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Article

A Road Map to Success of International Field Campaigns in Atmospheric and Oceanic Sciences

Chidong Zhang and James A. Moore

ABSTRACT: Understanding and predicting Earth's environment requires information and knowledge of detailed physical, chemical, and biological processes directly from observations. Well-organized and properly conducted field campaigns are powerful ways to make such observations. Major international field campaigns with participation from multiple countries bring together expertise and resources to address complex scientific issues that are difficult or impossible to be tackled by a few scientists in a single nation. This article describes the essential elements of international field campaigns, the necessary steps of planning and execution that need to be taken for their success, and other considerations that make international field campaigns successful. The intention of this article is to encourage early career professionals to participate in and learn to organize field campaigns in this exciting time of rapidly evolving technological observing capabilities and increasing efforts to seek global diversity, equity, and inclusion in science.

KEYWORDS: Field experiments; Planning; In situ atmospheric observations; In situ oceanic observations

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Corresponding author: Chidong Zhang, chidong.zhang@noaa.gov

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AFFILIATIONS: Zhang—NOAA/Pacific Marine Environment Laboratory, Seattle, Washington; **Moore***—National Center for Atmospheric Research, Boulder, Colorado
* Retired

Observing our world is one of the most fundamental steps toward understanding and predicting it. The same sensors operating continuously over a long period of time provide sustained observations with their main objectives of building long-term records to measure the mean state of the Earth system and its slow variations. An excellent example of sustained observations is the measurements of atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii, which started in 1958 (Keeling et al. 1976) and is continuing at the present time.[1] A field campaign deploys instruments for a short period of time to make observations that provide more detailed and comprehensive information than sustained observations. The distinction between a field campaign and sustained observations is not always well defined, as will be illustrated later.

The most fundamental approaches of field campaigns in natural science are to make human visual inspection, take photos or make drawings, collect material samples (e.g., water, sediment, ice cores, rocks, fossils, biological species), and record instrument data. Field campaigns can have a wide range of impacts, from helping fine-tune a single parameter, such as sea surface roughness (Donelan et al. 1993), to understanding a profound anthropogenic effect on the Earth system, such as the ozone depletion (Kurylo 2018). Some field campaigns are designed to test and calibrate platforms and sensors. New knowledge and improved understanding of detailed processes gained from field campaigns can lead to development of algorithms for satellite retrievals and parameterization schemes of numerical models.

Satellite observations have become a major source of environmental information, with their data amount and coverage surpassing Earth-based observations by several orders of magnitude. Ever-increased output from numerical models (e.g., global data assimilation products) have often been used in place of observations when in situ observations are insufficient for certain research purposes. It is indisputable that the accuracy of many types of satellite observations crucially depends on their calibration and validation against Earth-based observations and the reliability of data produced by numerical models is known only through verification against observations (Zhou et al. 2016; Peng et al. 2017). Field campaigns remain irreplaceable regardless of how many satellites are in orbit, because observations of the ocean interior and underground still cannot be made by satellites, and many detailed processes that govern how the Earth system operates have to be observed at high spatial (down to submeters) and temporal (down to milliseconds) resolutions only possible with Earth-based sensors. Observations from field campaigns and sustained observing networks are the closest we can get to the ground truth of the Earth system. These observations are and will be for a long time, if not forever, one of the main sources of foundational knowledge for Earth science.

The need for observations to support environmental studies will only increase in the future. To address complex regional and global environmental issues, it is necessary to conduct large and long duration field campaigns with multidisciplinary, multifacility approaches that require international cooperation. International field campaigns always face extra difficulties that are not common in single-country campaigns. International field campaigns are those

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[1] www.esrl.noaa.gov/gmd/ccgg/trends

conducted using observing platforms deployed in a country or countries on land, within exclusive economic zones (EEZs) or territorial waters, and/or national controlled airspace with participation from multiple foreign countries. Challenges to a successful international field campaign grow exponentially with its complexity and the number of countries involved.

This article discusses the common practices of international field campaigns. It focuses on aspects of international field campaigns that are often not included in research publications: their complexity, planning, and execution, with some perspective of how they have evolved through the past decades and may evolve in the future. The authors have written this article based on their combined experiences primarily from studies on atmospheric sciences, oceanic sciences, and air–sea interaction. Because of this, most examples given in this article are related to atmospheric and oceanic sciences. The principles ascribed here should generally apply to field campaigns within other disciplines. This article does not cover all geographic locations. For example, possible field campaigns organized and participated in by the former Soviet Union and Eastern Bloc countries during the Cold War are not included in this article because of a lack of data access and publications in English journals. This article was written independently of previous published materials on the similar topics (e.g., Doyle et al. 2019; Sprintall et al. 2020). Readers will find consistent but broader coverages in this current article.

Table A1 in appendix A lists examples of international field campaigns during the past six decades to illustrate the broad scope and complexity of scientific topics covered, particularly in atmospheric and oceanic physics and chemistry. Their approximate locations are shown in Fig. 1. Each number in Fig. 1 corresponds to the number in the far left-hand column in Table A1. In the text, field campaigns are cited with their respective numbers (e.g., VIMHEX-1) so they can be easily located in Table A1. It appears in Fig. 1 that vast areas of Earth have not been explored by field campaigns. This is only partially true as some of these areas may have been observed through field campaigns conducted by a single country or sustained observations.

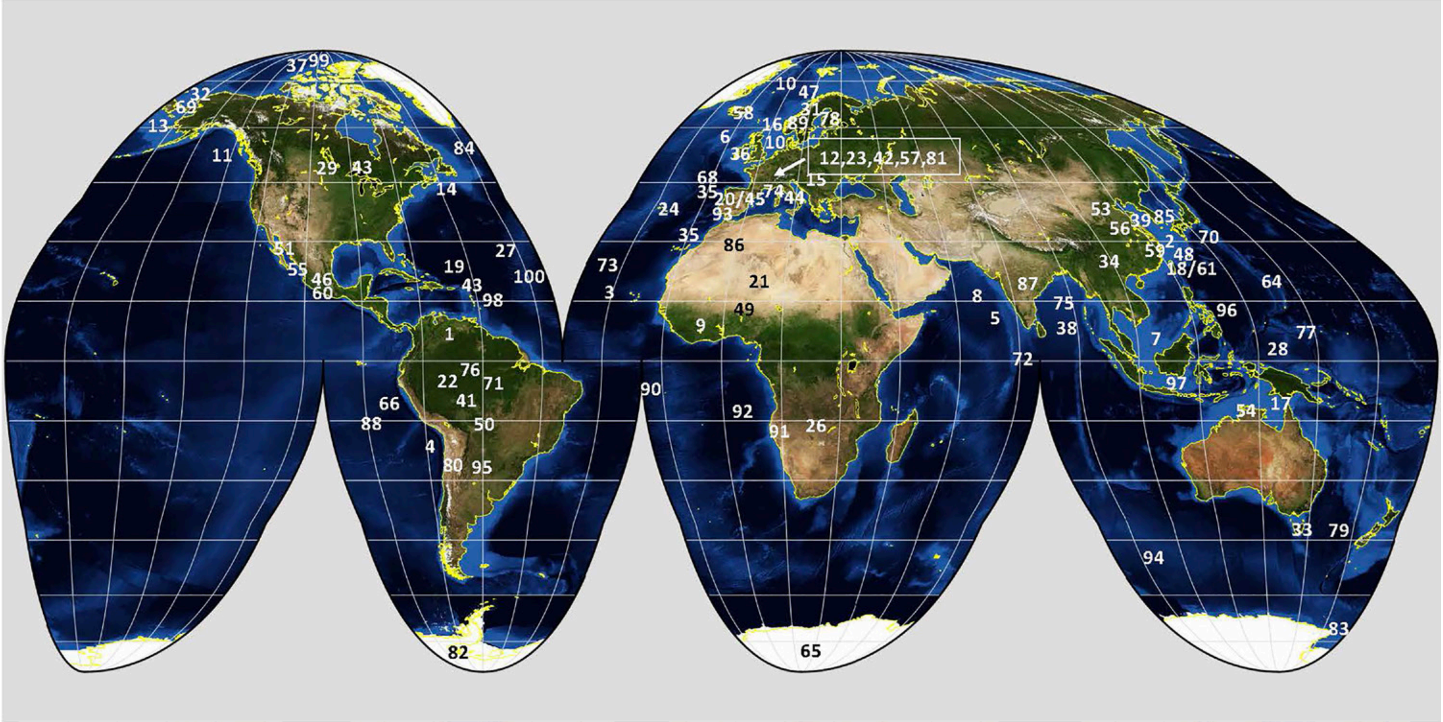

Fig. 1. Approximate locations of the international field campaigns listed in appendix A. Not included are those that covered an entire or several continents or ocean basins (WOCE/GO-SHIP-19, ITEX-30, ATLAS-40, POLARCAT-62, EUCAARI-LONGREX-63, HIPPO-67). Background map courtesy of NASA (www.giss.nasa.gov/tools/gprojector/help/projections/GoodeHomolosine-Interrupted.png).

It is acknowledged that the cutoff time of 1969 is arbitrary, and it is impossible to include all international field campaigns throughout history.

The rest of this article is arranged in the following way: Essential elements of international field campaigns are discussed first, which include observing platforms, complexity, planning, and execution. Special attention is paid to certain subjects, such as outreach and capacity building, hardship versus rewards, and postfield phase activities including data management and sharing. The evolution of field campaigns through the more recent decades is briefly summarized. Finally, a vision on field campaigns in the near future is given. Appendix B lists acronyms used in this article.

Essential elements

Some of the essential elements are common to all field campaigns; others are special for international deployments. The persons, groups, and organizations responsible for addressing issues related to these essential elements vary from project to project because of different requirements and structures of science enterprises in different countries. But these issues should be addressed collectively by the leaders of the science and facility teams and funding agencies.

Platforms. Many field campaigns take place at remote locations without easy access and any observing infrastructure. Instruments or sensors used in these field campaigns need to be mounted on a platform (e.g., aircraft, research vessel, transportable tower, land vehicle, balloon, uncrewed device). Facilities are complete systems (platform plus instrumentation) deployed in a field campaign. Ships and airplanes are the most commonly used mobile platforms, with rockets and long-duration balloons occasionally used as well (Wooldridge and Reiter 1970; McDermid et al. 1990). Ground mobile platforms, truck-mounted radars, for example, can observe rapidly moving atmospheric phenomena such as tornadoes (Biggerstaff et al. 2005; French et al. 2014). Fully instrumented transportable towers have also been deployed over land (Fernando et al. 2019) and the ocean (Simpson and Paulson 1979). The recent technology development of autonomous or uncrewed observing systems (UxSs) has provided a path to expand our observing capabilities for field campaigns and for sustained observations. There are many types of uncrewed aerial vehicles (UAVs), uncrewed surface vehicles (USVs), uncrewed underwater vehicles (UUVs), and other types of UxSs (e.g., Aeorclippers; Duvel et al. 2009). Each type of the uncrewed systems deserves overviews of their capabilities and applications (e.g., Lee et al. 2010; Whitt et al. 2020). In addition to these and other mobile platforms, stationary platforms on land and ice and in water as well as satellites remain as critical assets in many field campaigns.

Complexity. Field campaigns' complexity is in the length of their life cycle, the number of scientists, countries, disciplines, and platforms involved, strategies of facility deployment, and logistical support required. A field campaign can be as simple as deploying a single platform or sensor. The first measurement of Beijing's urban heat island was made by a scientist using a handheld thermometer sticking out of a window of a taxi running through the city from its suburbs on one side to another multiple times (Chang et al. 1982). Very large and extremely complex multidisciplinary, multiscale, international field campaigns during the International Geophysical Year (IGY) were conducted across the globe over 18 months in 1957–58. They involved some 68 nations and included research in 11 Earth science disciplines. Among the campaigns' major accomplishments was the establishment of three world data centers to house complete duplicates of data collected during IGY (Korsmo 2007). Another multiyear field observation program is the International Indian Ocean Expedition (IIOE) that consisted of 66 cruises conducted by six countries during 1961–64 (Snider 1961). The international field campaign related to atmospheric and oceanic sciences that employed the largest number of platforms and involved people from the largest number of countries was the GARP Atlantic Tropical Experiment (GATE-3) during June–September 1974. More than 5,000 scientists, technicians, and supporting staff from 72 countries of Africa, Asia, Europe, and North, Central, and South Americas participated in GATE-3. Observations were made by 13 airplanes, 39 ships, over 1,000 land surface stations, and six satellites (Kuettner 1974; Greenfield and Fein 1979). In the past few decades, large, complex field campaigns involving hundreds to thousands of scientists, many countries, a wide variety of observational platforms, and a duration of several months or longer (e.g., GATE-3, TOGA COARE-28, AMMA-49, DYNAMO-72, and MOSAiC-99) are few and far between. However, campaigns of this magnitude and complexity remain an important part of the scientific endeavor to address grand challenges in research on Earth's environment.

