May 2011

CINDY2011

Cooperative Indian Ocean experiment on intraseasonal variability in the Year 2011
- Science Plan (Ver. 3.1) -

CINDY2011 Science Plan Working Group*

Abstract

CINDY2011 (Cooperative Indian Ocean experiment on intraseasonal variability in the Year 2011) is a field experiment planned to take place in and around the Indian Ocean from October 2011 to January 2012. The experiment is designed to improve our knowledge on the intraseasonal variability in the tropical Indian Ocean with focus on the initiation process of convection in the Madden-Julian oscillation (MJO).

CINDY2011 can be regarded as a follow-up project of MISMO (Mirai Indian Ocean cruise for the Study of the MJO-convection Onset), which took place in the central Indian Ocean from late October to early December 2006. While MISMO captured the onset of a weak MJO-convection and analyses revealed that recharge-discharge process might play a key role for the development of the intraseasonal convection, it also suggests that equatorial waves might play a crucial role for the initiation process. However, it is difficult to deduce the relationship with such large-scale phenomena from MISMO's limited areal coverage and duration of only about one month. Hence, a new field experiment CINDY2011 is planned to collect in-situ atmospheric and oceanic data by constructing a long-time (over intraseasonal period) and large-scale observation network with a quadrilateral array as a multi-national effort.

In addition to the observational component of the experiment, numerical research is also an important component of this experiment to enhance the skill of MJO simulation. Our ultimate goal is to promote our knowledge of not only initiation process of MJO-convection but also the weather and climate prediction. Thus, results obtained from the field campaign will be tightly and timely incorporated into numerical studies.

* This document was summed up (originally April 2009, finally May 2011) based on the inputs from ;

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1. Introduction

It is now beyond doubt that the tropical intraseasonal variability has a great impact on global climate (Lau and Waliser 2005). In particular, the Madden-Julian oscillation (MJO; Madden and Julian 1994) is a crucial phenomenon which should be understood for improving the weather and climate prediction, since the MJO influences not only tropical climate but also weather and climate in the higher latitudes through the interaction with various phenomena, such as monsoon (e.g., Yasunari 1979; Hendon and Liebmann 1990), El Niño (e.g., McPhaden 1999), tropical cyclones (e.g., Maloney and Hartmann 2001), and others. In addition, accurate knowledge on the MJO is crucial to improve the climate models, as it also strongly affects the distribution of tropical ice clouds, which are important regulator of the radiative balance of the earth (e.g., Sassen et al. 2008; Fujiwara et al. 2009).

One of the major concerns of the MJO studies is the initiation process of convection. While many hypotheses have been proposed, there has been no definitive explanation on the onset of MJO-convection. For example, Hsu et al. (1990) described a situation where extratropical wave trains propagating into the tropics might excite convection in the MJO. On the other hand, several studies pointed out that circumnavigating signals along the equator in the upper troposphere may interact with the convection in the Indian Ocean (e.g., Knutson et al. 1986; Sperber 2003). Another important factor considered is a frictional convergence in the boundary layer (e.g., Wang and Li 1994; Seo and Kim 2003), as it can excite wave convergence in the lower troposphere. This hypothesis is consistent with many analytical studies (e.g., Maloney and Hartmann 1998; Kiladis et al. 2005), which showed that low-level convergence led the convective center of the MJO. On the one hand, Hsu and Lee (2005) noted that the tropical topography (e.g., the contrast between tropical Africa and western Indian Ocean) might contribute to the moisture convergence and initiation of MJO-convection in the Indian Ocean, since it is likely to produce more significant frictional convergence over the mountainous land area than over the open ocean. Furthermore, “discharge-recharge” theory (Bladé and Hartmann 1993) is also one of the key proposed mechanisms. This theory suggests that local convective instability contributes to the onset of convection and that the time scale of the oscillation is determined by the radiation-convection-surface fluxes interactions (e.g., Hu and Randall 1994; Raymond 2001; Kemball-Cook and Weare 2001). Most of hypotheses described above were derived from numerical or analytical studies using global scale data sets such as satellite and reanalysis data. However, as Tian et al. (2006) demonstrated that there were significant discrepancies in temperature and humidity data over the Indian Ocean between satellite and global reanalysis data sets, insufficient in-situ data constrain the accuracy of reanalysis data sets. This may partly cause the uncertainty on the proposed mechanisms. In addition, proposed mechanisms should be examined using observation data.

The above mentioned work indicates that fine temporal and spatial in-situ data can promote our knowledge on the MJO. However, while most MJO-convection occurs over the Indian Ocean, there had been no intensive observation focusing on MJO-convection onset. Hence, to address the atmospheric and oceanic conditions when convection in the MJO is initiated, the field experiment MISMO (Mirai Indian Ocean cruise for the Study of the MJO-convection Onset) took place from late October to early December 2006 in the central equatorial Indian Ocean, using the research vessel (R/V)

Mirai, land-based sites at Maldives, and a moored buoy array. While the extensive analyses using MISMO data have revealed some atmospheric and oceanic characteristics, several key questions have been also raised requiring another experiment to better understand the initiation process and others. Thus, we propose a new field experiment CINDY2011 (Cooperative Indian Ocean experiment on intraseasonal variability in the Year 2011) to collect data for the study of MJO-convection onset as well as intraseasonal atmospheric and oceanic features in the tropical Indian Ocean. The key component of this experiment is being conducted as a multi-national effort to ensure the collection of sufficient data. In this document, since CINDY2011 can be regarded as a follow-up project of MISMO, we will first mention about the selected results obtained from MISMO. Then the scientific questions, which should be solved by CINDY2011, will be listed. Finally, basic observational plan will be presented.

Note that some parts of this document are quoted from Yoneyama et al. (2008), which described the project overview as well as selected early results from MISMO. In addition, detailed information on MISMO can be found at http://www.jamstec.go.jp/iorgc/mismo/index-e.html.

2. Background

2.1 What was MISMO?

MISMO was the first ever field experiment which targeted the MJO-convection onset in the Indian Ocean. The aim of MISMO was to capture the atmospheric and oceanic features when convection in the MJO was initiated. For this purpose, an observational network was constructed with the R/V *Mirai*, a moored buoy array, and land-based sites at the Maldive Islands from October to December 2006 (Fig. 1). The *Mirai* was the major component of this campaign and stayed within the buoy array area centered at 0°, 80.5°E from October 24 through November 25 (Intensive Observation Period; IOP). On board the *Mirai*, atmospheric observations using C-band Doppler radar, radiosonde (8 times/day), and surface meteorological measurement systems and oceanic observations using CTD and shipboard ADCP systems were conducted by JAMSTEC. In addition, many researchers from various institutes and universities joined the cruise and conducted their observations including wind profiler, lidar, cloud profiling radar, video-sonde, and so on. Around the *Mirai*, two m-TRITON (mini-Triangle Trans Ocean Buoy Network) buoys and four ADCP sub-surface mooring systems were deployed for about one month to detect the oceanic response from/to the MJO. Along the 80.5°E line, ATLAS (Autonomous Temperature Line Acquisition System) buoys had already been deployed as a part of RAMA (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction) buoy array (McPhaden et al. 2009) using the Indian oceanographic research vessel Sagar Kanya by National Institute of Oceanography (NIO), India and the U.S. National Oceanic and Atmospheric Administration (NOAA) / Pacific Marine Environmental Laboratory (PMEL). Before arriving at the stationary observation site, ten Argo-floats whose ascent was set at every day from 500 m depth were deployed along 80°E line. Furthermore, we also conducted observations at Maldive Islands with the aid of Maldives Meteorological Office to construct the radiosonde sounding array with the *Mirai*. Surface meteorological measurement systems and GPS receivers were deployed on Hulhule, Kadhdhoo, and Gan islands, while radiosonde soundings were carried out at Hulhule and Gan islands 6- or 12-hourly during the intensive observation period. A Doppler radar was deployed at Gan Island site under the collaborative work between JAMSTEC and the Hokkaido University.

