



Fig. 1 RV Investigator

office of the Intergovernmental Oceanographic Commission (IOC).

science research themes identified in the IIOE-2 Science Plan. With the new 93.9 m Marine National Facility RV Investigator now commissioned (Fig. 1), various initiatives and planning are underway for Australia to contribute to the coordinated international research that will take place in the Indian Ocean in the next few years. Australia anticipates presenting a plan of its IIOE-2 activities at the Goa Symposium in November 2015 and will consult and collaborate with other nations in the preparation of this plan to ensure Australia is also part of emerging multinational IIOE-2 science proposals (e.g., the Eastern Indian Ocean Upwelling Research Initiative – EIOURI).

In an overarching programmatic sense, Australia will also continue to play an important role in the implementation of IIOE-2 through its support for the Perth Programme Office, which is a regional programme

# Perspectives/Programme and Cruise Reports

## Legacy from IIOE-1 to Potential of Space Observations

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### 1. Introduction

The participation of University of Washington in the first International Indian Ocean Expedition (IIOE-1) 50 years ago advanced marine technology and our understanding of ocean-atmosphere turbulent exchanges, as described in Section 2. The expedition made significant contribution to our knowledge of oceanic processes in the region and also made us aware of the need for long-term observing systems and numerical modeling. Observations from the vantage of space, which were not available during IIOE-1, have provided the coverage and resolution not possible from in situ measurements and the data needed for assimilation into numerical models. Satellite observations are not confined

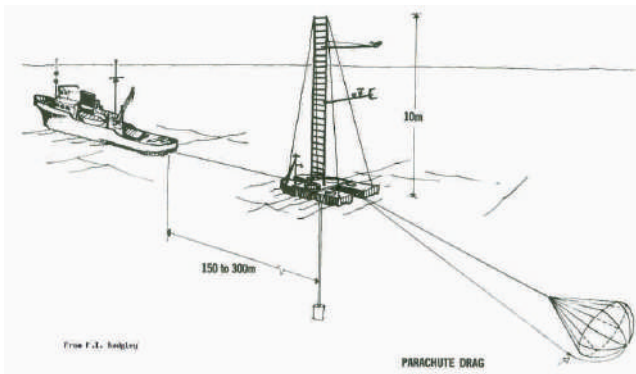


Fig. 1 Mentor deployment during IIOE-1

by geopolitical boundaries and we anticipate that the second expedition (IIOE-2) will transcend regional competitions and provide the platform to assure the distribution of the data from space observations for common good. New geophysical information could also be retrieved from space based observations that will bridge science disciplines. We will provide a few examples of the application of space based measurements that will help the design and complement IIOE-2 in Sections 3-5.

University of Washington deployed a floating platform towed behind a research ship in the Arabian Sea under winter conditions when cool air from land blew over warm ocean during IIOE-1. The catamaran-like platform, called "Mentor", carried an 8.5 m mast with a horizontal instrument boom that moved up and down the mast, as illustrated in Fig. 1. Vertical profiles of wind, temperature and humidity were measured, from which the turbulent fluxes of momentum, sensible heat and moisture were derived (Badgley et al., 1968). After the Expedition, Mentor was deployed in other experiments and was also used in an annual international summer course of air-sea interaction experiment at the University for over a decade. Kristina Katsaros and Mike Miyake taught the course in later years and Timothy Liu was one of the teaching assistants.

### 2. The Legacy

The expedition provided the first significant validation of the flux-profile relations (Similarity Profiles) over oceans. Before that, the relation was largely derived and validated with measurements over land. The flux-profile relations, as formulated by Paulson (1970), were used by Liu et al. (1979), in a new scheme of bulk parameterization of turbulent fluxes, including the effect of stability. The method of Liu et al. (1979) was later improved by Fairall et al. (1996) and has been extensively used up to the present. Adaptation of the bulk parameterization to use space observations relevant to the Indian Ocean will be discussed in Section 5.

### 3. Monitoring the Physics of Biogeochemistry

The alarmingly rapid increase of global atmospheric carbon dioxide (CO<sub>2</sub>) content has been well documented, but the distributions of surface sources and sinks have not been sufficiently known. NASA's Orbiting Carbon Observatory (OCO) is designed to give a more accurate measurement of the column-integrated CO<sub>2</sub> content from which surface sources and sinks could be inferred. The plan is to assimilate OCO data into atmospheric transport models, and, with inverse method, the surface sources and sinks will be derived. The results of such a top down approach may not be consistent with ocean-atmosphere CO<sub>2</sub> exchanges computed by the conventional oceanic approach of bulk parameterization.