Field campaigns adapt a variety of observational strategies. All platforms may operate simultaneously within a given intensive observing period (IOP) over the entire field deployment period (e.g., GATE-3). From there, variations are unlimited. A field campaign can include more than one IOP, with breaks in between (TOGA COARE-28). The IOPs can be defined by a single event such as a severe convective storm, or several of them over a few days (FASTEX-36, AMMA-49, MAP-42). They can be at different times (seasons) of the year (INDOEX-38; HIPPO-67), or in different years (YMC-97). They may include repeating observations at the same locations year after year (DBO-69, SCALEX-81) or decade after decade (WOCE/GO-SHIP-19). In an extended observing period (EOP), a subset of the full suite of instruments operates for a longer period than an IOP, typically for weeks or months, up to a year (e.g., SHEBA-37, MOSAiC-99). Observing a complex phenomenon, such as the monsoons, may require field campaigns in different regions and in different seasons under a single international program (W-MONEX-7, S-MONEX-8, GAME-34). A successful field campaign (e.g., ACE1-33) can be followed by its sequels (ACE2-35 and ACE-Asia-48) at different locations. When multideployment field campaigns span a long time (DBO-69), the distinction between them and sustained observations may become blurred. Nevertheless, each focused deployment within the continuous long-term programs is a field campaign. It has become more common that sustained and operational observing networks are part of a field campaign (TWP-ICE-54).

In the field of ecosystems, it is common that individual field observations are conducted by local scientists while their data are collected and synthesized internationally to provide global perspectives (Cinner et al. 2016; Vanderbilt and Gaiser 2017). Such collaborative field campaigns, when repeating over years, can also be viewed as sustained observations. The individual campaigns have the challenge of acquiring resources for longer-term data collection. The international collaboration that combines the data from the individual field observations must assume the responsibility for long-term data stewardship.

A complex international field campaign includes a life cycle of several phases, which is summarized in Fig. 2 using activities supported by the U.S. NSF as an example. It shows that field campaigns include three general components defined as the *planning phase* prior to a deployment, the actual *field or execution phase* when focused in situ and other supporting observations are made, and finally the *postfield phase* for data quality control, management, and analysis/synthesis. Scientific discussions that lead to the inception of the idea for a field campaign can take many years. The diplomatic arrangements that may be needed for a large international campaign could extend the planning component up to years. The data analysis effort of large international campaigns may last several decades.

A field campaign commonly includes a numerical modeling component. Direct involvement of numerical modeling efforts from both research and operational institutes can occur during the planning stage to guide the design of a field campaign, during the execution stage to provide prediction and analysis specifically tailored to the need of field operations, and

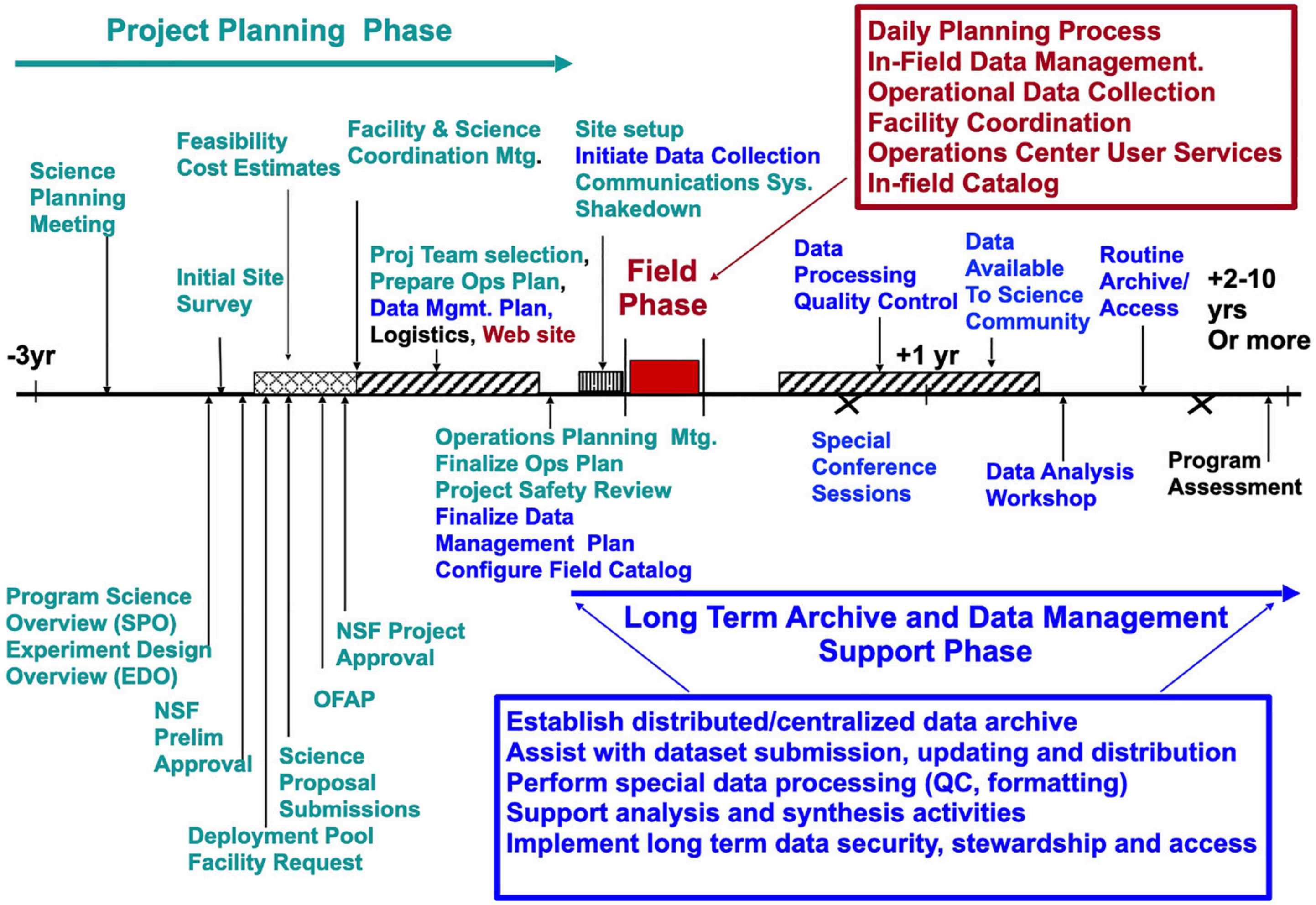

Fig. 2. An example of a life cycle timeline for a complex field campaign based on the U.S. NSF large campaign approval process. The timeline is in black across the middle of the figure from the left to right. The teal and blue areas before and after the field phase (in red) highlight key milestones and activities. The small "X" along the timeline represents special scientific conferences focused on campaign science results.

after a field campaign to help quantify results from the data analysis and hypothesis testing, and validate model output.

Planning phase. Most field campaigns are initiated by scientists who see the need for unique or improved (e.g., new instrumentation) observations to advance science. The inception of an idea from one or more scientists for a field campaign can take place in various ways including a drawing on a napkin, or recommendations from a workshop, conference, committee, or working group. Sometimes, an agency or international organization can initiate or encourage the science community to consider a field campaign.

SCIENCE AND IMPLEMENTATION PLANS. A group of scientific leaders would bring key science team members together to work on hypotheses and science objectives (described in the science plan), observing strategies, data management, and possible locations and assorted logistics (described in the implementation plan). The complexity of a field campaign comes naturally out of these plans. It is valuable to inform facility representatives in the early stage about the plans and seek their advice on the match of science goals with instrumentation measurement capabilities. These science and implementation plans are usually peer reviewed using established agency procedures. Once agency approval is given, these plans form the basis of specific campaign science proposals that request funding for the campaign. Both science and implementation plans at this stage must remain flexible. They may change depending on funding, facilities access, logistics, geopolitics, and other unforeseeable reasons. GATE-3 was originally planned by scientists to be over the tropical Pacific and was relocated to the Atlantic Ocean (Zhang et al. 2022).

Data management. Data management is critical to complex field campaigns and needs to be covered at all their three phases. It is essential that a campaign implementation plan includes a data management strategy, which can be developed by a data management committee as a part of the science team. Typically, a data management plan includes (i) the format and documentation of instrument data, (ii) the need and source of operational data (satellite, model, sounding, etc.), (iii) in-field data (both instrumental and operational) support for the field operation and scientific analysis, (iv) a policy for data release and sharing, and (v) postfield data archive and distribution, including an embargo period for instrument PIs to process their data before release them to the data archive centers. More discussions on data issues are given later in this article.

Funding support. The exact procedures for acquiring financial support of field campaigns depend on the agencies of each country. Funding is needed to support science teams for planning, execution, and analysis phases of the campaign and to support logistical groups (e.g., a project office) to handle deployment details. The cost for a large international field campaign can easily exceed any individual funding agency's annual operational budget (Avallone and Baeuerle 2017) and it must be covered collectively by multiple agencies from multiple countries. The science team is responsible to know the procedures of requesting funds, reach out to the agency program officers and facility managers, and coordinate proposals to different agencies early in the planning to get help in all aspects of the planning and funding process. Early engagement with funding agencies would allow them ample time to prepare and coordinate their budget arrangements as well as to conduct proposal reviews. Coordinated proposals must be complementary but not mutually dependent because it is possible that all proposals may not be funded. Nongovernment professional organizations and private companies/foundations have been alternative sources of support to field campaigns dated back to the nineteenth century (more commonly referred to as scientific expeditions then; Boothe 2011). In the modern days, they may provide resources to participate in an otherwise government sponsored field campaign (Rainville et al. 2019), charter and operate their platforms in a field campaign on behalf of scientists (Meinig et al. 2019), or underwrite their own field campaigns (Wurl et al. 2018).

Facility support. In some countries, funding requests for deploying observing facilities is separated from funding for the rest of the field campaign (travel, salaries, publications, etc.) and additional proposals for facilities are required. Planners should be aware of potential scheduling conflicts for observing facilities in high demand by multiple field campaigns. Coordinating multiple observing platforms from different hosting institutes in different countries are extremely difficult but possible (GATE-3, TOGA COARE-28). Without such coordination, each participating team may decide when and where to conduct their own IOPs over a span of several years (YMC-97).

Logistical support. Logistical issues for a large international field campaign can be daunting. The hosting institutes of observing facilities are usually responsible for the logistics related to their facilities. These groups should perform background studies, including site surveys if deemed necessary, to establish logistical, infrastructure (e.g., operations center, internet access) as well as safety and security considerations. The science team should be in close contact with the facility teams on the facility deployment. Planners should be aware of several issues common for international field campaigns and make sure these issues are properly addressed. For a complex international field campaign, a specific logistical support team, sometimes in the form of a project office, might be needed to cover project support issues. Some of these issues are discussed below.

Research permit. Field campaigns conducted in or near a country (on land, nearby waters, national controlled airspace) by the international community often require permits from that country, sometimes from local authorities, but mostly from its central government. This can be straightforward or extremely complicated, depending on the country's regulation on their air space and EEZs or a lack of it. Some countries require an MOU and IA to be established between government agencies or local and foreign scientific institutions before research permits are considered. Each of these takes time. The acquisition of research permits can be the responsibility of the science leaders, project office, or funding agencies but the approach must be agreed to early in the planning phase. It can take up to years for an international field campaign to go through the process of research permit applications. It has become more common that when considering an application for a research permit, a hosting country evaluates how a field campaign would benefit the local community, especially in terms of capacity building (discussed later). An additional complexity is obtaining permission for deployment of expendables from aircraft (e.g., rawinsondes, dropsondes) and ships (e.g., drifters, floats), especially when tax exemptions are needed. This may require additional approval from national air traffic and marine authorities. In some countries, military authorities are involved in this. Research permits for uncrewed systems can be different and many countries do not yet have policies and procedures in place for operating these systems.

