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Marine ARM GPCI Investigation of Clouds (MAGIC) Field Campaign Report

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ARM CLIMATE RESEARCH FACILITY

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Executive Summary

The Marine ARM GPCI Investigation of Clouds (MAGIC) field campaign, which deployed the second ARM Mobile Facility (AMF2) aboard the Horizon Lines cargo container ship *Spirit* as it ran its regular route between Los Angeles, California and Honolulu, Hawaii, measured properties of clouds and precipitation, aerosols, radiation, and atmospheric, meteorological, and oceanic conditions with the goal of obtaining statistics of these properties to achieve better understanding of the transition between stratocumulus and cumulus cloud regimes that occur in that region. This Sc-Cu transition is poorly represented in models, and a major reason for this is the lack of high-quality and comprehensive data that can be used to constrain, validate, and improve model representation of the transition. MAGIC consisted of 20 round trips between Los Angeles and Honolulu, and thus over three dozen transects through the transition, totaling nearly 200 days at sea between September, 2012 and October, 2013. During this time MAGIC collected a unique and unprecedented data set, including more than 550 successful radiosonde launches. An Intensive Observational Period (IOP) occurred in July, 2013 during which more detailed measurements of the atmospheric structure were made. MAGIC was very successful in its operations and overcame numerous logistical and technological challenges, clearly demonstrating the feasibility of a marine AMF2 deployment and the ability to make accurate measurements of clouds and precipitation, aerosols, and radiation while at sea.

Acronyms and Abbreviations

ACAPEX	ARM Cloud Aerosol Precipitation Experiment
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
ACI	aerosol-cloud index
ACRF	ARM Climate Research Facility
AIRS	atmospheric infrared sounder
AMF2	second ARM Mobile Facility
AMSR	advanced scanning radiometer
AOS	Aerosol Observing System
ARRA	American Recovery and Reinvestment Act
ARM	Atmospheric Radiation Measurement Climate Research Facility
ASSIST	Atmospheric Sounder by Infrared Spectral Technology
BOMEX	Barbados Oceanographic and Meteorological EXperiments
CAPE	Convective available potential energy
CCN	cloud condensation nuclei
CIN	convective inhibition
CN	condensation nuclei
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CPC	condensation particle counter
Cu	cumulus
CWV	column water vapor
DOE	U.S. Department of Energy
DQPR	Data Quality Problem Report
ECMWF	European Centre for Medium Range Weather Forecasting
FRSR	fast-rotating shadowband radiometer
GASS	Global Atmospheric System Studies
GCSS	GEWEX Cloud Systems Study (now GASS: Global Atmospheric System Studies)
GEWEX	Global Energy and Water Experiment (now Global Energy and Water Exchanges Project), a core program of the World Climate Research Programme
GPCI	GSCC Pacific Cross-section Intercomparison, a working group of GCSS
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HTDMA	Hygroscopic Tandem Differential Mobility Analyzer
IN	ice nuclei
IOP	Intensive Observational Period
IRT	infrared thermometer

ISCCP	International Satellite Cloud Climatology Project
ISAR	infrared sea surface temperature autonomous radiometer
ITCZ	Inter-Tropical Convergence Zone
JJA	June-July-August
JPL	Jet Propulsion Laboratory
KAZR	Ka-band ARM Zenith Cloud Radar
km	kilometer
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LWP	liquid water path
m	meter
MAGIC	Marine ARM GPCI Investigation of Clouds
MARCUS	Measurement of Aerosols, Radiation and Clouds over the Southern Oceans
MBL	Marine boundary layer
MODIS	moderate resolution imaging spectroradiometer
M/V	Merchant Vessel
MWACR	Marine W-band ARM Cloud Radar
NASA	National Aeronautics and Space Administration
NIR	near-infrared
NIST	National Institute of Standards and Technology
nm	nanometer
PI	Principal Investigator
PIR	precision infrared radiometer
PRP	portable radiation package
PSAP	particle soot absorption photometer
PSP	precision spectral pyranometer
RH	relative humidity
RMRCo	Remote Measurements & Research Company
RMSE	root-mean-squared error
RWP	radar wind profiler
SAS_Ze	solar array spectrophometer-zenith-pointing
Sc	stratocumulus
SPN	sunshine pyranometer
SSM/I	special sensor microwave imager
SSFR	solar spectral flux radiometer
SSST	sea surface skin temperature
SST	sea surface temperature
SW	shortwaves

TOGA-COARE	Tropical Ocean and Global Atmosphere-Coupled Ocean-Atmosphere Response Experiment
TSI	total sky imager
UHSAS	ultra-high-sensitivity aerosol spectrometer
UTC	coordinated universal time
VAP	Value-Added Product

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1.0 Background

1.1 Motivation

Clouds are essential to Earth's climate, weather, radiation budget, and hydrological cycle, but despite this great importance, many aspects of their properties and their roles in various processes are not well understood. Because of their vast extent, marine clouds play an especially critical role in the global radiation budget and hydrological cycle, and thus in climate and climate change. However, most non-satellite investigations of such clouds have been on relatively short-term (~1 month) research cruises or aircraft campaigns in fairly small regions. Among all marine clouds, those in the MBL in particular exert an outsized influence on climate and climate change, but this influence also remains poorly understood in spite of many field campaigns, with large differences among models resulting from differing parameterizations of cloud properties (e.g., Bony and Dufresne, 2005). Likewise, there are large differences in the radiative influences of clouds among current climate models and between models and observations (e.g., Bender et al., 2006). These differences translate, among other things, into poor knowledge of the effects of increasing greenhouse gas concentrations (and the resultant warming) on clouds, which constitute the largest uncertainty in modeled climate sensitivity (IPCC, 2013).

Cloud system modelers have long been interested in the Northeastern Pacific Ocean because of the types of clouds and the transitions between different cloud regimes that occur there. One of the earliest cloud modeling efforts was GCSS, the GEWEX (Global Energy and Water Exchanges Project, a core program of the World Climate Research Programme) Cloud Systems Study, which was initiated in the early 1990s (Browning et al., 1993; Randall et al., 2003) with the key objectives of developing the scientific basis for the parameterization of cloud processes and promoting the evaluation and intercomparison of parameterization schemes for cloud processes (GCSS has since become GASS, Global Atmospheric System Studies). One of the working groups within GCSS was GPCI, the GCSS Pacific Cross-section Intercomparison, the main goal of which was to evaluate and improve how climate and weather models represent subtropical and tropical cloud regimes and transitions between them, particularly the stratocumulus-to-cumulus (Sc-to-Cu) transition. In the GPCI study, models were analyzed along a transect extending from 35°N, 125°W to 1°S, 173°W (from the Sc regions off California, across the shallow convection trade-wind areas, to the deep convection regions of the ITCZ; Figure 1) to compare model results.

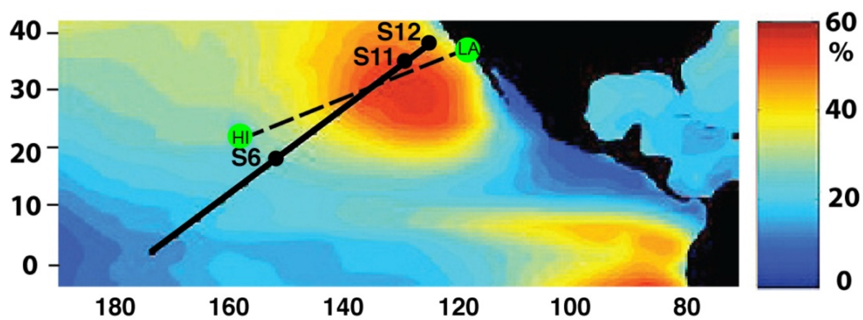

Figure 1. Average June-July-August low level cloud cover, with MAGIC route (dashed) from Los Angeles to Honolulu and GPCI transect (solid). Points S6, S11, and S12 used in CGILS are also shown. Based on Teixeira et al., 2011.

Twenty-three weather and climate models participated in the first phase of GPCI (Teixeira et al., 2011), which provided a detailed characterization of how models represent the Sc-to-Cu transition and helped identify some key model shortcomings. The results confirmed previous problems with climate models such as underestimating cloud amounts in the Sc regime and overestimating clouds in the shallow Cu regime, with corresponding consequences for shortwave radiation (SW); large spread in cloud cover, liquid water path (LWP), and SW among the models (Figure 2); and large inter-model differences of vertical properties of clouds, vertical velocity, and surface relative humidity (RH).

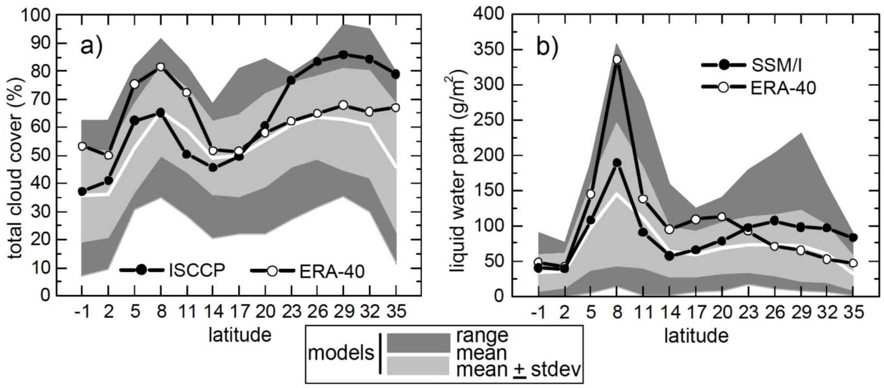

Figure 2. Model results for a) total cloud cover, and b) total liquid water path, along GPCI for June-July-August, 1998, shown as ensemble results from 23 models, the mean plus or minus the standard deviation; range extends from minimum to maximum values. Also shown are results from International Satellite Cloud Climatology Project (ISCCP), ECMWF reanalysis (ERA-40), and Special Sensor Microwave Imager (SSM/I), from Teixeira et al., 2011.

1.2 MAGIC Field Campaign

The MAGIC field campaign was designed to collect data on subtropical marine clouds by deploying the second ARM Mobile Facility (AMF2) on the Horizon Lines cargo container ship *Spirit* (Figure 3) as it ran its regular route making repeated transects between Los Angeles, California (33.7°N, 118.3°W) and Honolulu, Hawaii (21.3°N, 157.9°W). This MAGIC route (Figure 1), which goes directly through the Sc-to-Cu transition, is 4100 km (2550 miles, or 2200 nautical miles) long, and was selected specifically because it lies in a region of great climatic interest and because it lies closely along the GPCI transect used for climate model intercomparisons by several focused modeling efforts. In addition, this route has several strengths: conditions along this transect are rather mild and storm-free, the seas are generally calm, and the deployment is between two U.S. ports, both of which have good infrastructure for logistics and supplies, greatly simplifying customs, security, and labor issues. The cloud type and cover along this route vary from low marine Sc with high coverage near the California coast to puffy Cu with much lower coverage in the trade wind regions near Hawaii (Figure 1). The low marine Sc decks, with their high albedo and large areal coverage, provide an extremely important forcing of Earth's climate. The trade Cu play a large role in the global surface evaporation and also Earth's albedo. The Sc regions are accompanied by lower sea surface temperatures (SSTs), with transition occurring by Cu formation under Sc, and then Sc evaporation leaving a patchy Cu layer which is accompanied by higher SST (Wyant et al., 1997; Bretherton and Wyant, 1997). Probabilities of cloud thermodynamic quantities such as LWP also change east to west along this transect from Gaussian to skewed, and the MBL height increases from typical values near 500 m to more than 1 km. Additionally, the mean SST in June-July-August increases from ~290K to ~297K and the RH in the lowest several meters above the sea surface increases from slightly below 80% to near 90%. Climate models do not accurately represent this transition between cloud types, resulting in one of the largest uncertainties in knowledge of cloud feedback on climate.

Figure 3. Horizon *Spirit*. All AMF2 instruments and operations during MAGIC were on the bridge deck, which is near the mast at the front of the ship. The stacks are the white objects about two-thirds from the bow to the stern of the ship. Photo by Dennis Shum.

The key objectives of MAGIC were to characterize the essential properties of this transition and to produce the observed statistics of properties of clouds and precipitation, aerosol, and radiation, as well as meteorological and oceanic conditions and atmospheric structure, for a full year, thus allowing capture of the strong seasonal cycle of this transition. MAGIC, the first shipboard deployment, and the first true marine deployment, of AMF2, commenced in October, 2012. The first phase continued through January, 2013, and the second phase occurred from May to October, 2013; operations were ceased from January through May, 2013 when the *Spirit* underwent its routine dry dock period for maintenance. An Intensive Observational Period (IOP) occurred in July, 2013 during which more detailed measurements of the atmospheric structure were made (the IOP that was scheduled for January, 2013 was cancelled because of a change of shipping route).