The ocean surface CO<sub>2</sub> partial pressure (pCO<sub>2,sea</sub>) is critical in estimating the CO<sub>2</sub> flux and is the surface signature of change in ocean acidity, mixed layer dynamics, and biogeochemistry, but it has not been directly measured from space.

We have developed a statistical model to estimate pCO<sub>2,sea</sub> from space-based observations of sea surface temperature (SST), chlorophyll, and salinity. Over the years, we have collected a large number of ship measurements of pCO<sub>2,sea</sub>, starting with the Joint Global Ocean Flux Study (JGOFS) in the late 1980s, then World Ocean Circulation Experiment (WOCE) in the late 1990s, and recently through Surface Ocean CO<sub>2</sub> Atlas (SOCAT) Programs. We decided to collocate in situ measurements in the recent decade with satellite data and about a quarter million matches were compiled to train and validate the model. We have produced and made accessible 9 years (2002–2010) of the pCO<sub>2,sea</sub> at 0.5° and daily resolutions over the global ocean (Liu and Xie, 2014a). Fig. 2 shows the distribution of the in situ data available to train the model. The deficiency of the training and validation data in the Indian Ocean is obvious and the need for in situ data accessibility was discussed in a special session of PORSEC 2012 in Cochin, India.

IIOE-2 could make a significant contribution to facilitate the access of in situ data in the Indian Ocean by the international community.

#### 4. Linking Ocean Processes to Terrestrial Hydrology

Advancing the understanding ocean processes in IIOE helps fishery and shipping. Greater impact will be achieved if the ocean processes are linked to hydrologic balance of man's habitat on land. The monsoon is the seasonal reversal of wind transport between ocean and land, with rain on land as a consequence. The Indian monsoon has been well studied. Interannual and decadal modification of the monsoon as related to teleconnection between continental rain and global SST needs to be interpreted through regional moisture supplied from the ocean.

Local synoptic rain events and convection should be linked to seasonal oceanic moisture supply. A method to estimate moisture transport integrated through the depth of the atmosphere has been developed, using spacebased measurements of surface and cloud-drift wind vectors and integrated water vapor (Xie et al., 2008; Liu and Xie, 2014b). The decade-long data set has been applied to study water balance in South America (Liu et al., 2006) and Sahel rainfall (Liu et al. 2012). Fig. 3 shows that the rainfall over most of the Indian subcontinent is correlated with the moisture transport from the Arabian Sea. The exception is over Tamil Nadu and Sri Lanka. The seasonal change of rainfall in those areas does not agree well with moisture. While the lower monsoon rainfall in the shadow of the western mountain is expected, the disagreement with the annual cycle of both southwest (summer) and northeast (winter) remains to be investigated.

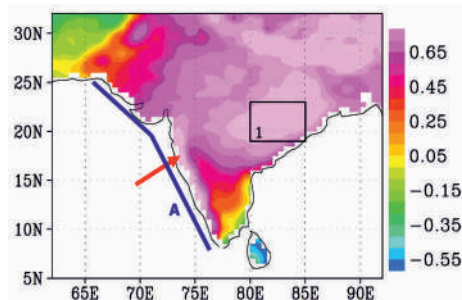


Fig. 3 Correlation coefficients between integrated water transport (Xie et al. 2008) across boundary A and precipitation from TRMM 3B42 data, using monthly data from 7/1999 to 11/2009.

has been vigorously modeled (Pinker et al. 2014). Latent heat flux has been estimated from bulk parameters retrieved from satellite data or directly from radiance observed (Liu and Xie, 2014b). Scatterometers provide the unique capability of measuring both wind and stress (Liu and Xie, 2014c). Multi-year data sets of the surface turbulent flux has been produced (e.g. Betamy et al. 2003; Yu et al. 2007).

Over the Indian Ocean, diurnal and intra-seasonal variation is important. They will be characterized by combining data from a constellation of polar orbiting sensors or from a satellite at low inclination with non-sun-synchronous orbit, such as Rapidscat deployed on the International Space Station or the cyclone Global Navigation Satellite System to be launched in 2016. Monitoring atmospheric convection driven by surface fluxes would be a challenge to be met (e.g. Levy et al., 2011).