Facility arrangements. They include 1) shipping, 2) customs, 3) storage, 4) installation of ground-based facilities, 5) locating seaports for upload and download equipment, supplies, and exchanges of science crew for multileg ship cruises, and 6) locating airports for airborne missions. For ground-based observations, selecting and preparing local deployment sites are essential. Electricity, water, sanitation, communication for data transfer, maintenance of facilities (e.g., secured warehouse), and prevention of instrument vandalism must be guaranteed.

Local coordination. A wide variety of local government entities, resident representatives, or tribal councils may need to be contacted and brought into the planning process to help assure smooth operations. An agreement may be as simple as a face-to-face acknowledgment with handshakes and head nods, or a complicated MOU, IA, and contracts. Support may include access to sensitive land and coastal waters, contract to build a new road or building, provision of utilities (power, water, food) and security guards.

Health, safety, and other logistical considerations. A field campaign conducted on foreign soil requires many personnel support details. The highest priority is human health. The most basic medical consideration is access to health care and coverage of medical expenses. In regions with infectious diseases, precautions of vaccines and preventive medicines need to be provided. The TOGA COARE-28 campaign took place in a tropical region infected by malaria. A physician was hired to be on site throughout the duration of the field deployment, and malaria prevention drugs were made available to participants. More recently, the global COVID-19 pandemic created unprecedented challenges to field campaigns as well as the entire science enterprise. Many field campaigns were delayed or canceled. A field campaign in a pandemic would have to carry extra logistical and financial burden to arrange for testing and quarantines before, during, and after as participants go to the field and come back home (MOSAiC-99). Field campaigns can be affected by natural hazardous events. An evacuation plan for campaign participants should be in place. During some field campaigns personnel and facilities needed to shelter or relocate in the face of tropical cyclones.

In addition to the health issues, all organizers of international field campaigns must be alert to regional or international conflict and terrorism activities in and near the field campaign domain. A field campaign involving ships over the equatorial central Indian Ocean took place when piracy was expanding eastward from the Somalian coast. A contingency plan was made in case the piracy activities were too close to the field campaign location, and the ships transporting campaign equipment had to move in a convoy through the region of piracy. A part of the ground observations of this field campaign were in a country where an unexpected change of hands in its government prompted riots in the community where the science team was located. This ground observing component of the field campaign was stopped two months early and all participants were evacuated immediately. Timely communication and swift decisions are the key to handle such an unusual, unanticipated situation.

Many field campaigns are conducted in remote locations where lodging can be a challenge and transportation to/from observing sites must be in place to permit equipment operations and maintenance as needed. This means power, fuel, and water (as needed) supplies, communication (telephone, internet), and sanitary service may have to be specially arranged. Even when all arrangements are made, surprises can come. During a field campaign, without warning when reservations were made, its field team members were evicted from the only hotel on an island to make room for foreign delegates coming to the island for an international conference.

Field campaigns can be affected by the global economy. For example, drastic changes in oil price may alter the duration of ship cruises and aircraft operations within a fixed budget. In 2019 and 2022, the global shortage of helium threatened field campaigns that used helium filled upper-air radiosonde balloons. These and other past experiences suggest that all reasonable precautions should be taken during the planning stage for safety and smooth operation, but the unexpected may still happen. A field campaign must be nimble to quickly react to all kinds of situations with improvision and creativity.

Dry run. The more complex a field campaign becomes the more the science and facility deployment teams may want to consider a “dry run” to test procedures before the planned full field phase. A dry run is an actual exercise of planning procedures, timing of the decision-making process and simulated deployment of facilities. A dry run can be conducted in the same season but a year ahead of the actual deployment to allow for realistic forecasting and identification of the phenomena of interest. Conducting a dry run benefits complex projects with improved practice of deployment and communication strategies, forecast delivery, and the identification of gaps in the logistics support strategy (CPEX-AW-100).

Field operations plan. For a complex field campaign, a field operations plan (Ops plan) is needed to (i) ensure that all platforms and participants work to a common goal and are aware of each other’s detailed plans, (ii) push all participants to finalize their plans according to a set timetable, and (iii) document the deployment objectives and procedures to be understood by all who will be involved (e.g., local agencies, air traffic control, collaborating scientists). An Ops plan should also define IOPs within the field phase, daily decision-making procedures, details on observing system performance and observation priorities, observing strategies and operations coordination, weather forecasting and modeling support, an overview of the data management approach, details of other support (e.g., code of conduct), and outreach activities. An Ops plan should also specify the percentage of key resources (e.g., flight hours and expendables, deck operations on a ship) to be allocated to each science objective or hypothesis. This allocation should be recorded as observations are made for each objective or hypothesis to maintain the integrity of the science objectives and to fairly share resources among participants.

An Ops plan is typically updated after a dry run as its outcomes and lessons learned will be integrated into the plan. An Ops plan is really the "best estimate" by the science and facilities teams as to how operations should proceed during the field phase. Portions of the document can become obsolete soon after the operations begin. Some typical unanticipated disruptive events include uncooperative environmental conditions (weather, sea state, etc.), air traffic clearances, facility maintenance issues, and provisions access. Therefore, the execution of an Ops plan can and will be modified as the field phase moves on and the participants gain knowledge for desirable practices.

Execution phase. The execution should follow the Ops plan most of the time but with exceptions. The following is a set of steps that are common during the execution phase:

Web services. A project specific website (e.g., ATOMIC-98, https://psl.noaa.gov/atomic/) needs to be activated so anyone can learn about the project. A dedicated field catalog (e.g., http://catalog.eol.ucar.edu/socrates for SOCRATES-94) can be established for access to data coming from a field campaign in near–real time, including operational and quick-look research facility data plots, flight and cruise tracks, mobile asset locations, forecast, nowcasts, facility status updates, operational plans, and mission summaries.

Deployment of facilities. The deployment includes shipping facilities and equipment, setting up ground-based instruments, uploading instruments (i.e., mounting and testing them) on ships or airplanes, and releasing uncrewed devices.

Setup of operation centers. Complex field campaigns require operation centers. Their primary function is to provide a place for scientists, engineers, technicians, and project managers to meet, discuss, make decisions, and communicate with personnel at different locations and platforms (airplanes, ships). Forecast briefings given either locally or remotely can be a key component of operations center activities. A computer laboratory can be set up where environmental information is received (through the internet or other satellite communications) and displayed. This computer laboratory can also be used by scientists to perform preliminary analysis of field observations. Sometimes, a building has to be built to house the operations center where there is no other option. For major international field campaigns that deploy multiple platforms covering a large geographic domain, more than one operation center may be needed (TOGA COARE-28, MAP-42).

Communications. Complex field campaigns require the implementation of communications hardware and procedures. In the modern era of satellites and wide bandwidth internet, it is now easier to link to multiple operations centers (TOGA COARE-28) and remote facilities than ever before. As an example, Fig. 3 shows a schematic of the communications for coordinating operations over thousands of kilometers across the Pacific Ocean during T-PARC-64. In this scenario, operations of five airplanes and several ships were synchronized across 11 time zones using dedicated voice and chat software to keep facility personnel (pilots, engineers, technicians), flight scientists, and the operations center fully integrated. In one case, deployment of airborne assets from different countries followed and sampled a super typhoon from its development stage (near the Philippines) through maturity (near Taiwan and the southern islands of Japan) and into an extratropical transition phase (east of Japan).

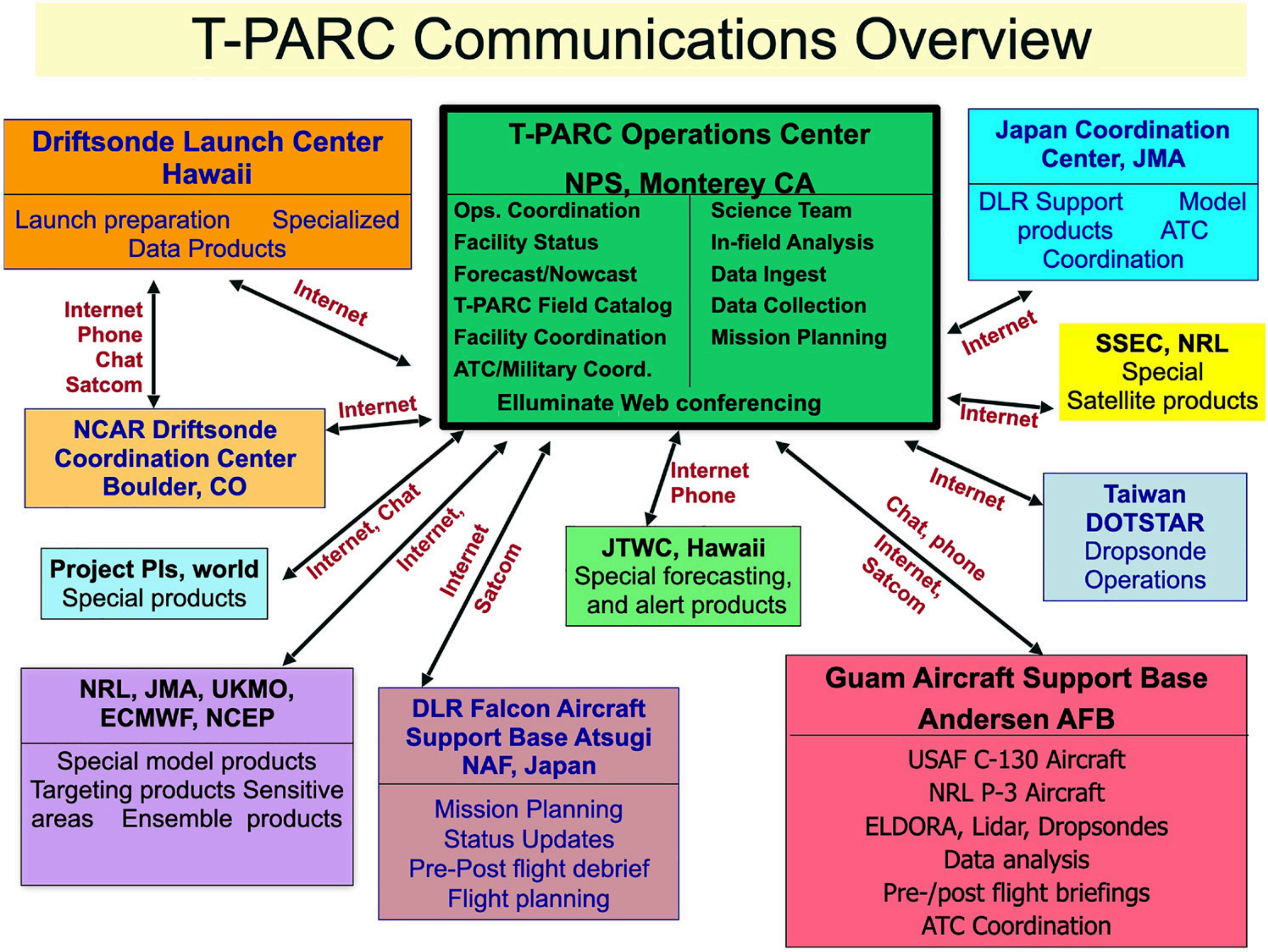

Fig. 3. Communications layout and tools for T-PARC-64. Each box is a different key location or data source that is required to be in contact with the main operations center (dark green). The double headed black arrows show the main communication mechanism connecting the project components.

These aircraft measurements were made during 11 individual missions over a 13-day period (Fig. 4). This kind of finely orchestrated international flight operation is only possible with advanced communication (Fig. 3).

Daily and science meetings. The timing of a daily planning meeting (DPM) depends on campaign specific issues such as the facility deployment targeting phenomena of interest (e.g., nocturnal convection). Keeping the DPM at the same time each day, if possible, would help assure full participation from field sites several time zones away. For aircraft operations, the DPM should include aircrew rest schedules, status of aircraft and instruments, proposed flight plans, remaining flight hours, science objectives already and remaining to be accomplished, and environmental conditions. Such information is briefed by different groups of the field teams, primarily for the PIs to make decisions and facility crew to deal with rapidly changing conditions. A DPM can also cover possible priorities, goals for the upcoming IOPs, and the best use of facilities to accomplish those goals. In more complex campaigns, PIs may conduct separated daily science meetings to focus on scientific issues and make decisions to guide discussions at the DPM. Daily meetings are also common for ship operations, especially those including multiple PIs with instruments that require different operation schedules and deck arrangement.

