, and biogeochemical measurements (chlorophyll fluorescence, particle backscatter, pCO_2 and air-sea CO_2 flux, pH). Expanded deployment of biogeochemical sensors on the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA; McPhaden et al., 2009) moorings, expanded biogeochemical Argo deployments and new multi-disciplinary glider measurements will also be of great value. Higher vertical resolution of temperature, salinity, and velocity in the mixed layer on the RAMA flux reference site mooring in the SCTR at 8°S, 67°E will be required to resolve the details of the diurnal cycle and its impact on modes of ocean-atmosphere interaction. Research vessels, including those servicing RAMA moorings, provide platforms for specialized measurements to test hypotheses related to SCTR variability and its impacts on climate, ecosystems and fisheries. Forced ocean models will also be valuable for studies of physical and coupled biophysical processes in the SCTR. Coupled climate models such as the CMIP5 (Coupled Model Intercomparison Project phase 5) can be used to address recent and future trends in the region under various greenhouse gas forcing scenarios.

Focused research cruises that conduct critical measurements or test hypotheses that cannot be done rigorously by remote observations or models should be motivated to advance the phenomenological and mechanistic understanding of physical, biogeochemical and ecological dynamics at the SCTR. Shipboard studies that address the current measurement deficiencies in physical processes related, for example, to atmospheric forcing variability, air-sea exchange and upper ocean mixing, can help provide insight into the relative importance of local versus remote wind stress forcing on the three-dimensional circulation of SCTR. Shipboard studies can also help constrain estimates of upwelling in the SCTR and the impacts of upwelling on SST. In addition, shipboard studies should be motivated to address the hypothesis that the thermocline ridge may function more as a concentration center for larger prey that are transported to the area from adjacent ocean regions. In this regard, large stocks of mesopelagic fish are thought to occur in the Arabian Sea to the north of the SCTR and off of Somalia to the west (Kinzer et al., 1993; Tsarin and Boltachev, 2006), but have not been assessed systematically in the region. Such systematic assessments, as well as characterization of the makeup and behavior (e.g., diel motions) of the planktonic communities supporting pelagic communities, can be performed through the combined utilization of modern imaging and acoustic technologies (Trevarrow et al., 2005). Shipboard experimental studies that address the measurement deficiencies in primary production, nutrient and light responses and limitations, new production and carbon export, community structure, food-web dynamics, carbonate system parameters, and biogeochemical process indices are also needed to enable regional models that can assess the relative importance of in situ productivity versus transport mechanisms in explaining the system's unique coupling to higher trophic levels, the implications of SCTR dynamics to Indian Ocean biogeochemistry, and their potential vulnerabilities to climate change.

2.2 Ocean Circulation

Background

The KUDOS research program involves studies of off-equatorial upwelling in SCTR which constitutes the ascending branch of the three-dimensional subtropical cell (STC) in the southern hemisphere. Variability in this upwelling and its effects in the SCTR region need to be understood in the context of the entire STC. The shallow STC also involves subtropical subduction (~25ºS) that ultimately feeds the upwelling in the SCTR (Fig. 4). How the STC and subduction vary in time and space and how upwelling in the SCTR varies in relation to other branches of the STC is poorly understood.

Scientific questions

The SCTR is a large region of significant upwelling in the Indian Ocean, which impacts on 1) ocean-atmosphere interaction processes and/thus the climate variability via winds, sea surface temperature (SST), sea surface salinity (SSS), air-sea heat and fresh water fluxes, vertical mixing, horizontal advection, barrier layer, etc, and 2) biogeochemical processes and/thus the marine ecosystem via nutrient supply, carbon cycling, biological productivity, etc. The temporal variability includes, but is not limited to, intraseasonal, seasonal, interannual, decadal, and longer-term changes in upwelling/subduction and STC intensity. In particular, regional modes of interannual, seasonal, and intraseasonal climate events like the Indian Ocean Dipole (IOD), Indian Ocean monsoon, and Madden-Julian Oscillation (MJO) are linked to the temporal variability of SCTR upwelling. Moreover, there is an asymmetric relationship between wind, SST, and the thermocline in the SCTR during positive vs. negative IOD events (Nyadjro et al., 2017). IOD development is also associated with Kelvin and Rossby wave dynamics that affect volume transport variations of the Wyrtki jets along the equator (McPhaden et al., 2015). Fundamental questions related to circulation in and around the SCTR are:

