Chapter 7

The ARM Tropical Western Pacific (TWP) Sites

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1. Introduction

One of the earliest and liveliest discussions of the ARM Program was about the number and possible locations of the proposed ground-based observing sites. Early versions of the ARM Program Plan (U.S. DOE 1990) envisaged placing ground-based remote sensing facilities at five or more locations, but the locations were not specified. As soon as ARM was approved in the Department of Energy budget, determining these locales became one of the highest priorities. The workshops and discussion sessions that were held to address this issue focused on two related questions:

1) What are the most climatically important regimes to sample?
2) For which regimes do we have the least available information?

Scientific and logistical considerations led to establishing the first locale in the continental interior of the United States, which led to the Southern Great Plains (SGP) site [see Sisterson et al. (2016, chapter 6)]. There was strong consensus that the next two locales should be established in the tropical warm pool and in the Arctic to span, as it were, the extremes of global climate. The selection of the warm pool locale, which led to the establishment of the Tropical Western Pacific (TWP) sites, occurred because of the recognized importance of the TWP in tropical and extratropical climate variability, about which relatively little was known at the time. The TWP area is typified by a strong east-to-west gradient in various climate characteristics, including sea surface temperature, column water vapor amounts, and frequency of convection (Ackerman et al. 1999) and is also characterized by strong solar heating.

a. Choosing the TWP sites

ARM Program management appointed site managers for each of these three locales (as well as for two locales that were never subsequently built because of financial considerations) and then selected site scientists through a competitive proposal process. The site scientist and manager were charged jointly with implementation of the locale choice, including choosing an actual site within the designated locale, identifying required instruments, and building the site. The TWP team of Site Scientist Thomas Ackerman (The Pennsylvania State University) and Site Manager William Clements [Los Alamos National laboratory (LANL)] convened several meetings to discuss the site location, most notably a workshop held in Santa Fe, New Mexico, in May of 1992. The consensus strategy that emerged for the TWP was that measurements should occur at three to five locations along the equator selected to sample the shifts in convection and the Walker circulation associated with El Niño–Southern Oscillation (ENSO) events; this strategy was later revised to three sites along the equator. The first site was to be located in the heart of the tropical warm pool, the second in the area of high variability in atmospheric and oceanic properties

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associated with ENSO cycles, and the third in the subsidence region of the eastern Pacific. The proposal included two additional sites, one north and one south of the equator in the region of high variability, in order to sample the movement of the intertropical convergence zone (ITCZ) and its consequences. These recommendations were summarized in two reports. The first report, entitled "Science and Siting Strategy for the Tropical Western Pacific ARM CART Locale," was authored by Ackerman et al. (1993). The second report is a final updating of that document issued in 1999, coauthored by the same individuals, and its title was expanded to "Tropical Western Pacific Cloud and Radiation Testbed: Science, Siting, and Implementation Strategies," because it includes the actual site design information (Ackerman et al. 1999).

At the same time that the TWP plan was being developed, extensive activities were underway to carry out the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE; Webster and Lukas 1992) in the warm pool region of the equatorial Pacific between 140°E and the date line. Much as the joint Spectral Radiance Experiment (SPECTRE)/FIRE experiments in Kansas provided a prototype for the SGP site [see Ellingson et al. (2016, chapter 1)], TOGA COARE provided a unique opportunity to test scientific ideas and deployment concepts for the proposed TWP site. The ARM TWP team participated in COARE by operating a ground-based remote sensing facility at Kavieng, Papua New Guinea (PNG), from November 1992 to February 1993. This Pilot Radiation Observation Experiment (PROBE) campaign (Renne et al. 1994) was the first ARM field campaign and TWP science contribution, providing useful radiation data for TOGA COARE (Waliser et al. 1996; Long 1996) and producing a landmark paper by Westwater et al. (1999), which won the 2000 Professor Dr. Vilho Vaisala Award in Atmospheric Sciences from the World Meteorological Organization. PROBE included high-spectral-resolution IR observations from a Fourier transform infrared radiometer that were used to update the then-current Clough–Kniezys–Davis (CKD) water vapor continuum formulation (Clough et al. 1989, 1992) and a dual-channel microwave water radiometer (MWR) for continuous column water vapor amount observations (Westwater et al. 1999).

TOGA COARE also provided an opportunity for the TWP team to assess possible locations for a permanent site in the TWP warm pool region. Based on a climatological assessment, largely done using satellite observations, the team settled on Kavieng or Manus Island, PNG. Both places are within a few degrees of the equator in the heart of the warm pool. After careful consideration, the team chose Manus Island primarily for two reasons. The ARM site on Manus could be located at Momote Airport, which is on the eastern shore of the island in a geographically flat area. This location was deemed superior to the possible site near Kavieng because it was next to the open ocean and largely undeveloped, other than the airport runway itself. Second, and equally important, the provincial government of Manus is very supportive of educational activities on the island and was willing to work closely with the ARM team in developing the necessary logistics. In retrospect, Manus has proved to be an excellent choice in terms of science, political stability, and long-term relationships.