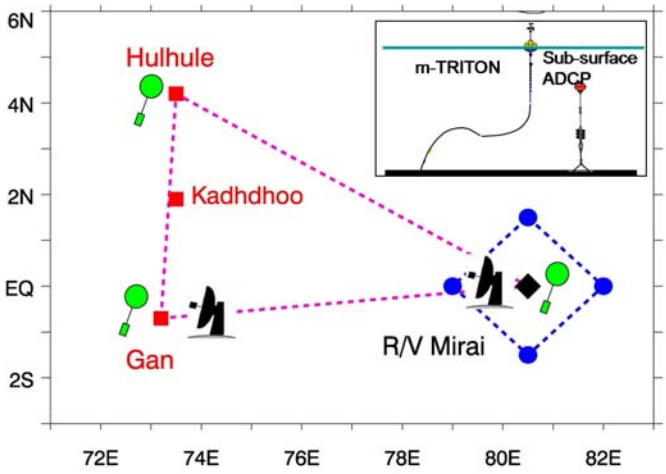

Fig. 1. MISMO observational network. Red-dashed line indicates atmospheric sounding array, and blue-dashed line indicates oceanic buoy array.

2.2 What we learned from MISMO

a. Relationship to Convectively Coupled Equatorial Waves

The intensive observation period of MISMO corresponded to the mature and decaying phases of an Indian Ocean Dipole event (Horii et al. 2008; Masumoto et al. 2008). While convective activity was suppressed from late October to early November, convection started to develop in mid-November, and finally much deep convection developed in the central Indian Ocean in late November. After that, eastward movement of large-scale cloud systems was observed in early December. By applying the wavenumber-frequency filtering to the satellite-based outgoing longwave radiation (OLR) data following the work of Wheeler and Weickmann (2001), we could confirm that cloud systems developed in late November was associated with the MJO, although their signal was weak and dissipated before arriving over the maritime continent region (Fig. 2). Therefore, we can say that MISMO campaign could capture the onset of large-scale cloud system associated with the weak MJO in mid-November 2006. (Note that there might be a controversy whether this event can be regarded as an MJO-convection or not due to its weakness. However, hereafter we refer it as MJO-convection for simplicity.) We also find that large-scale cloud systems drastically developed when the equatorial Rossby wave arrived over the observational area. Thus, it is possible to speculate that the equatorial Rossby wave might play a role for the onset of the MJO-convection, as recently Masunaga et al. (2006) pointed out.

Yasunaga et al. (2010) examined the moisture variability using GPS-derived water vapor data and found a prominent 3-4-day cycle associated with meridional wind variations (Figs. 3 - 5). Based on the analyses using reanalysis data known as JCDAS (Japan Meteorological Agency Climate Data Assimilation System), they concluded that this 3-4-day variation has characteristics of westward propagating mixed Rossby-gravity wave. Although it is not apparent how this wave interacts with moisture variations over the equator, it is indicative that mixed Rossby-gravity wave which has the largest amplitude of meridional wind component may play some roles in accumulating water vapor prior to the onset of MJO-convection in mid-November. Yasunaga et al. (2010) also noted the dominance of the 6-8-day disturbances associated with westward propagating Rossby wave. These results suggest the importance of equatorial waves, which have meridional wind component peak near the equator, onto the development stages of MJO-convection.

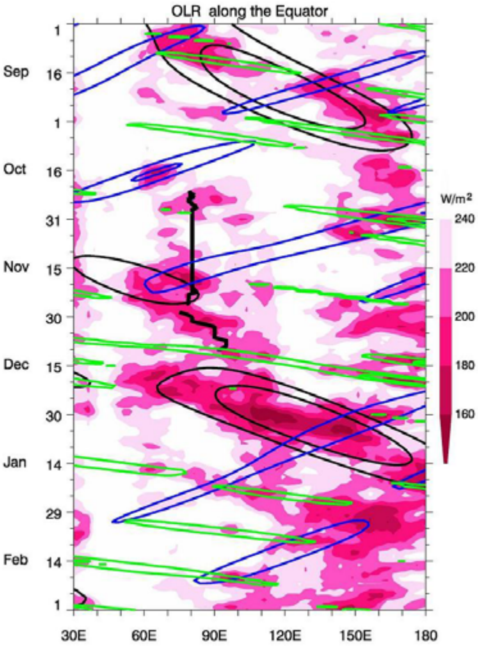

Fig. 2. Time-longitude cross section of OLR along the equator averaged over 7.5°S - 7.5°N (shading). Contours are the wavenumber-frequency filtered OLR anomalies indicating the signals identified as MJO (black), Kelvin wave (green), and equatorial Rossby wave (blue). Contours indicate the negative anomalies and contour interval is 7.5 W m^{-2}. The position of the *Mirai* is superimposed as black thick line. From Yoneyama et al. (2008).

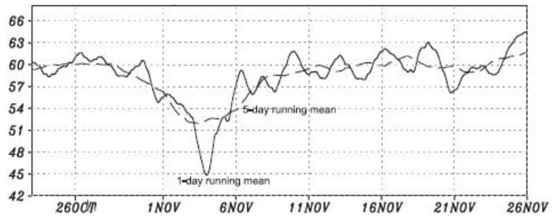

Fig. 3. Time-series of GPS-derived water vapor. Solid/dashed lines indicate 1-day/5-day running mean values. From Yasunaga et al. (2010).

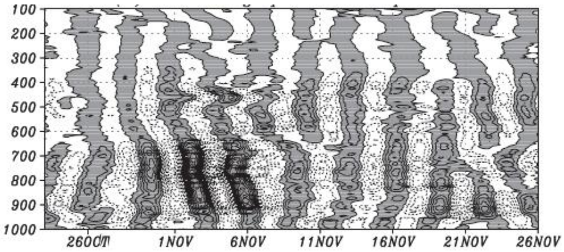

Fig. 4. Variations of 3-4-day filtered mixing ratio as a function of height and time. Positive area is shaded. From Yasunaga et al. (2010).

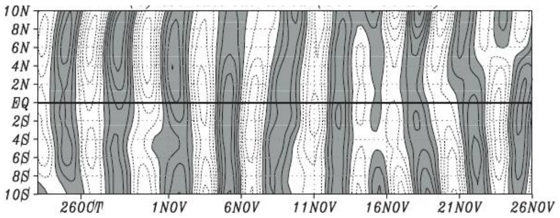

Fig. 5. Time-latitude cross section of 3-4-day filtered meridional wind component at 500-400 hPa along 80E. From Yasunaga et al. (2010).

b. Role of Meso-scale Convective System

Atmospheric sounding array with the *Mirai* and two islands clearly captured the feature of the MJO-convection onset. Figures 6 and 7 depict the time-height cross sections of mass divergence and moist static energy anomaly from the IOP-mean calculated over three sounding sites, respectively. It illustrates low-level convergence is dominant throughout the IOP, and it also shows a pair of the strongest low-level convergence and upper-level divergence in November 15 - 18 as indicated by vertical arrow with mark "C", when the drastic development of large-scale cloud system was observed. In particular, two significant features can be found. First, the gradual deepening of the strongest divergence layer from early November to mid-November is obvious, suggesting development of convection over the MISMO area as indicated by a dashed line. Second feature is that this gradual deepening was followed by several pairs of strong low-level convergence and upper-level divergence as indicated by vertical arrows with marks “A”, “B”, and “C”. Katsumata et al. (2009) examined their behavior and noted that their appearance corresponded to the passage of eastward propagating meso-scale convective systems. They suggested that those MCSs are main sources to moisten the middle and upper troposphere. In addition, those eastward propagating systems have characteristics of frictional Kelvin waves.

Time evolution of moist static energy anomaly (Fig. 7) supports the idea of discharge-recharge theory, as it shows the deepening of high moist static energy while it constrains in the lower troposphere before the onset of MJO-convection. It is interesting that although divergence field shows the gradual deepening as indicated by a black dashed line, top of high moist static energy shows a stepwise deepening as indicated by gray dashed lines. The latter feature corresponds to the trimodal characteristics of tropical convection (Johnson et al. 1999; Kikuchi and Takayabu 2004).