All operations and associated activities during MAGIC occurred in the bridge region of the *Spirit* (Figure 4), which proved to be a convenient and safe location for this deployment. It is near the galley and cabins, allowing convenient and safe access at all hours and in all conditions; it is ahead of the stacks, which are mid-ship; and it is sufficiently high above the water (~20 m) that spray is minimal. The bridge deck of the *Spirit* was reinforced by ARM in accordance with Horizon's specifications and approval by the American Board of Shipping before installation of the three AMF2 SeaTainers at the commencement of MAGIC. The radar SeaTainer was placed on the aft, port side, the operations SeaTainer on the starboard side, and the SeaTainer that contains the Aerosol Observing System (AOS) forward on the port side. All other instruments were installed on the bridge deck, railings, or mast. For instance, the W-band radar (MWACR) and associated stable table and its hydraulics were also located on the bridge deck, the infra-red sea surface temperature autonomous radiometer (ISAR) and the infrared sea surface thermometer (IRT) were attached to the railing of the bridge, and the meteorological system was located on the mast. These locations worked well for MAGIC; they offered excellent exposures of open sky for radars and for sampling clean marine air for aerosol measurements, ready access to SeaTainer interiors, and clear access to life rafts. Additionally, this location did not see heavy foot traffic by ship personnel and was well removed from commercial container handling activity. Wireless communications proved to be straightforward as equipment was close together. Storage of helium tanks and the balloon launching apparatus were located near the operations SeaTainer, and sonde launches were safely performed in all conditions from this area.

Figure 4. Bridge of *Spirit*. Radar SeaTainer with KAZR and RWP on the roof is on left, Operations SeaTainer with instrumentation on railings is to the right of the mast, and helium tanks are in front of the mast.

The *Spirit* is 272 m long, 30 m wide, has a dead weight of 46,000 tons, and a maximum speed of 21.5 knots. Built in 1980, the *Spirit* contains sufficient non-revenue-generating deck space for the AMF2 SeaTainers (a feature absent in newer ships), and it is located well upwind of the stacks (Figure 3). The *Spirit* is a Jones Act ship, making it possible for technicians and passengers who are U.S. citizens to disembark in Hawaii after embarking in Los Angeles and vice versa, something not allowed for a non-Jones Act vessel. The so-called Jones Act (actually the Merchant Marine Act of 1920, modified several times) requires that all transportation of cargo and people between U.S. ports be conducted exclusively by companies that are controlled and at least 75%-owned by U.S. citizens and are incorporated in the U.S., using ships built and registered in the U.S., and employing predominantly American crews.

The challenges of ship-based measurements are much greater than those from land-based deployments. Key concerns are: (1) ship motion, which affects vertically pointing instruments and those such as radiometers that require accurate knowledge of sun position; (2) screening by ship structures, which limits views of the sky; (3) ship-induced flow perturbations, which affect determination of wind speed and direction and thus flux determinations; and (4) ship effects on radiation and meteorological measurements through screening, reflection, and heating. The logistical challenges of ship-based operations are also much greater than those encountered by land-based operations and include a suite of issues such as obtaining supplies, making repairs while underway, communications, etc. MAGIC, as the first shipboard deployment of AMF2, encountered numerous obstacles to be overcome, but in doing so gained much experience that can be fruitfully applied to the MAGIC-2 deployment. Stabilized tables, placement of multiple sensors, and calibration/validation using other instruments such as the psychrometer resolved many difficulties and created confidence that accurate measurements can be obtained at sea.

The MAGIC science team extends our sincere thanks to Horizon Lines and the Captain and crew of the *Spirit* for their hospitality, support, and assistance, without which MAGIC would not have been possible. Since MAGIC ended, Horizon Lines no longer exists; it closed its Puerto Rico business, sold its Hawaii routes to Pasha Hawaii, and sold the rest of its routes to Matson.

Figure 5. Horizon Lines logo.

1.3 MAGIC Timetable

The *Spirit* made one round trip every two weeks: 4.5 days from Los Angeles to Honolulu, one day in port in Honolulu, 6.5 days for the return trip, and two days in port in Los Angeles. The average speed on the trip to Hawaii was ~10 m s^{-1} (~21 knots), and that on the return was ~7 m s^{-1} (13 knots), the lower speed resulting in lower fuel usage and cost. Each voyage was given a unique "leg" designation: "LegxxA" for transects from Los Angeles to Honolulu, and "LegxxB" for transects from Honolulu to Los Angeles; thus Leg03A was the third trip from Los Angeles to Honolulu. This designation has worked well, and is a better way of categorizing and discussing the temporal aspect of the data than merely using time, as each leg consists of one snapshot of the transition. The start and stop times for the legs were determined as follows. The "A" legs (LegxxA), which consist of trips from Los Angeles to Honolulu, are defined to commence when the latitude decreases below 33.72ºN and to end when the latitude is increasing and becomes greater than 21.30ºN. The "B" legs, which consist of trips from Honolulu to Los Angeles, are defined to commence when the latitude is decreasing and becomes less than 21.30ºN, and to end when the latitude increases above 33.72ºN. These criteria provide unique times for the beginning and ending of each leg, and are very near the times the ship left or arrived in port; these times are listed in Table 1.

Table 1. MAGIC leg start and end times (all times are UTC).

	A			B	
	Depart LA	Arrive HI		Depart HI	Arrive LA
Leg00	2012-02-11, 13:24	2012-02-16, 05:58		2012-02-17, 09:31	2012-02-23, 15:00
Leg01				2012-09-14, 23:20	2012-09-20, 13:40
Leg02	2012-09-22, 12:53	2012-09-27, 05:14		2012-09-28, 10:11	2012-10-04, 13:51
Leg03	2012-10-06, 11:43	2012-10-11, 05:39		2012-10-12, 10:04	2012-10-18, 13:04
Leg04	2012-10-20, 11:49	2012-10-25, 05:37		2012-10-26, 07:09	2012-11-01, 12:56
Leg05	2012-11-03, 18:16	2012-11-08, 13:57		2012-11-09, 17:57	2012-11-15, 14:18
Leg06	2012-11-17, 12:46	2012-11-22, 06:42		2012-11-24, 10:41	2012-11-30, 00:08
Leg07	2012-12-01, 14:12	2012-12-06, 08:16		2012-12-07, 08:49	2012-12-13, 14:14
Leg08	2012-12-15, 13:29	2012-12-20, 07:46		2012-12-22, 08:42	2012-12-27, 23:42
Leg09	2012-12-29, 12:58	2013-01-03, 06:18		2013-01-05, 05:18	2013-01-09, 20:02[1]
Leg10	2013-05-11, 11:47	2013-05-16, 05:43		2013-05-17, 16:59	2013-05-23, 13:33

[1] During Leg09B, the *Spirit* had its engines off for approximately 14 hours on 2013-01-06 and 2013-01-07; thus the trajectory will look abnormal for this time as the ship was drifting. Soon thereafter the entire ship, including the AMF2, was without power for approximately one hour, and some instruments might not have resumed operations before the end of the leg. Data acquisition ceased on 2013-01-11 for some instruments and on 2013-01-12 for all instruments. After the *Spirit* arrived in port in Los Angeles after Leg09B, the AMF2 was removed from the ship (it was completely off the *Spirit* by 2013-01-13, 21:00 UTC) and placed in storage, where it remained until reinstallation on 2014-05-09.

	A			B	
	Depart LA	Arrive HI		Depart HI	Arrive LA
Leg11	2013-05-25, 11:48	2013-05-30, 05:57		2013-05-31, 11:43	2013-06-06, 12:56
Leg12	2013-06-08, 11:39	2013-06-13, 05:53		2013-06-14, 16:59	2013-06-20, 13:11
Leg13	2013-06-22, 11:57	2013-06-27, 07:05		2013-06-28, 17:55	2013-07-03, 22:48
Leg14	2013-07-07, 18:00	2013-07-12, 06:07		2013-07-13, 12:12	2013-07-18, 22:47
Leg15	2013-07-20, 12:35	2013-07-25, 05:13		2013-07-26, 13:37	2013-08-01, 12:57
Leg16	2013-08-03, 13:55	2013-08-08, 05:06		2013-08-09, 10:35	2013-08-15, 13:41
Leg17	2013-08-17, 18:45	2013-08-22, 09:41		2013-08-23, 17:39	2013-08-29, 12:58
Leg18	2013-08-31, 12:09	2013-09-05, 05:57		2013-09-06, 12:28	2013-09-12, 13:17
Leg19	2013-09-14, 12:48	2013-09-19, 05:44		2013-09-20, 11:45	2103-09-26, 13:27
Leg20	2013-09-28, 11:59	2013-10-03, 05:52		2013-10-04, 10:33	2013-10-09, 18:58[2]

The first MAGIC leg with instrumentation was Leg01B during which M. Reynolds embarked on the *Spirit* from Honolulu to Los Angeles (departing September 15, 2012) and installed the meteorological mast and the ISAR. During Leg02A and Leg02B, the radars and other instruments were being set up; some collected data during these legs. During Leg03 most of the instruments were up and collecting data. On Leg09B, the instruments were without power for extended times and were being shut down. The instruments were removed from the ship after Leg09B and no data were collected between January, 2013 and May, 2013. MAGIC instruments were redeployed during Leg10A in May, 2013, and the campaign continued until the end of Leg20B in October, 2013.

1.4 Instruments

The instruments used during MAGIC included those in the core AMF2 suite, other ARM instruments, and guest instruments from other researchers. These are categorized into four groups in Tables 2-5, depending on the type of information they provide.

Table 2. Instruments that provide information on clouds or the atmosphere.

Ka-band radar (KAZR; 35 GHz) (unstabilized; vertically pointing)	reflectivity and Doppler spectra
W-band radar (MWACR; 95 GHz) (stabilized; zenith-pointing)	reflectivity and Doppler spectra
radar wind profiler (RWP; 1290 MHz)	wind profiles in lower troposphere
high spectral-resolution lidar	cloud height
multi-pulse lidar	cloud height
microwave radiometer (two channel)	column integrals of liquid water and water vapor
microwave radiometer (three channel)	column integrals of liquid water and water vapor
ASSIST (Atmospheric Sounder by Infrared Spectral Technology)	infrared zenith spectral radiance

[2] MAGIC instrumentation was being turned off and packed during Leg20 and all MAGIC instrumentation was removed from the *Spirit* on 2013-10-10 by 22:00. The time shown is when the data acquisition system was turned off.

total sky imager	images of the sky (every 30 sec)
ceilometer	cloud base height

Table 3. Instruments that provide information on aerosols.

CPC (condensation particle counter)	aerosol number concentration
CCN (cloud condensation nuclei)	cloud condensation nuclei concentration at different RH
UHSAS (ultra-high-sensitivity aerosol spectrometer)	aerosol size distribution
HTDMA (hygroscopic tandem differential mobility analyzer)	aerosol hygroscopic growth
ambient ("dry") nephelometer	aerosol scattering and backscattering at ambient conditions
humidified ("wet") nephelometer	aerosol scattering and backscattering at humidified conditions
PSAP (particle soot absorption photometer)	Aerosol absorption
ozone	ozone concentration
aerosol sampling	individual particle morphology and chemical composition, bulk chemical composition, RNA, and ice nucleation ability

Table 4. Instruments that provide information on radiation.

portable radiation package	contains a precision spectral pyranometer (PSP), precision infrared radiometer (PIR), sunshine pyranometer, and fast rotating shadowband radiometer (FRSR)
microtops	aerosol optical depth at five wavelengths
CIMEL sun photometer (in cloud mode)	zenith radiance at six wavelengths
solar array spectrophometer (SAS-Ze; zenith-pointing)	zenith spectral radiance
solar spectral flux radiometer	zenith spectral radiance

Table 5. Instruments that provide information on ship motion, meteorology, and sea surface temperature.

Navigational information	ship position (lat/long), orientation (pitch, roll, yaw; surge, way, heave) and time derivatives of these quantities, and motion (speed over ground, course over ground)
Meteorology	multiple sensors for temperature, pressure, RH, wind speed and direction, precipitation

radiosonde launches	profiles of temperature, pressure, RH, wind speed and direction every six hours
disdrometers	raindrop size distribution (at ship level)
Infrared (IR) thermometer	sea surface skin temperature
ISAR (Infrared Sea Surface Autonomous Radiometer)	sea surface skin temperature

Several of the instruments deserve further discussion, as they were unique to MAGIC in their deployment or their application, or both. The three radars deployed during MAGIC comprised a unique instrument combination that allowed examination of both clouds and precipitation, as well as wind profiles, in the MBL and above. The MWACR, whose primary utility was examination of cloud drops, was zenith-installed on a stabilized table to ensure that it was always pointing to the zenith. To the extent that the vertical motions of the ship at its location could be accurately determined, Doppler velocities can be retrieved. The KAZR was vertically pointing, but not stabilized, and the radar wind profiler is electronically stabilized.

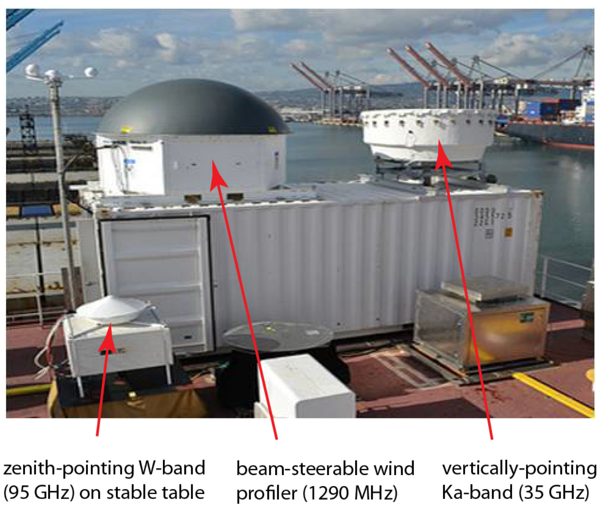

Figure 6. Radars on the bridge of the *Spirit*.