The focus of the team then shifted to the selection of a site farther to the east. Using long-time series of outgoing longwave radiation (OLR) data, the team identified the region around 170°E longitude as being the most variable with regard to OLR (and presumably cloud occurrence). For logistical reasons, the team narrowed its options to either Nauru or Tarawa Atoll. Nauru is an independent republic, while Tarawa is part of the far-flung Republic of Kirabati. Both sites presented challenges. Nauru is a small rocky island once covered by guano deposits but now almost completely devastated in the interior by strip mining. The mining generated considerable revenue at the time, but the island was suffering economically by the mid-1990s. Finding a good site was constrained by the relatively high population density along the island shore. This latter problem was even greater at Tarawa. Tarawa is a small atoll with a very high population density and little available land. It also has severe environmental problems with freshwater availability and sanitation. The consensus was to locate in Nauru in large part because the only available site in Tarawa was too small and too impaired by surrounding development.

As a result of financial constraints within the ARM Program, the additional sites in the equatorial Pacific were never developed. A third site, however, was developed in Darwin, Australia, in conjunction with the Australian Bureau of Meteorology. This site arose in part from the need to provide a more local staging area for maintenance of Manus and Nauru and in part from the excellent existing scientific infrastructure and data collection in the area. The Darwin climate is driven heavily by the Australian monsoon and thus provides an interesting contrast to the more oceanic convection typical at Manus and the ENSO-driven variability at Nauru. Figure 7-1 shows the three ARM TWP site locations.

b. *Establishing the sites*

The first challenge in establishing the TWP was how to construct a continuously operating facility in a remote

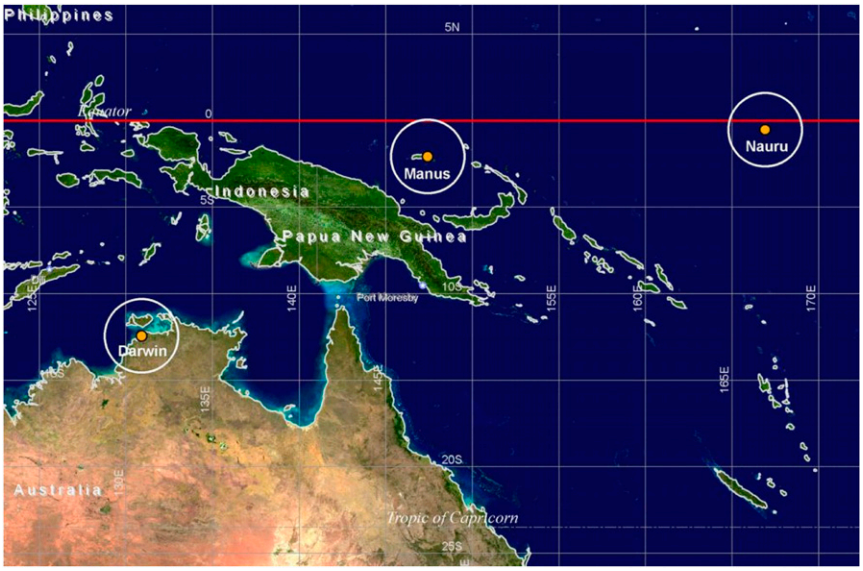

FIG. 7-1. ARM TWP sites. Image courtesy of the U.S. Department of Energy ARM Climate Research Facility.

location that had no long-term scientific or technical personnel posted to the area. Besides the landmark observations, the lessons learned from PROBE had a significant role in design of the Atmospheric Radiation and Cloud Station (ARCS). As noted in Ackerman et al. (1993, 9–18): "The logistical issues sharpened in our perception as a result of our experiences in PROBE [. . .]. A good deal of thought has gone into the proposed ARCS. The current conceptual design has been heavily influenced by the design of the Integrated Sounding Systems developed and deployed by the National Center for Atmospheric Research (NCAR) and the National Oceanographic and Atmospheric Administration (NOAA), and by our experiences with PROBE." Important elements of the ARCS design included the use of International Standards Organization (ISO)-certified shipping containers as instrument shelters, integrated backup power, a centralized redundant site data system (SDS), connectivity for the site management team, and near-real-time health and status monitoring.

The TWP team decided to build the site in the United States using sea containers and then ship the rebuilt containers to the TWP. This added some complexity to the choice of sites, since ports and cranes were now required to offload the containers, as well as heavy equipment to position them at their destination; however, it allowed the containers to be handled relatively easily at commercial ports. These containers did double duty as shipping containers and, in the field, as shelters for instruments, computer systems, and work space.

Another key element of the site infrastructure was integrated backup power. The ARCS was designed with a combination of a backup diesel generator that could support the entire site and uninterruptible power supplies that would keep instruments and computers running during a power outage while the generator kicked on. This provided much better operational continuity than would have been available otherwise.

The SDS was designed to provide a single virtual point of entry to the site. The SDS managed data collection from all the instruments, as well as environmental monitoring systems, control of off-site communications, bundling of data, and the creation of compact health and status files. Originally, there was very limited bandwidth to the tropical sites. Routine transmission of data was managed over a geostationary satellite link and was limited to about a kilobyte per hour. Careful thought was given to packing information from instruments and infrastructure systems into that tiny data packet, but it was sufficient to gain a remarkable amount of information about the site conditions and was used to identify system failures.