- **What is the three-dimensional structure and temporal variability of the STC? How does upwelling and the relationship between wind, SST, and thermocline depth in the SCTR vary in relation to changes in the STC circulation on: 1) intraseasonal time scales related to the MJO; 2) seasonal time scales related to the monsoons; 3) internannual time scales related to the IOD; and 4) decadal and longer time scales?**

The SCTR is dynamically connected to strong zonal currents like the SEC and SECC, to zonal and meridional volume transports, and to turbulent vertical and horizontal processes. It is also influenced by both local wind forcing and by horizontal divergence and convergence associated with remotely wind forced equatorial Kelvin and Rossby waves. These considerations lead to the following questions:

- **What are physical drivers of the SCTR circulation and its temporal variability? How do local wind stress curl variations and remote wind-forced equatorial waves affect the three-dimensional SCTR circulation? How are the SCTR upwelling and subtropical subduction dynamically linked to the SEC/SECC, large-scale circulation in the Indian Ocean, and turbulent mixing processes?**

Implementation Strategies

The existing Indian Ocean Observing System, including but not limited to the fixed RAMA mooring array and moving platforms like gliders, floats, and drifters, need to be maintained and enhanced to complement various satellite measurements. A pilot mooring and ultimately a new time series reference station (tentatively named 'Station K') consisting of multiple fixed and moving platforms should be developed, and a large number of drifters with a 100-m long TC sensor chain (GeoDrifters) should be deployed in and around the SCTR center. These experimental observations should be incorporated into IndOOS. In addition to operational space-borne and sustained in-situ measurements in IndOOS, short-term, process-oriented observations with multiple ADCP moorings, underwater gliders and wavegliders, ship-based water sampling (for sensor calibration as well as biogeochemical and physical measurements) should be conducted focusing on the SCTR region. The new Korean research vessel, *R/V Isabu*, can be best utilized to conduct critical measurements and service key platforms in the region. Global and regional ocean models and coupled climate models can be used in combination with observational results to address scientific questions.

2.3 Biogeochemistry and Carbon Cycles

Background

The SCTR is an open-ocean upwelling region in the western Indian Ocean and an active center of strong ocean-atmosphere interaction, and biogeochemical and ecosystem responses. Over the last two decades, more attention has been paid to understanding the physical mechanisms that are responsible for upwelling and its relation to large-scale climate like ENSO and the IOD than to biogeochemical processes and marine ecosystem dynamics in the SCTR region. However, biogeochemical processes are in part responsible for the oceanic uptake of atmospheric carbon dioxide and its export to the deep ocean and material flux to higher trophic levels. The important scientific questions of the KUDOS research program in relation to the biogeochemical cycles and carbon cycles in the SCTR regions are as follows.

Scientific Questions

Understanding of the factors that drive primary production variability in the surface ocean is crucial for understanding biogeochemical processes and ecosystem dynamics. During photosynthesis, phytoplankton convert dissolved inorganic carbon into particulate organic carbon, which initiates biogeochemical cycles in the ocean and forms the basis of marine ecosystems. Since the fate of primary production in the surface ocean depends on the sources of nitrogen, it is important to understand whether primary production is based on regenerated or new nitrogen. Ultimately, potential fisheries yield scales with the supply of new nitrogen.

- **How much primary production occurs in the SCTR? What are the seasonal and annual rates of net community production (NCP) in the system? What controls the variability in these rates?**

The availability of nutrients is essential to primary production in the surface ocean (Fig. 7). Understanding the mechanisms of nutrient supply in the SCTR region is key to enhancing our ability to predict the response of biogeochemical cycles and marine ecosystems to perturbations covering scales from intraseasonal to decadal, with the latter including anthropogenic perturbations. Since the availability of trace metals is a critical factor that can limit primary production and control the community structure of phytoplankton, it is important to evaluate whether or not primary production in the SCTR is limited by the availability of trace metals (e.g. iron).

