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Celebrating 50 Years since GATE

Andrea M. Jenney,[a] Robert A. Houze Jr.,[b] Margaret LeMone,[c] Elizabeth J. Thompson,[d]
Kelly M. Núñez Ocasio,[e,c] Chidong Zhang,[f] and Terrence R. Nathan[g]

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ABSTRACT: The Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) took place from June to September 1974. It remains the largest field campaign in atmospheric science history. Its 50th anniversary was celebrated at the 104th AMS Annual Meeting in Baltimore on 1 February 2024. The celebration featured a series of events including town halls, sessions, and a luncheon. These events provided a platform for reflection and knowledge sharing among surviving participants and others and highlighted GATE's foundational role in advancing our understanding of tropical meteorology and oceanography. GATE was motivated by the need to address the challenge of global weather forecasting, and its science objectives remain relevant today. The campaign led to discoveries that continue to influence modern thinking about tropical meteorology and oceanography. It also impacted the design and goals of subsequent tropical field studies. This article briefly describes the 50th anniversary celebration, including some of the experiences of the participants, and summarizes seminal findings about tropical convection, the tropical atmospheric boundary layer over the ocean, easterly waves, oceanography, and air–sea interaction—fields where GATE's insights have guided subsequent research.

SIGNIFICANCE STATEMENT: The Global Atmospheric Research Program Atlantic Tropical Experiment (GATE), conducted from June to September 1974, remains the largest field campaign in the history of atmospheric sciences. 2024 marks its 50th anniversary, which was celebrated at the 104th AMS Annual Meeting. The purpose of this article is to briefly summarize the 50th anniversary celebration and highlight the GATE science. Our commemoration piece showcases GATE's achievements, challenges, and enduring legacy.

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Corresponding author: Chidong Zhang, chidong.zhang@noaa.gov
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AFFILIATIONS: [a] College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon; [b] Department of Atmospheric Sciences, University of Washington, Seattle, Washington; [c] NSF National Center for Atmospheric Research, Boulder, Colorado; [d] NOAA/Physical Sciences Lab, Boulder, Colorado; [e] Department of Atmospheric Sciences, Texas A&M University, College Station, Texas; [f] NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington; [g] Department of Land, Air, and Water Resources, University of California, Davis, Davis, California

1. Introduction

The 104th AMS Annual Meeting in Baltimore, 1 February 2024, celebrated the 50th anniversary of the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) that took place from June through September 1974. This anniversary event highlighted GATE's uniqueness among atmospheric field projects. GATE featured a staggering number of facilities from around the world. Deployed across the tropical Atlantic were 39 ships, while 13 aircraft flew research missions out of Dakar, Senegal, over a tight network of ships in the eastern tropical Atlantic (Fig. 2). Besides deploying the largest number of platforms ever used in a meteorological field project, GATE was unusual in other respects, the most prominent being teamwork between the United States and the Soviet Union at a time of Cold War tension (Zhang et al. 2022). In the United States, close interagency cooperation, including NSF, National Oceanic and Atmospheric Administration (NOAA), NASA, and other agencies, brought scientists from universities and laboratories across the country together to accomplish the campaign. New technologies in radar, aircraft sampling, boundary layer sensing, upper air sounding, and oceanographic observations were put to use in a coordinated plan. Altogether, 72 nations and over five thousand people took part in GATE. Younger meteorologists were able to mingle with this international team and launch careers in GATE. The observations made in the project were pivotal in the understanding of tropical meteorology and oceanography, and GATE's motivating research areas remain highly relevant today. This commemoration article summarizes the most important of GATE's groundbreaking scientific achievements across the scales of tropical atmospheric and oceanic processes.

The commemorative event at the 2024 AMS Annual Meeting, made possible with support from NOAA, included a town hall discussion, three scientific sessions, and a luncheon. Personal anecdotes added a rich layer of human experience to the scientific discourse. See section 2 for a photo of the attendees and some of their personal stories of their time in GATE.