Instrument selection was based on a combination of scientific needs and instrument robustness. The instrument suite closely matched those previously deployed at the SGP site. Some of the more experimental instruments, like the Raman lidar, were not deployed. The ARCS deployment was also much more compact than the SGP. Whereas the SGP site was distributed over a large portion of north-central Oklahoma and south-central Kansas, the ARCS concept mirrored the SGP central facility. Among other things, this compact design enabled continuous remote contact with all the instruments.

Mark Ivey (Sandia National Laboratories), working closely with Site Managers Bill Clements and Fairley Barnes (of Los Alamos National Laboratory), was largely responsible for the organization and supervision of the ARCS development for both the Manus and Nauru sites. The TWP development team included the site management team, data system developers, instrument technical leads, communications specialists, and representatives from the TWP site science office and met regularly in Albuquerque, New Mexico, to develop and implement the ARCS concept.

After several years of dedicated effort, the TWP team established the first TWP site at Momote Airport on Manus Island in August 1996. Members of the team spent more than 6 weeks on Manus establishing the site and making sure that all systems were working properly. The installation period was a time of intense effort for everyone, with long days and many hours spent out in hot, humid weather. It was also a time of great satisfaction watching the system come to operational life after so many years of preparation. The site at Nauru followed in November of 1998 with a similar period of installation and testing.

The TWP operations were, for many years, the only part of the ARM Program that dealt with foreign governments. The Manus and Nauru sites were established in collaboration with the governments of PNG and Nauru, respectively. This process was long and occasionally frustrating but ultimately necessary and extremely helpful. The initial step was to negotiate permission for an ongoing U.S. scientific presence in these countries. Both countries were wary of a western presence, having previous experiences with broken promises and a perceived lack of reciprocity. The ARM Program and TWP team came to the negotiations with two specific offers: namely, training and employment of local individuals to operate and maintain the sites, including launching of meteorological balloons and open sharing of data. Both were very important to the national governments and led to an acceptance of the ARM Program and permission to install the sites. The radiosonde data were critical because they fulfilled obligations that PNG and Nauru had to the World Meteorological Organization to provide soundings for forecast model initialization. At the level of the local government in Manus, engagement with their secondary education program was the key factor in accepting the ARM Program. It is important to recognize the positive role that both governments played in the site selection and the approval process. Without their participation, the ARM Program could not have established these sites and would not have had the ongoing success in operations and data collection.

c. *Outreach*

The principal outreach activity of the TWP site has been its interactions with the secondary education systems on Manus Island and Nauru. As part of the early siting negotiations in Manus, a commitment was made to the Provincial Governor to provide educational resources to the secondary schools on the island. As the TWP effort progressed, responsibility for this education program was given to Fairley Barnes (LANL), who had a tremendous heart for the students and the education program. She worked with school administrators and teachers to determine how the ARM Program could help them, organized presentations (by herself and others with relevant expertise) at the schools, arranged tours of the ARM facility for teachers and students, and facilitated the donation of personal computers to the schools.

The outreach program organized more formally in 1998 and adopted three goals: 1) inform and enrich primary, secondary, and college programs in the tropical western Pacific region; 2) focus on basic science concepts, through activities and study of climate, climate change, and the effects of climate change relevant to the region; and 3) foster career goals in science for students in the region. It organized workshops for teachers in both countries, working with several regional partners in the South Pacific island nations and Australia. It also worked to develop curriculum units and a variety of teaching tools, including a traveling kiosk that could be used for interactive learning and viewing the data.

In the mid-2000s, in response to a general lack of funding for ARM activities, the ARM Program moved to consolidate its education activities into a single education office rather than funding them through the site offices. While this achieved a desired fiscal efficiency, it had a negative impact on TWP outreach and education. The TWP is historically the only permanent ARM site located outside the United States, and the teachers and students in its locale have substantially different interests and needs. With the consolidation, these were given lower priority to other considerations; as a result, the current educational outreach program has a reduced flexibility and capability to address the unique issues in the TWP and became less engaged with the TWP nations.

2. The TWP sites

a. *Manus*

Developing an ideal measurement strategy for the TWP is challenging because multiple factors play roles in determining the distribution of convection: most

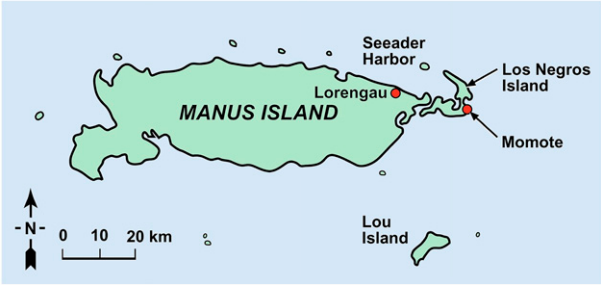

FIG. 7-2. Map of Manus and Los Negros Islands showing the Momote site, where the ARM Manus facility is located.

FIG. 7-3. October 1996 picture of the Manus site, as originally configured.

notably, sea surface temperature gradients and surface heating associated with the Maritime Continent (e.g., Ramage 1968; Neale and Slingo 2003; Shibagaki et al. 2006). Furthermore, the Maritime Continent is characterized by a broad spectrum of island sizes ranging up to the large islands of New Guinea, Borneo, and Sumatra and the adjacent continents of Australia and Asia. The first ARM TWP site was established on Manus Island (2.1°S, 147.4°E; Fig. 7-1) in Papua New Guinea and represents a moderate-size island at 100 km long on the eastern edge of the Maritime Continent (see Fig. 7-2).