The meteorological mast system was installed on the mast, approximately 27 m above mean sea level, to allow for measurement of meteorological conditions as unperturbed by the ship as possible. This system consisted of a wind monitor, a sonic anemometer that also measures T/P/RH on each side (WTX), an optical rain gauge, a syphon rain gauge, and an aspirator with a temperature/RH probe. Psychrometer readings taken three times daily provided a continuous calibration of the temperature and RH sensors. Measurements from the meteorological mast system allowed determination of the surface fluxes of sensible and latent heat.

Figure 7. Meteorological mast system: a) view from bow of *Spirit* (shown as cross-beam on mast), b) close-up showing instruments.

A portable radiation package (PRP; Figure 7a) consisting of a precision spectral pyranometer (PSP), a precision infrared radiometer (PIR), and a sunshine pyranometer (SPN) was placed on each side of the ship, and one of these contained a fast rotating shadowband radiometer (FRSR; Figure 7b). This redundancy ensured that one of the PRPs would always have a view of the sun that was not obstructed by ship superstructure. The measurements from the PRP allowed determination of shortwave (SW) and longwave (LW) downwelling and upwelling fluxes.

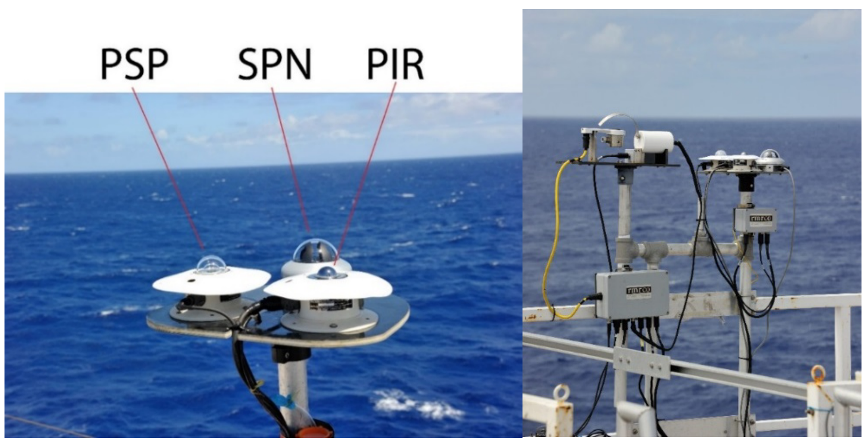

Figure 8. a) Portable radiation package, b) PRP with fast rotating band shadow radiometer.

The radiosondes were a core measurement that provided one of the most valuable data sets collected during MAGIC, that of vertical profiles of P, T, RH, and wind speed and direction. These data provided detailed information on the structure and thermodynamics of the atmosphere, especially in the MBL, that could not have been obtained in any other way. Radiosonde launches during MAGIC were attempted four times daily: near 05:30, 11:30, 17:30, and 23:30 UTC, except during an Intensive Operational Period (IOP) on Leg14A and Leg14B in July, 2013, when eight sonde launches per day were attempted (the IOP originally planned for January, 2013, which would have provided a seasonal contrast, did not occur because of a change of shipping route).

Launching radiosondes from a moving platform is quite challenging, especially with flow perturbations and downdrafts due to ship superstructure, and hazards such as wires and containers. Most attempts were from the launching basket, which was on the bridge deck near the helium tanks and the operations van

(Figure 8a), but sometimes, when gust conditions were bad, launches were moved to one of the bridge wings (Figure 8b) or even to a lower deck (Figure 8c). Nets were sometimes used to hold the balloon while filling when launching from a different location (Figure 8d), as transporting the balloon from the launching basket, where it was filled, could be challenging. The canvas launching basket was destroyed by winds during the deployment, and another one had to be obtained.

Figure 9. Radiosonde launches, a) from bridge deck, b) from bridge wing, c) from lower deck, d) using net.

Despite these challenges, the technicians were extremely persistent and resourceful, and launches were successfully made at relative wind speeds greater than 24 m s^{-1}, far greater than those at which launches are generally attempted from ground sites. In total, there were more than 550 successful radiosonde launches out of nearly 700 attempts, yielding a success rate of greater than 80%—a truly remarkable value under the conditions experienced. This rate of success provided high coverage, both spatially and temporally, throughout the deployment (Figure 9).

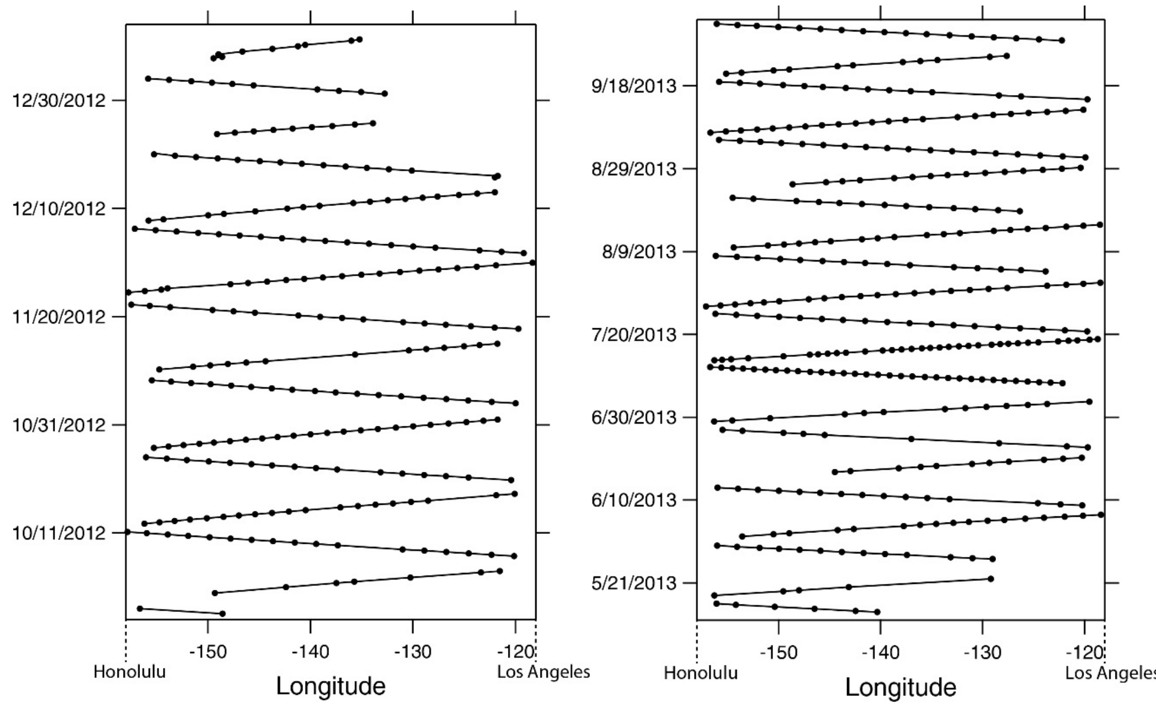

Figure 10. Sonde launch coverage for the first part of the MAGIC deployment (left) and the second half (right).

Aerosol sampling occurred during the second part of the MAGIC deployment. A sampling unit provided by Dr. Yuan Gao of Rutgers University was installed and collected nearly 150 24-hour filter samples from Leg12A through Leg19B, and a sampling unit provided by Dr. Paul DeMott of Colorado State University was installed and collected 40 24-hour filter samples from Leg13A through Leg19B. The samples collected for Dr. Gao were to be analyzed for individual particle size, shape, morphology, and chemical composition, and bulk chemical properties. Those collected for Dr. DeMott were to be analyzed for ice nucleation properties of the particles, chemical properties of the ice nuclei, and bacterial abundance.

1.5 Instrument Status

At the request of the Principal Investigator (PI), the technicians compiled brief notes at the end of each leg describing the performance of the instruments. These notes represented their judgment as to whether an instrument was mostly working well (no issues), required corrective maintenance or had partial data coverage, produced questionable data, was not operating, or was not deployed. Additionally, the PI attempted to keep track of which instruments were deployed and the performance status of such instruments throughout the deployment. This information is presented in Tables 6 and 7. Some of the designations have been changed from what the technicians originally recorded because of later information, such as failure of a drive to back up data. These tables are meant only as rough guides, and may be subject to change in the future, but they are expected to serve as a first look when selecting time periods to investigate. The large amount of green visible in these tables demonstrates that the vast majority of the instruments functioned well for most of the deployment.

Table 6. Instrument status Leg03A to Leg09B.

	Leg												
Instrument	**03A**	**03B**	**04A**	**04B**	**05A**	**05B**	**06A**	**06B**	**07A**	**07B**	**08A**	**08B**	**09A**
Ka-band radar - reflectivity													
Ka-band radar - spectra													
W-band radar - reflectivity													
W-band radar - spectra													
Radar wind profiler													
High-spectral-resolution lidar													
Multi-pulse lidar													
Microwave radiometer (2C)													
Microwave radiometer (3C)													
ASSIST													
Total Sky Imager													
Ceilometer													
Portable radiation package													
Microtops readings													
CIMEL sun photometer													
Solar array spectrophotometer													
Solar spectral flux radiometer													
CPC													
CCN													
UHSAS													
HTDMA													
Ambient ("dry") nephelometer													
Humidified ("wet") nephelometer													
PSAP													
Ozone													
Aerosol sampling													
Navigational information													
Meteorology													
Radiosonde launches													
Disdrometers													
IR thermometer													
ISAR													

No issues	Corrective maintenance or partial data	Questionable data	Instrument down	Not in service

Instruments were being set up during Leg02A and Leg02B. Most instruments started collecting data during Leg03A. On Leg09B, the instruments were without power for extended times and were being shut down.

Table 7. Instrument Status Table Leg10A to Leg18B.

	Leg																	
Instrument	**10A**	**10B**	**11A**	**11B**	**12A**	**12B**	**13A**	**13B**	**14A**	**14B**	**15A**	**15B**	**16A**	**16B**	**17A**	**17B**	**18A**	**18B**
Ka-band radar - reflectivity																		
Ka-band radar - spectra																		
W-band radar - reflectivity																		
W-band radar - spectra																		
Radar wind profiler																		
High-spectral-resolution lidar																		
Multi-pulse lidar																		
Microwave radiometer (2C)																		
Microwave radiometer (3C)																		
ASSIST																		
Total Sky Imager																		
Ceilometer																		
Portable radiation package																		
Microtops readings																		
CIMEL sun photometer																		
Solar array spectrophotometer																		
Solar spectral flux radiometer																		
CPC																		
CCN																		
UHSAS																		
HTDMA																		
Ambient ("dry") nephelometer																		
Humidified ("wet") nephelometer																		
PSAP																		
Ozone																		
Aerosol sampling																		
Navigational information																		
Meteorology																		
Radiosonde launches																		
Disdrometers																		
IR thermometer																		
ISAR																		

No issues	Corrective maintenance or partial data	Questionable data	Instrument down	Not in service

The technicians did not report instrument status designations for Leg19A and Leg19B, but these were probably similar to those for Leg18B. During Leg20A and Leg20B the instruments were being turned off, so few data were collected during these legs (although sonde launches occurred on Leg20A, meteorological data were collected until the ship returned to port, and both radars were operating for most of these last two legs).

1.6 MAGIC Science Team

The Principal Investigator was Ernie R. Lewis of Brookhaven National Laboratory; co-investigators were:

- Bruce A. Albrecht (University of Miami)
- Geoffrey L. Bland (NASA GSFC, Wallops Flight Facility)
- Charles N. Flagg (Stony Brook University)
- Stephen A. Klein (Lawrence Livermore National Laboratory)
- Pavlos Kollias (McGill University)
- R. Michael Reynolds (Remote Measurements & Research Company)
- Stephen E. Schwartz (Brookhaven National Laboratory)
- A. Pier Siebesma (KNMI, The Netherlands)
- Joao Teixeira (Jet Propulsion Laboratory/California Institute of Technology)
- Warren J. Wiscombe (NASA Goddard Space Flight Center)
- Robert Wood (University of Washington)
- Minghua Zhang (Stony Brook University)

1.7 History of MAGIC

The concept for MAGIC was proposed by Joao Teixeira (JPL, Caltech) to Warren Wiscombe (formerly of NASA, and then ARM Chief Scientist), whom he met at the ARM booth at AGU meeting in December, 2009. For personal reasons, J. Teixeira was unable to continue with the project, and W. Wiscombe enlisted the help of E. Lewis (Brookhaven National Laboratory), who, in turn, enlisted the assistance of Michael Reynolds of RMR Co. of Seattle, Washington.

In June, 2010, M. Reynolds visited the Matson office in Oakland, California and met with the Manager of Fleet Operations and the Director of Vessel Engineering, and in July, 2010 he visited the Matson Lines M/V *Maui* in Seattle.

On December 9, 2010, E. Lewis, M. Reynolds, and W. Wiscombe met with Matson personnel (the Manager of Fleet Maintenance, Director of Vessel Operations, Director of Technical and Marine Engineering, and Manager of Vessel Site Support) at the company headquarters in Oakland, where we made presentations on our proposal and left a prepared document. They seemed very interested and we had the impression that they were favorable toward the proposal, but they called M. Reynolds on the 13th and said that they could not support the proposal (in an email to me, one of them said that they "failed to convince senior management."