- **What are the sources of nutrients (macro-nutrients such as nitrate and micro-nutrients such as iron) that support primary production in the SCTR? Is the mechanism of iron supply primarily aeolian transport, lateral transport in the SECC from African coastal region to the open ocean, or upwelling from below?**

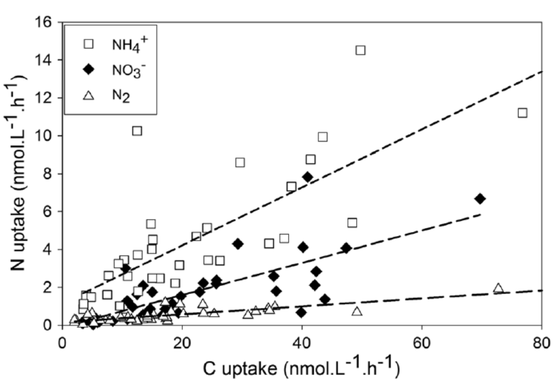

Figure 7. Dissolved inorganic nitrogen assimilation (nmol L^{-1} h^{-1}) versus inorganic C fixation rates (nmol L^{-1} h^{-1}) for different N sources. From Raes et al. (2015)

Along with SST, the fate of organic matter produced in the surface layer determines the ocean's capability to sequester carbon from the atmosphere. A portion of the organic matter produced in surface waters is exported to depth, and the depth interval over which exported organic carbon is regenerated determines the time scale over which physical mixing returns the regenerated carbon dioxide to the atmosphere; carbon exported to below the STC will be sequestered for longer periods. Consequently, the greater the depth of regeneration the larger the amount of carbon that can be sequestered in the deep sea (Kwon et al., 2009). Thus, it is important to understand the fate of organic matter as well as the amount of organic matter produced in the surface ocean.

- **What is the fate of organic matter produced as a function of NCP in the SCTR region? What fraction of NCP goes into DOC and what is the fate of that accumulated DOC? What fraction of NCP is exported to the deeper layer? What is the regeneration depth scale of POC?**

Implementation Strategies

To better understand long-term and large-scale variability of primary production and NCP in response to natural and anthropogenic perturbations, the use of satellite based primary production estimates is essential. The comparison between in-situ primary production measurements and satellite estimates using various algorithms is needed in the SCTR region to verify the satellite estimates of primary production (e.g., Westberry et al., 2008). Primary production measurements should be made in the SCTR (as for example was done on the 2018 KIOST Indian Ocean Study (KIOS2018) cruise in April 2018 using a double labeling technique with 13C and 15N stable isotopes). To understand the mechanisms of nutrient transport into the surface mixed layer, it is highly recommended to carry out synoptic / discrete ship board nutrient measurements as well as continuous time-series measurements using biogeochemical sensors (nitrate sensor, pH, Chlorophyll-a sensor) deployed on existing RAMA moorings or new pilot moorings (Station K) in the SCTR region. Shipboard measurements of physical and biogeochemical parameters should also be conducted in the SCTR region. Deployments of autonomous sensors (e.g., gliders with physical and biogeochemical sensors, Biogeochemical-Argo, etc.) should be motivated to supplement the shipboard and satellite observations.

NCP can be assessed through nitrate mass balance assessments, with nitrate determined using sensors on autonomous systems. NO_3^- upwelled and biologically consumed provides an estimate of NCP (using Redfield ratios) and also how much 'new' carbon accumulates as DOC; POC export can be estimated by mass balance of these variables (POC_{export} = NCP - ΔDOC). These mass balance estimates of export should be cross-checked by deploying traps to measure export directly; traps will be required to quantify export to depths below the STC and to assess regeneration profiles of sinking POC. DOC export is assessed by evaluation of the DOC content of water subducted at convergence zones.

Coupled physical-biogeochemical models of increasing sophistication can be used to link the growth of phytoplankton at the base of the food web to their physical and chemical environment (e.g., Wiggert et al., 2006; Resplandy et al., 2009). These models should be used in conjunction with the in situ physical and biogeochemical measurements to further our understanding of the relationships between physical forcing and biogeochemical response in the SCTR. Furthermore, novel techniques in molecular biology (e.g., transcriptomics and proteomics) can now be used to test and validate the model sensitivity of marine taxa to variability of their physical and chemical environment. These emerging technologies should be applied to improve predictions of the ocean's response to global change, from CO_2 sequestration to fisheries productivity.