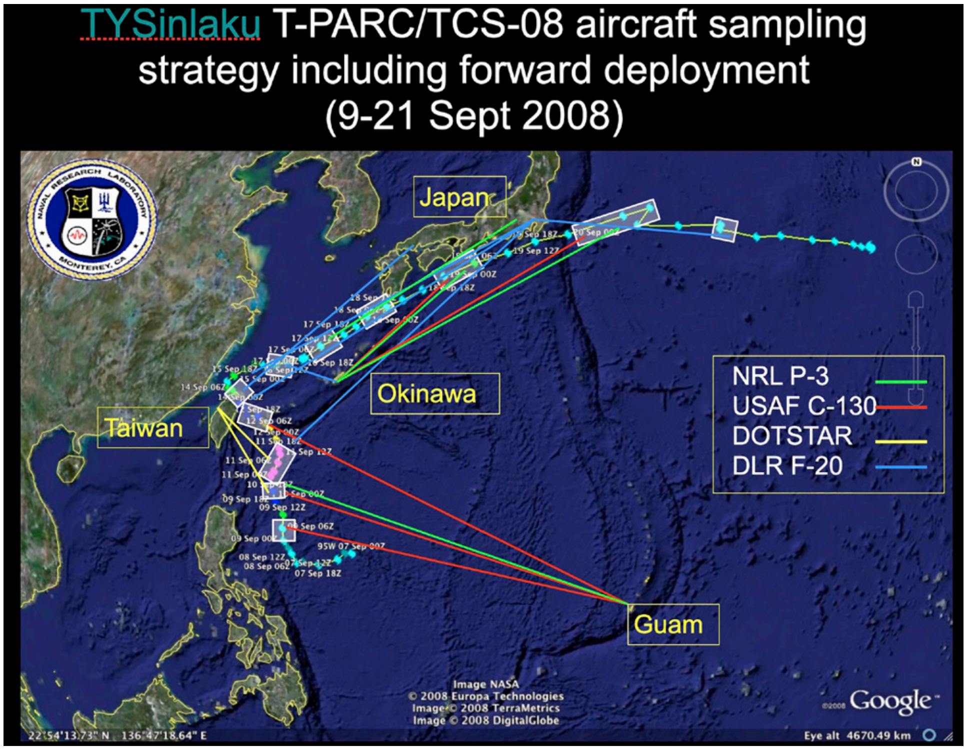

Fig. 4. Aircraft sampling strategy for Supertyphoon Sinlaku during T-PARC-64. Missions were from Guam (United States), Okinawa and Honshu (Japan), and Taiwan. Sustained operational planning and real-time coordination was maintained from an operations center in Monterey, California. Flight tracks of 11 missions over 13 days for four aircraft are highlighted with colored lines. Focused aircraft observations are within the 11 shaded boxes. Typhoon track (gray line) and position (green dot) shown from 1800 UTC 7 Sep every 6 h. (Figure courtesy of Pat Harr and NRL.)

It is always a good idea to include as much science discussion as possible throughout a field campaign (CONTRAST-77, SOCRATES-94). While most field campaigns are very intense and time consuming, scientists always find time to have deep discussions and exchanges of ideas with project participants. Field science meetings or seminars allow them to do so in an organized way. These meetings can provide a broad perspective of a multidisciplinary campaign and let different groups appreciate each other's work. Unexpected findings are the best gifts from field campaigns and can influence observing strategies. Discussions right after new discoveries can be the best moment of a field campaign. Field science meetings also provide opportunities for modelers and theoreticians to interact with instrument specialists to gain each other's perspective on freshly acquired observations. Seminars can be extremely beneficial to students and early career professionals, for example, as occurred during RELAMPAGO-95 (Rasmussen et al. 2021).

Campaign science assessment. For a long field campaign (from months to a year) with multiple science objectives and a variety of facilities, it is a good idea to have midterm or periodic assessments. Issues to be covered include used/remaining resources (e.g., aircraft flight hours, airborne dropsondes, radiosondes), accomplished and unaccomplished objectives, unanticipated issues (e.g., facility malfunction or total failures), major personnel issues (e.g., sickness), anomalies in environmental conditions, and possible adjustment of the observation strategy if needed.

Public and scientific outreach. This has become an important integrated part of many field campaigns, and must be a critical component for international field campaigns of the future. A detailed discussion on outreach activities is provided later in this article.

Local customs and religious practices. Deployment must be carefully selected to stay away from indigenous sacred sites or other historical locations. It is vital that participants understand and obey local laws. The process of explaining, paying for, and even adjudicating a traffic accident in a foreign land can be a minefield of paperwork and legal issues. In some countries it is a good idea to hire cars and drivers for local transportation. Local cultural norms, such as dress codes, religious beliefs, and gender and sexual orientation behaviors must be handled with care. Local religious practices (e.g., daily prayer, weekly services, special events and holidays) may delay field activities, and must be taken into account when designing and implementing field campaign deployment, including day-to-day activities, especially when using local support. Understanding and respecting local customs and culture will go a long way to assure a field campaign is welcomed in a foreign host country.

Postfield phase.

Campaign closing-out. Once an international field campaign is completed, instruments may need to be repacked or unloaded from a ship, and shipped home. Special contracts with local business and governments for supplies and land/building use need to be concluded with all bills paid. For ground-based instruments, their sites are usually prepared before a field campaign to meet special requirements (e.g., leveling the ground; setting up fences, power and internet lines, and sanitation; building roads). Returning sites to their original condition is critical to minimize any adverse environmental impacts. An additional important final step is for the field campaign organizers and managers to make special visits to local community and government leaders or write letters of thanks to express gratitude for their support. It may be possible to establish long-term relationships that include continuing outreach and capacity building (discussed more later). There have been several instances where an initial established good relationship with a nation and community (e.g., INDOEX-38 in 1999 in the Maldives) allowed for a subsequent field campaign to be conducted with excellent local support and minimal government approval delays (DYNAMO-72 in 2011).

Data archive and sharing. Data archive can start during the execution phase. Ideally, archived field observations should include both quality controlled (QC'ed) and un-QC'ed data with supporting documentation of specific data information (metadata). Operational data collected during the campaign should be made available to the broad community as well. It has become a more common practice that field observations are archived in centralized repositories. There are several modern examples of data centers that handle all types of data from field campaigns and complementary operational sources (e.g., World Data Center System[2]). The resources needed to support data centers must be provided to assure long-term access to field data into the future. It is also important to provide duplicated data repositories to avoid a single point of failure.

It is an art to design and build a user-friendly interface for a data repository. Sufficient data documentation, standard formats, and easy search and download with a broad range of users in mind are among the most basic features of a good user interface. Users who did not participate in field campaigns and are not experts on observing instruments can easily get lost in a data repository with a huge amount of field observations without a well-considered standard in data format, metadata, documentations, and easy-to-use data search. This is one of the reasons that many field observations have not been fully used by the modeling community. A search engine that facilitates applications (e.g., visualization) of field observations by a broad user community should allow one to choose their data in terms of variables, instruments, platforms, time, and location supplemented with detailed information of the field campaign design and operation. One example is the DYNAMO-72 Legacy Data Product

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[2] https://community.wmo.int/meetings/world-data-centres

(https://orca.atmos.washington.edu/dynamo_legacy/). There is also a need for open access to software for data quality control, processing, analysis, and visualization. This would increase the transparency and reproducibility of scientific procedures, products, and results.

Submitting data to GTS in real time is one of the best ways of sharing field observations. Initial conditions including observations in both atmosphere and ocean are needed for predictions by ocean–atmosphere couple models with a lead time beyond two weeks. It takes special arrangements to access the GTS "gateway" (relay through local meteorological services to regional meteorological centers or specific government institutes). Parker et al. (2008) describes the steps that successfully led to the data transfer in AMMA-49.

How field observations should be released for public use has always been a subject of debate. The WMO has spoken directly to the principle of free and open access to meteorological, oceanic, and hydrological data and products around the globe as spelled out in WMO Resolutions 25 and 40. These principles apply, in many cases, to field campaigns. Some field observations were never released for public use, which is a shame. The more field observations are used the greater their value. But there are critical considerations for the timing of release. Field scientists need time to complete quality control of their data, analyze them, and publish their research resulting from their field observations. Graduate students who participate in field campaigns need time to finish their theses and dissertations using the field data in order to graduate. This can be jeopardized by quicker publications of similar results by others. Ideally, all field observations should be released immediately after the completion of a field campaign that is supported by taxpayers. This is the case for field observations made by the DOE ARM facilities. Some sponsoring agencies have procedures allowing for the delayed release of data to the broader community. Releasing data with digital object identifiers (DOIs), publishing dataset documentation articles, and including data PIs as coauthors of journal articles are among ways to accelerate the availability of field data to broad user communities.

Archives were established to house campaign data and documentation with the best of intentions to maintain the data and their access in perpetuity. The unfortunate reality is that in many cases archives disappeared after several years due to personnel and organizational changes, or a lack of funding and software/hardware upgrades. This is an ongoing issue that must be addressed.

Outreach and capacity building. Our planet's atmosphere and oceans know no political boundaries and their properties are connected globally. Environmental observations from a field campaign that advance science should benefit humanity at large. Because of this, many scientists think they have the right to collect environmental data anywhere they want, and they resent any roadblock to hinder their attempt to do so. In some countries, however, environmental information, including data of the atmosphere, ocean, and land, are considered their national resources, are not free for the taking, and can be subject to very restricted access by foreigners. This can lead to difficulties in conducting international field campaigns in these countries. The challenges of getting the research permit can be overcome through active engagement with national and local governments as well as research and general communities (it can take years to build mutual trust), and through promotion of sharing resources, data, analysis, and scientific advancement gained from international field campaigns to benefit participants and local populations as well.

In the past, many field campaigns were conducted in foreign countries without participation from local communities and without indication of any benefit to the local population. The foreign science teams came and went with their equipment and were never heard from again by the local people hosting the campaigns. This practice of coming, getting, and leaving has been viewed in some countries as science imperialism or colonialism. The chair of the Marine Scientific Committee of a Pacific island country said about 20 years ago, "I am sick and tired of western scientists coming to my country to making measurements that advance their careers, but all we get out of it is a copy of an article from an international journal that not a single person in this country can read. If you want to work here you have to do better than that." Science imperialism exists not only in how field campaigns are conducted, but also in how they are reported by the science team and media. All who plan and conduct international field campaigns should honestly ask how much this science imperialism still remains in the research community and within each of its individuals.

Meanwhile, engagement with the local population (outreach) as well as local scientists, engineers, and technicians (capacity building) has been an element of many field campaigns. The purpose of the outreach activities (e.g., open houses, school visits) is to express the appreciation for the tolerance and welcome by the local communities, inform the local communities of the science being explored and the tools used for observations, learn indigenous knowledge, solidify local interest and support, open the door for following up interactions that benefit all involved, and to the degree possible, inspire younger generations to be interested in science. During recent field campaigns, more than 300 visitors attended well-publicized open houses (DEEPWAVE-79, SOCRATES-94). Science fairs let children have hands-on experience. School visits by the field team provide detailed explanations or lectures on science (Fig. 5). Social media can reach younger generations, but the global digital inequity can hinder its broad use. Outreach has been such an important part of field campaigns that designated personnel have joined field campaigns to coordinate this effort full time as an integral part of the deployment (DYNAMO-72). Some field campaigns have received funding from their sponsoring agencies to return to the indigenous people to share results from their observations and, as importantly, to learn from the native populations in order to put the campaign observations in context with generations of knowledge passed down through the local indigenous groups (DBO-69). This type of outreach has been well received by both scientists and the local residents. When languages form a barrier to communication, participation from local institutes become critical.

Capacity building also takes on different forms. One common practice is to entrain early career scientists, engineers, and technicians from the host countries to join science teams even if there is no PI from the host countries. Another common practice is to provide scientific lectures at local universities, civic groups, and government agencies to discuss the science being studied in the field campaigns. Meetings with local scientists and residents to learn from their experience, and to exchange common interests are mutually beneficial. Another very positive activity during field campaigns is to engage local operational weather forecasters in forecasting and decision-making for the campaigns, e.g., air and ground facility operations, and two-way knowledge exchange between scientists and local forecasters (RICO-52, EUREC^{4}A-98). In the case of AMMA-49, this resulted in a forecaster's handbook (Parker and Diop-Kane 2017). Establishing field data archives in the host country can help promote local research. Recruiting graduate

Fig. 5. Alison Rockwell, the NCAR/EOL outreach officer, discusses science with students from a local women's academy at Addu Atoll, Maldives, during the field campaign of DYNAMO-72. (Photo courtesy of NCAR/EOL.)

students and postdoctoral associates, and hosting visitors at home institutes of the field campaign organizers are effective ways to help train local scientists. Capacity building can extend beyond scientific research. An excellent sample is AMMA2050[3] that addressed the challenges of integrating the scientific knowledge into planning and management structures to support climate-compatible development in the region many years after the field campaign of AMMA-49, the largest international multidisciplinary research effort ever undertaken in several African countries.