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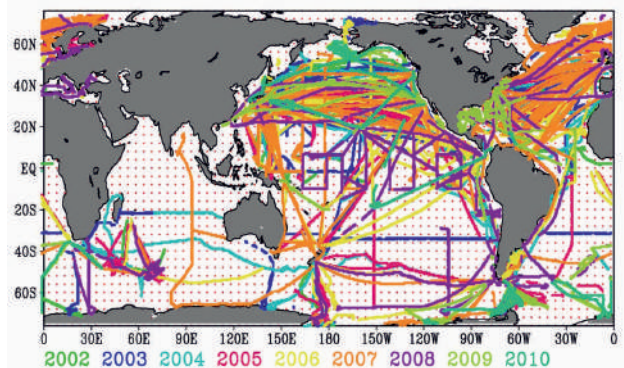


Fig. 2 Collocated pCO<sub>2,sea</sub> measurements with satellite observations during 2002–2010, for a total of 206,265 data points at daily and 0.5 degree resolution.

Several international efforts are producing high-resolution sea surface temperature (SST) from both infrared and microwave radiometers. Ocean surface dynamic height and chlorophyll are continuously measured. The Soil Moisture and Ocean Salinity (SMOS), Aquarius, and Soil Moisture Active and Passive (SMAP) sensors will measure ocean surface salinity. There are several methods to derive ocean surface currents and together with salinity, demonstrate the effect of seasonal change of salinity advection around India. Aside from the rain measured by the Global Rain Measuring Mission (GPM) and change of water storage measured by the Gravity Recovery and Climate Experiment (GRACE), soil moisture measured by SMOS, Aquarius, and SMAP will reveal the water balance over India with respect to the ocean's influence through moisture transport. Soil moisture would be an indispensable parameter for monitoring the pre-monsoon drought and regional response to the vagary of monsoon onset (Liu and Xie, 2015).

#### 5. Coupling the Ocean to the Atmosphere

Since the pioneering effort to estimate evaporation and latent heat flux from space (Liu and Niiler, 1984) and to examine oceanic response to combined solar heating and evaporative cooling (Liu and Gautier, 1990), significant improvements have been made in the estimation of surface radiative and turbulent fluxes. The effect of aerosols on radiative fluxes



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## Agulhas System Climate Array (ASCA) Sihlo’ uLwandle – Investigating the Oceans

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Long-term measurements are essential to understand the impacts of climate variability and global change on the oceans and vice versa. Around South Africa, the warm Agulhas system influences both regional and global weather and climate patterns through its key role in the global thermohaline circulation and hence the international community has recognised the Agulhas as a priority for sustained observations as part of the Global Ocean Observing System (GOOS). Observations of the Agulhas system need to be targeted. As a dynamic and divergent system, observations at the western boundary are not achieved effectively with floats and drifters, because they have a short residence time. Sea surface height data is contaminated at the land-ocean boundary by small-scale tropospheric moisture changes and aliased tides. Sea surface temperature data are often obscured by clouds as a result of the expansion of the marine boundary layer and enhanced convection over the warm waters of the Agulhas. High density XBT sections can provide upper ocean heat content in the Agulhas Current off Durban (IX21, ~ quarterly) and in the Agulhas leakage off Cape Town (AX25, ~ semiannually), but lack the temporal resolution and density information to provide decadal variability of heat and mass transports.



Fig. 2 Tammy Morris (ASCA coordinator) onboard the RV Algoa, with the ASCA moorings on the aft deck

The Agulhas System Climate Array (ASCA) will provide long term observations of volume, heat and salt fluxes, both within the Agulhas Current and over the African shelf, along descending TOPEX/Jason satellite ground track # 96. The array will consist of ten full-depth moorings, measuring pressure, velocity, temperature and salinity as well as five Current- and Pressure-recording Inverted Echo Sounders (CPIES) which extend the array to 300 km offshore. The first ASCA deployment cruise was recently completed (April 2015) aboard the South African Research Vessel Algoa. The Agulhas is a challenging region for mooring operations because of the strong current, steep topography, notorious rogue waves and severe weather (during late austral autumn). Nevertheless, two shelf moorings and four tall moorings were successfully deployed, along with CTD

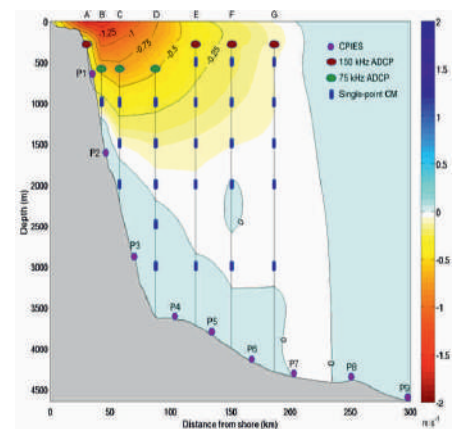


Fig.1 Mooring positions overlaid on a three year average of current speeds (m/s), negative flow indicates a poleward direction