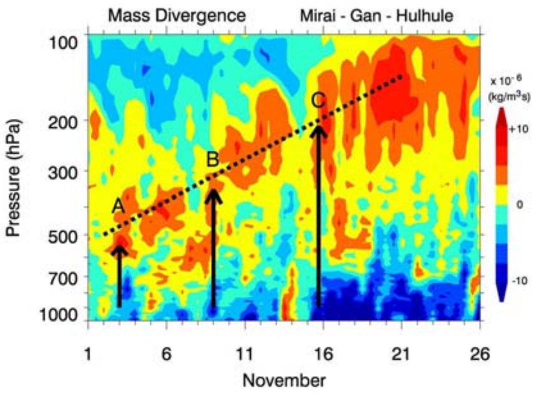

Fig. 6. Time-height cross section of mass divergence calculated over the three sounding sites. From Yoneyama et al. (2008).

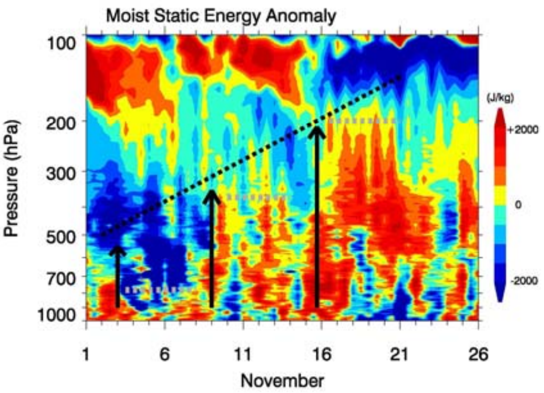

Fig. 7. Same as Fig. 4, but for moist static energy anomaly from the IOP-mean. Black dashed line and arrows are taken from Fig. 4.

As for the analyses using Doppler radar data and satellite-based data, it is worth noting that both do not always show the consistent features. For example, when the *Mirai* cruised eastward in early December 2006, westward propagating cloud system passed over the *Mirai* as shown by satellite-based infrared data (black dot-dashed arrow in the left panel of Fig. 8). However, shipboard Doppler radar observed eastward propagating precipitating system as shown by red dashed arrow. As illustrated in the vertical cross section of precipitating systems (right panels of Fig. 8), this cloud system moved eastward with developing, but this feature could not be obtained from satellite data only. Namely, in-situ observation surely provides important information on the developing cloud systems which are usually hard to be detected by satellite infrared observations.

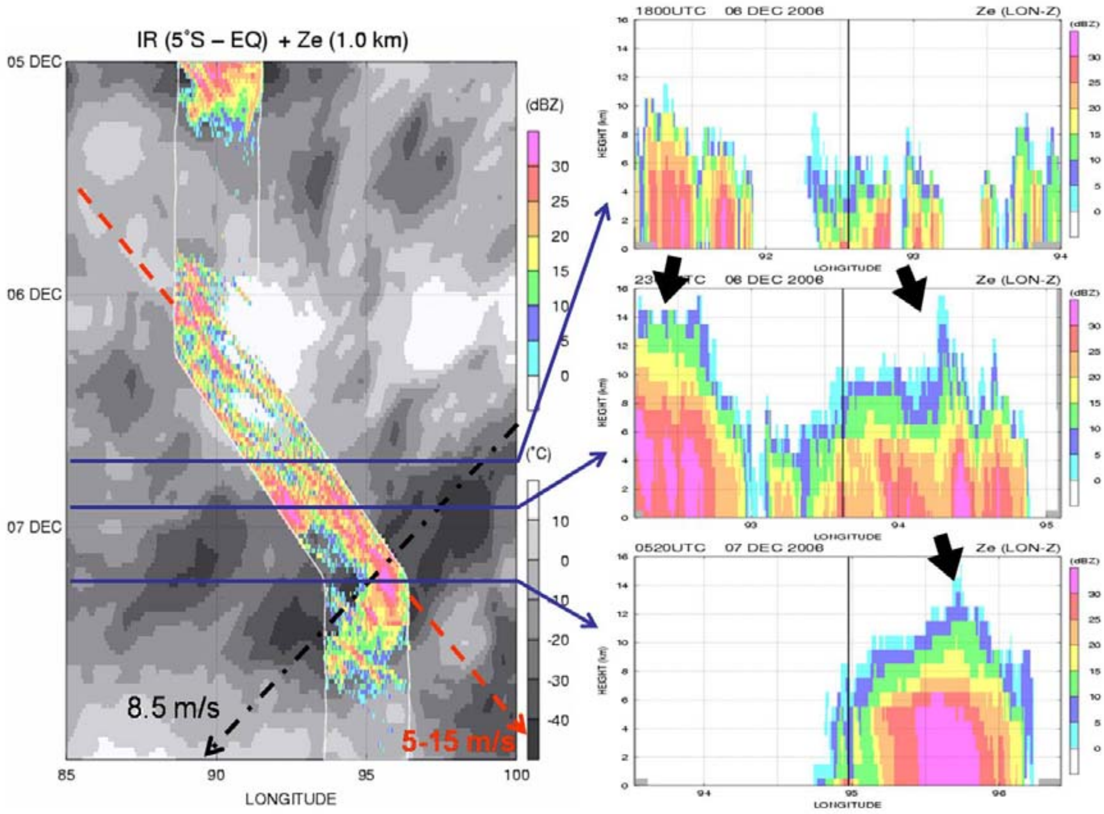

Fig. 8. (left) Time-longitude cross section of IR averaged over 5°S – equator (monochrome) and echo intensity at 1-km height obtained by *Mirai*'s Doppler radar (color). (right) Vertical cross-sections of echo intensity for three different times. Adapted from Yamada et al. (2010).

c. Observation array

Recently, Katsumata et al. (2011) found a large discrepancy in the temporal variation of rainfalls estimated from two different data sets, one is from MISMO three triangle sites and the other is from satellite-derived products, when an equatorial Rossby wave arrives over the MISMO observational array in mid-November 2006 (Fig. 9). By assuming that wind patterns associated theoretical MJO-like disturbances passed over the MISMO observation area, which consist of Rossby, Kelvin, and gravity wave components, they compared divergence filed calculated by using discrete three points for MISMO and areal average within the triangle domain. Figure 10 shows that the discrepancy found for the comparison of Rossby wave component resembles the difference found in rainfall budget in Fig. 9. It suggests that triangle array is inadequate to capture the exact budget analysis for Rossby wave, which has rotational component.

Aforementioned two sub-sections emphasized an important role of equatorially trapped large-scale waves, and its relation to meso-scale convective systems. Therefore, an appropriate observation array should be formed to observe exact budget analyses. Namely, at least, quadrilateral shape is needed, as suggested in Fig. 11.

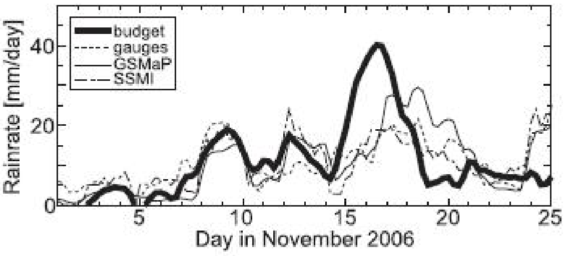

Fig. 9. Time series of observed and estimated rainfall rates. A large discrepancy is found in Nov. 15 - 20. From Katsumata et al. (2011).

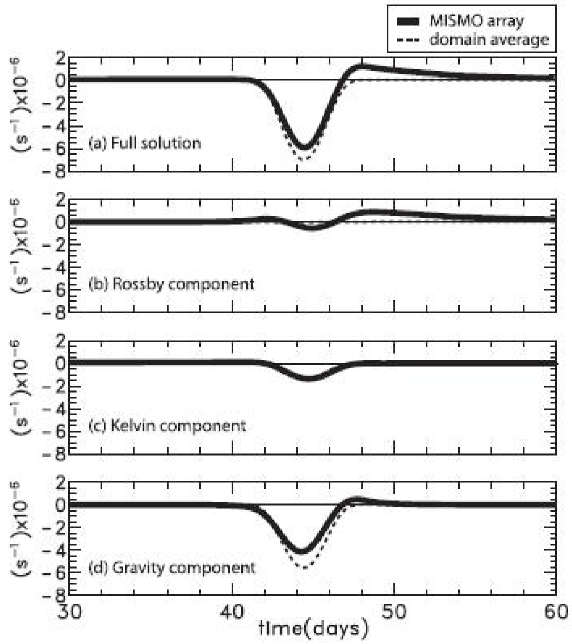

Fig. 10. Time series of divergence at 850 hPa calculated by assuming that theoretical wind patterns associated with MJO-like disturbances passed over MISMO array. Solid/dashed lines indicate the case for three/all data within MISMO triangle domain. From Katsumata et al. (2011).