Hardship and reward

Field campaigns affect participants in different ways. Various forms of hardship on people are unavoidable during field campaigns: extended time away from families, dietary discomfort, health issues, extreme environmental conditions, long stretches of work without breaks, communication barriers because of differences in cultures and languages, and others. In a field campaign that took place in a region where rampant malaria had capped the life expectancy of the local male population to under 40, participants had to take malaria pills and suffer through their side effects. In a field campaign, the hotel where the science team stayed turned on water for guest use for only one hour every two days because of a regional drought. For the most part these kinds of hardships can be addressed by selecting more resilient staff and implementing reasonable individual deployment rotations. It is the science and facility teams' responsibility to be proactive in informing potential participants about known conditions of a planned campaign. The reports and personal experiences from site survey trips to the campaign locations is one important way to get the flow of information started. Individuals need to assess for themselves their comfort and tolerance level in participating in a campaign and make their concerns known early in the planning process.

A field campaign is a temporary workplace. Problems experienced at home institutes can also occur in field campaigns. In-field discussions on what should be done can lead to heated arguments. While most of the time, such arguments are genuinely based on science, with a hierarchy of seniority in the team (lead and senior PIs, junior PIs, postdoctoral associates, students), power struggles are inevitable. Sometimes arguments can be influenced by one's unconscious or conscious bias. Unacceptable behaviors occur more often when people become less attentive after working too many hours/days without a break. Despite the inclination to work at all times during a long campaign, a down day can really help calm hurt feelings, revitalize support staff, and lead to better results. Most well-organized facilities that demand a high level of support and safe operations at all times during operations (aircraft, ships, radars, etc.) manage their deployment schedule using crew duty day rules (e.g., only so many working hours per day), mandatory down days during deployment, and limits on staff time in the field.

People have various creative ways to deal with workplace hardships. A regular workout is a common way to reduce stress during a field campaign just as at home. Another way is to celebrate holidays as one would at home. During an international field campaign, people enjoyed their Halloween costumes when working in front of computers. Explorations of local cuisines and culture often bring joy and excitement. A well-known scientist drew cartoons to log memorable events during field campaigns. One of them for TOGA COARE-28 is shown in Fig. 6. Other field campaigns (e.g., T-PARC-64) have logged memorable phrases spoken by scientists, support staff, and managers.

Terrible incidents occur during field campaigns. A shark attack ended with a loss of a leg of a swimmer off a research ship, which also psychologically affected many people on the cruise. During a field campaign, one of the four engines on a research airplane failed and a second one on the same side of the airplane was damaged after the airplane went through 5.3 g-force up and 3.5 g-force down when it penetrated a hurricane eyewall (Masters 1999).

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[3] www.amma2050.org/Home

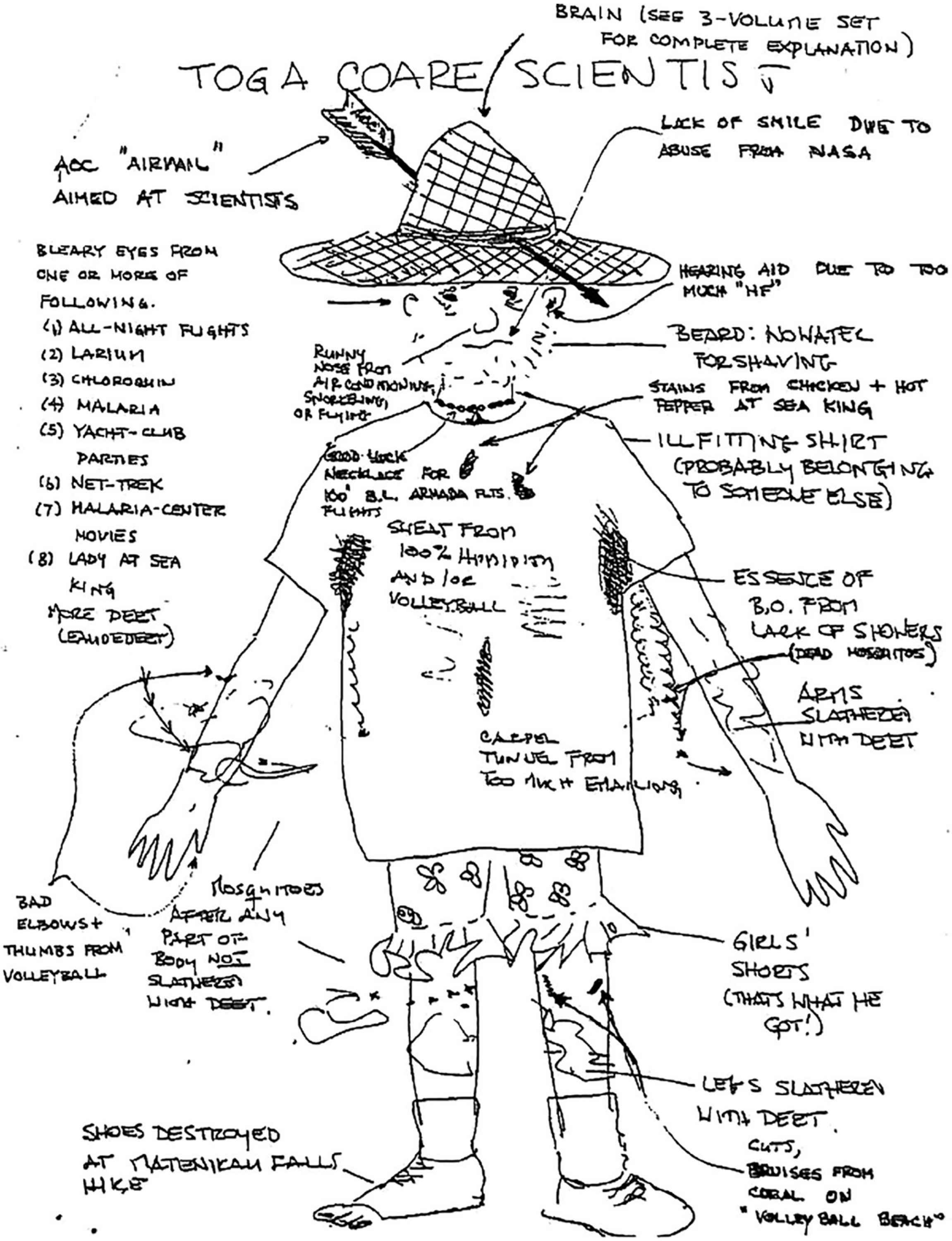

Fig. 6. A portrait of a scientist during the field campaign of TOGA COARE-28 in Honiara, Solomon Islands, by Margaret "Peggy" LeMone. Courtesy of Margaret "Peggy" LeMone.

Fatal incidents with lives lost due to small research airplanes crashes or personal accidents have occurred. These extremely rare incidents have made some people change jobs. Others, however, continued their love for and participation in field campaigns.

Verbal, physical, and sexual harassment and assaults can happen during international field campaigns. It is extremely important to eliminate them by establishing a code of conduct, implementing training of bystander intervention and nonthreatening reporting process, supporting junior colleagues, and collecting information on harassment and continuing participant engagement after each field campaign (Fischer et al. 2021).

The hardship and potential danger notwithstanding, international field campaigns can be very rewarding personally and professionally. You have chances to learn the local history, politics, geography, and culture, including languages. You meet new people and make new friends, and they can be collaborators of your future work. These new relationships can last a lifetime. You can experience local cuisines and make decisions whether you are one of those who have the palate for local delicacies (e.g., insects, larvae-infused cheese, live octopus). You can experience awe of nature around the world, which can be breathtaking and unforgettable. Professionally, there is so much you can learn from others during the campaigns. You can contribute to outreach and capacity building. Many modelers who participated in field campaigns had their eyes open to scientific adventures they had never experienced before. Field campaigns provide opportunities for early-career professionals to take on new responsibilities, to learn and polish their organizing and communicating skills, and to recalibrate their passion for their careers. The first field campaign one of the authors participated in soon after his graduate study completely turned him from a trained theoretician to an observation enthusiast.

Field campaigns can be punishing, disappointing, addictive, hilarious, and exciting all at the same time. Memories from field campaigns stay with you for the rest of your life. Trust that the authors are making that statement with laughter and nightmares still both possible.

Evolution

Over the past decades, field campaigns practices have evolved in many ways. If there is a single unchanged recipe for the success of international field campaigns, it would be patience, perseverance, and teamwork to build mutual trust between campaign teams and local communities, in addition to careful planning and execution based on a combination of novel scientific ideas, advanced observing technologies, and solid logistics support. But make no mistake, the success of many complex international field campaigns is achieved through 50% planning and 50% luck from nature's cooperation.

The technological development and breakthrough in the area of communication (data, voice, image, and textual transmission as well as novel hardware and software tools) have changed field campaign planning and execution. In the 1970s, people in the field could only communicate by international mail delivery, telex, and sometimes HF radios (VIMHEX-1, AMTEX-2, and GATE-3). By the 1990s low-bandwidth satellite communication allowed text, voice, and some data sharing at remote locations. Now in the 2020s, large volume data exchange is possible because of wide-bandwidth technologies. Sadly, even today, such modern communications are not equally available globally.

Before the era of desktop computers, scientific questions and hypotheses were mostly built upon theoretical (mathematical) calculations, laboratory experiments, and field observations. One major advantage of today's field campaigns over those of the past is the availability of massive data produced by synthesizing existing observations through data assimilation using numerical Earth system models, known as global reanalyses. Reanalysis products can provide background knowledge at the location of a planned field campaign, even if observational input to the reanalysis is sparse or nonexistent there. Satellite observations and ground-based observing networks accumulated over years serve the same purpose. Numerical simulations provide possibilities that may or may not happen in the real world. All these data form the information base on which a modern field campaign can be planned, and its scientific questions and hypotheses are formulated in ways not possible in the past.

Obviously, new instruments and new platforms can now make observations that were impossible in the past. One revolution in field observations is the use of robotic, autonomous, or uncrewed mobile devices, which has become more common in modern field campaigns.

Another major difference between current and past field campaigns is data sharing. The science community has been more aware of the importance of real-time data release to support environmental predictions. Modern technologies of data transmission, especially through satellite, and data storage make real-time data release from field campaigns more feasible. Many professional organizations and government agencies have paid more attention to data sharing through their data policies. Reputable scientific journals have established data release policies for publications. All of these have led to more real-time data release from field campaigns and shorter embargo periods of postfield data release than in the past. The role of professional data managers in the success of field campaigns, first recognized in the large deployments of the 1970s (WAMEX-9), is even more important today.

There have been signs of shifting patterns of journal publications related to major international field campaigns. As examples, Fig. 7 shows yearly publications related to four large international field campaigns over a period of nearly three decades (27 years) starting from the year after the conclusion of their field deployment. Publications continue to emerge decades after the completion of the field campaigns (GATE-3, TOGA COARE-28). Such a long legacy of field observations requires long-term commitment to campaign data archival. The number of publications appear to rise more rapidly for the recent field campaigns (AMMA-49; DYNAMO-72) than the earlier ones (GATE-3, TOGA COARE-28), and their peaks of publications seem to be shortened from 6–7 years after the end of the field deployment (LeMone 1983) to 3–4 years. These can be related to increasing data sharing and technological advancement for data archive, dissemination, and processing; faster manuscript preparation (word processing) and publication (online submissions, review, and release); more field campaigns following each other, and requirement for more publications for promotion and grant renewal. It would be interesting to see whether these shifts hold for more recent field campaigns (EUREC^{4}A/ATOMIC-98, MOSAiC-99).

Outreach activities during field campaigns were extremely rare, if ever present, 40 years ago. Now they are common practice. More science teams have planned for outreach, by preparing materials and activities in advance, to bring the campaign closer to the local communities and carry out innovative interactive programs during their deployments. Many communities have started to experience local impacts of global climate change. This makes outreach more effective when local experience is connected to the science of the field campaign conducted in their homeland.