In January, 2011 E. Lewis and W. Wiscombe submitted a preproposal for MAGIC to ARM.

In February, 2011, M. Reynolds visited the Horizon M/V *Spirit* while it was docked in Los Angeles, California and met with Captain Walt Rankin.

In March, 2011, E. Lewis and M. Reynolds met with Mike Bohlman, Director of Marine Services of Horizon Lines at Kenilworth, New Jersey and presented out proposal for a deployment on the Horizon M/V *Spirit*. He approved on the spot and asked that I send him a draft of the letter of commitment that we needed from him for the proposal.

In May, 2011 E. Lewis and W. Wiscombe submitted a proposal for MAGIC to ARM, with the *Spirit* listed as the vessel upon which the deployment would occur. The proposal was accepted in September, 2011.

In October, 2011, E. Lewis and M. Reynolds, and Brad Orr and Jimmy Voyles from ARM, met with Mike Bohlman at Horizon Headquarters in Kenilworth, New Jersey, and by phone Mark Van Houtte and Don Watters of Horizon Lines, and discussed installation issues and other items.

In November, 2011, E. Lewis, M. Reynolds, and B. Orr and his team, Mike Ritchie and Nicki Hickmon, visited the *Spirit* in port in Los Angeles and met with Captain Tom McCarthy, to investigate siting possibilities and logistics.

In February, 2012, E. Lewis, M. Reynolds, and B. Orr embarked on the *Spirit* for one round trip, "Leg0," from Los Angeles to Honolulu and back. This was an exploratory leg with the goals of developing familiarity with ship operations, evaluating radiosonde launch conditions, characterizing the ship's motion, and evaluating wind flow conditions.

Installation of the AMF2 on the *Spirit* was originally scheduled for September 6-7, 2012 when it was supposed to be in port in Los Angeles, but problems with the ship rendered this impossible.

The first leg with MAGIC measurements being taken was Leg01B, when M. Reynolds embarked on the *Spirit* from Honolulu to Los Angeles (departing September 15, 2012), during which trip he installed the meteorological mast and the ISAR.

The AMF2 was installed on September 20-21, 2012, before the start of Leg02A, and during this leg the SeaNav was set up and turned on, stable tables were installed, sonde launches commenced, and many systems (although not the AOS) were up and running. The AOS was set up and turned on during Leg02B, and regular operations began.

2.0 Notable Events or Highlights

MAGIC was a unique field campaign in numerous ways. It was ARM's first true marine field campaign, with measurements unperturbed by islands or coastal artifacts. It was also the first large collaboration between ARM and a private company, allowing use of a wonderful platform for making measurements over the ocean. Finally, with AMF2's suite of instruments, the scope and amount of data collected far surpassed those from any previous marine measurement campaign. Several notable events occurred during the deployment.

In February, 2012, E. Lewis, M. Reynolds, and B. Orr travelled on the *Spirit* for one round trip, "Leg0," from Los Angeles to Honolulu and back, during which the SeaNav system and the meteorological mast system were installed and collected data for the entire round trip, and several balloon launches were attempted. This was an exploratory leg with the goals of allowing us to become familiar with ship operations, evaluate radiosonde launch conditions, characterize the ship's motion, and evaluate wind flow conditions. The SeaNav system and the meteorological mast system were installed and collected data for the entire round trip, and several balloon launches were attempted. This leg was very successful with regard to each of these topics, which are described in the Leg0 cruise report, and proved to be incredibly valuable in providing insight that would help realize a successful deployment. The ability to have first-hand information on ship routines and activities and to measure and scout locations so that MAGIC activities and van placement could occur with minimal disruptions to, and likewise encounter minimal influence from, ship personnel and activities, was something that could not be obtained otherwise. This leg also provided an opportunity for MAGIC personnel to forge good relations with the Captain and crew of the *Spirit*; these relations were essential to the success of MAGIC.

Installation of the AMF2 on a working cargo container was the first challenge, requiring coordination between the shipping company, the ship itself, the Port of Los Angeles, Dockside Machine (the company that handles repair and supply of the *Spirit*), and other entities so that scheduling, access, labor, cranes, and other concerns were addressed. N. Hickmon and her crew handled these difficult activities remarkably. The bridge deck of the *Spirit* had to be reinforced to obtain ABS (American Bureau of Shipping, an organization that approves modifications to ships for insurance purposes) approval, and this work had to be completed before the vans could be installed. Much of this work required that the crew not be in their cabins, which were directly below the bridge deck. The first attempted installation, September 6-7, 2012, was postponed for two weeks (the time for the *Spirit* to make one round trip) due to ship issues. This installation, once undertaken, was successful, and the technicians soon had boxes unpacked and many instruments placed and operational. Leg02A commenced and the remaining instruments were put on line during this leg and the return (Leg02B). There were a limited number of passengers that could be on the *Spirit* at any one time, which dictated the timing of instruments being turned on.

Many of the instruments ran quite well for the subsequent legs, although there were various issues, some of them purely bad luck, and some of them a consequence of instruments obtained as a result of ARRA that did not operate as advertised. For instance, the AOS had a pump failure that resulted in water in the lines, and most of the aerosol instruments were out for part of Leg03A (Table 6). The IRT was found to have been improperly coded, invalidating measurement of sky temperature for Leg02A, Leg02B, and Leg03A. The psychrometer temperature values were not read to sufficient accuracy, rendering the data useless until Leg06A. There were no ozone (O_3) data before Leg05A, there were issues with the TSI throughout this time, and there was no MWR-3C for Leg04A through Leg05B. There were continual issues with the lidars for the first part of the deployment due to random events (diodes dying, etc.).

The f(RH) and the HTDMA, both of which were new instruments, did not perform well at any time during the deployment. The poor performance of the f(RH) was due mainly to intrinsic design flaws, whereas the poor performance of the HTDMA was due both to the novel design and to birthing pains in integrating the instrument into the AOS. There were other issues with some of the aerosol instruments as well. The UHSAS and CCN were not on the same time base as the other instruments, and thus there were sometimes offsets, making it impossible to determine the exact times for the data. For the UHSAS the offsets were up to ~6 min ahead (that is, the time on the UHSAS was fast compared to the actual time). The CCN was set one hour ahead for Legs02-09, and during this time it was fast by ~55-~72 min; for

Leg10-Leg20 it was fast by up to 10 min. These issues were a result of the design of the instruments, which would store the data until a buffer was full and then send the entire data set to the ARM computer, which placed a time stamp on the data at that time. Additionally, there were a number of spikes–exceedingly high values–in some of the aerosol data from different instruments, varying in duration from a few seconds to many minutes. The cause of these is unclear, but the lack of accurate timing made it difficult to align these spikes from different instruments to attempt to determine their cause.

Perhaps the most important event that occurred was the failure of the SeaNav shortly into the campaign during Leg04A. As this was the key instrument recording time, ship location, attitude, and motion, this was a critical loss. The laser (for the gyroscopic system), which was rated at 10,000 hrs, failed as this lifetime had been used during the previous year when it was being used to develop the stable table for the W-band radar. A new instrument was installed during Leg07A. As a consequence of the SeaNav failure, there was not a clear data stream for ship position, and it was not until November, 2015 (more than two years after the end of the deployment) that final values for ship location and attitude were compiled from a variety of sources.

During Leg09B, on 2013-01-06, the *Spirit* had engine problems and the power was off for ~14 hrs: thus the trajectory will look abnormal for this time. Data acquisition may have ended for some of the instruments at this time, and on 2013-01-11 it ended for the rest of the instruments. When the *Spirit* arrived in Los Angeles on 2013-01-12, the AMF2 was removed and placed in storage, where it remained until reinstallation in May, 2013. There was a previously scheduled dry dock period for late January, 2013, but this was moved up two weeks (one round trip), and as a result, the IOP that was scheduled for January, 2013 did not occur.

An IOP did occur for Leg14A (2013-07-07 to 2013-07-12) and Leg14B (2013-07-13 to 2013-07-18), during which radiosondes were launched every three hours, providing an especially detailed characterization of the MBL and lower troposphere (Figure 9). During the IOP on 2013-06-18 by Paul Lawson of SPEC. we had access to a Learjet, but unfortunately this was in a military zone, and without advanced notice there was a restriction on flights of less than 5000 feet. This would have been a wonderful opportunity to perform in-cloud samples to compare with ship-based ones.

Most of the instruments performed well most of the time, as seen by the amount of green in Tables 6 and 7. The stable table that kept the MWACR zenith-pointing worked remarkably well, with an rms deviation from vertical of a few tenths of a degree or less over the entire campaign. This permitted determination of Doppler spectra unperturbed by horizontal winds. The meteorological mast system also performed very well, allowing determination of a valuable meteorological data set and of fluxes of moisture and energy. The radiosonde launches, made under extremely challenging conditions, had a phenomenal success rate, and created one of the most useful data sets of the deployment.

Overall, the deployment was exceedingly productive and successful–a tribute to ARM and to the AMF2 team. The technicians were of extremely high quality; they worked hard, cared about the data, and did all they could to ensure that the campaign was successful. AMF2 personnel were responsive, diligent, and highly professional. They had to work under extremely challenging conditions (dealing with the scientists, technicians, the shipping company, the longshoreman's union, etc.) and handled all of these challenges positively and competently.

3.0 Lessons Learned

As a result of being one of the first deployments of AMF2, and with instrumentation purchased as part of the American Reinvestment and Recovery Act (ARRA) still being integrated, MAGIC was, in large measure, a beta test of ARM's protocols and systems. As such a bold and innovative campaign, there were multiple challenges throughout the deployment. Several of the instruments did not perform especially well, and some had continual problems. There was little time before the deployment to test instruments and develop routines, and many of the data analysis needs and protocols were not developed before the campaign. Some of the issues were unavoidable, although not all of them. However, despite the novelty of the deployment and the unique challenges it provided, MAGIC was a resounding success, due in no small part to the hard work, careful planning, and technical expertise of N. Hickmon (Argonne National Laboratory), AMF2 Site Manager, who was in charge of the deployment, her crew, and the motivated technicians. MAGIC proved a steep learning curve for all involved, but everyone was up to the task, and the knowledge and experience gained from the MAGIC deployment have guided subsequent marine ARM campaigns (ARM Cloud Aerosol Precipitation Experiment—ACAPEX) and are being applied to future ones (Measurement of Aerosols, Radiation and Clouds over the Southern Oceans—MARCUS) as well.

A number of factors led to the success of MAGIC. The close relationship between the scientific community and ARM infrastructure, especially between the Principal Investigator (E. Lewis) and Nicki Hickmon, allowed for quick dissemination of information regarding logistical changes and the flexibility to adapt to such changes. In June, 2012, well into the planning for the MAGIC deployment (installation was to occur in September, 2012 and planning was progressing slowly), N. Hickmon became AMF2 Site Manager and instituted weekly conference calls updating all relevant parties on how the deployment was proceeding. During the deployment she continually updated the Principal Investigator on the status of instruments, logistics, etc. Her communications proved very valuable in ensuring that everyone involved was aware of the status of the deployment, informing them about issues and concerns, allowing opportunities to provide feedback and ask questions, and planning for changing conditions.

The close relationship that was established by E. Lewis and N. Hickmon with Horizon Lines and with the Captain and crew of the *Spirit* was also invaluable to the success of MAGIC. In ship-board deployment, good relations with the Captain and crew are paramount. Although having two technicians and often science observers in close living quarters for extended periods was a disruption of their normal routines, the Captain and crew of the *Spirit* went out of their way to support and assist us, from turning the ship to see if a different heading would facilitate radiosonde launches, to assisting with hardware and repairs, to assisting in coordination of overflights. Such a deployment would not have been possible without their support and assistance. Additionally, M. Reynolds and his knowledge of ship-based investigations also proved invaluable to the entire deployment, not only from a technical point of view (placement of instruments, development of meteorological and radiometric sampling protocols, etc.), but also because of disseminating information on ship etiquette, protocols, and other information that reflects the difference between shipboard deployments (and life on a ship) and land-based deployments.

Before the deployment, PI Lewis, AMF Site Manager (at that time) B. Orr, and M. Reynolds took the ship for one round trip (Leg0), which proved crucial in several ways, as discussed above. Additionally, several scientists were able to participate as observers and cruise on the *Spirit* for one or more legs during the deployment. PI E. Lewis was on the ship as an observer on Leg03, and E. Lewis and T. Ferguson (graduate student of G. Mace at U. Utah) took the ship and assisted with radiosonde launches during the IOP on Leg14 in July, 2013. M. Jensen (BNL) and Y. Gao (Rutgers U.) were on the ship on Leg17 in August, 2013, during which Y. Gao deployed her aerosol sampler. P. Kalmus (JPL) took the ship on Leg 19 in September, 2013. These opportunities allowed the scientists to see first-hand the operation of the deployment, and to experience the conditions under which the data were taken. It is difficult to overestimate the importance of such opportunities, as they provide context for the quality of the data, understanding of issues with continuity of data streams, and the like. These opportunities also facilitated positive interactions between MAGIC personnel and the Captain and crew of the *Spirit*.