2. Personal experiences

The 50th anniversary celebration provided an opportunity for those at the AMS meeting who participated in the GATE observations (Fig. 1) to recall some of the human dimensions of scientific research in action. The event shed a special light on the challenging roles of women at the time of GATE and the varying approaches to gender inclusivity across participating nations in the 1970s. For the United States, GATE happened at the beginning of the affirmative action era, with expanding efforts to improve the participation of women in science. While some notable senior women scientists participated in the planning (Pauline Austin) and execution (Joanne Simpson) of aircraft missions, female students from United States universities applying for participation in GATE found themselves barred from ship duty.

Fig. 1. Photo of GATE field project veterans who attended the GATE 50th anniversary event at the 2024 American Meteorological Society Annual Meeting. (from left to right) Robert (Bob) Houze, Ed Zipser, Margaret (Peggy) LeMone, Becky Meitin, William Pennell, Alan Betts, Bruce Albrecht, Howie Bluestein, Dave Emmitt, Sharon Nicholson, and David Fitzjarrald. Photo courtesy of Christi Huang and the AMS.

Lesley Julian took legal action to gain permission to work aboard the United States Naval Ship (USNS) *Vanguard*. The remaining female students remained in Dakar doing aircraft work. In contrast, multiple GATE participants recounted at the anniversary event how the Soviet ships had many women onboard.

While aircraft participants based on land in Dakar were able to mingle throughout the experiment, participants on the ships could mix only between the phases (each of the three phases lasted roughly 3 weeks, with about 2 weeks between them). Shipboard life was mostly hardworking and lonely in that pre-internet era, but some occasional fun was had. GATE participant Dave Emmitt, aboard the U.S. Coast Guard ship *Dallas*, recounted how the captain brought out gunners to shoot sharks in case they appeared during a fourth of July swim. On the NOAA ship *Researcher*, Bob Houze noted limited entertainment options beyond one movie night, but when an empty oil barrel drifted by the stationary vessel, it became a spectacle for the crew. One sailor attempted, unsuccessfully, to sink it by shooting at it with a rifle. Between phases, when ships were in port in Dakar, meetings to discuss scientific discoveries and solve problems, as well as parties held by different nations, eased feelings of isolation for the shipboard scientists.

The research flights were exhausting marathons, often extending beyond 10 h to accommodate travel to and from Dakar, where the aircraft operations were based, to the ship array some distance away. On the French *DC-7*, however, for 2 h each day, some data collection paused as the crew and scientists indulged in elaborate luncheons. Participants fondly reminisced about being handed a menu upon boarding the French aircraft (instead of, for example, a safety card outlining what to do in case of an emergency). The same seven-course spreads were also served on the NOAA *DC-6* (minus the wine). Yet, most of the crew on the NOAA aircraft preferred the emergency forest-ranger box lunches containing canned soggy pasta. C-rations (military meals developed during WWII) were used on the National Center for Atmospheric Research (NCAR) *Electra*. One of the coauthors (LeMone), eating her C-ration lunch at Dakar-Yoff airport, was approached by a WWII veteran who recognized the container and was delighted when LeMone gave him part of the meal.

The news was limited for GATE participants, who remained largely insulated from events unfolding back home. Nonetheless, the resignation of President Nixon on 9 August 1974 precipitated interesting discussions among the international scientific teams. On a visit to a small village outside Dakar, a U.S. scientist from the *Researcher* in port between phases visited a Senegalese village and was greeted by a young boy chanting, "Watergate, Watergate."

3. Motivation, planning, execution, and experience of GATE

At the 50th anniversary celebration, Ed Zipser recalled that the scientific motivation of GATE was to address the "little problem with the tropics" (i.e., poor representation of the tropics in general circulation models), which led to frustratingly large errors in global weather prediction. The atmospheric campaign had the goal of observing how tropical oceanic convection related to both synoptic scales of motion and the atmospheric boundary layer to advance the numerical modeling of these processes (Kuettner 1974). To achieve this goal, five subprograms—convection, boundary layer, oceanography, radiation, and synoptic—were created to ensure an efficient flow of objectives and knowledge between them and the main goals of GATE. Central to developing this mission were the efforts of "the big three"—Vern Suomi, Jule Charney, and Joseph Smagorinsky—who spearheaded the initial discussions and planning for the experiment. Their shared vision was further realized through the lessons learned from the 1967 Line Islands Experiment (Zipser 1970) and two experiments in Barbados (Garstang and LaSeur 1968; Kuettner and Holland 1969), which served as precursors to GATE and refined the approaches that would be employed in the main experiment.