2.4 Climate Variability, Change and Extreme Events

Background

Climate variability affecting the physical and biogeochemical conditions of the SCTR is mainly driven by intraseasonal variability associated with the MJO, the seasonal monsoons, and the interannual IOD and ENSO (Vialard et al., 2009; Wiggert et al., 2009). The interannual Indian Ocean Basin Mode (Zheng et al., 2011), which is often excited by ENSO variations, also has a prominent impact on the SCTR. Extreme weather events in the form of tropical cyclones are modulated interannually by variations in SST immediately south of the SCTR between 10°-20°S (Xie et al, 2002). These extreme events have devastating consequences for Madgascar and other nations in the region.

The Indian Ocean is also warming more rapidly than any other ocean basin due to anthropogenic greenhouse gas forcing (Alory et al., 2007), but is cooling below the surface in the SCTR region. How future global warming may affect the SCTR, its biogeochemistry, and the frequency, amplitude, and impacts of extreme weather events in the region are uncertain. Hence, studies of the SCTR in the broader context of the Indian Ocean can provide insights into how future climate change impacts are likely to manifest in the region.

Scientific Questions

Fundamental questions remain unanswered with regard to our understanding of how climate variability and change affects the physical, biogeochemical, and ecological dynamics of the region. Among these are:

- **How well do climate models simulate variability in the SCTR in the present climate? Why is the surface warming in the SCTR region but the subsurface cooling? How will global warming affect variability in the SCTR? How will global warming affect cyclone genesis, strength and impacts in the region?**

- **How is climate variability and change in the SCTR region related to broader scale variations in the Indian Ocean-atmosphere system and especially to East Asian weather and climate?**

- **What are the key processes (local vs remote forcing, heat flux and buoyancy forcing) that affect variability in the region? How does this forcing vary on intraseasonal, seasonal and interannual time scales?**

Implementation Strategies

Climate analyses based on long-term observational data sets and modeling experiments for both the current climate and for future greenhouse warming projections should be undertaken to assess the importance of climate variability and change and their impacts on weather extreme events in the SCTR region. Satellite monitoring of physical and biogeochemical variables such as sea surface temperature, sea level height, winds, rainfall and chlorophyll *etc.* should be continued along with in-situ observation needed for calibration and validation of the satellite data. IndOOS and the RAMA moorings, along with proposed new pilot moorings at Station K, will provide multi-disciplinary observational platforms for observing SCTR variability across many time scales into the future. Biogeochemical Argo float deployments as well as measurements using wave- and underwater gliders with multidisciplinary sensors are new and valuable technologies that should be deployed in this region. Research vessels provide opportunities for shipboard measurements that cannot be made autonomously; ships can be used to help maintain IndOOS through mooring, drifter, Argo float, and other robotic platform deployments. The new Korean *R/V Isabu* observed various physical-biogeochemical variables along the 67°E meridian and serviced three RAMA buoys successfully on her maiden voyage in 2017; it is planning to visit the Indian Ocean at least once a year for the next several years.

Forced ocean models and coupled physical-biogeochemical models will also be valuable for studies of climate variability and marine ecosystem processes in the SCTR (e.g., Wiggert et al., 2006; Resplandy et al., 2009; Dilmahamod et al, 2016). Coupled climate models are key tools for the assessment of past change and variability and for the projections of future trends under various climate change scenarios. Current models should be validated for their performance in reproducing SCTR variability in the current climate. Coupled physical-biogeochemcial models that are carefully validated against observations should play a significant role in studying the linkage between physical and biogeochemical variability in the SCTR region. Coupled regional climate system models with fine resolution around the SCTR should be developed and validated for the assessment of climate change under future greenhouse gas forcing scenarios.