Naming the transects by leg number (e.g., LegxxA for transects from Los Angeles to Honolulu, and LegxxB for transects from Honolulu to Los Angeles) proved to be a very effective mechanism for categorizing and discussing the data. This method is superior to using the traditional use of date/time, as it clearly denotes discrete time periods, each one of which contains a crossing of the Sc-to-Cu transition. Such a system is recommended for future marine deployments that consist of discrete or repeated voyages between ports.

Field campaigns of all sorts, and especially this one, are unique opportunities that cannot be repeated. Thus, it is essential that to the extent possible everything involved in a deployment be planned in advance. Partly though lack of an AMF2 chief scientist, there was little coordination among all the mentors in working toward the goals of the campaign. There was no meeting of the mentors and the PI and science team during which the goals of the deployment could be explained, and each mentor was allowed to make his/her best decision as to the operating parameters of the instruments. However, oceanic field campaigns are very different from land-based ones, and few if any of the mentors had experience making measurements at sea. Additionally, it is not clear if any of the mentors had read the science plan or were familiar with the scientific goals of the campaign. Thus, some of these operating conditions were less than optimal for achieving the goals of the program.

For instance, during the first part of the deployment (September, 2012 to January, 2013), the radars were optimized to measure high clouds, but the deployment was designed to study marine boundary layer (and hence low) clouds. The data obtained are still of value, although perhaps not as good as they could have been. For part of the deployment (until Leg06A) the ceilometer averaged for 16 seconds rather than 2 seconds, the shortest possible. At the speed of the ship, the longer sampling time may have averaged over several small cumulus, rendering such an average of little value. The locations (lat/long values) of all the radiosondes were all set to a fixed position for the entire deployment, an issue that was remedied later, but illustrates the point made above about the unique aspects of a shipboard campaign.

The lesson to be learned is that planning well in advance of the deployment, visits to the ship, and communication among all parties involved are important aspects of a successful deployment of this nature. It is gratifying to see that such early planning and communication are integral in future campaigns such as MARCUS.

The lack of quick feedback on data quality created some issues. The data were stored on disc and at the end of each leg, in Los Angeles, they were shipped to the data facility to be backed up and then ingested into the archive. However, when problems were discovered, the ship was already well into its next leg, thus resulting in more missing data before the issue could be remedied. This occurred in some instances in which IP addresses were changed (without notification of mentors), resulting in data that could not be written to the storage computer, or when a drive did not fully mount. Instituting a procedure that would allow for a small subset of data to be sent daily, and which mentors would look at routinely, would alleviate some problems of this sort. Having near-real-time inspection of data for availability, quality, and consistency is important in that it allows issues of all sorts to be corrected and maximizes the amount and quality of the data. This is especially the case for field deployment in that each presents a unique opportunity that is impossible to recapture.

The failure of the SeaNav early in the deployment had repercussions that lasted well beyond the campaign, requiring much post-cruise work to determine ship position and attitude from many sources. The final version of this information was not concluded until November, 2015, more than two years after the end of the deployment. Having additional Global Positioning System (GPS) units (which are relatively inexpensive and quite robust), and logging the values independently of the main computer, would have been beneficial and would have alleviated some of these issues. The deployment of additional GPS units independent of the main computer is strongly recommended for future marine campaigns as a low-cost, low-tech means to ensure a continuous data stream.

A related issue was the lack of a plan before the deployment on how/when the data would be processed. As noted, it was more than two years before basic and crucial information such as ship location and attitude was finalized. Some other data were not finalized until even later, and some of the measurements have not yet been processed, with the momentum and interest of some investigators who wanted to use MAGIC data suffering as a consequence. One of the major topics at the MAGIC workshop held six months after the end of the deployment was data availability.

The inclusion of guest instruments and other IOPs was a very successful and productive aspect of MAGIC. These opportunities provided redundancy in some cases, but complementary information in others, to measurements from instruments in the AMF2 suite, and thus proved valuable by providing validation, constraints, and auxiliary data to the core measurement suite. The use of the psychrometer to calibrate the RH sensors was vital in producing high-quality meteorological and flux data sets. Likewise, the ISAR provided National Institute of Standards and Technology (NIST)-traceable measurements of sea surface skin temperature that were also necessary for the flux data sets. Measurements from the CIMEL were used to develop a new method (Fielding et al., 2015) of simultaneously retrieving vertical profiles of cloud and drizzle in drizzling boundary layer clouds, as discussed below. The solar spectral flux radiometer (SSFR) from NASA, which was deployed from Leg14A through the end of the campaign, provided complementary information to that provided by AMF2's SAS-Ze. Besides the data from the SSFR being important in their own right (cf. the discussion below on Wang et al., 2016), comparison of the data from the two instruments revealed problems with the SAS-Ze that have been subsequently repaired.

Only one of the aerosol sampling projects was funded for subsequent analysis, and this one has resulted in one publication so far (DeMott et al., 2015). Failure to fund analysis of the more than 100 aerosol filter samples is a missed opportunity that could have provided valuable information on the chemical composition and morphology of marine aerosol particles in a very different part of the ocean from where most sampling has occurred, and this information would be useful to considerations of cloud formation, sea surface aerosol production, and the like.

As noted above, some of the aerosol instruments worked well, but some did not. The measurements from the UHSAS were especially valuable, as they provided size distributions from diameters 60 nm to 1000 nm. This instrument was not at the time a baseline instrument in the AOS, although it has subsequently been added as such. The timing issues with the UHSAS and CCN are problematic and limit the ability of these instruments to provide high-temporal-resolution data, although for most purposes the data of interest would be averages over much longer time scales. The f(RH) and the HTDMA, both of which were new instruments, did not perform well at any time. The lesson to be learned is obvious–it is crucial to understand the instrument performance and be familiar with it before deployment–although because of the timing of ARRA and the acquisition and deployment of the instruments, this was not possible for these instruments.

At the request of the PI, the technicians made brief notes after each leg on the instrument status and also kept a separate spreadsheet of radiosonde launch information. This metadata yielded near-real-time looks at how the deployment was proceeding and was useful in determining radiosonde launch positions, (lat/long) for instance. This type of metadata is not part of the ARM protocol, but would be useful to have for future investigators. There is much legacy knowledge/contextual information on the deployment, and on any field campaign, that is not reflected in the data streams and is difficult to access in the Data Quality Problem Reports (DQPRs). Some mechanism for collecting and distributing this metadata, such as a brief summary report after each leg discussing any notable events, meteorological conditions, or the like, and a list of what instruments did or did not work, would provide extremely valuable information for future users of the data. Information of this sort for MAGIC is available at the RMR website at http://www.rmrco.com/cruise/magic/, which contains summaries of individual legs, including synopses of meteorological and radiometric measurements and comparisons from various instruments, large-scale sea surface pressure maps to provide context for the measurements, and similar information.

In conclusion, the lessons learned can be summarized as follows. ARM has proven that it can undertake successful field campaigns in a marine environment, but this success hinges on strong personal relations and clear and open communication between the Site Manager, the Principal Investigator, and other parties involved in the deployment (in this case, Horizon, the Captain and crew of the *Spirit*, support organizations in port, etc.). There can be no substitute for careful planning and time before the deployment to visit sites and have meetings with mentors and others so that they can become familiar with instruments and protocols, develop backup plans in case of instrument failure or other issues, and develop data analysis routines so that at least some of the data can be processed during the deployment to ensure that high-quality measurements are being made. If data are not processed until after the deployment and issues are found, it is too late to fix them. Opportunities for redundant measurements and the deployment of guest instruments should be encouraged to the fullest extent possible. Both of these opportunities were exploited during MAGIC with very positive results.

4.0 Results

The unique aspects of the MAGIC deployment and the instrument suite contained within the AMF2, and the guest instruments deployed, facilitated a number of data sets that would not have been possible to obtain by other methods. Satellites typically sample a large swath, and satellite retrievals generally have difficulty in the lowest kilometer or so of the atmosphere–a key region that encompasses most of the MBL, and especially below clouds. However, even when MBL properties can be obtained by satellite retrievals, validation by in situ or surface-based measurements is required. There has been great interest in the data sets obtained during MAGIC, and they have already contributed to more than a dozen publications, with more manuscripts accepted and more on the way. It is expected that this interest will continue for a considerable time. For instance, the 1969 Barbados Oceanographic and Meteorological

EXperiments (BOMEX) and the 1992-1993 Tropical Ocean and Global Atmosphere-Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE) are still the subject of scientific publications, and the data obtained during those field campaigns remain useful today.

The three radars, together with lidars and ceilometer, provided insight into the dynamics and structure of the MBL, including cloud and precipitation properties. The more than 550 successful radiosondes provided an unprecedented detailed characterization of atmospheric thermodynamics and structure, especially in the marine boundary layer and lower troposphere. The meteorological mast instruments, radiometers, and ISAR allowed determination of air-sea fluxes of latent and sensible heat and of radiation. These are crucial inputs as boundary conditions in models and are used to validate and evaluate biases in satellite retrievals. Guest instruments such as the Microtops and the solar spectral flux radiometer, both from NASA, provided comparison and validation to ARM instruments such as the FRSR and the solar array spectrophotometer–zenith (SAS-Ze), in addition to providing complementary information to these instruments. Other guest instruments, such as aerosol sampling units from P. DeMott (University of Colorado) allowed probing of the composition and properties of aerosol particles that could not have been done in other ways. The following discussion will summarize some of the results obtained so far from the MAGIC deployment, although it is by no means exhaustive.

An extensive examination of clouds, precipitation, and marine boundary layer structure along the MAGIC transect and a detailed characterization of the Sc-to-Cu transition in this region was presented by Zhou et al. (2015), based primarily on measurements obtained with the KAZR, ceilometer, radiosonde launches, and the meteorological data set compiled by M. Reynolds (discussed further below). Clouds in the MBL far exceeded in occurrence other cloud types (such as deep convective or cirrus), and they were primarily stratiform as opposed to cumuliform (Figure 10). The presence of stratocumulus clouds was strongly correlated with a shallow MBL with a strong inversion and weak transition, as opposed to that of cumulus clouds, the formation of which was associated with a much weaker inversion and stronger transition. Precipitation that did not reach the surface, i.e., drizzle and virga, was prevalent (Figure 11).

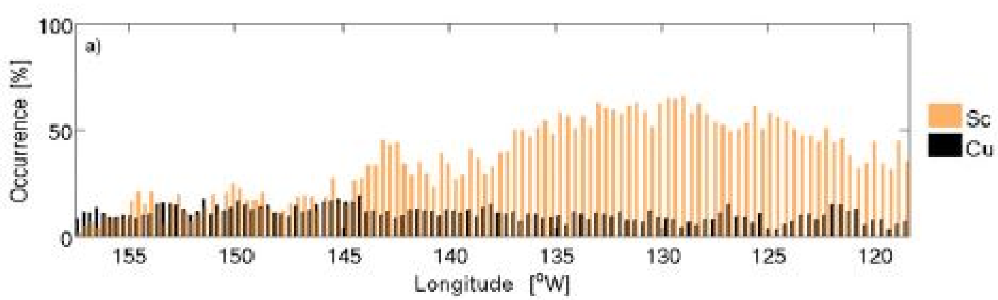

Figure 11. Clouds in the marine boundary layer during MAGIC; from Zhou et al. (2015).

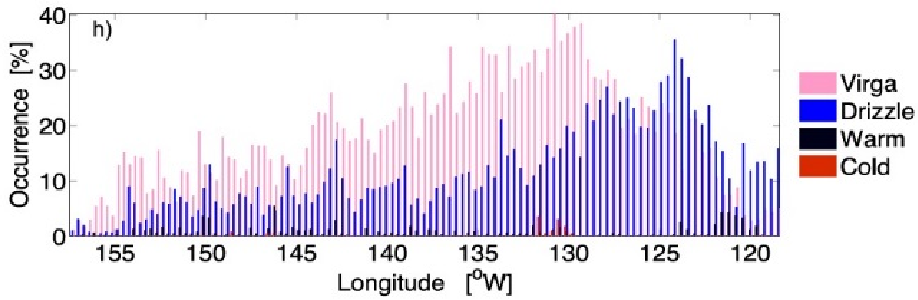

Figure 12. Types of precipitation during MAGIC; from Zhou et al. (2015).

Decoupling of the MBL (DE) and cloud breakup (CB) were also investigated by Zhou et al. (2015), who determined that the commencement of systematic decoupling in the MBL always occurred eastward of the locations of cloud breakup (Figure 12), and that there was a strong moisture stratification associated with decoupling. They concluded that the dominant factor triggering the systematic decoupling of the MBL, and the subsequent transition from Sc to Cu, was entrainment of dry warm air above the inversion, and that surface heat flux, precipitation, and diurnal circulation did not play major roles. Additionally, the transition occurred over short spatial regions (Figure 12) due to the changes in the synoptic conditions, implying that MBL clouds do not have enough time to evolve as in the idealized models.