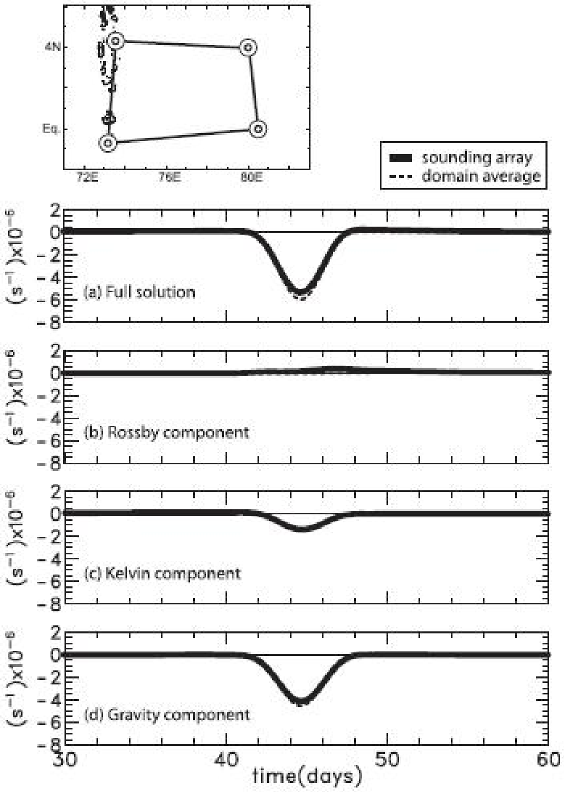

Fig. 11. Same as Fig. 10, but for the case that assuming quadrilateral array. From Katsumata et al. (2011).

d. Air-Sea Interaction and Diurnal Cycle

The role of diurnal cycle of the sea surface temperature (SST) was one major concern of MISMO, as it might play a critical role of development of convection (Slingo et al. 2003). These diurnal cycle of SST are linked to the formation of Diurnal Warm Layers (DWL) that can be characterized by very steep temperature gradients near the surface (e. g. Soloviev and Lukas 1997). Therefore, we deployed Infrared SST Autonomous Radiometer (ISAR; Donlon et al. 2008) to measure skin SST and precisely capture its diurnal variations. Interestingly we observed strong SST diurnal cycles during the developing stage of an intraseasonal convective event.

Yasunaga et al. (2008) examined diurnal variation of precipitable water vapor (PWV) measured by global positioning system and confirmed that the increase of PWV and radar echo area (rainfall) in daytime corresponded to the rise of skin SST during the undisturbed period, suggesting an important role of SST for development of convection. However, they also pointed out that although the surface heat flux observed by eddy correlation method as well as calculated by bulk formula (Fairall et al. 1996) showed similar diurnal variation with PWV, it cannot explain the total amount of increase of PWV. Therefore, contribution from large-scale convergence should also be observed in detail to explain this discrepancy.

DWLs may be moreover responsible for the observed change in the phase of the diurnal cycle of convection. During MISMO, the diurnal cycle of convection for days with DWLs indeed exhibits a clear maximum in the afternoon whereas a maximum in the early morning is observed for the more convectively active days during which no DWL forms. Bellenger et al (2010) showed that the increase of convection is linked with a decrease of the Convective Inhibition (CIN) that appeared to be controlled by boundary layer processes rather than by changes in the free troposphere. Finally, they showed that the DWL-induced increase in turbulent sensible and latent heat fluxes can explain this decrease in CIN and thus the triggering of convection in the early afternoon. DWLs are strongly linked with MJO in the Indian Ocean (Bellenger and Duvel 2009) and may thus participate to precondition the troposphere through triggering shallow convection on large regions. However, this remains to be more quantitatively studied.

d. Oceanic Features

MISMO was conducted under the mature and decaying phase of Indian Ocean Dipole (IOD) event. As illustrated in Fig. 2, although MJO-convection developed over the central Indian Ocean and moved eastward, they dissipated just before arriving at the Indonesian maritime continent region. Instead, after the MISMO IOP, another large-scale system, which developed in late December and was clearly identified as an MJO from the filtered OLR data, reached to the tropical western Pacific Ocean. McPhaden (2008) suggested that warming of the eastern Indian Ocean in the wake of the 2006 IOD event preconditioned the onset of the December MJO-convection. The relationship between the MJO and IOD requires further studies to verify this speculation.

MISMO oceanic observation network captured many unique features during the positive IOD such as strong vertical shear above the shallow thermocline with eastward subsurface zonal flow under westward surface current (Masumoto et al. 2008). Observations also showed the strong short-term variations in the meridional current and strong upwelling of over 10 ms^{-1} during early November, and the relationship to oceanic mixed Rossby-gravity waves was suggested (Fig. 7). Such short-term variation of upwelling strongly affects chlorophyll-a distribution (Prasanna Kumar et al. 2009, in preparation). Although oceanic observations revealed some interesting features, the above results require further long-term data sets to interpret the mechanism, especially in relation to oceanic equatorial waves. In addition, it seems that equatorial Indian Ocean has unique shallow structure such as surface current, so the oceanic mixed layer should be observed with high resolution in space and time. Furthermore, as physical conditions affect biogeochemical features significantly, biogeochemical studies should be also involved in the experiment.

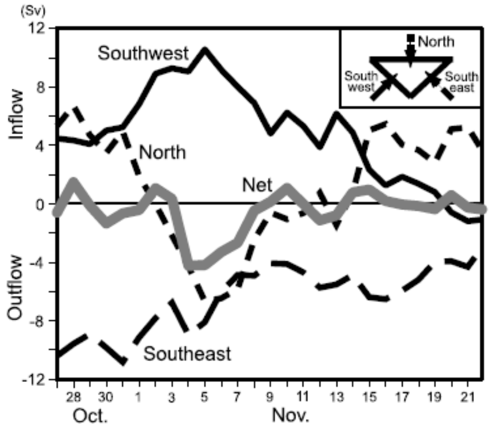

Fig. 7. Time-series of transports across three vertical sections of the triangle mooring buoy array integrated between 40 m and 270 m depth. Thick grey line indicates a sum of three components. From Masumoto et al. (2008).

2.3 Scientific needs from recent relevant studies

Recent studies have emphasized the importance of in-situ observations to get key physical parameters in order to evaluate the hypotheses on the initiation mechanism of MJO convection and relevant phenomena in and around the Indian Ocean.

While MISMO was originally designed to address the mechanism mainly from the viewpoint of local convective instability, the results as shown in previous section indicated the importance of external large-scale forcing such as equatorial Rossby wave. Recently, Ray et al. (2009) pointed out from their numerical study that lateral boundary condition is a critical component for the initiation mechanism of MJO convection and extratropical influences are important. In addition, recent several analytical studies using climate model products emphasize the importance to monitor the column-integrated moist static energy as a key parameter in evaluating recharge-discharge theory (Maloney 2009, Raymond and Fuchs 2009). In particular, horizontal advection in the lower troposphere seems to play a key role in regulating their budget (Maloney 2009). These results require the exact budget analysis over the initiation region to quantitatively evaluate the contribution from outside.

On the one hand, other recent studies using idealized models and general circulation models suggest a critical role for surface heat fluxes in supporting the MJO (e.g., Maloney and Sobel 2004, Sobel et al. 2008). As of now, the surface energy balance of the MJO has not been sufficiently characterized in the Indian Ocean. For example, recent analyses with satellite-derived wind speed and precipitation suggest a strong covariance between MJO rainfall and the wind-driven component of latent heat flux in the Indian Ocean (Araligidad 2007), in contrast with previous analyses of latent heat flux data from model assimilation products that have suggested a near quadrature relationship between Indian Ocean MJO convection and surface latent heat flux, in the sense that maximum latent heat flux lags to the west of precipitation (e.g., Hendon and Salby 1994; Jones and Weare 1996; Zhang and McPhaden 2000). Such a strong covariance was also obtained from satellite and in-situ TAO buoy data in the western Pacific (Araligidad and Maloney 2008). Recent field programs and establishment of surface monitoring systems in the western Pacific demonstrate how high quality surface measurements can improve understanding of the MJO surface energy budget. Thus, a critical need exists for good in-situ measurements of the surface energy budget in the Indian Ocean during MJO events to determine how surface fluxes contribute to MJO initiation and maintenance and to answer to these discrepancies.