The colossal scale of GATE, its international makeup, and its ambitious goals made the planning and execution of the campaign challenging for its unprecedented levels of logistical and sociopolitical collaboration within and across nations (GARP 1970; GATE 1971; Kuettner 1974). The challenge was met by a unique experimental design, organized by process scales ranging from synoptic to mesoscale to convective and even microphysical scales (Fig. 2).

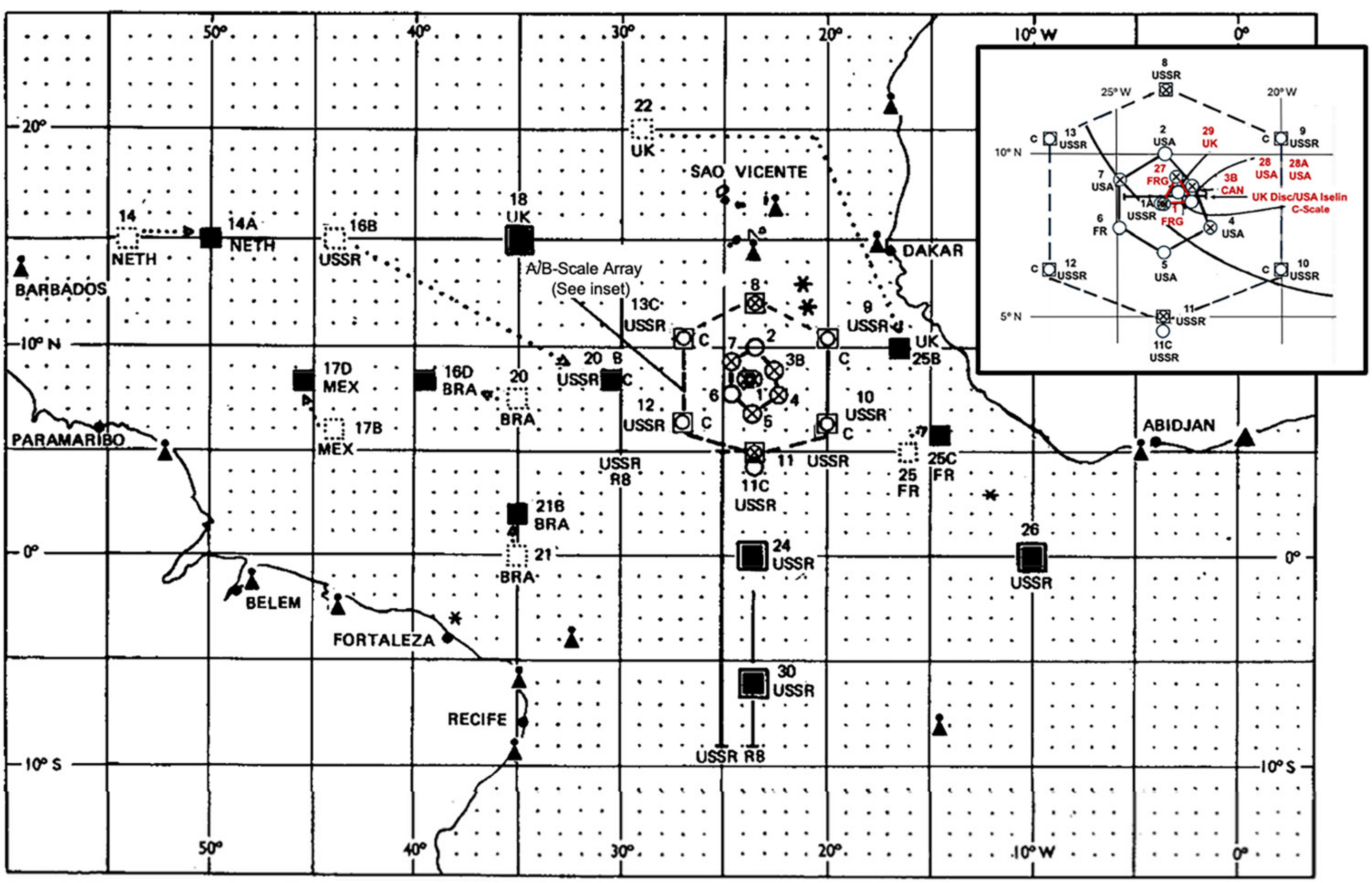

Fig. 2. **The GATE array during phase III (30 Aug–19 Sep 1974). Ships (squares) are labeled by participating country; numbers correspond to a list in Kuettner and Parke (1976). Ships stretching across the Atlantic represent the so-called A-scale, while the large and small hexagons form the A/B and B-scale arrays, respectively. The northeast triangle of ships constitutes the C-scale array. Aircraft were based at Dakar-Yoff Airport. Inset shows A/B-scale (dashed lines), B-scale (solid black lines), and C-scale arrays (dark red lines). Radar ships are marked with X. Arc in the inset marks 1000-km distance from Dakar. From Figs. 2 and 3 of Kuettner and Parker (1976).**

In the field, Mission Selection Team Chair Joachim Kuettner of the United States and the Soviet vice-chair, Yuri Tarbaev, skillfully and diplomatically led the daily international flight planning under the guidance of lead forecasters Richard Reed and Robert Burpee.

The cooperation in GATE extended to the aircraft and shipborne scientists from nations charged with GATE observations. Scientists at the GATE Operations Control Center (GOCC) in Dakar planned and organized missions coordinating aircraft and ships of multiple nations. The international leadership of Kuettner, Tarbaev, Reed, and Burpee facilitated the everyday planning of flights. The diversity of shipborne and airborne platforms and instruments enabled scientists to combine the insights of different disciplines. The resulting synergism, social and scientific, contributed to GATE being the most ambitious meteorological field campaign in history.

4. GATE's scientific achievement