2.5 Ecosystems and Fisheries

Background

The main activity in tuna purse-seine fishing effort is searching for the rare times and regions where large numbers of tuna schools are concentrated to obtain high catch per unit effort (CPUE). These tuna concentrations can be described as a localized high density of tuna schools that gather temporarily (for a few days to several weeks) within a small zone (hundreds of square nautical miles) and are usually linked to feeding or spawning activities. Observational studies have documented concentrated tuna fishing activities associated with tuna schools at the precise locations in the SCTR where surface phytoplankton blooms had been observed in satellite observations 2-3 weeks previously (Fonteneau et al. 2008, Figure 3). This indicates a strong connection between SCTR-forced phytoplankton blooms and the prey required by large tuna. In contrast, biogeochemical modeling results indicate that both phytoplankton biomass and carbon export from the euphotic zone change little in response to seasonal and interannual variability of the SCTR thermocline depth (Resplandy et al., 2009). These contrasting scenarios define a paradox in the current understanding of ecological dynamics in the SCTR upwelling region: It seems unlikely that episodic nutricline intrusions into surface waters in the SCTR would produce no biogeochemical signals and equally unlikely that the ecosystem response would be efficient enough to produce an almost instantaneous population response of the large long-lived prey that tuna consume. The linkages between physical forcing, ecosystem response and higher trophic level behavior need to be examined in the SCTR in order to resolve this paradox.

Moreover, recent yellowfin tuna stock assessments indicate that this fishery is subject to overfishing driven by unsustainable catches combined with relatively low recruitment levels estimated by models (IOTC, 2017). Yet, these assessments are based on fisheries models that are not informed by an understanding of the food web dynamics of the SCTR. Studies focused on the physical, biogeochemical and ecological dynamics of the SCTR will provide the understanding that is needed to determine the connection between the marine food web and the prey required by large tuna in the SCTR which will, in turn, improve management of the fishery.

Scientific Questions

There is a pronounced seasonal cycle of Chl-a in the SCTR with a maximum in August at a time when SST is seasonally at its coldest and wind speeds are highest. However, this is the time of year when the mixed layer, thermocline and presumably the nutricline are deepest. The seasonally cool SSTs are related to enhanced wind-driven vertical mixing.

- **How do physical processes and related biogeochemical factors affect the seasonal cycle of primary productivity and ecosystem dynamics? How will global warming affect the upwelling circulation in the SCTR and what will its impacts be on sea level, SST, nutrient and carbon budgets and ecosystems in the region?**

Ocean warming reduces the solubility of oxygen and changes physical mixing of oxygen in the oceans. Oxygen minimum zones (OMZs) are expanding worldwide, including in the Indian Ocean, as a result of this warming (Stramma et al., 2008; 2010).

- **How might oxygen concentrations change in response to climate change in the SCTR region? Is the OMZ of the Arabian Sea expanding southward into the SCTR region? How might these oxygen changes in the SCTR region affect marine ecosystems and higher trophic levels?**

Increasing greenhouse gas emissions also lead to increased ocean uptake of CO_2. This uptake drives ocean acidification and decreasing pH in the ocean. Acidification can be exacerbated in upwelling areas like the SCTR where more acidic deep water is brought up to the surface.

- **What will be the future changes of pH in the SCTR region? How will ocean acidification affect ecosystem dynamics in the SCTR? What are the relative**

effects of ocean acidification, deoxygenation and warming on the regional ecosystems and fisheries?

In addition, studies need to be undertaken that are specifically focused on improving current understanding of the SCTR food web dynamics and higher trophic level responses.

- **Is the prey required by large tuna in the SCTR supported by local upwelling of nutrients that enhances primary and secondary productivity? Or does the thermocline ridge function more as a concentration center for larger prey that are transported to the area from adjacent ocean regions and made available to top predators at high densities under conditions of strong isopycnal doming or hydrographic fronts? Alternatively, could the presence of large numbers of tuna schools in the SCTR be related to spawning?**

Implementation Strategies

Addressing scientific questions related to ecosystems and fisheries in the SCTR will benefit from a variety of satellite measurements - in particular, ocean color. The deployment of biogeochemical sensors (chlorophyll fluorescence, particle backscatter, pCO_2 and air-sea CO_2 flux, pH) in the SCTR as part of IndOOS would provide valuable complementary measurements to the satellite ocean color data. Specifically, deployment of biogeochemical sensor-equipped moorings (e.g., RAMA and the proposed Station K), BioArgo floats and gliders in the SCTR would be of great value. Research vessels, including those servicing RAMA moorings, provide platforms for specialized measurements to test hypotheses related to SCTR ecosystems and fisheries. All of these assets can and should be leveraged in Korean led studies of the SCTR. Studies using coupled physical, biogeochemical and ecosystem models (e.g., Wiggert et al., 2006; Resplandy et al., 2009) can also potentially provide important insights into ecosystem dynamics and fisheries in the SCTR. Coupled climate models can be used to address recent and future trends in the region under various greenhouse gas forcing scenarios.