3. Objectives and Scientific Questions

The aim of CINDY2011 is to collect in-situ atmospheric and oceanic data to study the intraseasonal variability in the equatorial Indian Ocean, with focus on the initiation process of convection in the MJO. It is expected to promote our knowledge on the MJO as well as its numerical simulation and prediction, which leads to improve the prediction of weather and climate in not only the tropics but also higher latitudes.

Based on the analyses of MISMO data as well as recent results related to MJO, detailed scientific questions, which should be studied by CINDY2011, are set as below.

3.1 Atmospheric research

a. Although gradual moistening in the middle and upper troposphere was observed during MISMO and it might act as a preconditioning for deep convection developed in late November, it seems that several meso-scale convective systems which appeared with 5 to 7 day periods might play a key role for this moistening. If so, how did such meso-scale systems develop and what was their exact role during the preconditioning period? Do any large-scale phenomena such as equatorial waves affect the behavior of these meso-scale systems? or meso-scale systems have any upscale effect ?

b. Large-scale cloud systems developed when the equatorial Rossby wave arrived over the central Indian Ocean. Did the equatorial Rossby wave excite the deep large-scale convection in late November? If yes, how did they interact with convection?

c. Bottom-heavy heating profile was obtained from MISMO. Evaluation is necessary based on longer data taken at more appropriate sounding configuration to reduce the calculation error. Then, the role of bottom-heavy heating for large-scale convection should be examined in detail.

d. A diurnal and even semidiurnal cycle to convection with one peak during the afternoon was reported from MISMO data. What is the role of the diurnal cycle of convection in lofting moisture and preconditioning the atmosphere for deep convection to follow? Does meso-scale organization of shallow convection (bands, cells) during the early stages enhance the vertical extent of the moistening from what it would be without such organization?

e. MJO simulation by global cloud resolving model NICAM revealed that many squall-type precipitation occurred and cold pool near the ocean surface might play an important role for meso-scale circulation. Do the observation data support this?

f. The robust MJO simulations in the “super parameterization” GCM runs at Colorado Sate University suggest a very strong relationship between rainfall and column integrated humidity, whereas GCMs with a poor representation of the MJO show a much weaker relationship and one where it rains at much too low humidity. What do the observations support?

g. The vertical population of clouds and its relation to the MJO is uncertain in the Indian Ocean. There is thus an ever increasing need for observations of cloud properties that can both compliment/ground truth satellite observations and directly provide increased understanding of MJO behavior.

3.2 Air-sea interaction

a. Although MJO-convection developed over the central equatorial Indian Ocean in late November, they dissipated before arriving at the Indonesian maritime continent. Because of this weakness, it was questioned whether it was an MJO-convection or a localized intraseasonal variation. Instead, another MJO-convection developed in December could reach to the tropical western Pacific Ocean, when the positive IOD event deceased (i.e., SST in the eastern Indian Ocean increased). Do the SST distribution play a critical role of MJO-convection propagation? In addition, in general convection in the formative region of the MJO appears to develop in a region of east-west SST gradient in the central Indian Ocean. What is the role of the SST gradient in the initiation and properties of convection?

b. Diurnal cycle of precipitable water vapor well corresponds to that of skin-SST during undisturbed period. However, total amount of water vapor increase could not be explained by surface flux alone. This discrepancy should be studied. In addition, the role of diurnal cycle of SST to the development of convection needs further examination.

c. Recent studies using idealized models and general circulation models suggest a critical role for surface heat fluxes in supporting the MJO. The role and nature of surface fluxes of heat, moisture, and momentum should be a fundamental component of CINDY.

3.3 Oceanic research

a. As for the variation of SST in the central equatorial Indian Ocean, the role of ocean mixed layer has not been investigated. Detailed observation of mixed layer is inevitable.

b. The role of diurnal warm layers for the MJO is also mostly unknown and requires detailed in-situ observations.

c. Short-term variability was found in surface current meridional component suggesting to the relationship to oceanic mixed Rossby-gravity waves. Other studies have also investigated oceanic intraseasonal Kelvin and mixed Rossby-gravity waves, and that there is both a wind forced component (i.e., directly forced by the MJO) and an internally generated part. Estimating the relative role of each will be an interesting question for CINDY to address.

d. Biogeochemical response to the change of physical conditions near the ocean surface is expected. What is the typical distribution of chlorophyll? and how they response to the change of the oceanic physical conditions?

4. Observational plan

4.1 Basic Strategy

While MISMO has proved that in-situ observations can provide very useful information on the study of MJO-convection, key questions listed in the previous section cannot be solved only from one-time limited field campaign. In addition, key questions suggest that the long-time and large-scale observation network is essential to capture the relationship between meso-scale convective systems and large-scale equatorial waves. Actually, since ship and land-based sites are limited, large-scale features will be studied mainly using satellite data and numerical studies. However, it is possible to construct the observation network which is suitable for the comparison between in-situ data and satellite data so that we can interpret the large-scale features revealed by satellite and reanalysis data using in-situ data by considering the typical scale of large-scale disturbances and appropriate configuration. For example, as noted in MISMO budget analysis, it is possible that triangle sounding array might fail to capture the phenomena which has a rotational component such as equatorial Rossby wave. Based on the theoretical calculation for the idealized wind pattern associated with the MJO, we confirmed that quadrilateral configuration is more appropriate to detect a divergence component from equatorial Rossby wave than triangle one (Figs. 9 - 11). Furthermore, since the MISMO was one-month campaign, we missed to capture the December MJO event. Thus, much longer time-series data is strongly desired. Therefore, it is impossible to accomplish this campaign by one or a few institutes, and it should be done as a multi-national effort. Basic strategy of the campaign is to construct a long-time (over intraseasonal period) and wider areal observation network with ships and land-based sites in collaboration with IndOOS (Indian Ocean Observing System, http://www.clivar.org/organization/indian/IndOOS/obs.php) including RAMA buoy array.

4.2 Observation Period and Location

Figure 12 shows the climatological MJO activity as a function of time and longitude. Here, MJO activity is defined as outgoing longwave radiation (OLR) variance for the MJO band in the wavenumber-frequency domain following the work of Wheeler and Kiladis (1999), and calculation is conducted for 1979 - 2007 period. Major MJO activity can be found in the central - eastern Indian Ocean from November to January period. This result is consistent with previous studies (e.g., Zhang and Dong 2004; Matthews 2008). Therefore, to study the initiation process of convection, the most appropriate location is central Indian Ocean and the best period is from October to January. Thus, we decide the main observation area around 80°E on the equator and intensive observation period will be from October 2011 to January 2012. In addition, as some cases shows the development in the western Indian Ocean, it is strongly required to extend the site to the west of Maldives to surely capture the features related to initiation.

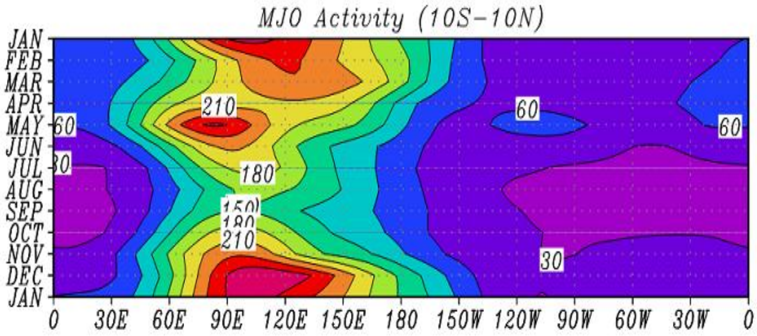

Fig. 12. Longitude-time cross section of the OLR variance for the MJO band which is defined in the wavenumber-frequency domain following Wheeler and Kiladis (1999). Calculation is done along the equator averaged between 10S - 10N for 1979 - 2007 period.