The Manus site was the first TWP site deployed; thus, it became the first test of the remote ARCS operations paradigm. The operation of the Manus site is a collaborative effort between ARM and the Papua New Guinea National Weather Service, who supply the on-site observers, who are trained to handle day-to-day and weekly maintenance, such as cleaning radiometer domes, changing desiccant in radiometers, and swapping data system tapes. For maintenance and support that required more specialized knowledge and experience, a regional service team (RESET) visited the site nominally every 6 months or more frequently, as needed (Mather et al. 1998a).

The Manus deployment was planned to occur in early 1995 (Ackerman et al. 1993) in plenty of time to participate in the primarily NOAA-sponsored Combined Sensor Program (CSP) campaign (Post et al. 1997) but was delayed when an intensive predeployment internal review led the design team to postpone the installation. Because of the expected challenges of deploying a permanent station at a remote location (e.g., it would be very difficult to get any forgotten items), a beta test of the installation was carried out. In the test, the entire ARCS was packed up at Sandia National Laboratories, where it had originally been developed, and then unpacked and deployed for several weeks in San Diego, near the ultimate port of departure. This beta test provided an important dry run for the set up process and a review to ensure that the team would have everything it needed for the real deployment. During this exercise, it was decided that some technical issues with integration of this first ARCS system warranted a delay in the deployment scheduling. For the CSP campaign, a subset of ARCS instruments was deployed in collaboration with the NOAA–NCAR long-term Integrated Sounding System (ISS) operated at the Momote Airfield site, as the land-based ARM contribution to the CSP campaign. The technical issues were addressed, and the ARCS was deployed; observations began in October 1996 (Mather et al. 1998a), with GPS rawinsondes added in 1997, a Whole Sky Imager in 1998, and the Millimeter Cloud Radar (MMCR) in 1999. Figure 7-3 is a photo from October 1996 showing the original site configuration.

Deep within the warm pool, Manus experiences persistent cloudiness and convective activity and is influenced by the Madden–Julian oscillation (MJO; Madden and Julian 1994; Zhang 2005), as shown by Wang et al. (2011). Because the Manus area is so deeply embedded in the warm pool, it shows little intraseasonal or interannual variability in sky cover, downwelling radiative fluxes, and surface cloud radiative effect due to ENSO (McFarlane et al. 2013). The Manus observations were of immediate interest to the ARM research community and led to early studies in subjects such as cloud regimes (Jakob and Tselioudis 2003) and atmospheric state and surface radiation budget (Mather et al. 1998b).

The TWP area is primarily oceanic in nature. From the start, there was concern that observations made on a tropical island would be influenced so significantly by the land presence that they would not be representative of the larger surrounding oceanic area. One aspect of the CSP campaign was to compare the ship and land site measurements as the ship got closer to the site. Unfortunately, the ship time near the island combined with the limited land instrumentation due to the ARCS

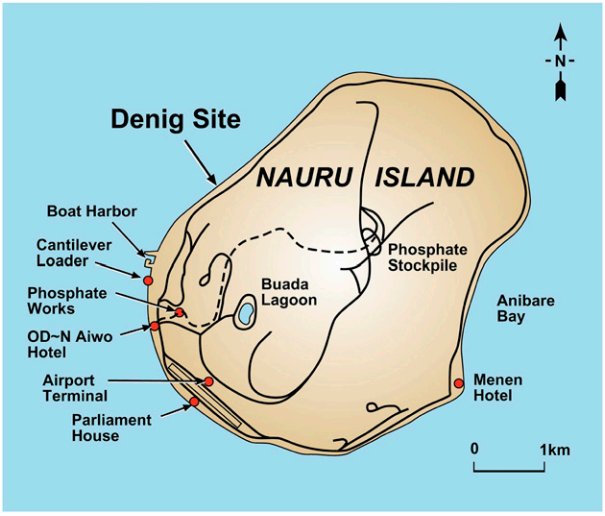

FIG. 7-4. Map of Nauru Island showing the location of the ARM site at Denig.

FIG. 7-5. Picture of the Nauru site less than a year after start of operations during the Nauru99 campaign.

deployment delay was inadequate to answer the question but did suggest that there was no major land influence on the limited site observations that were available. To better understand the local representativeness of the Manus ARM site, the ARM-funded Manus Variability Study campaign collected surface radiation, meteorological, and cloud-base height observations at the ARM C-band scanning radar site just over 7 km away at the naval base at Lombrum. The C-band site was installed as part of the Recovery Act upgrades (see next paragraph) and started operations in November of 2010. The 15 months of data collected there (August 2011–November 2012) in conjunction with the again ARM-funded ARM MJO Investigation Experiment on Manus (AMIE-Manus; Long et al. 2010) are currently being analyzed to identify any statistical differences between the two sites in variables such as low-cloud-base heights, fractional sky cover, downwelling shortwave (SW) and longwave (LW) radiation, and cloud radiative effects.