While the five subprograms provided a good framework for designing the GATE observational network, the weather encountered and data collected dictated what scientists wrote about. For example, papers dealing with mesoscale convection often had a boundary layer component, and blending "synoptic" and "convection" topics became common in studies of easterly waves, which dominated the synoptic papers. Air–sea interaction papers could fall into three categories—boundary layer, radiation, or oceanography. Thus, rather than forcing results into the five GATE subprograms, the topics covered here differ slightly from the categories used to design the observational network, covering tropical convection, the boundary layer, air–sea interaction, oceanography, easterly waves, and radiation. The results presented here represent the perspective of the United States and atmospheric participants in the AMS GATE reunion.

a. Tropical convection. The primary motivation for GATE was to improve the parameterization of tropical convection over the ocean. GATE observations provided a more accurate and quantitative observational knowledge of convective structure, spatial distribution, precipitation characteristics, and relation to the large-scale environment than had previously been available. Key to obtaining this improved knowledge was the three-dimensional coverage by quantitative radar aboard four ships, instrumentation on 13 aircraft, many of which flew repeatedly through and around the mesoscale convective systems (MCSs) at several levels, and ship-based soundings. Radar showed that precipitation areas were of a wide range of sizes and that echoes' areal coverage, height, and duration followed a truncated lognormal distribution (Houze and Cheng 1977). The largest echoes drew the most attention from GATE analysts because GATE planners did not foresee MCSs as a major part of the oceanic convective population (WMO 1970), although Zipser (1969) had shown their existence over the tropical Pacific Ocean and Caribbean (Zipser 1977). The GATE shipborne radars' three-dimensional scanning observations quantified the role of such MCSs in the tropical cloud population, as seen in the eastern Atlantic tropics. The GATE radars showed the precipitation of the MCSs to be neatly divided into convective and stratiform structures (see Figs. 3a,b). The stratiform component of MCS precipitation was roughly 40%, while the overall GATE precipitation was also about 40% stratiform, indicating the strong contribution of MCSs to rainfall and latent heating and cooling over the GATE area (Houze 2018).