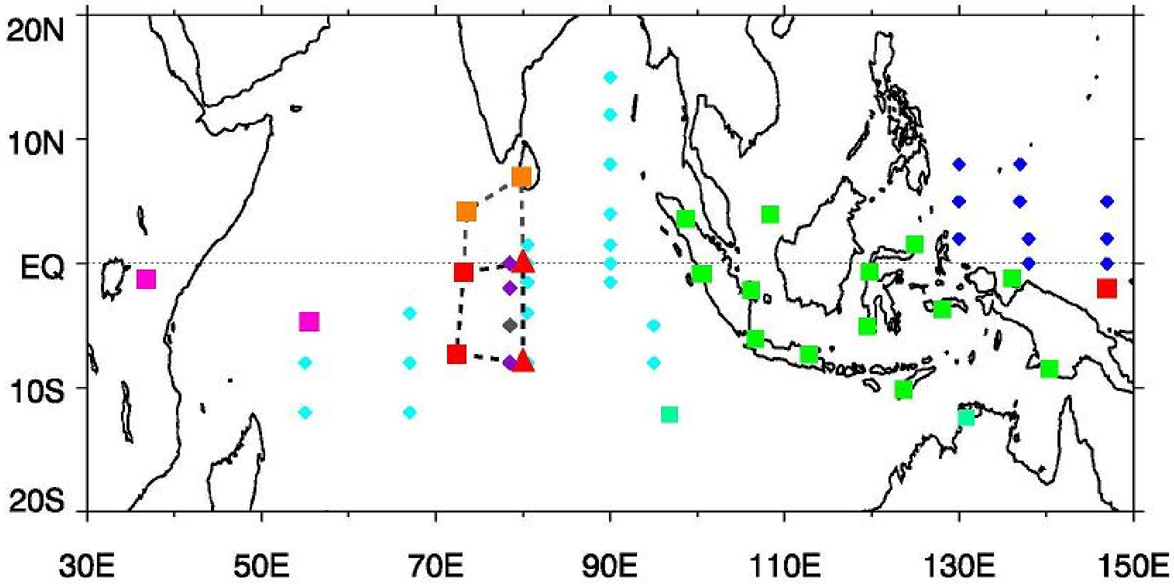

Fig. 13. A proposed observational network for CINDY2011/DYNAMO. Black dashed lines indicate intensive observation sounding array, which consists of Gan Island, Diego Garcia Island, and two ship-sites at 0°, 80°E and 8°S, 80°E. Grey dashed lines indicate northern sounding array with Male, Maldives and Colombo, Sri Lanka. Square indicates land-based radiosonde sounding sites. Each color indicates as below; red: enhancement to 4-8 times/day in IOP, orange: 2-4 times/day in SOP, pink: 2-4 times/day in IOP, green: no enhancement. Diamonds indicate surface moorings of TAO/TRITON (dark blue) and RAMA (light blue). Purple diamonds along 78.5°E are DYNAMO surface buoys planned to be deployed only during IOP.

Table 1. Radiosonde sounding sites in and around the Indian Ocean. Soundings will be enhanced at several sites in a certain period (right two columns). Radiosonde type are shown as V92 (Vaisala RS92), M06 (Meisei RS-06G), and M2K(Modem, M2K2DC).

Site	Location	Height(m)	Type	Frequency (times/day)	
Nairobi	1.30°S 36.75°E	1798	V92	1	2 (IOP)
Seychelles	4.68°S 55.53°E	4	V92	1	4 (Oct) / 2 (IOP)
Male	4.19°N 73.53°E	2	V92	0	4 (SOP)
Gan	0.68°S 73.15°E	2	V92	1	8 (EOP)
Diego Garcia	7.30°S 72.40°E	3	V92	0	8 (SOP) / 4 (IOP)
Colombo	6.90°N 79.87°E	7	M06	3 / week	2 (SOP)
Medan	3.57°N 98.68°E	25	M06	2	2
Padang	0.88°S 100.35°E	3	M06	2	2
Pangkal Pinang	2.17°S 106.13°E	25	M06	2	2
Cengkareng	6.12°S 106.65°E	8	M06	2	2
Ranai	3.95°N 108.38°E	2	M2K	2	2
Surabaya	7.37°S 112.77°E	3	M06	2	2
Makasar	5.07°S 119.55°E	14	M06	2	2
Pan	0.68°S 119.73°E	6	M06	2	2
Kupang	10.17°S 123.67°E	108	M06	2	2
Manado	1.53°N 124.92°E	80	M06	2	2
Ambon	3.70°S 128.08°E	12	M06	2	2
Biak	1.18°S 136.12°E	11	M06	2	2
Merauke	8.47°S 140.38°E	3	M06	1	1
Cocos Island	12.18°S 96.82°E	3	V92	1	1
Darwin	12.40°S 130.87°E	30	V92	2	2
Manus	2.07°S 147.43°E	5	V92	2	8 (EOP)

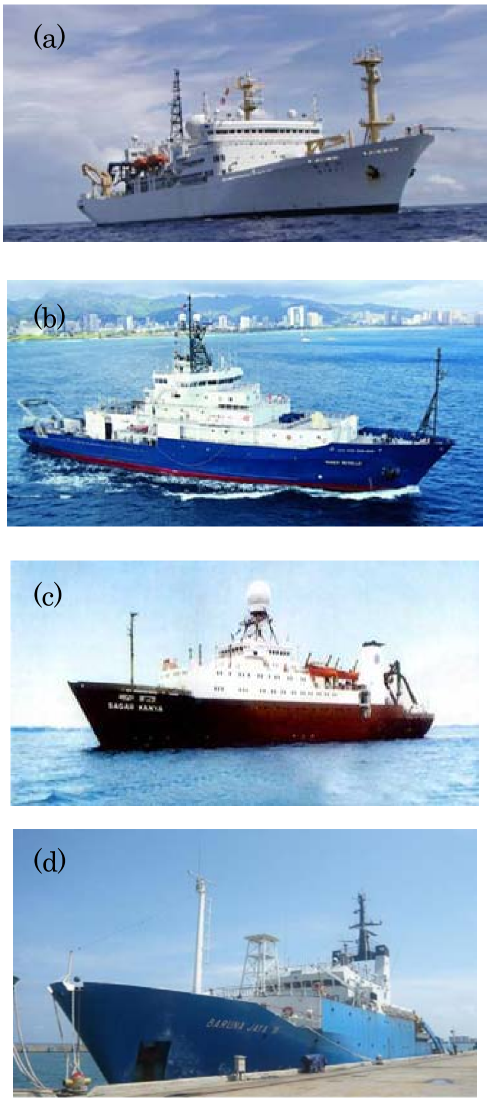

Fig. 14. Participant ships. (a) Mirai, (b) Revelle, (c) Sagar Kanya, and (d) Baruna Jaya.

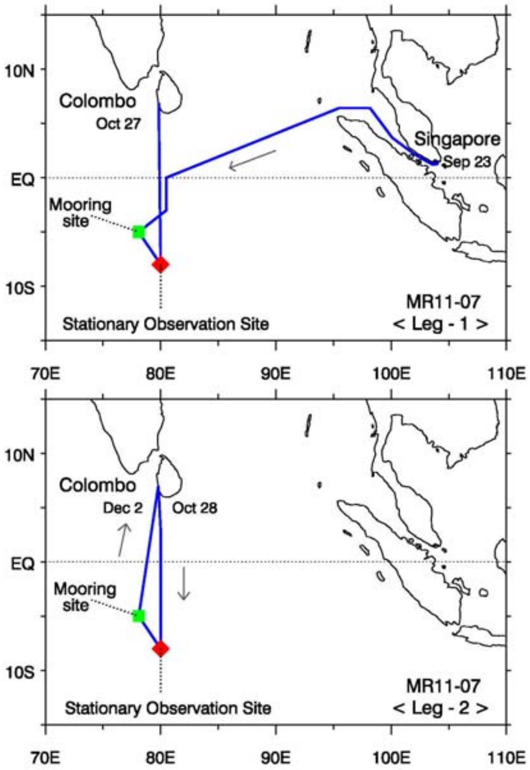

Fig. 15. Planned R/V Mirai Cruise Tracks

4.3 Methods and Platforms

Here, we describe the possible observation facilities as of May 2011.