As noted in Long et al. (2013), the new challenge at the TWP sites is to expand from the vertically pointing, or "soda straw," view that the ARM remote sensors have used since operations began to examine the local spatial variability in clouds and precipitation. Meeting this challenge requires enhanced measurement capabilities, which were facilitated by funding from the American Recovery and Reinvestment Act,[1] along with development of new data processing and retrieval algorithms. The C-band (6 GHz) scanning precipitation radar, along with scanning X-band (9.5 GHz) and Ka-band (35 GHz) radars (Bharadwaj et al. 2011) deployed on Manus, will enhance the upgraded vertically pointing cloud radars and lidars. The temporal integration of this expanded spatial view will allow new genres of process-oriented data analysis and modeling studies of cloud field evolution.

b. Nauru

The second TWP site was established on Nauru Island (0.5°S, 166.9°E; Fig. 7-1), which is a small island located on the eastern edge of the warm pool, with virtually all ARCS instruments operating by the start of 1999. As noted above, land is at a premium on the small island, which, as shown in the island map (Fig. 7-4), is only 6 km long by 4 km wide. Consequently, the physical location literally had to be built up in order to give sufficient area for the site (Fig. 7-5; photo taken from the Flinders University's Cessna aircraft during the Nauru99 campaign). Although our preference was for a site on the southern coast of the island near the airport, negotiations for that location broke down when a local family objected to the need for dump trucks to unload crushed coral and phosphate material from the island center (referred to locally as "top side") next door to their homes. We then obtained a second location on the western shore, where the site was built, becoming operational in late November of 1998. Figure 7-5 shows the white surface of crushed coral material that was used to build up the site area. The interior center of the island is now almost completely devastated by strip mining of the nearly depleted guano deposits for phosphate, leaving behind mostly unvegetated and impassible karst fields (Fig. 7-6).

Like those from Manus, the Nauru observations were of immediate interest for the ARM research community

[1] For more information on all Recovery Act instruments and upgrades, see Mather and Voyles (2013) and http://www.arm.gov/about/recovery-act/instruments.

FIG. 7-6. Picture of a Nauru karst field remaining after phosphate mining in the central part of the island taken in April of 2004. The vertical structures remaining are extremely hard petrified coral, with the deep intervening spaces virtually impossible to walk through.

and led to early studies in subjects such as albedo (Matthews et al. 2002), atmospheric humidity (Westwater et al. 2003), tropical cirrus (Comstock et al. 2002), and Kelvin waves (Holton et al. 2002). Unlike Manus, Nauru exhibits strong variability associated with ENSO; thus, it is an important site for documenting this variability and its effect on cloudiness and the surface radiation budget. Time series of OLR data show the region around the Nauru area as being the most variable with regard to OLR and, as found in studies using Nauru data (e.g., Jensen and Del Genio 2006; Porch et al. 2006; McFarlane et al. 2013), in cloud occurrence as well. Nauru experiences convectively active periods (including El Niño) when cloudiness characteristics are similar to those of Manus and times of suppressed convection when the area is embedded in the descending branch of the Walker circulation (including La Niña). Nauru experiences about 40% overcast skies during daylight hours for convectively active El Niño conditions, but, during convectively suppressed La Niña conditions, overcast occurs only 10% of the time, and the sky cover is 50% or less during 67% of the observations (McFarlane et al. 2013).

The Nauru99 campaign occurred in June and July of 1999, several months after the Nauru site became operational. Nauru99 was an international research collaboration conducted on and around the island of Nauru (Reynolds 1998).[2] Participants, along with ARM, included the NOAA R/V *Ronald H. Brown* and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) R/V *Mirai*, which measured surface and radiation fluxes at sea for comparison with the land-based ARCS systems and the Tropical Atmosphere Ocean (TAO) buoy array. During the campaign, which occurred during an episode of convectively suppressed conditions, a stream of small clouds was observed to start forming over the island in late afternoon and advect downstream. This "cloud street" was studied using satellite data by Nordeen et al. (2001) and was shown to stretch up to more than 200 km downstream of Nauru. The Nauru cloud street is formed by low-level flow over and around the small island when a heat island occurs because of solar heating of the center of the island, where the phosphate has been removed, leaving mostly bare ground (Savijarvi and Matthews 2004). The downstream cloud street is maintained through a pair of island-generated vortices maintained by the convection that occurs between them (Matthews et al. 2007) and does have some impact on the ARM site measurements.

The evidence of the Nauru cloud street prompted the ARM-funded Nauru Island Effect Study (NIES; Long 2001), which deployed a set of instruments on the eastern side of the island for comparison to the ARM site data on the western side in order to attempt to quantify what measurements might be affected and to what extent. McFarlane et al. (2005) showed that only low-level cloud amounts and downwelling SW radiation values were affected when an island effect was occurring. Additionally, a method of detecting the occurrence of the island effect was developed from the NIES data, prompting the deployment of a small set of radiometers on the southern end of the island near the airport. These data have been used by the TWP site scientist team to produce a Nauru Island effect dataset,[3] which denotes the times of occurrence. Five years of data from this dataset were then used to quantify the Nauru Island effect by Long and McFarlane (2012), showing that the island effect occurs about 11% of the time during daylight hours. Over the long term, the effect increases the low-level (500–1000 m) cloud occurrence by 1% overall and decreases the overall average downwelling SW by 1%. However, for shorter-term studies or those that separate data by conditions such as convectively active or suppressed regimes, the effect can have significant impacts, and use of the Nauru Island effect dataset is advised to determine occurrence and impact.