Cooling characterized the lower portions of the stratiform regions owing to melting and evaporation of precipitation particles. Thus, a major GATE finding was that the heating of the large-scale environment by the convective population was more concentrated in upper levels ("top heavy") than previously recognized (Houze 2018). These revelations indicating mesoscale impact on heating profiles were inconsistent with contemporary

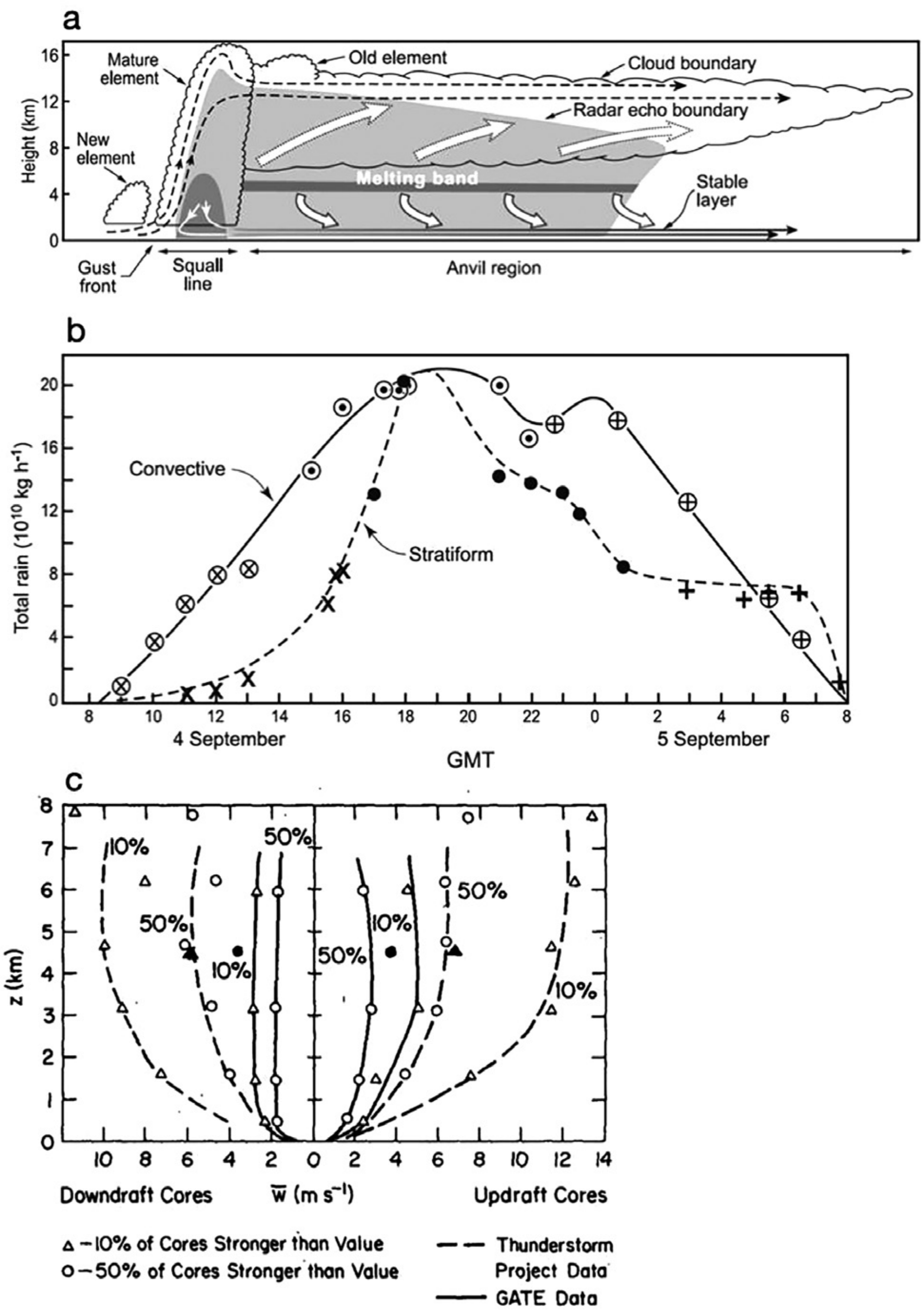

Fig. 3. GATE findings about tropical oceanic convection. (a) The conceptual model of a tropical ocean MCS deduced from GATE radar and aircraft data. Schematic cross section through a squall-line system observed over the eastern tropical Atlantic Ocean during GATE. Streamlines show flow relative to the squall line. Thin dashed streamlines show convective updraft circulation. Thin solid streamlines show the convective downdraft circulation, and wide arrows show the mesoscale downdraft below the base of the anvil cloud. Wide arrows show mesoscale ascent in the anvil. Dark shading shows strong radar echo in the melting band and in the heavy precipitation zone of the mature squall-line element. Light shading shows weaker radar echoes. The scalloped contour indicates visible cloud boundaries. From Houze (1977). (b) The first GATE result to show the quantitative result derived from GATE radars that stratiform regions accounted for ~40% of tropical oceanic MCS rainfall. Total rain amounts from the convective (circled points) and stratiform regions of a squall-line MCS located over the GATE array. The data were obtained by three shipborne radars. The three types of symbols indicate different methods used for combining the information from the three radars. From Houze (2018). (c) Results derived from GATE aircraft measurements showing that tropical oceanic convective updrafts are weak compared to continental convection. Mean vertical velocity in updraft and downdraft cores as a function of height, comparing different datasets. The GATE data for strong (10% level) and median (50% level) cores. Data from The Thunderstorm Project (Byers and Braham 1949) are from convective cells over land. Black symbols at 4.5 km are for hurricanes (Gray 1965). From Zipser and LeMone (1980).

parameterization theories at the time, which were based on a spectrum of individual convective-scale clouds.

In addition to the radars providing a quantitative understanding of tropical oceanic convection's stratiform component, instrumented GATE aircraft obtained quantitative information on the convective-scale updrafts and downdrafts in the convective systems. Vertical velocity measurements made by inertial navigation and gust-probe sensors aboard aircraft revealed that compared to drafts over land, tropical oceanic convective systems' up- and downdrafts are weaker by a factor of 2.5–3 than in convection over land (Fig. 3c) (Zipser and LeMone 1980; LeMone and Zipser 1980).