In this regard, it should be noted that major contribution to CINDY2011 is a US component known as DYNAMO (Dynamics of the MJO) project, which is supported by NSF (National Science Foundation), NOAA (National Oceanic and Atmospheric Administration), ONR (Office of Naval Research), DOE (Department of Energy), and NASA (National Aeronautics and Space Administration). DYNAMO consists of two major components; field observations (ship, moorings, land-based sites, aircraft, etc.) and numerical models (forecast, hindcast, and reanalysis). These themes are conducted by many US federal institutes and universities. Since DYNAMO plays a key role for most of all plans, we mention as CINDY/DYNAMO.

Figure 13 shows a proposed observation network. A main intensive observation sounding array which consists of two islands and two ships to form a quadrilateral array is shown by thick dashed lines. In addition, we define several key observation periods as below; SOP (Special Observation Period; October 1, 2011 - November 28, 2011), IOP (Intensive Observation Period; October 1, 2011 - January 15, 2011), and EOP (Extended Observation Period; October 1, 2011 - March 31, 2012). SOP is characterized as an intensive radiosonde sounding (8 times/day) with the northern array (indicated by grey dashed lines), and many radar observations will be carried out. IOP is characterized as a period in forming a quadrilateral array with two islands and two ship sites to capture an intraseasonal event and to assess budget analysis precisely. During EOP, some observations at land-sites will be continued.

a. Research vessels

i) R/V Mirai

JAMSTEC will send the research vessel (*R/V*) *Mirai* (Fig. 14a) to the Indian Ocean to occupy one apex of the intensive observation sounding quadrilateral array at 8°S, 80°E for two months from October 2011. Currently, she is scheduled to leave Singapore on September 23, 2011 and arrive at the stationary site on September 30. Then, she will occupy there about two months except late October to exchange the legs. Expected cruise track is shown in Fig. 15. Many scientists can join the *R/V Mirai* cruise to conduct their own measurement through the prescribed public selection. As a result, various atmospheric and oceanic observations will be carried out. For atmospheric measurements, those include 5.3-GHz scanning Doppler radar (every 10 min interval for volume scan), radiosonde (launch every 3 hours), surface meteorological station including precise radiation measurements, turbulent flux, ceilometer, vertical pointing 95 GHz cloud radar, Mie-scattering lidar, sky-radiometer, multi-axis differential optical absorption spectroscopy, as well as special designed radiosonde such as video-sonde and cryogenic frost-point hygrometer sonde. On the one hand, as for the oceanic observations, measurement systems include CTD with water sampler for biogeochemical analysis such as chlorophyll and nutrients, microstructure profiler, shipboard ADCP, surface water monitoring system, and so on. In addition, sea surface temperature will be measured by three different methods; one is by so-called in-take method at 5m depth, second is by floating thermistor (Sea-snake) for 2-3 cm below the surface, and last one is Infrared Sea surface temperature Autonomous Radiometer (ISAR) for real skin temperature.

For more details, refer “*R/V Mirai* MR11-07 Cruise Operational Plan”.

ii) R/V Roger Revelle

DYNAMO will send the *R/V Revelle* (Fig. 14b) to occupy one key apex of quadrilateral array at 0°, 80°E for almost three months from late September to early January as 3 legs. During on-station, atmospheric observations such as Doppler radar, radiosonde, turbulent flux, lidar, aerosol measurements and oceanic observations such as ocean surface turbulence profiler, CTD, Sea-soar, ADCP will be extensively carried out.

For more details, refer “DYNAMO Operations Plan; Chapter 3: R/V Revelle Operations”.

iii) ORV Sagar Kanya

National Institute of Oceanography (NIO), India will have one-month biogeochemical cruise in 2011 using the ORV *Sagar Kanya* (Fig. 14c) and stationary observation is being planned. It is now being discussed to coordinate their cruise period will be in October - November to participate in CINDY2011 and to occupy one of quadrilateral intensive observation array at 0°, 80°E while *R/V Revelle* leaves. During their cruise, radiosonde sounding will also be conducted at least 4 times per day.

In addition to this biogeochemical cruise, another cruise for maintaining their deep sea current-meter mooring array 77°E, 83°E, and 93°E along the equator as well as several RAMA buoys along 80°E line also contribute to the campaign.

iv) R/V Baruna Jaya

JAMSTEC is planning to charter the *R/V Baruna Jaya* (Fig. 14d) with help of BPPT (Agency for the Assessment and Application of Technology), Indonesia. Her cruise is expected to be conducted in December 2011 for 3 weeks, and she cruises along 8°S after leaving her mother port near Jakarta. It is expected that stationary observation about 7-10 days at 8°S, between 80°E - 90°E will be carried out. During this cruise, radiosonde sounding will be carried out 4 times per day for 2 weeks.

v) Chinese vessel

Researchers from Chinese institutes (South China Sea Institute of Oceanology and First Institute of Oceanography) have a project to study eastern Indian Ocean using ships. They are now trying to coordinate their project to collaborate with CINDY/DYNAMO, and there is a possibility to send their ship to the central Indian Ocean in January 2012.

b. Land-based sites

To construct the atmospheric sounding array, sounding stations at lands in and around the Indian Ocean are inevitable components. Therefore, in addition to temporal intensive observation sites, routine sounding sites will be incorporated into the campaign.

i) Intensive Sounding Array (ISA)

Gan Island (or strictly speaking, Addu Atoll, which contains several islands), Maldives at 0.7°S, 73.2°E and Diego Garcia at 7.3°S, 72.4°E will be apices of the western part of a quadrilateral ISA. US DYNAMO project is mainly responsible for these sites. In particular, Gan Island will be a super site with S/C/X/Ka/W-bands Doppler radar, 3-hourly radiosonde soundings, precise radiation measurements as well as basic surface meteorology. US Department of Energy's ARM (Atmospheric Radiation Measurement) Mobile Facility is deployed as a key observation platform as a part of AMIE project (see Section 4.4a for AMIE). On Diego Garcia, Integrated Sounding System (ISS) will be deployed during the IOP.

Detailed information can be found in "DYNAMO Operations Plan; Chapters 4 and 5".

ii) Northern Sounding Array (NSA)

Based on the statistical studies on MJO-convection occurrence (Zhang and Dong 2004), it is highly possible that main MJO-convection occurs north of the equator in the boreal fall. Therefore, it is desired to form an array for this region as MISMO campaign did. Thus, currently radiosonde soundings at Male (Hulhule Island, 4.2°N, 73.5°E) and enhancement of soundings at routine site at Colombo, Sri Lanka (7.3°S, 72.4°E) are scheduled with the aid of Maldives Meteorological Services and Department of Meteorology, Sri Lanka.

iii) Routine sounding sites with enhancement

While intensive sounding array is formed in the central Indian Ocean, western and eastern Indian Ocean region should also be monitored, as MJO is characterized as eastward-propagating disturbance. In particular, since it is reported that many shallow convections relevant to MJO-related large-scale cloud system develop over west of Maldives, frequent soundings are desired. Based on this requirement, currently Seychelles National Weather Services and Kenya Department of Meteorology have agreed to join the campaign, and enhanced radiosonde soundings are scheduled.

In addition, BMKG (Meteorological, Climatological and Geophysical Agency of Indonesia) is expected to join the campaign by providing their routine sounding data with fine vertical resolution taken at many sites deployed over the Indonesian maritime continent.

c. Moored buoy array

RAMA buoy array is essential to provide basic and long-term information on the surface ocean conditions. Therefore, contribution to maintain and extent the existing buoys is highly required. The coordination of ship time for the RAMA buoy array is extensively discussed at the CLIVAR/GOOS Indian Ocean panel and it has been maintained by institutes from many countries including USA, India, Indonesia, France, Japan, China, and African nations of ASCLME (Agulhas and Somali Current Large Marine Ecosystems Project). In particular, intensive mooring line with sub-surface ADCP moorings along 80.5°E will directly relate to the campaign.

In addition to above, surface and sub-surface moorings (three each) will be deployed as a part of DYNAMO project at 0°, 2°S, 8°S along 78.5°E during entire IOP, while one sub-surface ADCP mooring with PAL (Passive Aquatic Listener) will be deployed at 5°S, 78.1°E by JAMSTEC during SOP.

d. Floats

While an international Argo project provides ocean data for a long period by Argo floats which usually ascend every 10 days, several types of floats will be temporarily deployed during the campaign. It is planned to deploy one Argo float whose parking depth is set at 500 m and is scheduled to ascend once per day from the *R/V Mirai* to resolve the intraseasonal variability with fine temporal resolution.