Private entities have always been involved with scientific field observations or expeditions in the past. In addition to manufacturing instruments and other equipment, private companies have recently established partnerships with government and academic institutes to support

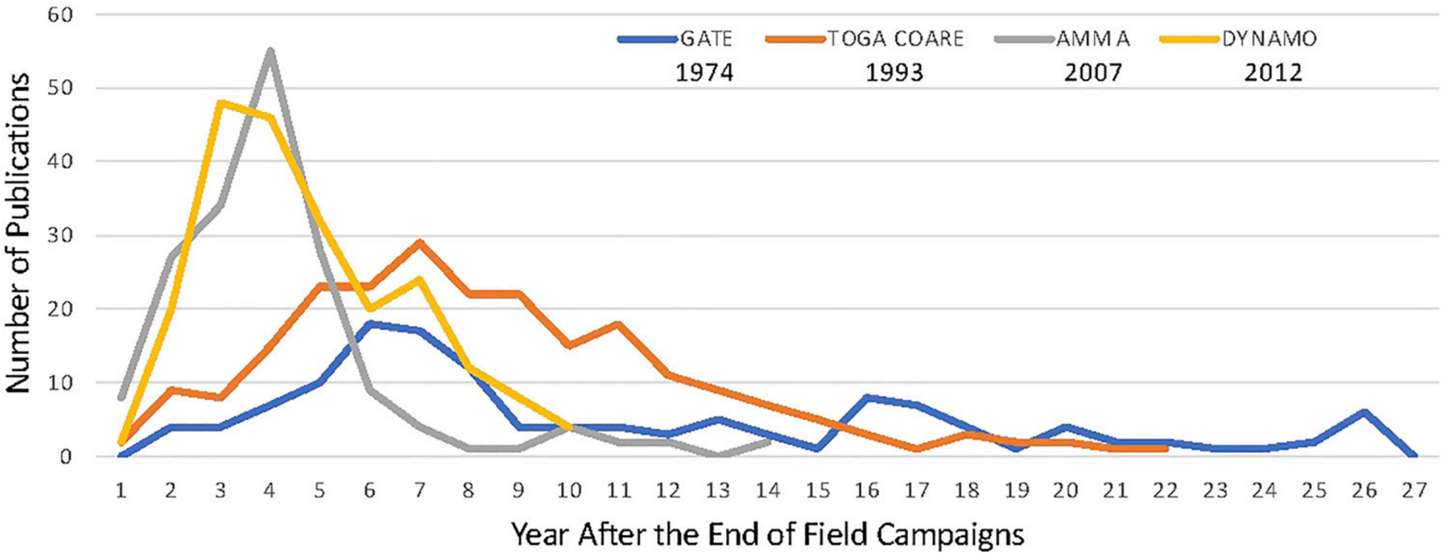

Fig. 7. Examples of yearly publications after the field deployment phase conclusion of four large international field campaigns. The years of their field phase conclusions are given in the legend. Data are from EOL Field Projects Database project publication lists (www.eol.ucar.edu/all-field-projects-and-deployments) and Google Scholar (https://scholar.google.com).

and operate field campaigns (Meinig et al. 2019). Such private–public partnership has already led to scientific achievement (Mordy et al. 2017; Zhang et al. 2019; Kuhn et al. 2020; Chiodi et al. 2021; Sutton et al. 2021; Zhang et al. 2022) that otherwise would be impossible or very difficult to make based on the conventional model of field campaigns sponsored by the government alone.

Society in general and certainly the science community are becoming more aware and intolerant of physical and verbal harassment. As the science community becomes more diverse and inclusive, so do the participants in field campaigns. This requires a nurturing and respectful environment, regardless of individual background or personal preferences. Only in recent field campaigns were these issues directly addressed and strategies/procedures offered to encourage respect and inclusiveness for all participants and to prevent and manage unacceptable behaviors (Fischer et al. 2021).

Future

The unanticipated pace with which communication technologies, uncrewed systems, and artificial intelligence have been developed and applied has taught us a lesson that future field campaigns will be as exciting scientifically as they are unpredictable technologically. Extrapolating from the recent progress, it might be safe to say that international field campaigns in the near future will deploy more robotic, uncrewed, and autonomous platforms, involve more applications of artificial intelligence and machine learning, cover more disciplines, include more sophisticated satellite data and high-resolution Earth system model output, engage in more public–private partnership and citizen science, including crowd-sourcing, share data more broadly with less data release latency, include more outreach and capacity building activities, and embrace more diversity, equity, and inclusion in participations. Expendable devices (e.g., balloon radiosondes, airborne dropsondes and ocean expendables, UxSs, floats, and drifters) will have to be made with materials that have low environmental impact. Other environmental footprints and potential impacts (e.g., consumptions of energy and water, pollution, land use, waste) of future field campaigns will need to be considered during their planning.

A challenge that the community continues to face is ensuring the long-term stewardship of the data from international field campaigns. Figure 7 shows that the data analysis of major international field campaigns may last over several decades. Field campaign participants and the larger science community may return to the field data long after the campaigns are completed as new science questions arise that can benefit from the rich legacy of these major international efforts. It is important that every effort is made by the science team and resource agencies to find and secure mechanisms and space in archives (e.g., WMO WDC, NOAA NCEI) that are focused on long-term stewardship of field data by helping guarantee their lasting and broad access (e.g., search and download). The sciences of big data, cloud technologies, and artificial intelligence allow combinations of data from many sources, including field campaigns, to be integrated and more effectively analyzed. Conversely, the fast advancement of technology can also lead to unintended consequences. One example is the constant emergence of new data storing and sharing methods that may require frequent migrations of huge amounts of data from outdated archiving and sharing protocols.

New technologies will continue to influence how we plan and conduct campaigns. They include new communications and information exchanges via high-speed Wi-Fi networks, instantaneous language translation, wearable technologies, holographic video conferencing, and finally, advanced data exchange and archive capabilities for searching, mining, downloading, and visualizing petabytes of information at high speed. Now only on the ragged edge of communications technology, work is apparently well underway to develop the brain implant–computer interface (BCI) allowing direct person-to-person telepathic exchange

(Brunner et al. 2015; Stetka 2021). New uncrewed mobile devices, aided by machine learning and high-resolution models, will enable in situ observations of highly transient and irregular phenomena (e.g., clouds, ocean eddies, wildfire smoke, volcanic plumes) with more efficiency and less environmental impact than conventional platforms (e.g., airplanes, ships).

Education and outreach must be an integral part of future international field campaigns. The public in the campaign domain expects to be informed about activities and outcomes that may impact them or the environment around them. A comprehensive education and outreach approach will likely involve social media, printed material, and in-person and/or hands-on activities. Funding agencies must support such activities not only during campaigns but also afterward to sustain engagement. We must end science imperialism in any sense by all means (Ryan-Davis and Scalice 2022).

Participation in future field campaigns must be far more diverse and inclusive than they are today. While there are shining examples where focused efforts were made to recruit broad participation, focus activities to share scientific insights, inform and train participants in proper conduct, provide an intervention process to squelch any misbehavior whenever it occurs, and address other issues such as child care and family care in general, much remains to be done (Powell 2014; Fischer et al. 2021; Rasmussen et al. 2021; Jones and Bendixen 2022). Future campaign leaders need to actively improve diversity, equity, and inclusion and not rely on the historically slow gains in this aspect in sciences.

There will be no lack of ideas coming from the science community that require large multidisciplinary, multiagency international field campaigns to address global and regional environmental issues. There will not be adequate financial support for all of them. Creativity is needed to use new technologies to bring the cost down and to forge more collaboration and coordination to consolidate and efficiently use available resources. Science teams must be innovative in their strategies to maximize the outcome from field campaigns within given fiscal, logistical, natural, and political constraints. The planning and execution framework offered in this article hopefully will be helpful along the path to successful international field campaigns.

Field campaign scientists of the future may be able to sit in the comfort of their office with their chosen refreshment and direct the new generation of autonomous measurement tools to study this planet's secrets that are yet to be discovered. While such remote field campaigns have started to take place and even are appealing, there is something to be said for feeling the salt air on your face, the rush to duck inside from the baseball-size hail about to rain down on you, and the comfort of a five-point harness as the aircraft passes through the eyewall of a major hurricane. A combination of experiencing the natural phenomena in the field and the novel analysis of the field data will still be the best experience for understanding our planet.

If the next 40 years are anything like the past 40 years, there should be more opportunities ahead for environmental observations. Technical innovations and a workforce with more diversity, equity, and inclusion bode well for the new generations of scientists to learn and guide mankind into a more enlightened care for our planet. This is an exciting time for early career professionals to be involved to revolutionize the way we take field observations.

Acknowledgments. This article is dedicated to the many unknown heroines and heroes whose names never appeared in any document or publication but who worked diligently on every piece of equipment or instrument, and managed the logistical and technical details to ensure the completion and success of field campaigns that advanced science and trained new generations of scientists. The authors appreciate the helpful specific information and comments on earlier versions of this article from Shuyi Chen, Richard Feely, Kristina Katsaros, Peggy LeMone, Zhanqing Li, Michelle McClure, Michael McPhaden, Laura Pan, John Park, Jeffery Reid, Jeffery Stith, Alison Rockwell, Gregory Stossmeister, Steve Williams, and Kunio Yoneyama. The authors thank Douglas Parker, Angela Rowe, and two anonymous reviewers for their careful and constructive reviews of previously submitted manuscripts of this article, which led to its substantial improvement. This is PMEL Contribution 5251.

Data availability statement. Data used in Fig. 7 are from Google Scholar.

Appendix A: Examples of international field campaigns

Table A1 presents examples of international field campaigns.

Table A1. Examples of international field campaigns. Numbers in the far left-hand column are used in the text when a field campaign is cited (e.g., VIMHEX-1) and in Fig. 1 to mark its rough location.

	Name	Time	Location	Subject	Major participating countries and regions	References
1	Venezuelan International Meteorological and Hydrological Experiments (VIMHEX)/VIMHEX-II	1 Jul–30 Sep 1969/ June to September 1972	Northeast Venezuela	Mesoscale weather systems	Venezuela, U.S.	Simons et al. (1971), Fernández (1998)
2	Air Mass Transformation Experiment (AMTEX)	17 Feb 1974–28 Feb 1975	East China Sea	Air–sea interaction and convective clouds	Australia, Canada, Japan, U.S.	Lenschow (1972)
3	Global Atmospheric Research Program's (GARP) Atlantic Tropical Experiment (GATE)	15 Jun–23 Sep 1974	Equatorial Atlantic	Tropical convection	Brazil, Canada, France, Germany, Mexico, the Netherlands, U.K., U.S., USSR	Kuettner (1974)
4	JOINT-II	March–May 1977	Peruvian coast	Coastal upwelling	Peru, U.S.	Stuart et al. (1976)
5	Monsoon Experiment 77 (MONEX-77)	May–August 1977	The equatorial Indian Ocean, Arabian Sea, and the Bay of Bengal	Planetary circulation, perturbations, cloud and rainfall of the monsoon	India, Malaysia, Mozambique, Oman, Pakistan, Singapore, Sri Lanka, Somalia, Thailand, U.S., USSR	Murakami (1979)
6	Joint Air Sea Interaction project (JASIN)	8 Jul–16 Sep 1978	Scotland and northern Atlantic Ocean	Air–sea interaction	Australia, Canada, Germany, Ireland, the Netherlands, Sweden, U.K., U.S., USSR	Pollard (1978)
7	Winter Monsoon Experiment (W-MONEX)	1 Dec 1978–31 Mar 1979	South China Sea	Winter monsoon circulation over East Asia, the Maritime Continent, and Australia	Australia, China, Japan, U.S., USSR	Johnson and Chang (2007)
8	Summer Monsoon Experiment (S-MONEX)	1 May–31 Aug 1979	Arabian Sea	Summer monsoon	Australia, China, France, India, Japan, U.S., USSR	Fein and Kuettner (1980)
9	West African Monsoon Experiment (WAMEX)	14 Jul–15 Aug 1979	West Africa	West African monsoon	Algeria, Belgium, Benin, Central African Republic, Congo, France, Gabon, Gambia, Cameron, Ivory Coast, Madagascar, Mali, Nigeria, Senegal, Sierra Leone, Togo, Upper Volta	GARP (1978)
10	Marine Remote Sensing (MARSEN)	15 Jul–15 Oct 1979	North Sea	Remote sensing of air–sea interaction	Canada, Germany, Portugal, the Netherlands, U.K., U.S.	Katsaros et al. (1983)
11	Storm Transfer and Response Experiment (STREX)	1 Nov–31 Dec 1980	Gulf of Alaska	Air–sea interaction	Canada, U.S.	Fleagle et al. (1982)
12	Alpine Experiment (ALPEX)	1 Sep 1981–30 Apr 1982	Alpine massif in southern Europe	Airflow over and around mountains	France, Germany, Italy, Poland, Switzerland, Czechoslovakia, U.S.	Davies and Pichler (1990)

(*Continued*)

Table A1. (*Continued*).