Research cruises that make critical measurements for testing hypotheses and calibrating models should be undertaken to advance the phenomenological and mechanistic understanding of ecological dynamics and higher trophic level responses in the SCTR. Shipboard studies should address the hypothesis that the thermocline ridge may function as a concentration center for larger prey that are transported to the area from adjacent ocean regions and/or a place of spawning by large tuna. In this regard, large stocks of mesopelagic fish are thought to occur in the Arabian Sea to the north of the SCTR and off of Somalia to the west (Kinzer et al., 1993; Tsarin and Boltachev, 2006), but have not been assessed systematically in the region, as they could be, for example, by surveys with modern acoustical technology. A systematic sampling and analysis of fish eggs and larvae and plankton community size structure should be carried out to help test these hypotheses and to better understand food-web dynamics in the region. Behavioral studies should also be carried out to help determine whether or not the presence of large numbers of tuna schools in the SCTR could be related to spawning. Shipboard experimental studies that address the measurement deficiencies in primary production, nutrient and light responses and limitations, new production and carbon export, community structure, food-web dynamics, carbonate system parameters, and biogeochemical process indices are also needed to develop and validate regional models. These models can be used to assess the relative importance of in situ productivity versus transport mechanisms in explaining the system's unique coupling to higher trophic levels, the implications of SCTR dynamics to Indian Ocean biogeochemistry and ecology, and their potential vulnerabilities to climate change.

3 Coordination

KUDOS is designed to be a Korean-US contribution to IIOE-2. It will therefore coordinate with those committees, programs, organizations and institutions that are directly or indirectly involved in IIOE-2. These include for example, the IIOE-2 Steering Committee, the steering committee of the U.S. contribution to IIOE-2, the CLIVAR/GOOS Indian Ocean Regional Panel, the Indian Ocean GOOS (IOGOOS) program, the GEOTRACES Program, the Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) program, and other related efforts. Coordination will be carried out through a KUDOS steering committee whose interim membership consists of the KUDOS workshop steering committee that organized the meeting in Seoul, South Korea in November-December 2017 and that led the drafting of this science and implementation plan. That Steering Committee consists of

Michael McPhaden, NOAA/PMEL
Raleigh Hood, University of Maryland
Jerry Wiggert, University of Southern Mississippi
Uwe Send, Scripps Institution of Oceanography
TaeKeun Rho, KIOST
Chan Joo Jang, KIOST
Hyoun-Woo Kang, KIOST
SungHyun Nam, Seoul National University

This steering committee will be reconstituted once the KUDOS plan is adopted and endorsed by the IIOE-2 Steering Committee.

The overall KUDOS coordination strategy will be to both lead the development of new research initiatives in the SCTR region and leverage Korean and U.S. investments in the region for the benefit of both KUDOS and IIOE-2. Coordination will take the form of widely communicating KUDOS progress and plans to other IIOE-2 programs, inviting IIOE-2 participants from other programs to KUDOS workshops, jointly planning field work and modeling activities with others in the IIOE-2 community, and sharing resources for the common good where feasible. KUDOS welcomes broad based scientific collaboration and will be open to participants from any nation who are willing and able contribute to the furtherance of KUDOS interdisciplinary goals.

4 Data Policy

The data and information management policy that will guide KUDOS is that of the International IIOE-2 program as articulated in the IIOE-2 implementation strategy document (IPC, 2015). The guidelines described in that document are intended to further individual science project objectives and overall IIOE-2 program goals. IPC (2015) explicitly highlights the need to ensure data quality for all types of data collected in IIOE-2, to encourage early sharing and widespread dissemination of data, to provide for the archival and curation of data in national and international data centers, and to publish the data so as to ensure maximum scientific benefit. Existing data and information management systems should be used to the extent possible to facilitate quality assurance, dissemination, and archival. Where feasible, data collected in KUDOS such as from moorings and other autonomous systems should be transmitted in real-time for operational ocean, weather, and climate analyses and forecasts. Within each country, national data policies will take precedence in those rare situations where the IPC (2015) guidelines and national policies are at variance.

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