A research group from University of East Anglia will deploy a sea-glider from the *R/V Revelle*. Sea-glider can swim along intended sections and collect temperature and salinity data with fine resolution between fixed moorings.

e. Aircrafts

Two aircraft observations are scheduled. One is NOAA P-3 measurement done by US DYNAMO project during November - December. Diego Garcia will be the base for P-3, and they have 105 science mission hours with 70 ferry hours. Since their main target is to study air-sea boundary layer process, dropsonde, AXBT, C/X-bands radars as well as in-situ measurements will be performed. Another aircraft observation is done by French researchers using Falcon-20. Forty hours can be used for scientific missions during November 1 to December 15. Their main target is meso-scale cloud systems to develop an algorism which can be applied to Megha-Tropiques satellite data calibration in future. It will be operated to fly between 3 - 9 km height within 1,000 km from their base at Gan Island.

f. Satellites

Satellite data will provide basic large-scale atmospheric and ocean surface features and they are inevitable factors for the study of MJO-convection and any intraseasonal variations. We expect the following satellite data are available during the campaign; MTSAT and METEOSAT (brightness temperature), TRMM (precipitation), SSM/I (water vapor), A-Train (3-d temperature and humidity, 3-d clouds, aerosol) and many.

These satellite data sets can be merged and used for analyses as well as evaluation of numerical models. The Satellite Data Simulator Unit (SDSU), which is a Fortran package to simulate synthetic observations for passive microwave sensors, radars, visible and infrared imagers, will be one of key tools for this purpose (Masunaga et al. 2010).

4.4 Relevant Projects

To construct longer and wider observation network in order to surely capture the lifecycle of MJO convection, collaboration with relevant projects are inevitable. Currently, collaboration plans with the following projects have been established.

a. AMIE

The Atmospheric Radiation Measurement (ARM) program of the US Department of Energy will conduct the intensive observation named AMIE (ARM MJO Investigation Experiment). Six months intensive observations with AMF-2, C-band radar, and radiosonde sounding (3-hourly) will be carried out at ARM tropical western Pacific site on Manus Island, Papua New Guinea (this campaign is called AMIE-Manus). This project will also carry out on Gan Island, Maldives as AMIE-Gan, which is a key component of Gan super site. AMIE project enable us monitor a life cycle of MJO-convection from birth place to mature phase via modulation phase over the maritime continent by combining with HARIMAU/SATREPS projects described below.

Detailed information on AMIE project can be found at http://campaign.arm.gov/amie/.

b. ONR-DRI

The US Office of Naval Research has initiated a Departmental Research Initiative (DRI) to develop a better understanding of coupled air-wave-sea process, and their primary goal is to improve the representation and prediction of the boundary layer in both ocean and atmosphere on time scales from one to thirty days, which also fits to the goal of CINDY/DYNAMO. Thus, this project is currently joining and playing a key role of DYNAMO from both observations and numerical studies.

c. HARIMAU and follow-on

HARIMAU (Hydrometeorological Array for ISV-Monsoon Automonitoring), which was supported mainly by the Japan Earth Observing System Promotion Program of the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) and in part by a Special Grant for Higher-Level Science, Technology and Research of the Government of the Republic of Indonesia, had been conducted in Indonesia from April 2005 to March 2010 (Yamanaka et al. 2008). A follow-on project “Climate variability study and societal application through Indonesia - Japan ‘Maritime Continent COE’ - Radar-buoy network optimization for rainfall prediction (http://neonet.bppt.go.id/satreps/)” is now conducted under the SATREPS (Science and Technology Research Partnership for Sustainable Development), which is a collaboration between the two Japanese government agencies; The Japan Science and Technology Agency, and the Japan International Cooperation Agency. In addition, HARIMAU project itself continues as a part of Indonesian effort. While these projects obtain radar data, it is also expected that one-month intensive observation will be carried out in conjunction with CINDY/DYNAMO, so that it is possible to monitor the interaction between MJO and maritime continent, and it links the projects in the Indian Ocean and the Pacific.

5. Numerical studies

Many numerical research groups from universities, research institutes and operation centers are expected to join this campaign to promote their skill of simulation and prediction of MJO. Observations and numerical studies must work together to advance our knowledge of MJO initiation process. Therefore, for example, radiosonde sounding data should be sent to meteorological communities through the global telecommunication system (GTS) immediately after the observations, so that operation centers can incorporated those enhanced data into their assimilation. This process enable us to further use their products for observations and analyses as well as numerical model studies.

Forecast / Hindcast / Reanalysis

Numerical model researchers from the world will join this campaign in various stand points of view such as forecast, hindcast (simulation), and producing reanalysis data.

Needless to say, to interpret the physical processes of observed features, numerical study is essential. Recently Miura et al. (2007) successfully simulated an MJO event by using the global cloud resolving model called NICAM (Nonhydrostatic icosahedral atmospheric model; Satoh et al. 2008).

NICAM research group has also simulated the event observed during MISMO (Miura et al. 2009). While NICAM will be run with high resolutions to examine the behavior of convections developed during the campaign, NICAM research group is also planning to conduct the quasi-real time forecast using a stretched-grid technique (Tomita 2008). Several operation centers also intend to provide real-time forecast. While these products will be used for decision making of flight schedule at Gan and Diego Garcia, intercomparison of MJO prediction will be made following the work by WCRP/WWRP-THORPEX YOTC MJO Task Force (Gottschalck et al. 2010). These products will be opened not only to the field participants but also to anyone on the CINDY and DYNAMO web sites.

It is planned that the impact of assimilation of observation data taken during the campaign will be accessed using experimental reanalysis called ALERA, which is produced by by the local ensemble transform Kalman filter with the atmospheric global circulation model for the Earth Simulator (cf. Miyoshi et al. 2007, Moteki et al. 2011).

6. Data Policy

All data taken during the campaign should be released to scientific community timely with easy access. All CINDY2011/DYNAMO participants are requested to follow the the Data Policy below.

--- begin ---

General Guideline:

CINDY2011/DYNAMO adopts “timely release and free/open sharing data policy” for all data obtained during field campaign.

Data Submission and Availability:

Within six months following the end of the field campaign, all data shall be promptly shared by CINDY2011/DYNAMO investigators responsible for data acquisition to other CINDY2011/DYNAMO investigators upon request and notification of the intent of data use. During the first 12 months following the end of the field campaign, all CINDY2011/DYNAMO data will be accessible only to CINDY2011/DYNAMO investigators to facilitate inter-comparison, quality control checks and inter-calibrations, as well as an integrated interpretation of the combined data set. No public release of the data (sharing with non-CINDY2011/DYNAMO colleagues, conference presentations, publications, commercial and media use, etc.) is allowed without the permission of the CINDY2011/DYNAMO PIs who are responsible for collecting the data.

Quality control procedures should be carried out by CINDY2011/DYNAMO investigators within 12 months following the end of the field campaign, unless unforeseeable issues emerge. After 12 months, CINDY2011/DYNAMO field data will be made available to the broader scientific community. Any remaining data quality issues should be made clear in the data documentation files. Improving CINDY2011/DYNAMO data quality will be a continuous effort. The suitability of the released data for scientific investigations and publications should be decided at the discretion of the CINDY2011/DYNAMO investigators responsible for field data collection and quality control and data users.

Data Authorship and Acknowledgements:

The authorship decision for publications resulting from using CINDY2011/DYNAMO data should follow the ethic rules of the journals and professional organizations (e.g., AMS, AGU). CINDY2011/DYNAMO investigators responsible for field data collection are encouraged to make contributions to data analysis and writing of manuscripts, in addition to providing the data, to be co-authors or acknowledged in the publications using CINDY2011/DYNAMO data.

All publications using CINDY2011/DYNAMO data are suggested to include the following acknowledgement: The xxxx data was collected as part of the CINDY2011/DYNAMO project, which was sponsored by DOE, JAMSTEC, NASA, NOAA, NSF, ONR, [other responsible funding agencies]. The involvement of the Data Center is acknowledged. [The acquisition of the xxx data was carried out by YYYY using the zzzz instrument and was funded by wwww (if YYYY is not a co-author)].

--- end ---

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