	Name	Time	Location	Subject	Major participating countries and regions	References
13	Marginal Ice Zone Experiment (MIZEX)	5–27 Feb and June–July 1983; May–July 1984; March–April 1987	Bering Sea, Greenland Sea	Marginal ice zone	Canada, France, Germany, Norway, U.K., U.S.	Cavalieri et al. (1983), MIZEX Group (1986), MIZEX'87 Group (1989)
14	First and second Canadian Atlantic Storms Program (CASP-I)	15 Jan–15 Mar 1986; 15 Jan 1992 to 15 Mar 1992	Nova Scotia waters	Mesoscale structure and dynamics of winter storms and the associated oceanic response	Canada, U.S.	Stewart (1991)
15	Hydrologic Atmospheric Pilot Experiment (HAPEX)–Modélisation du Bilan Hydrique (MOBILHY)	9 May–15 Jul 1986	Southwest France	Hydrological budget and evaporation flux	France, U.S.	André et al. (1986)
16	Humidity Exchange Over the Sea (HEXOS)	6 Oct–28 Nov 1986	North Sea	Air–sea interaction	Canada, France, the Netherlands, U.K., U.S.	Katsaros et al. (1987)
17	Equatorial Mesoscale Experiment (EMEX)	14 Jan 1987 to 13 Feb 1987	North Australia/Pacific Ocean	Diabatic heating profiles	Australia, China, U.S.	Webster and Houze (1991)
18	Taiwan Area Mesoscale Experiment (TAMEX)	1 May–29 Jun 1987	Taiwan	Mesoscale dynamics and microphysical processes	Taiwan, U.S.	Kuo and Chen (1990)
19	World Ocean Circulation Experiment (WOCE) and Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP)	1990s–present	Global oceans	Physical oceanography, ocean carbon, oxygen and nutrient cycles, and biogeochemistry	Argentina, Australia, Canada, Chile, France, Germany, Indonesia, Ireland, Japan, Norway, South Africa, Spain, Sweden, Russia, U.K., U.S.	www.ewoce.org Talley et al. (2016)
20	European Field Experiment in a Desertification-threatened Area (EFEDA)	June 1991	Central Spain	Land–atmosphere energy and water transfer	France, Germany, Spain, the Netherlands, U.K., U.S.	Bolle et al. (1993)
21	Hydrological and Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel)	1991/92	Niger	Large-scale hydrological and meteorological behaviors of the Sahel	France, the Netherlands, Niger, U.S.	Goutorbe et al. (1994)
22	Anglo-Brazilian Climate Observation Study (ABRACOS)	1991–95	Amazonia	Climatic impacts of Amazonian deforestation	Brazil, U.K.	Gash and Nobre (1997)
23	Regional climate project (REKLIP)	Winter and May 1992	Middle and southern upper Rhine Valley	Land–atmospheric interaction	Austria, France, Germany, Switzerland, U.S.	Parlow (1996)
24	Atlantic Stratocumulus Transition Experiment (ASTEX)	4–27 Jun 1992	Azores and Madeira Islands	Marine boundary layer clouds	France, Germany, U.K., U.S.	Albrecht et al. (1995)
25	Surface of the Ocean, Fluxes and Interaction with the Atmosphere (SOFIA)/Structures des Echanges Mer-Atmosphere, Proprietes des Heterogeneites Oceaniques: Recherche Experiment (SEMAPHORE)	June 1992/October–November 1993	Canary Basin	Mesoscale air–sea interaction	France, U.K., U.S.	Weill et al. (1995), Eymard et al. (1996)

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Table A1. (*Continued*).

	Name	Time	Location	Subject	Major participating countries and regions	References
26	Southern African Regional Science Initiative (SAFARI)	August–October 1992, March 1999–March 2001	Southern Africa	Earth–atmosphere–human interaction	Australia, Belgium, Brazil, Botswana, Canada, France, Germany, Lesotho, Malawi, Mozambique, Namibia, Portugal, South Africa, Swaziland, Sweden, Congo, U.S., Zambia, Zimbabwe	Lindesay et al. (1996), Swap et al. (2002)
27	Transport and Atmospheric Chemistry near the Equator-Atlantic (TRACE-A)	21 Sep–24 Oct 1992	Atlantic Ocean	Ozone	Brazil, South Africa, U.S.	Fishman et al (1996)
28	Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE)	1 Nov 1992–28 Feb 1993	Western Pacific Ocean	Air–sea coupling	Australia, China, France, Japan, New Zealand, South Korea, U.K., U.S.	Webster and Lukas (1992)
29	Boreal Ecosystem Atmosphere Study (BOREAS)	August 1993–September 1994	Central Canada	Forest and atmosphere interaction	Canada, France, Russia, U.K., U.S.,	Sellers et al. (1995)
30	International Tundra Experiment (ITEX)	1 Jan 1993–31 Dec 2002	Circumpolar Arctic region	Arctic tundra biome	Canada, Finland, Greenland, Iceland, Norway, Sweden, U.S.	Keenan et al. (1989)
31	Northern Hemisphere climate-Processes land surface Experiment (NOPEX)	27 May–23 Jun 1994, 18 Apr–14 Jul 1995	Scandinavia	Land surface–atmosphere interaction	Denmark, Norway, the Netherlands	Halldin et al. (1999)
32	Beaufort and Arctic Storms Experiment (BASE)	1 Sep–26 Oct 1994	Southern Beaufort Sea and Northern MacKenzie River basin	Mesoscale weather systems	Canada, U.S.	Pinto et al. (2001)
33	Aerosol Characterization Experiment 1 (ACE1)	1 Oct 1995 to 25 Dec 1995	Hobart, Tasmania	Aerosol	Australia, U.S.	Bates et al. (1998)
34	GEWEX Asian Monsoon Experiment (GAME)	1996–2005	Asia	Asian monsoons	Bangladesh, China, Korea, India, Japan, Myanmar, Nepal, Taiwan, Thailand, Philippines	Yasunari (1994)
35	Aerosol Characterization Experiment 2 (ACE2)	16 Jun–24 Jul 1997	Tropical northeast Atlantic	Aerosol	France, Germany, Netherlands, Spain, U.K., Ukraine, U.S.	Raes et al. (2000)
36	Fronts and Atlantic Storm-Track Experiment (FASTEX)	1 Jan–28 Feb 1997	Shannon, Ireland; North Atlantic Ocean	Eastern oceanic storms	Canada, Denmark, France, Germany, Iceland, the Netherlands, Portugal, Spain, Switzerland, U.K., Ukraine, U.S.	Joly et al. (1999)
37	Surface Heat Budget of the Arctic Ocean (SHEBA)	15 Sep 1997–1 Nov 1998	Arctic	Surface energy budget and the sea ice mass balance in the Arctic	Canada, U.S.	Uttal et al. (2002)
38	Indian Ocean Experiment (INDOEX)	18 Feb–31 Mar 1998, 1 Jan–31 Mar 1999	Central Indian Ocean	Aerosol, clouds, and chemistry–climate interactions	India, U.S.	Ramanathan et al. (2001)

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Table A1. (*Continued*).

	Name	Time	Location	Subject	Major participating countries and regions	References
39	South China Sea Monsoon Experiment (SCSMEX)	1 May–30 Jun 1998	South China Sea	Southeast Asian monsoon	Australia, China, Taiwan, U.S.	Lau et al. (2000)
40	Arctic Transitions in the Land–Atmosphere System (ATLAS)	1 May 1998–31 Dec 2002	Arctic	Terrestrial processes in the Arctic	Russia, U.S.	McGuire et al. (2003)
41	Tropical Rainfall Measuring Mission Large-Scale Biosphere–Atmosphere Experiment (TRMM-LBA)	1 Nov 1998–28 Feb 1999	Rondonia, Brazil	Tropical convection in the Amazonia	Brazil, U.S.	Cifelli et al. (2002)
42	Mesoscale Alpine Programme (MAP)	7 Sep–15 Nov 1999	Innsbruck, Austria	Atmospheric and hydrological processes over mountainous terrain	Austria, Canada, EU, France, Germany, Italy, Switzerland, U.K., U.S.	Bougeault et al. (2001)
43	Alliance Icing Research Study (AIRS)	29 Nov 1999–18 Feb 2000	Ottawa/Mirabel, Canada	Aircraft icing region	Canada, U.S.	Isaac et al. (2001)
44	Mineral Dust and Tropospheric Chemistry (MINATROC)	1 Jun–5 Jul 2000, 15 Jul–15 Aug 2002	Mount Cimone, Italy; Canary Islands, Spain	Interaction of mineral dust with atmospheric chemistry	France, Germany, Italy	Balkanski et al. (2003), Umann et al. (2005)
45	Evaluation of the Effects of Elevation and Aerosols on the Ultraviolet Radiation (VELETA)	July 2002	Sierra Nevada, Spain	Elevation and atmospheric aerosol effects on the solar ultraviolet irradiance	Austria, Italy, Portugal, Spain,	Alados-Arboledas et al. (2001)
46	Mexico City Metropolitan Area (MCMA)	April 2003, March 2006	Mexico City	Atmospheric chemistry	Mexico, U.S.	de Foy et al. (2005), Dusanter et al. (2009)
47	Arctic Study of Tropospheric Aerosol and Radiation (ASTAR)	12 Mar–25 Apr 2000, 18 May–7 Jun 2004, March–April 2007	Svalbard and Storfjord, Norway; Greenland Sea	Aerosol	France, Germany, Japan, Sweden, U.S.	Yamanouchi et al. (2005), Ehrlich et al. (2008), Engvall et al. (2008)
48	Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia)	15 Mar–10 May 2001	Asia/Pacific	Climate forcing due to aerosol particles	China, South Korea, Japan, Taiwan, U.S.	Huebert et al. (2003)
49	African Monsoon Multidisciplinary Analysis (AMMA)	2005–07	West Africa	West African monsoon	France, Germany, Senegal, U.K., U.S.	Redelsperger et al. (2006), Lebel et al. (2010)
50	South America Low-Level Jet (SALLJ)	15 Nov 2002–15 Feb 2003	South America	South America low-level jet	Argentina, Chile, Bolivia, Brazil, Peru, U.S.	Vera et al. (2006)
51	North American Monsoon Experiment (NAME)	1 Jun–30 Sep 2004	Gulf of California	North American monsoon	Mexico, U.S.	Higgins et al. (2006)
52	Rain in Cumulus over the Ocean (RICO)	24 Nov 2004–24 Jan 2005	Eastern Atlantic and western Caribbean	Shallow cumulus	U.K., U.S.	Rauber et al. (2007)
53	East Asian Study of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE)	March–April 2005	Northeast of Beijing	Aerosol effects on weather and climate	China, U.S.	Li et al. (2007)
54	Tropical Warm Pool International Cloud Experiment (TWP-ICE)	January–February 2006	Darwin, Australia	Cloud, aerosol, tropical convection	Australia, Japan, Germany, U.K., U.S.	May et al. (2008)

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Table A1. (*Continued*).