In addition to these major quantitative discoveries about convective clouds over tropical oceans, the GATE radar and aircraft observations led to several new findings of a qualitative nature:

- Using a nonquantitative radar aboard a Soviet ship, Shupiatsky et al. (1975, 1976a,b) showed the existence of a radar bright band in two GATE MCSs. GATE's quantitative radar observations aboard U.S. ships combined with shipboard drop size measurements allowed further diagnosis of the specific microphysical processes of precipitation particle growth in the massive stratiform regions. Specifically, Leary and Houze (1979a) deduced that snow aggregates and wet graupel was falling through the melting layer and evaporating below. This picture was verified three and half decades later by dual-polarimetric radar observation in the Dynamics of the Madden–Julian Oscillation (DYNAMO) project over the Indian Ocean (Rowe and Houze 2014).
- GATE ship-based soundings together with radar showed that the radar-observed convective systems were not always fast moving. Barnes and Sieckman (1984) and Leary and Houze (1979b) analyzed examples of the slow-moving lines. Both types had strongly sloping leading edges (LeMone et al. 1984b).
- LeMone et al. (1984a) showed that a hydrostatic low pressure center occurred below the tilting leading edges of both fast- and slow-moving lines of convection. This low pressure center has important implications in that momentum transports by tropical oceanic convective lines cannot be treated as a simple downgradient turbulent transfer because the updraft elements are accelerating rearward in the cross-line direction, thus taking on momentum as they rise. At lower levels, the low and the cold-pool high pressure anomaly accelerates downdraft elements forward on average, further contributing to nonclassical momentum transport.

b. Easterly waves. A major outcome of the Synoptic-Scale Subprogram of GATE was a better understanding of the structure and properties of African easterly waves (AEWs). Before GATE, studies suggested that AEWs were disturbances originating from barotropic–baroclinic dynamical instabilities of the African easterly jet (AEJ; Burpee 1972). This work led to Robert W. Burpee being chosen as lead forecaster, along with Richard J. Reed, for GATE operations. Earlier studies had indicated that the occurrence of deep convection is not only controlled by the waves but also can contribute to their growth and modulation (Erickson 1963; Carlson 1969), making AEWs and their associated convection the primary synoptic-scale feature affecting North Africa during boreal summer.