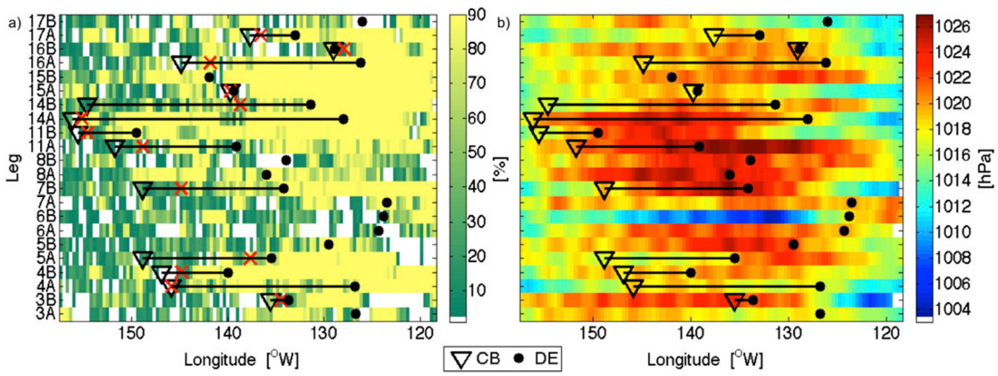

Figure 13. Cloud fraction (left) and surface pressure (right) along MAGIC transect for individual legs, with locations of cloud breakup (triangles), MBL systematic decoupling (dots), and where cloud fraction drops below 50% (crosses); from Zhou et al. (2015).

The radiosonde data set is exceptional in that it yields detailed thermodynamic properties of the MBL and lower troposphere at good resolution (Figure 9) along a transect in a marine region. These data, which could not be obtained by other means, provides evaluation, validation, and constraints of models, satellite retrievals, and reanalyses. Several examples of the type of information these radiosonde launches can provide, and how these data have been applied, are shown below.

Convective Available Potential Energy (CAPE) and Convective INhibition (CIN) for the first part of the MAGIC deployment are shown in Figure 13, and MBL heights for the two parts of the deployment (cold and warm seasons) are shown in Figure 14. Vertical profiles of temperature and RH are shown in Figure 15 for a stratus deck near 125ºW with a strong inversion at the top of the MBL (left) and for a decoupled MBL near 156ºW with a weaker inversion (right).

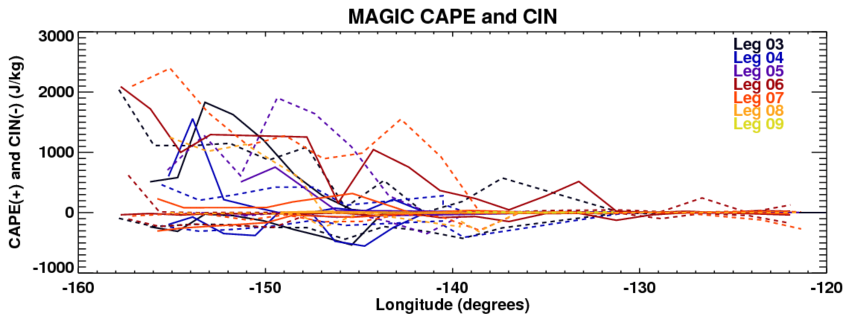

Figure 14. Convective Available Potential Energy (CAPE) and Convective INhibition (CIN) for different legs during the first phase of MAGIC; figure by T. Toto (BNL).

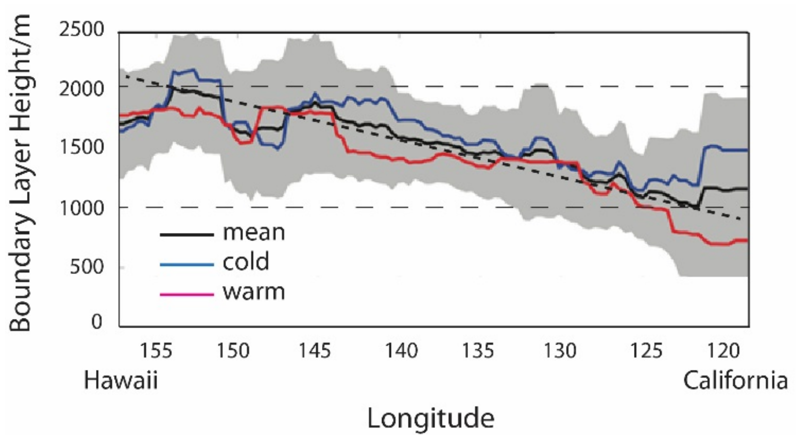

Figure 15. Marine boundary layer heights, with gray denoting standard deviations, during the cold and warm seasons, from Xhou et al. (2015).

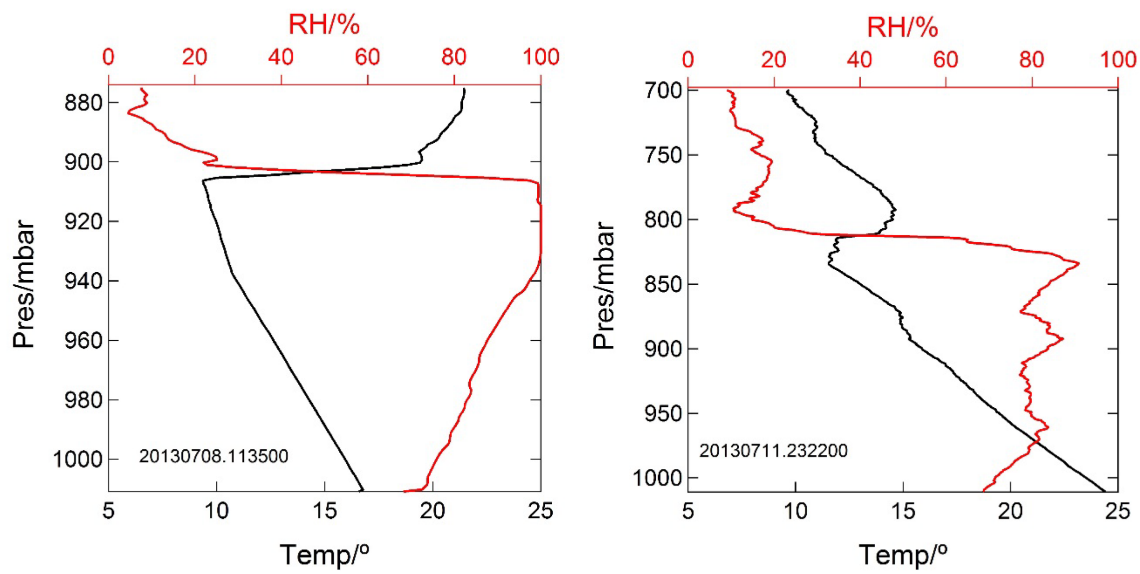

Figure 16. T and RH profiles for a stratus deck near 125ºW (left) and for a decoupled MBL near 156ºW (right).

The large sonde data set also allows for comparison of formulations for determining MBL heights. Xhou et al. (2015) presented a method for determining MBL heights and applied it to MAGIC sonde launches, and ARM has a VAP that employs four other methods for determining this quantity: the Heffter method, the Liu-Liang method, and the Richardson method with two different critical values. These are compared in Figure 16, which clearly demonstrates that the Heffter method yields values that are generally near those obtained by the Xhou et al. method, but that the other methods (Liu-Liang and the two Richardson criteria methods) do not yield reasonable values for the MAGIC region.

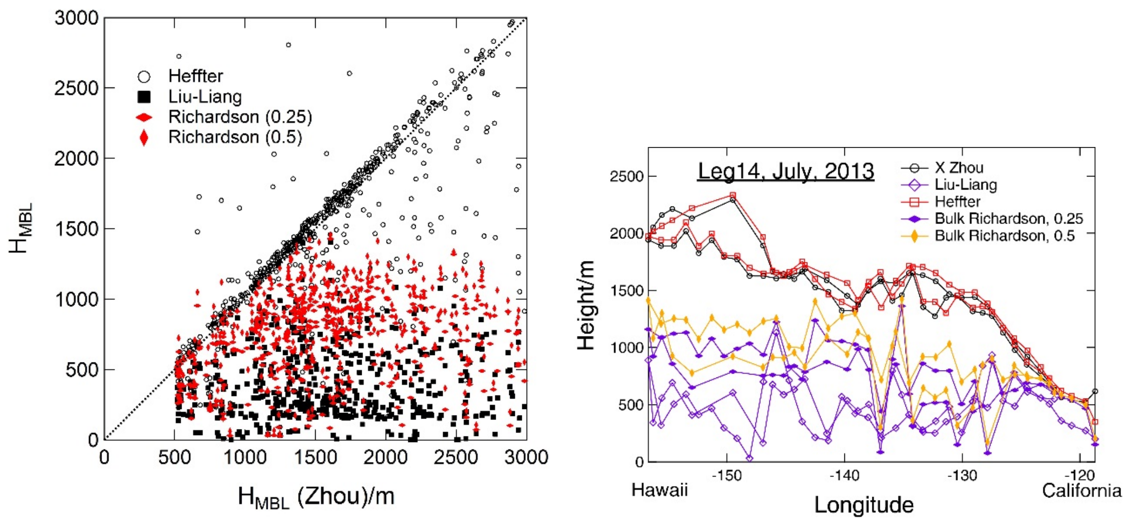

Figure 17. Comparison of MAGIC MBL heights from four methods to those determined by the Xhou et al. method. Scatterplot for entire deployment (left), and example for Leg14 (right).

The radiosonde data were used by other investigators as well. Kalmus et al. (2014) used data from 212 radiosondes launched during MAGIC to determine MBL heights, which were used to estimate MBL moisture and energy budgets and entrainment rates along the GPCI transect for June-July-August (JJA) of 2013. They use radio occultation data from Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) microsatellites, which intercept signals from GPS satellites. Additionally, they used flux estimates from MAGIC to compare the sensible and latent heat fluxes to those estimated by the European Centre for Medium Range Weather Forecasting (ECMWF), and determined that although the ECMWF latent heat flux is generally less than the MAGIC results, the ECMWF sensible heat flux is systematically larger (Figure 17). The RMS differences were 18 and 10 W m-2, respectively.

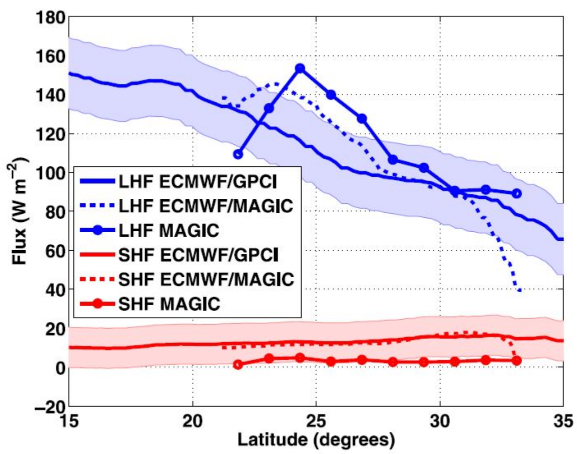

Figure 18. MAGIC and ECMWF surface fluxes of latent and sensible heat; from Kalmus et al. (2014).

Kalmus et al. (2015) used data from 550 radiosonde launches from MAGIC to examine biases in temperature and specific humidity profiles and in MBL heights determined by the Atmospheric Infrared Sounder (AIRS) satellite instrument aboard the Aqua platform and from the ECMWF ERA-Interim reanalysis (Figure 18). These investigators concluded that the AIRS temperature profiles are less biased than ECMWF reanalysis in the MBL, but that both AIRS and ECMWF distort the sharp inversions such as those along the MAGIC transect. The MAGIC radiosondes are especially valuable for satellite data validation because they provide a unique set of measurements over an important atmospheric regime and they are not assimilated into reanalysis models.

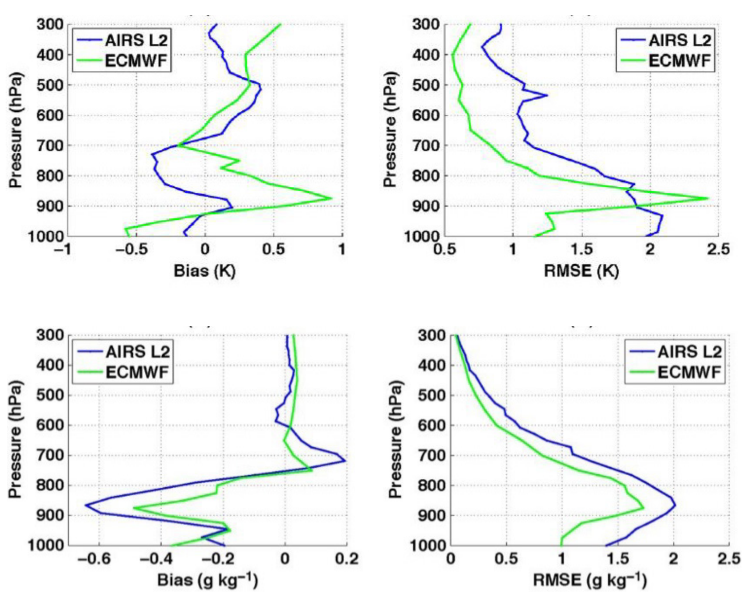

Figure 19. Bias and root-mean-squared error (RMSE) of temperature (top panel) and specific humidity (bottom panel) for AIRS and ECMWF compared to MAGIC sonde launches; from Kalmus et al. (2015).

Millan et al. (2016) used data from 192 MAGIC radiosonde launches to evaluate an algorithm to determine MBL column water vapor (CWV) from moderate resolution imaging spectroradiometer (MODIS) NIR imagery and advanced scanning radiometer (AMSR) measurements. The former measures

CWV above cloud top and the latter measures the total CWV. Based on MAGIC radiosonde data, they determined that ECMWF overestimates cloud-top pressure, and thus underestimates boundary-layer height.