	Name	Time	Location	Subject	Major participating countries and regions	References
55	Intercontinental Chemical Transport Experiment B (INTEX-B)	1–21 Mar, 17 Apr–15 May 2006	Mexico and the Gulf of Mexico	Pollution outflow	Canada, Germany, U.S.	Singh et al. (2009)
56	Mount Tai Experiment (MTX2006)	June 2006	Mount Tai, China	Atmospheric chemistry	China, Japan	Inomata et al. (2010)
57	Convective and Orographically-induced Precipitation Study (COPS)	1 Jun–21 Aug 2007	Southwestern Germany/eastern France	Orographic precipitation	Austria, France, Germany, Italy, Switzerland, the Netherlands, U.K., U.S.	Wulfmeyer et al. (2011)
58	Flow Over and around Hofsjökull (FLOHOF)	21 Jul–24 Aug 2007	Hofsjökull, Iceland	Mountain-induced gravity waves	France, Germany, Iceland, Norway	Reuder et al. (2012)
59	MIRAGE-Shanghai	September 2009	Shanghai, China	Air pollution	China, U.S.	Tie et al. (2013)
60	Megacity Initiative: Local and Global Research Observations (MILAGRO)	1 Mar–30 Mar 2006	Mexico City	Pollutants, aerosol	Mexico, U.S.	Molina et al. (2010)
61	Terrain-influenced Monsoon Rainfall Experiment (TiMREX)	30 Apr 2008–30 Jun 2008	Taiwan	Asian summer monsoon rainfall	Taiwan, U.S.	Jou et al. (2011)
62	Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models, Climate, Chemistry, Aerosols and Transport (POLARCAT)	Spring–summer 2008	Arctic	Pollution, aerosol, trace gas	Germany, France, Norway, Russia, U.K., U.S.	Law et al. (2014)
63	European Integrated Project on Aerosol Cloud Climate and Air Quality Interactions Long Range Experiment (EUCAARI-LONGREX)	May 2008	Europe	Tropospheric aerosol	Germany, Finland, Ireland, the Netherlands, Norway, Sweden, U.K., U.S.	Hamburger et al. (2011)
64	The Observing System Research and Predictability Experiment Pacific Asian Regional Campaign (T-PARC)	1 Aug–3 Oct 2008	Hawaii, Guam, and Japan	Predictability of high-impact weather events	Japan, Taiwan, U.S.	Nakazawa et al. (2010)
65	Concordiasi	September–November 2008, December 2009, and September–December 2010	Antarctica	Antarctic land surface, lower stratosphere, and troposphere	France, U.S.	Rabier et al. (2013)
66	VAMOS Ocean–Cloud–Atmosphere–Land Study Regional Experiment (VOCALS-REX)	October and November 2008	Southeast Pacific	Coupled climate system of the southeast Pacific	Chile, Peru, U.K., U.S.	Wood et al. (2010)
67	HIAPER Pole-to-Pole Observations (HIPPO)	January 2009, November 2009, April 2019, June 2011, August 2011	North to South Poles	Carbon cycle and greenhouse gases	Canada, Japan, France, New Zealand, U.K., U.S.	Wofsy (2011)
68	Clouds, Aerosol, and Precipitation in the Marine Boundary Layer (CAP-MBL)	April 2009–December 2010	Graciosa, Azores	Clouds, aerosols	Canada, China, Finland, U.K., U.S.	Wood et al. (2015)
69	Distributed Biological Observatory (DBO)	2010–present	Northern Bering Sea, Chukchi Sea, Beaufort Sea	Arctic marine ecosystems	Canada, China, Japan, South Korea, Russia, Sweden, U.S.	DBO Implementation Plan (2015–24)

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Table A1. (*Continued*).

	Name	Time	Location	Subject	Major participating countries and regions	References
70	Impacts of Typhoons on the Ocean in the Pacific (ITOP)	17 Aug–20 Oct 2010	Tropical western Pacific	Ocean response to typhoons	Taiwan, U.S.	D'Asaro et al. (2014)
71	South American Biomass Burning Analysis (SAMBBA)	September–October 2012	Brazil	Biomass burning emissions	Brazil, Germany, U.K.	Brito et al. (2014)
72	Dynamics of the Madden–Julian Oscillation (DYNAMO)	1 Oct 2011–31 Mar 2012	Equatorial Indian Ocean	Initiation of the Madden–Julian oscillation	Australia, Japan, France, Kenya, South Korea, India, Indonesia, Maldives, Papua New Guinea, Poland, Seychelles, Singapore, Sri Lanka, Taiwan, U.K., U.S.	Yoneyama et al. (2013)
73	Salinity Processes in the Upper-ocean Regional Study 1 (SPURS1)	August 2012 and October 2013	Northern central Atlantic	Upper-ocean salinity	France, U.S.	Lindstrom et al. (2015)
74	Hydrological Cycle in the Mediterranean Experiment (HyMeX)	October–November 2012, 27 Jan–15 Mar 2013	Northwestern Mediterranean	Heavy precipitation and flash flood	France, Germany, Italy, Spain, Switzerland, the Netherlands, U.S.	Ducrocq et al. (2014), Estournel et al. (2016)
75	Air–Sea Interactions in the Northern Indian Ocean (ASIRI)	2013–17	Bay of Bengal	Air–sea coupling related to the Indian monsoon	India, Sri Lanka, U.S.	Wijesekera et al. (2016)
76	Observations and Modeling of the Green Ocean Amazon (GoAmazon)	1 Jan 2014–31 Dec 2015	Manaus, Brazil	Interactions among vegetation, atmospheric chemistry, and aerosol	Brazil, Germany, U.S.	Martin et al. (2016)
77	Convective Transport of Active Species in the tropics (CONTRAST)	15 Jan–28 Feb 2014	Western Pacific	Convection redistributes atmospheric gases	U.K., U.S.	Pan et al. (2016)
78	Biogenic Aerosols–Effects on Clouds and Climate (BAECC)	February–September 2014	Hyytiälä, Finland	Aerosols, clouds, and precipitation	Austria, Finland, Germany, Italy, U.K., U.S.	Petäjä et al. (2016)
79	Deep Propagating Gravity Wave Experiment (DEEPWAVE)	May–July 2014	New Zealand and Tasmanian	Orographic gravity waves	Australia, New Zealand, U.S.	Fritts et al. (2016)
80	Chilean Coastal Orographic Precipitation Experiment (CCOPE)	22 May–15 Aug 2015	Nahuelbuta Mountains, Chile	Landfalling storms	Chile, U.S.	Massmann et al. (2017)
81	Scale-Crossing Land Surface and Boundary Layer Processes (SCALEX)	June–July 2015, 2016, 2019	German Alps	Biogeochemical and biophysical cycles, land–air interaction	Germany, Italy, Switzerland,	Wolf et al. (2017)
82	Atmospheric Radiation Measurement (ARM) West Antarctic Radiation Experiment (AWARE)	4 Dec 2015–17 Jan 2016	West Antarctica	Atmospheric forcing on West Antarctica	Canada, Chile, EU, Germany, U.K., U.S.	Lubin et al. (2020)
83	Polynyas and Ice Production and seasonal Evolution in the Ross Sea (PIPERS)	Autumn 2017	Ross Sea, Antarctica	Air–ice–ocean–biogeochemical interactions	Belgium, U.S.	Ackley et al. (2020)
84	North Atlantic Aerosols and Marine Ecosystems Study (NAAMES)	November 2015 and April 2018	Western subarctic Atlantic	Ocean ecosystem–aerosol–cloud	Austria, Norway, U.K., U.S.	Behrenfeld et al. (2019)
85	Korea–United States Air Quality Study (KORUS-AQ)	1 May–12 Jun 2016	South Korea	Air quality	South Korea, U.S.	Choi et al. (2019)

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Table A1. (*Continued*).

	Name	Time	Location	Subject	Major participating countries and regions	References
86	Dynamics–Aerosol–Chemistry–Cloud Interactions in West Africa (DACCIWA)	June–July 2016	West Africa	Impact of aerosol	France, Germany, Ghana, Ivory Coast, Nigeria, Senegal, U.K.	Knippertz et al. (2017), Flamant et al. (2018)
87	Interaction of Convective Organization with Monsoon Precipitation, Atmosphere, Surface and Sea (INCOMPASS)	June–July 2016	India	Monsoon convection	India, U.K.	Turner et al. (2020)
88	Observations of Aerosols above Clouds and their interactions (ORACLES)	September 2016; August 2017; October 2018	Southeast Atlantic	Aerosol	Canada, France, Greece, Israel, Namibia, New Zealand, South Africa, Switzerland, U.K., U.S.	Redemann et al. (2021)
89	Arctic Cloud Observations Using Airborne Measurements during Polar Day/Physical Feedbacks of Arctic Boundary Layer, Sea Ice, Cloud and Aerosol (ACLOUD/PASCAL)	May–June 2017	Svalbard, Norway	The role of Arctic clouds and aerosol particles in the Arctic climate system	France, Germany, U.S.	Wendisch et al. (2019)
90	Layered Atlantic Smoke Interactions with Clouds (LASIC)	1 Jun 2016–31 Oct 2017	Ascension Island	Smoke interactions with clouds	Canada, U.K., U.S.	Zuidema et al. (2018)
91	Aerosols, Radiation and Clouds in southern Africa (AEROCLO-A)	23 Aug–12 Sep 2017	Northern Namibia	Aerosol	France, German, Greek, Italian, South African, Namibian	Formenti et al. (2019)
92	Cloud–Aerosol–Radiation Interaction and Forcing (CLARIFY)	August–September 2017	Southeast Atlantic	Cloud–aerosol–radiation interaction	France, Israel, the Netherlands, U.K., U.S.	Haywood et al. (2021)
93	Perdigão	15 Dec 2016–15 Jun 2017	Portugal	Wind resource	Portugal, U.S.	Fernando et al. (2019)
94	Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study (SOCRATES)	15 Jan–26 Feb 2018	Southern Ocean, Australia	Cloud, aerosol, and precipitation	Australia, U.S.	McFarquhar et al. (2014)
95	Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations (RELAMPAGO) and Cloud, Aerosol, and Complex Terrain Interactions (CACTI)	1 Jun 2018–30 Apr 2019	West-central Argentina	Convective storm development	Argentina, U.S.	Nesbitt et al. (2017)
96	Propagation of Intra-Seasonal Tropical Oscillation (PISTON)	21 Aug–12 Oct 2018	Tropical western Pacific	Boreal summer intraseasonal oscillation	Japan, Philippines, Taiwan, U.S.	
97	Years of the Maritime Continent (YMC)	2017–23	The Indo-Pacific Maritime Continent	Weather and climate processes	Australia, China, Indonesia, Japan, Malaysia, Philippines, Poland, Taiwan, Vietnam, U.K., U.S.	Yoneyama and Zhang (2020)

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Table A1. (*Continued*).

	Name	Time	Location	Subject	Major participating countries and regions	References
98	Elucidating the Role of Cloud-Circulation Coupling in Climate (EUREC^{4}A)/Atlantic Tradewind Ocean–Atmosphere Mesoscale Interaction Campaign (ATOMIC)	January–February 2020/January–June 2020	Western tropical Atlantic	Air–sea interaction and trade wind clouds	Barbados, France, Germany, U.K., U.S.	Bony et al. (2017), Stevens et al. (2021)
99	Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC)	September 2019–October 2020	Central Arctic	Coupled climate processes in the central Arctic	Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Italy, Japan, Korea, the Netherlands, Norway, Poland, Russia, Spain, Sweden, Switzerland, U.K., U.S.	The MOSAiC Science Plan (https://mosaic-expedition.org/wp-content/uploads/2020/12/mosaic_scienceplan.pdf)
100	Convective Processes Experiment–Aerosols and Wind (CPEX-AW)	August–October 2021	Tropical Atlantic	Calibration and validation of satellite observations of aerosol, wind, and convection	France, U.S.	https://cpex.jpl.nasa.gov/cpex-aw/

Appendix B: List of acronyms

AFB	Air Force Base
ARM	Atmospheric Research Measurement
ATC	Air traffic control
COVID-19	Coronavirus disease 2019
DOTSTAR	Dropsonde Observations for Typhoon Surveillance near the Taiwan Region
DOE	Department of Energy
DOI	Digital object identifiers
DLR	German Aerospace Center (Deutsches Zentrum für Luftund Raumfahrt)
DPM	Daily planning meeting
ECMWF	European Centre for Medium-Range Forecasting
ELDORA	Eldora Doppler radar (NCAR)
EOL	Earth Observing Laboratory (NCAR)
F-20	Falcon 20 jet research aircraft
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Program
GTS	Global Telecommunications System
HF	High frequency (radio)
IA	Implementation agreement
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JMA	Japan Meteorological Administration
JTWC	Joint Typhoon Warning Center
MOU	Memorandum of understanding
NAF	Naval Air Facility
NCAR	National Center for Atmospheric Research
NASA	National Aeronautics and Space Administration

NCDC	NOAA National Climate Data Center
NCEI	National Center for Environmental Information (formerly NCDC)
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
NOAA	National Oceanic and Atmospheric Administration
OFAP	Observing Facilities Assessment Panel (NCAR/EOL)
PI	Principal investigator
P-3	Orion P-3 turboprop research aircraft
QC	Quality control
SSEC	Space Science and Engineering Center (University of Wisconsin)
UKMO	Met Office
USAF	U.S. Air Force
UxSs	Uncrewed observing systems
WDC	World data centers
WMO	World Meteorological Organization

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