While the Nauru site observations have been shown to be scientifically useful, continuing economic decline and deteriorating infrastructure has made working there too

[2] Additional details are available at http://www.arm.gov/campaigns/twp1999nauru.

[3] See http://www.arm.gov/data/pi/45.

FIG. 7-7. Map of the Darwin, Australia, area showing the location of the ARM (ARCS) site near the Darwin airport and the nearby seas.

FIG. 7-8. November 2004 picture of the Darwin site viewed from a landing flight at the Darwin airport. ARM facilities are located in the right half of the photo; on the left side are the Darwin Airport Australian Bureau of Meteorology Office facilities.

difficult. The active sensors (cloud radar, lidar, etc.) at the ARM site at Nauru were removed in February of 2009, and, sadly, all ARM observations on Nauru have now ended. The remaining site infrastructure was handed off to the Nauruan government as the foundation for establishing a meteorological station in August of 2013.

c. *Darwin*

While the original sampling strategy called for distributing additional sites to more fully explore the prevalent north–south and east–west convection gradients, logistics also plays an important role. Identifying suitable sites in the TWP region that meet the science requirements and have the infrastructure necessary to support an ARM site was challenging. Further adding to the logistical challenges was a strong interest in having the capability of periodically making airborne measurements in conjunction with the site, as was often done at the SGP. From this perspective, Darwin, Australia (12.4°S, 130.9°E; Fig. 7-1), is an ideal location in the region. Darwin has been a cornerstone of tropical meteorological measurements since the beginning of the last century (e.g., Allan et al. 1991) and boasts an excellent support structure for long-term measurements and intensive field campaigns, including a major airport, a regional Bureau of Meteorology forecasting office, and a research-grade C-band radar (Keenan et al. 1998).

Darwin is firmly within the tropical latitude band; however, while the variability of convection is dominated by ENSO and the MJO at Nauru and Manus, respectively, the dominant source of variability at Darwin is the annual Australia monsoon (Wang et al. 2011; May et al. 2012; McFarlane et al. 2013). The Australia monsoon is characterized by a dry season extending from approximately May through October, a transition or buildup season from October through November–December, and a wet season from December through April (e.g., Holland 1986; Drosdowsky 1996; Pope et al. 2008; Evans et al. 2012). The wet season is modulated by active and suppressed convection periods that are related to other modes of tropical variability (e.g., the MJO; Evans et al. 2014), but the dominant signal is the monsoon.

While Darwin is a coastal site and not an island site, as shown in the map of the Darwin area (Fig. 7-7), an argument can be made that, in addition to the logistic attractions, it also serves as a good location for studying west Pacific tropical convection from a scientific perspective. During the convectively active period of the monsoon, widespread cloud cover reduces surface radiative heating (May et al. 2012). Consequently, instead of land–sea circulations and associated coastal convection that is common in the coastal tropics, convection is driven by large-scale dynamical forcing associated with the monsoon trough. Convection in these conditions has similar characteristics to periods of widespread convection (e.g., during the active phase of the MJO) over the open ocean (May et al. 2008). Meanwhile, during periods when local heating dominates forcing, often referred to as break periods, conditions are not unlike those found along the coasts of large islands in the Maritime Continent (Pope et al. 2008). Therefore, during the wet season, Darwin can be, and often has been, used as a base for studying tropical convection. Prior to the deployment of the ARM site at Darwin, campaigns focusing on the Darwin area have included the Island Thunderstorm Experiment (ITEX; Keenan et al. 1989), the Stratosphere–Troposphere Exchange Experiment (STEP; Russell et al. 1993), the Maritime Continent Thunderstorm Experiment (MCTEX; Keenan et al. 2000), and the Darwin Area Wave Experiment (DAWEX; Hamilton et al. 2004). MCTEX, in particular, was a collaboration with the DOE that deployed millimeter-wavelength radars, a microwave radiometer, and a suite of radiometers in the Tiwi Islands.

Data collection at the ARM Darwin site began in March of 2002. An aerial photo from November 2004 (Fig. 7-8) shows the site layout on the right side of the photo, while the left side is the Darwin Airport Australian Bureau of Meteorology facilities. Operations at the site began somewhat slowly because it is a significant challenge to operate instruments continuously at the tropical sites. For the first several years, the Manus and Nauru sites were assigned a higher priority than the Darwin site, so some of the key instruments at Darwin, notably the cloud radar and micropulse lidar, saw reduced operation time during the first few years because parts were used to keep equipment running at the other sites. However, beginning in approximately 2003, planning began for a major field campaign largely driven by ARM to be based in Darwin. The Tropical Warm Pool–International Cloud Experiment (TWP-ICE)[4] was held in January and February 2006 and brought together a number of measurement components and also coincided with two European-supported campaigns: Aerosol and Chemical Transport in Tropical Convection (ACTIVE) and Stratosphere–Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere (SCOUT-O3; Vaughan et al. 2008). TWP-ICE was designed to study the life cycle and properties of tropical convective systems and included the ARM Darwin site, the Bureau of Meteorology measurement assets in the Darwin region, a five-site radiosonde array centered on Darwin (in addition to the operational soundings at Darwin), three aircraft, a ship, and a variety of ground-based guest instruments (May et al. 2008).