The surface fluxes of radiation, heat, and moisture provide important, and often dominant, contributions to the energy and moisture in the MBL, and thus play a fundamental role in the state and dynamics of the MBL and in the development of MBL clouds and their transitions. This role is especially large where boundary layers are shallow, such as the broad subsidence regions along the MAGIC transect. These quantities are also necessary as boundary conditions in models. During MAGIC, several data sets were collected that allow determination of these fluxes. The meteorological mast suite of instruments provided temperature, relative humidity, and wind speed at mast height. The ISAR measured sea surface skin temperature (SSST), which together with the measurements from the meteorological mast allowed calculation of fluxes of sensible and latent heat. The PRPs measured downwelling fluxes of SW and LW radiant energy, and upwelling SW and LW fluxes were calculated from SSST and solar zenith angle. Data sets containing the best estimate 1-min sea surface temperature, best estimate 1-min downwelling radiation, best estimate 1-min meteorology, and fluxes calculated from these can be ordered at the MAGIC campaign page on the ARM website at http://www.arm.gov/campaigns/amf2012magic. There are "readme" files written by M. Reynolds describing how these data were processed that should be consulted by anyone using these data sets; these are available with the data at the website given above or on the RMR website at http://www.rmrco.com/cruise/magic/data/OnDataProcessing/.

A time series of the various energy flux components for a leg during the winter (Leg07A, 2012-12-01 to 2012-12-06) and one during the summer (Leg15A, 2013-07-20 to 2013-07-25) are shown in Figures 19 and 20, respectively. The dominant energy flux components throughout the MAGIC campaign were downwelling SW radiation and latent heat. The daily mean SW downwelling radiation flux averaged ~200 W m^2 for the entire campaign, and was nearly twice as high (~240 W m^2) during the summer as during the winter. Because of the low albedo of the ocean (~0.05-0.10), there was little upwelling SW radiation (mean around 10 W m^2 throughout the year). The downwelling and upwelling longwave fluxes were near ~380 W m^2 and ~420 W m^2, respectively, nearly independent of season, but their differences resulted in an overall net upward flux of ~45 W m^2. The (upward) latent heat flux varied from ~50 W m^2 during the winter to ~130 W m^2 during the summer, whereas the sensible heat flux was typically less than 10 W m^2 and may be upward or downward. Rainfall provided little contribution to the energy flux, with a deployment average of 1.5 W m^2. The mean net flux for the entire campaign was ~30 W m^2 downward, but this may be biased due to differing day/night sampling times. MAGIC used redundant measurements from different locations on the ship coupled with the best ship navigation data to produce estimates for the bulk coefficient flux algorithm.

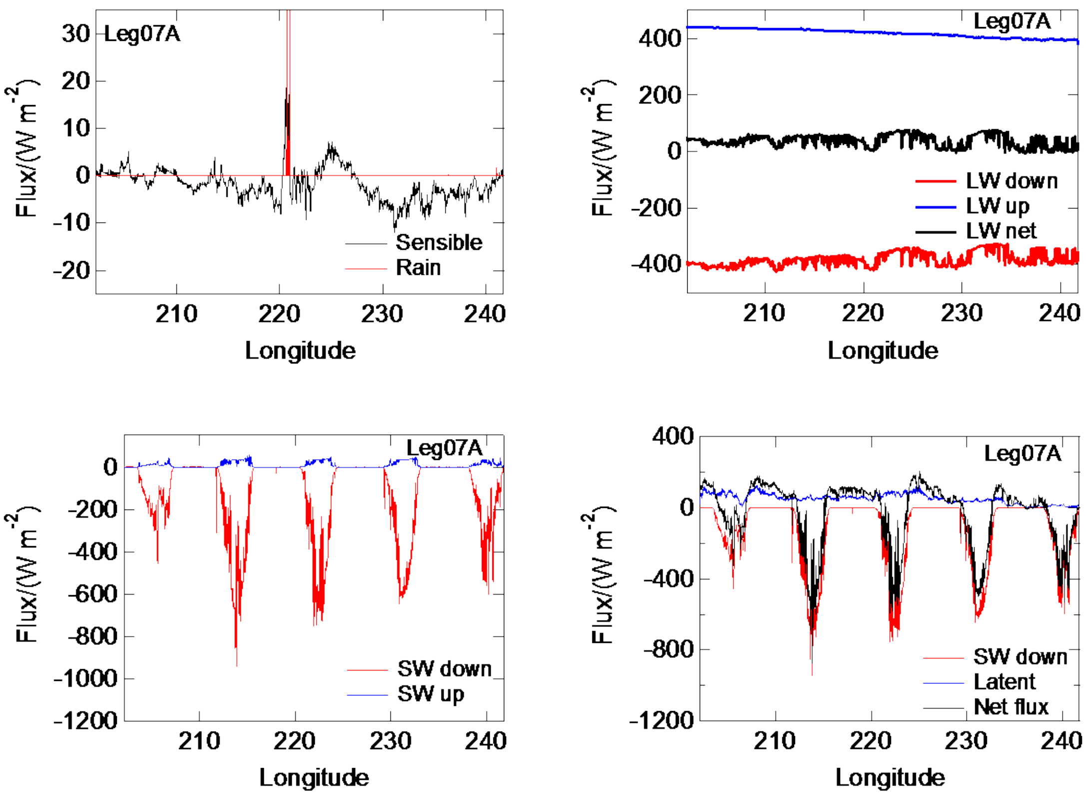

Figure 20. Energy fluxes during MAGIC Leg07A, 2012-12-01 to 2012-12-06.

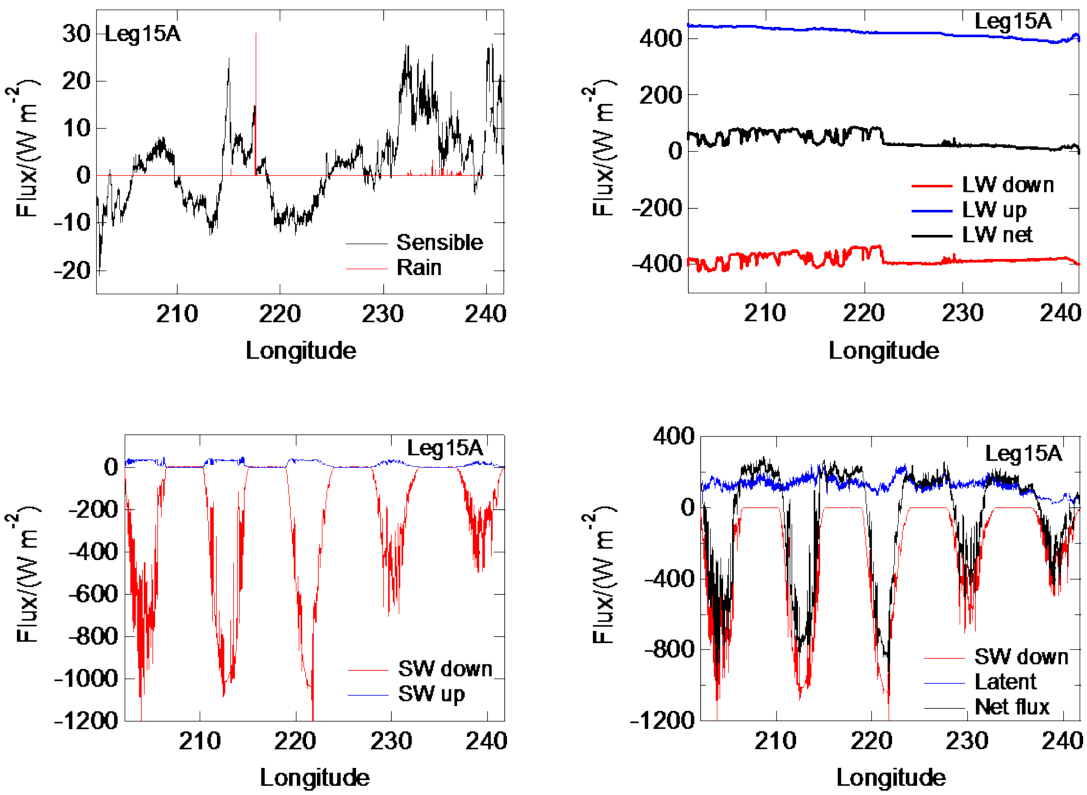

Figure 21. Energy fluxes during MAGIC Leg15A, 2013-07-20 to 2013-07-25.

The MAGIC flux data were used by S. Kato (NASA) and D. Rutan to investigate the SYN1Deg NASA global flux profile product, and they reported biases up to 2% (15 W m^2) in clear sky conditions and up to 7% (30 W m^2) under multi-level cloudy conditions; see asr.science.energy.gov/meetings/stm/2015/presentations/Thurs-BrkOut-5-rutan-MAGIC.pdf.

MAGIC measurements have also been used to determine properties of clouds, including their susceptibility to aerosols, as reported in several recent publications. Painemal et al. (2015) used MAGIC data to investigate the dependence of the synoptic and monthly variability of both condensation nuclei (CN) and cloud condensation nuclei (CCN) in the boundary layer on circulation patterns. They found that both CN and CCN are lower during autumn/winter than in spring/summer and typically decrease toward the west (Figure 21). They concluded that boundary-layer winds are mainly responsible for the aerosol variability, especially near the coast. Using MODIS satellite-derived cloud drop number concentration, they determined an aerosol-cloud interaction (ACI) index, defined as $ACI \equiv \frac{\partial \ln(N_d)}{\partial \ln(N_a)}$, relating cloud drop number concentration (Nd) and aerosol number concentration, CCN (Na), as high as 0.9 (Figure 22), substantially greater than values from previous ARM land-site deployments, as well as those inferred from climate models and from previous satellite studies.

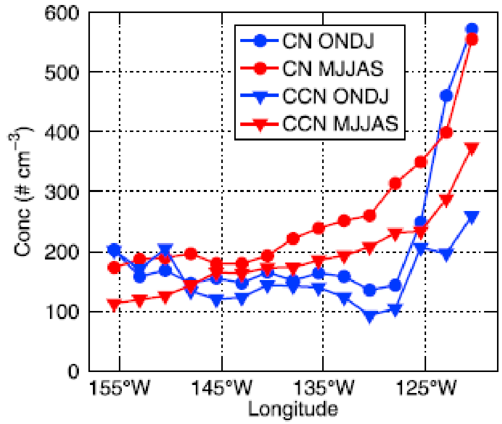

Figure 22. Condensation nuclei (CN) and cloud condensation nuclei (CCN) at 0.6% supersaturation averaged for two time periods, October, 2012 to January, 2013, and May to September, 2013; from Painemal et al., 2015.

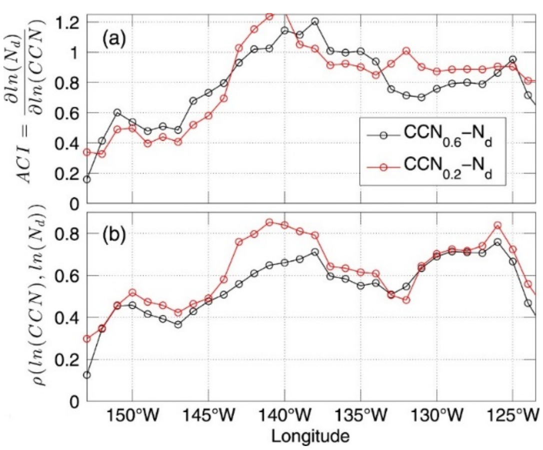

Figure 23. Aerosol-cloud index (ACI) relating cloud drop number (N_d) and cloud condensation nuclei at both 0.6% and 0.2% supersaturation averaged over the MAGIC transect; from Painemal et al. (2015).

Liquid water path measurements from the 3-channel microwave radiometer during MAGIC from May to August, 2013, comprising 80 days at sea and eight legs, were used by Painemal et al. (2016) to compare retrievals from four microwave satellite sensors. They made a total of 251 comparisons, and reported that although the agreement was rather good, the satellite retrievals overestimate LWP determined from ship with an overall mean bias of 9.3 g m^{-2} for all-sky situations, and a bias of 5.2 g m^{-2} for clear-sky situations (Figure 24).

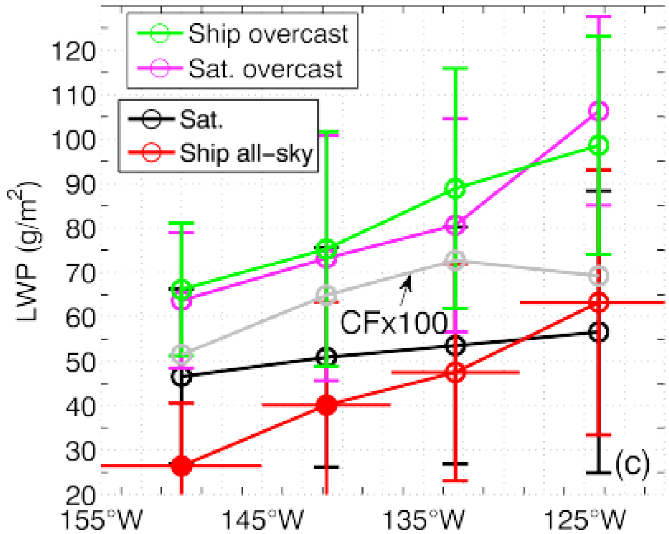

Figure 24. Overcast and all-sky zonally-binned LWP from satellite retrievals and from MAGIC; from Painemal et al. (2016).