The ACTIVE and SCOUT campaigns had different science goals than ARM's TWP-ICE but provided a very useful set of complementary measurements. ACTIVE was focused on aerosol processes and added two aircraft and a series of ozonesondes launched from Darwin (Vaughan et al. 2008). ACTIVE was actually held in two phases: the first phase was in November–December 2005 during the so-called buildup monsoon phase and the early part of the wet season; and the second phase overlapped with TWP-ICE. These two periods have distinctly different aerosol loading with much more aerosol typically present during the buildup period than during the later stages of the wet season (Bouya et al. 2010), as well as somewhat different convective characteristics, as the buildup phase tends to be more characterized by coastal-heating-type convection (Pope et al. 2008).

SCOUT, meanwhile, was focused on upper-tropospheric humidity and the exchange of water vapor, aerosols, and chemicals between the upper troposphere and lower stratosphere (Vaughan et al. 2008). Because of the focus on stratosphere–troposphere exchange, there was interest by the SCOUT planning team in particularly deep and, if possible, predictable convection. These considerations led the SCOUT group to focus on the buildup period, during which they could study deep, island-based convection just north of Australia in a relatively predictable natural laboratory.

While it would have been desirable to completely align all three campaigns, the scientific focus of TWP-ICE was on the maritime convection associated with the active monsoon periods [see Evans et al. (2012) for a monthly summary of synoptic states and convective activity]. Consequently, SCOUT and TWP-ICE occurred at different times during the 2005/06 wet season. By spanning both periods, the ACTIVE campaign provides context for the full period.

The diversity of measurements has provided input for a broad range of research topics, including the boundary layer (May et al. 2012), convective clouds (e.g., Frederick and Schumacher 2008; Cetrone and Houze 2009; Collis et al. 2013), gravity waves (Hecht et al. 2009), precipitation (Giangrande et al. 2014), and satellite evaluation studies (Liu et al. 2010). A particular goal of the TWP-ICE campaign was to provide a dataset that could be used for climate model evaluation. One key component to support this type of research is the development of a model forcing dataset [Zhang and Lin (1997); Zhang et al. (2016, chapter 24)] that provides dynamical boundary conditions for running cloud-resolving models. The model output can then be compared with observations of cloud life cycle and properties. The radiosonde array provided a key component of this forcing dataset, as did surface heat fluxes and area precipitation from the C-band radar (Xie et al. 2010).

The combination of a well-constrained forcing dataset with extensive observations has led to a number of modeling studies that include analyses of cloud-resolving models (e.g., Fridlind et al. 2012; Mrowiec et al. 2012; Wang et al. 2009) and climate models (e.g., Wu et al. 2009; Song and Zhang 2011) to study the effects of model resolution (Lin et al. 2012) and processes such as entrainment and diabatic heating (Xie et al. 2010; Del Genio and Wu 2010). These data and model simulations point to the problems inherent in simulating subgrid-scale phenomena, such as vertical velocity (Collis et al. 2013) and precipitation (Varble et al. 2011).

Similar to our experiences with Manus and Nauru, interest in the areal representativeness of the ARM Darwin site motivated the ARM-funded Darwin ARM Climate Research Facility (ACRF) Representativeness Experiment (DARE). As in the Manus Variability

[4] For more information about TWP-ICE, see http://www.arm.gov/campaigns/twp2006twp-ice.

Study, a small radiometer system was deployed at the Gunn Point C-band polarimetric radar system (C-POL) site located about 25 km northeast of the ARM site. Data were collected from October 2009 through June 2011 and are currently being analyzed to identify any statistical differences between the two sites in variables such as fractional sky cover, downwelling SW and LW radiation, and cloud transmissivity and radiative effects.

3. Scientific contributions

The measurements at the ARM TWP sites have resulted in significant scientific contributions to our understanding of tropical processes and their variability. In a recent paper, Long et al. (2013) summarized these contributions, focusing on the use of the Manus and Nauru observations to study the tropical radiation budget, cloud properties, and cloud radiative effects, which are all components of the original science questions that drove ARM to deploy sites in the TWP. In addition, the paper identifies contributions to model evaluation, parameterization development, and satellite comparison and validation. While many of these research areas were included in the original ARM science vision for the TWP, the scope of the research has notably surpassed expectations.

For decades, Darwin has been an important center of respected scientific observations and tropical research, certainly long before the ARM site was deployed at the Darwin airport. The ARM Darwin site is now contributing to this legacy in unique ways. In particular, the addition of cloud radar data and support for aircraft measurements has provided new and important avenues for the study of cloud properties and processes. The examples cited here serve to illustrate the types of additional studies enabled by ARM but are certainly not an exhaustive accounting.