MAGIC measurements of surface air temperature and from the motion-stabilized W-band radar were used by Zheng and Rosenfeld et al. (2015) to validate a method of estimating maximum and cloud-base updraft speeds from cloud-base height for non-precipitating clouds. The goal of the investigation was to determine these updraft speeds from satellite-derived, cloud-base temperature and ECMWF surface temperature. As the cloud-base updraft directly relates to supersaturation and thus to CCN concentration, such a retrieval would be of great utility in investigating aerosol-cloud interactions. The work was continued in Rosenfeld et al. (2016), who used MAGIC data to validate the feasibility of estimating CCN and updraft velocities at cloud base for boundary-layer clouds from satellite.

Fielding et al. (2015) developed a new method to use surface-based measurements of radar reflectivity, lidar attenuated backscatter, and zenith radiances to simultaneously retrieve vertical profiles of cloud and drizzle (i.e., drop size and water content of both cloud and drizzle) in drizzling boundary-layer clouds when the precipitation does not reach the surface. The method was applied to MAGIC observations and the retrieved cloud water path agrees with the 3-channel MWR measurements to within an rms difference of 10-20 g m^{-2}.

Wang et al. (2016) applied a spectrally invariant method (to study the variability of cloud optical thickness and drop effective radius in the transition zones near cloud edges) to measurements from ARM's solar array spectrophotometer-zenith (SASZe) and NASA's solar spectral flux radiometer (SSFR), which was deployed on MAGIC from Leg14 through Leg20. Spectra are normalized and represented as a linear combination of clear and cloudy spectra, with slope and intercept to characterize the transition zone. They determined that although cloud optical thickness during the cloudy-to-clear transition decreased, the cloud drop effective radius did not change when cloud edges were approached, supporting the hypothesis that inhomogeneous rather than homogeneous mixing dominates near cloud edges in the cases studied.

Aerosol samples were collected on filters (24-hour samples) during MAGIC for Dr. Paul DeMott (Colorado State University) for ice nucleation studies. This activity was the most comprehensive sampling for ice nucleation over the oceans since the 1970s. The samples were frozen for offline processing to determine immersion freezing ice nuclei (IN) temperature spectra of particles washed from the filters, the inorganic/organic proportions of IN, the concentrations of known ice-nucleating bacteria, and RNA abundance and diversity. The collections represent a critical in situ data set for characterizing IN concentrations over warmer and relatively lower productivity ocean regions for comparison to future data from other regions. The samples collected during MAGIC were compared with those from ambient samples, including those from aircraft flights in the Caribbean and others taken from ship-based deployments in the Canadian Arctic and the Bering Sea by DeMott et al. (2015), and the data set is being used to develop a parameterization for oceanic (e.g., sea spray) ice nuclei emissions in modeling of aerosol connections to cloud phase and properties on regional and global scales.

There are many further research opportunities relating to MAGIC. Despite the number of publications to date, the data have only begun to be examined and used. We expect that the MAGIC data will continue to be used for model constraint, intercomparison, evaluation, and development, satellite retrieval validation, and reanalysis comparisons. The upcoming Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) campaign will provide ample opportunities for comparison and contrast or MBL clouds in different regions of the world.

MAGIC did not capture the full seasonal cycle of the Sc-to-Cu transition, and future deployments would provide information on interannual variability. Deployment of a subset of the MAGIC instrument suite that could be operated without technicians on board would allow determination of many quantities of importance. For instance, the meteorological mast, a PRP, and an ISAR would allow determination of fluxes; a ceilometer would provide cloud base height; and a CIMEL in cloud mode and a microwave radiometer would enable determination of LWP, cloud optical depth, and effective drop radius.

5.0 Public Outreach

Public outreach efforts included ARM Climate Research Facility postings (ARM Blog, Field Notes, etc.), a list of which is available at https://www.bnl.gov/envsci/cloud/campaigns/MAGIC/index.php (on the right side of the page) and MAGIC updates, which are informal newsletters distributed during the deployment by the PI (available at https://www.bnl.gov/envsci/cloud/campaigns/MAGIC/updates.php). The First MAGIC Science Workshop (https://www.bnl.gov/magic2014/) was held at Brookhaven National Laboratory in May, 2014 and had more than 40 attendees. An overview article on MAGIC appeared in the September, 2014 *SOLAS* (Surface Ocean, Lower Atmosphere Study) newsletter (http://www.solas-int.org/files/solas-int/content/downloads/pdf/NL/SOLAS%20newsletter%2016.pdf) and a similar article appeared in the June 14, 2015 *EOS* publication of the American Geophysical Union (https://eos.org/project-updates/dispelling-clouds-of-uncertainty). Presentations on MAGIC have been given at multiple venues at Brookhaven National Laboratory (listed below under Presentations).

6.0 MAGIC Publications

6.1 Journal Articles/Manuscripts

The following articles on MAGIC have appeared in the scientific literature.

2014

Kalmus, P, M Lebsock, and J Teixeira. 2014. "Observational boundary layer energy and water budgets of the stratocumulus-to-cumulus transition." *Journal of Climate*, 27(24): 9155-9170, doi:10.1175/JCLI-D-14-00242.1.

Lewis, E. 2014. "MAGIC studies clouds, aerosols, radiation, and fluxes in the Eastern North Pacific." *SOLAS Newsletter* 16, Summer: 24-25.

2015

Kalmus, P, S Wong, and J Teixeira. 2015. "The Pacific subtropical cloud transition: A MAGIC assessment of AIRS and ECMWF thermodynamic structure." *IEEE Geoscience and Remote Sensing Letters* 12(7): 1586-1590, doi:10.1109/LGRS.2015.2413771.

Zhou, X, P Kollias, and ER Lewis. 2015. "Clouds, precipitation, and marine boundary layer structure during the MAGIC field campaign." *Journal of Climate* 28: 2420-2441, doi:10.1175/JCLI-D-14-00320.1.

Painemal, D, P Minnis, and M Nordeen. 2015. "Aerosol variability, synoptic-scale processes, and their link to the cloud microphysics over the Northeast Pacific during MAGIC." *Journal of Geophysical Research–Atmospheres* 120: 5122-5139, doi:10.1002/2015JD023175.

Lewis, E, and J Teixeira. 2015. "Dispelling clouds of uncertainty." *EOS* 96(12): 16-19, https://eos.org/project-updates/dispelling-clouds-of-uncertainty.

Zheng, Y, and D Rosenfeld. 2015. "Linear relation between convective cloud base height and updrafts and application to satellite retrievals." *Geophysical. Research Letters* 42: 6485-6491, doi:10.1002/2015GL064809.

Fielding, MD, JC Chui, RJ Hogan, G Feingold, E Eloranta, EJ O'Connor, and MP Cadeddu. 2015. "Joint retrievals of cloud and drizzle in marine boundary layer clouds using ground-based radar, lidar and zenith radiances." *Atmospheric Measurement Techniques* 8: 2663-2683, doi:10.5194/amt-8-2663-2015.

2016

Millán, L, M Lebsock, E Fishbein, P Kalmus, and J Teixeira. 2016. "Quantifying marine boundary layer water vapor beneath low clouds with near-infrared and microwave imagery." *Journal of Applied Meteorology and Climatology* 55: 213-224, doi: 10.1175/JAMC-D-15-0143.1.

DeMott, PJ, TCJ-Figueroa, MD Stokes, GB Deane, OL Mayol-Bracero, Hill, CS McCluskey, KA Prather, DB Collins, RC Sullivan MJ Ruppel, RH Mason, VE Irish, T Lee, CY Hwang, TS Rhee, JR Snider, GR McMeeking, S Dhaniyala, ER Lewis, JJB Wentzell ,J Abbatt, C Lee, CM Sultana, AP Ault, JL Axson, MD Martinez, I Venero, G Santos-Figueroa, MD Stokes, GB Deane, OL Mayol-Bracero, VH Grassian, TH Bertram, AK Bertram, BF Moffett, and GD Franc. 2016. "Sea spray aerosol as a unique source of ice nucleating particles." *Proceedings of the National Academy of Sciences of the United States of America* 113(21): 5797-5803, doi:10.1073/pnas.1514034112.

Rosenfeld, D, Y Zheng, E Hashimshoni, JL Pöhlker, A Jefferson, C Pöhlker, X Yu, Y Zhu, G Liu, Z Yue, B Fischman, Z Li, D Giguzin, T Goren, P Artaxo, HMJ Barbosa, U Pöschl, and MO Andreae. 2016. "Satellite retrieval of cloud condensation nuclei concentrations by using clouds as CCN chambers." *Proceedings of the National Academy of Sciences of the United States of America* 113: 5828-5834, doi:10.1073/PNAS.15140441113.

Painemal, D, T Greenwald, M Cadeddu, and P Minnis. 2016. "First extended validation of satellite microwave liquid water path with ship-based observations of marine low clouds." *Geophysical Research Lett*ers 43, doi:10.1002/2016GL069061.

Yang, W, A Marshak, PJ McBride, JC Chiu, Y Knyazikhin, KS Schmidt, C Flynn, and ER Lewis. 2016. "Observation of the spectrally invariant properties of clouds in cloudy-to-clear transition zones during the MAGIC field campaign." *Atmospheric Research* 182: 294-301, doi:10.1016/j.atmosres.2016.08.004.

6.2 Meeting Abstracts/Presentations/Posters

MAGIC has been discussed and MAGIC results presented via oral or poster presentation at a large number of meetings, conferences, and other venues.

ARM/ASR meetings: There was a Marine Deployment breakout session at the March, 2011 ASR Science Team Meeting and one at the September, 2011 ASR Fall Working Group Meeting, both of which centered on MAGIC. MAGIC breakout sessions with multiple presentations were held at the March, 2012 ASR Science Team Meeting; the March, 2013 ASR Science Team Meeting; the November, 2013 Fall Working Group Meeting; the March, 2014 ASR Science Team Meeting; the November, 2014 ASR Fall Working Group Meeting; the March, 2015 Joint ARM/ASR Joint User Facility/Principal Investigator Meeting; and the May, 2016 Joint ARM/ASR Joint User Facility/Principal Investigator Meeting. At each of these meetings, numerous posters discussing MAGIC activities and data were also presented.

The following **plenaries** relating to MAGIC were presented at ASR/ARM meetings: Xiaoli Xhou (McGill University) at the March, 2014 Atmospheric System Research Science Team Meeting; Dr. David Painemal (NASA) at the March, 2015 Joint ARM/ASR Joint User Facility/Principal Investigator Meeting; PI Lewis at the May, 2016 Joint ARM/ASR Joint User Facility/Principal Investigator Meeting; and Dr. Christine Chui (University of Reading) at the May, 2016 Joint ARM/ASR Joint User Facility/Principal Investigator Meeting.

Brookhaven National Laboratory presentations: Presentations on MAGIC were made by PI Lewis at BNL in Upton, New York and locally to Partners in Science (2011-11), The Science Learning Center Journal Club (2011-12), The Community Advisory Council (2013-03), Islip Science Symposium at Islip, New York High School (2013-07), Office of Educational Programs Brown Bag Lunch Seminar Series (2013-06), U.S. Department of Energy Site Office (2013-08), and to the New York University SHERP - Science, Health, and Environmental Reporting Program (2013-11).

Other conferences and meetings: Oral or poster presentations on MAGIC were made by PI Lewis (or others, as noted) at the American Geophysical Union Fall Meeting in San Francisco, California (2012-12), the Joint CFMIP/EUCLIPSE Meeting in Hamburg, Germany (2013-06, presented by Chris Bretherton, University of Washington), the Atmospheric Chemistry Gordon Research Conference in Mt. Snow, Vermont (2013-08), the Jet Propulsion Laboratory in Pasadena, California (2013-08), the

OceanFlux Sea Spray Aerosol Workshop in Galway, Ireland (2013-10), the 2013 Sea Surface Temperature Science Team Meeting in Seattle, Washington (2013-10, by Mike Reynolds of RMR Co.), the American Geophysical Union Fall Meeting in San Francisco, California (2013-12), the Ocean Sciences Meeting in Honolulu, Hawaii (2014-02), the 7th International Scientific Conference on the Global Energy and Water Cycle in The Hague, Netherlands (2014-07), the American Geophysical Union Fall Meeting in San Francisco, California (2014-12), the American Meteorological Society Meeting in Phoenix, Arizona (2015-01), the American Geophysical Union Joint Assembly Meeting in Montreal, Canada (2015-05), the SOLAS Open Science Conference in Kiel, Germany (2015-09), and the American Geophysical Union Fall Meeting in San Francisco, California (2015-12).

Workshops: The First MAGIC Science Workshop was convened at BNL in Upton, New York in May, 2014, with more than 40 attendees from multiple federal organizations, national laboratories, and countries. There was a MAGIC workshop at the American Geophysical Union Fall Meeting in San Francisco, California in December, 2014 with 25 attendees.

Webinars: PI Lewis presented a US CLIVAR Process Study and Model Improvement (PSMI) Panel Webinar in March, 2016. It is available for viewing on the web at http://usclivar.org/panels/psmi-panel-webinars.

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