As with all of ARM, research studies in the TWP are based on both the continuous measurements and shorter-term, more intensive campaign efforts. For the TWP, most field campaign efforts have had significant TWP site scientist team participation and leadership. Larger campaigns, such as Nauru99 (Tom Ackerman, TWP site scientist at the time as co-primary investigator), TWP-ICE (Jim Mather, associate site scientist at the time as co-primary investigator), and AMIE-Manus and the corresponding AMIE-Gan (Chuck Long, current TWP site scientist as primary investigator for both) have focused on the larger science questions of the tropical regime. But there have also been more targeted campaigns, such as the NIES, DARE, and the Manus Variability Study all with the TWP site scientist as PI that are geared toward making the TWP data more useful and understandable to the science community. From its inception, the TWP site scientist team has worked both to advance our scientific understanding and to enable the TWP observations to be more useful to the entire community.

4. Summary

The TWP features the warmest sea surface temperatures on Earth and is typified by strong solar heating, plentiful evaporation, and abundant convection and precipitation. Significant inter- and intraseasonal variability driven by phenomena such as ENSO and the MJO, along with migration of the intertropical convergence zone, drives teleconnections that affect many other parts of the globe. Thus it is no surprise that the ARM Program targeted the TWP for long-term cloud and radiation measurement sites.

As discussed here and in summary papers (e.g., Long et al. 2013), significant use has been made of the TWP site data to improve our understanding of the TWP regime. This substantial body of work has targeted many of the original science questions of the initial ARM plan (Ackerman et al. 1999), making considerable progress. The research has addressed many of the original questions but has also shaped new and refined older science questions.

With time and maturity, factors that influence the practical and technical aspects of long-term observational activities have evolved. For instance, for Manus and Nauru, communications available to monitor instrument health and status in near-real time were restricted to a small transmit package time slot of the GOES satellite system once per hour. Thus, the site data system produced a packet of hourly averages of a subset of the measurements and system information for transmission back to TWP Operations. This was certainly a significant limitation for monitoring data quality, since reasonable-looking hourly averages could mask a multitude of issues, especially for the active sensors. For example, only an hourly average of the cloud radar transmission power could be included as the monitoring variable for radar performance, which gave no information on the receivers or calibration. The full data were shipped back to Operations initially via 4-mm tapes and later via hard drive every several months. Verbal communications with on-site observer staff also were limited, initially through a landline telephone that was often inoperable, particularly at Manus, where there was initially an emergency satellite phone with limited minutes but that had fax and 1200-bps modem capability. At Nauru, there was an Internet link through Nauru Telco via a link to Australia for a while before Nauru dropped the link. But this Internet had a very low data rate because the phone lines between the Nauru site and

the Telco were poor. One solution that was installed in late 1999 to early 2000 was an Inmarsat B satellite phone on site to be used for site communications when the landline phones were down. This amounted to a significant cost, however, and was soon abandoned. Application for Very Small Aperture Terminal (VSAT) licenses was started in July 2002, and satellite Internet installations were done in October (Manus) and November 2002 (Nauru). Needless to say, having satellite Internet connectivity available amounted to a quantum improvement in the ability to monitor and remotely operate the on-site instruments and systems. With satellite internet communications came a significant improvement in overall data quality and continuity. We note that the Darwin site came online in 2002 with good quality Internet availability from the start. Nonetheless, the large volumes of data generated by some instruments, such as the cloud radar, continue to be shipped on hard disk periodically back to the United States.

The deterioration of the economic and political situation on Nauru, along with the changing funding and operational demands of the ARM Program, prompted the withdrawal of ARM activities and instrumentation from Nauru. The Nauru data have been beneficial to the scientific community in studies of the tropical regime (e.g., see Long et al. 2013) and will undoubtedly see continued application. One of the most critical losses for the atmospheric science and weather forecasting communities, however, is likely to be the absence of sonde launches in this data-sparse, yet critically important, region. The nearest upper-air station to Nauru that is currently active is located at Majuro Atoll, more than 950 km to the northeast, with the next nearest at Pohnpei, Micronesia, more than 1250 km to the northwest. One hope is that programs such as the WMO Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) effort might sponsor and fund sonde launches by the Nauruans.

At the same time as the loss of the Nauru site, a new phase of tropical cloud studies commenced at the Manus and Darwin sites. New scanning cloud and precipitation radars will allow expansion from the vertically pointing view that has typified ARM sites and data from the beginning, adding a critical spatial view for characterization of the cloud and precipitation fields. One weakness of the TWP observational efforts with respect to model evaluation has been the lack of adequate dynamic and thermodynamic context needed as input to drive cloud-resolving and single-column modeling studies. Results from TWP-ICE show that the combination of large-scale precipitation estimation from scanning precipitation radar, centrally located soundings, and reanalysis products may provide an adequate constraint to construct useful model forcing datasets (Xie et al. 2010) using the variational analysis methodology [Zhang and Lin (1997); Zhang et al. (2001, 2016, chapter 24)]. Forcing data can be further augmented by enhanced sounding periods. Thus, the Darwin site and now, with the progress being made regarding single-sonde-site forcing datasets, the Manus site with its scanning C-band radar, when combined with extended periods of frequent sonde launches and likely NWP data, offers the opportunity of producing model-forcing datasets for single-column and cloud-resolving modeling efforts. While the existing long-term measurements of clouds, radiation, and atmospheric state provide a distinctive observational record that will continue to be utilized by the research community, the coming decades offer significant new opportunities for atmospheric research in this challenging region thanks to ongoing observations and the new improved instrumentation.

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