Using GATE's network of radars, upper-air observations, and land stations from GATE, Burpee (1975) developed AEW-centered composites documenting the vertical structure of AEWs: eastward-tilted trough and ridge axes with height due to easterly shear from the AEJ mean zonal wind from the surface to 600 hPa and westward tilt with height from westerly shear above 600 hPa. Burpee and Reed (1982) summarized the GATE's AEW findings in the GATE monograph published by the World Meteorological Organization. The GATE work motivated AEW-related studies over the last two decades that have applied similar compositing methods to satellite-derived datasets (Thorncroft and Hodges 2001; Kiladis et al. 2006), reanalysis (Hopsch et al. 2010; Brammer and Thorncroft 2015; Núñez Ocasio et al. 2020), and modeling (Russell et al. 2020; Tomassini et al. 2017; Núñez Ocasio and Rios-Berrios 2023; Núñez Ocasio et al. 2024) to further inform the structure and properties of AEWs.

A major contribution of GATE to understanding AEWs was the documentation of their wavelength, found to be between 2000 and 6000 km (Reed et al. 1977). This finding spurred studies on wave detection methods using mean wave tracks (Reed et al. 1988; Diedhiou et al. 1999). This led to the objective identification and tracking of AEWs, enabling climatological and statistical analyses (e.g., Thorncroft and Hodges 2001; Berry et al. 2007; Bain et al. 2014; Belanger et al. 2016; Brammer and Thorncroft 2015; Lawton et al. 2022; Hollis et al. 2024).

Carlson (1969), Burpee (1972), and Reed et al. (1977) showed that AEW activity primarily occurs along two distinct tracks: one to the north of the AEJ, characterized by dry convective processes, and one to the south of the jet, associated with moist convection. Both tracks can later merge over the Atlantic. This finding led to research studying the differences in the energetics and properties of both AEW tracks. We now know that southern-track AEWs are associated with monsoon convection and are energized by dynamic instabilities from the AEJ and shear interactions between the monsoon and the AEJ (Diedhiou et al. 1998; Nicholson 2009; Thorncroft and Hodges 2001; Zawislak and Zipser 2010; Pytharoulis and Thorncroft 1999; Skinner and Diffenbaugh 2014; Hamilton et al. 2017, 2020). Moreover, AEWs are now understood to be Rossby waves that exist on either side of the AEJ and interact unstably with the reversed surface temperature gradient south of the Sahara, resulting in these two distinct tracks of AEWs (Pytharoulis and Thorncroft 1999). Following GATE, Payne and McGarry (1977) and Norquist et al. (1977) detailed a strong relationship between southern-track AEWs and convection for further growth and amplification. This relationship was further evaluated by Berry and Thorncroft (2005) and Thorncroft et al. (2008) through the study of latent heat release associated with embedded convection. The southern-track AEWs exhibit coupled convection located initially ahead, or west, of the trough over Africa, where atmospheric conditions are most conducive to convection (Reed et al. 1977; Fink and Reiner 2003; Núñez Ocasio et al. 2020). This understanding of southern-track AEWs initiated numerous studies on AEW–convection interaction's role in tropical cyclone formation in the Atlantic. Robert Burpee, GATE participant, researcher, and later director of the U.S. National Hurricane Center (1995–97), applied GATE knowledge to Atlantic hurricane forecasting.

More recent research on the structure of AEWs generally supports many of the key findings from the GATE field campaign, such as the role of convection and AEWs as tropical cyclone precursors. However, there have also been important developments in understanding their structure, behavior, and role in tropical weather systems. Specifically, modern research continues to refine and expand upon these observations using more precise data and advanced models, as discussed in this section. While our knowledge of the core structure and dynamics of AEWs have not changed drastically, the growing body of research provides a more nuanced view of their behavior and interactions with other atmospheric systems, particularly in terms of how AEWs interact with systems like the monsoon and the ITCZ, as well as their relationship to moisture, climate variability, and climate change.

Recent studies highlight the importance of the coupling and phasing of AEWs with embedded convection over the continent, prior to reaching the eastern Atlantic waters (Zawislak and Zipser 2014; Núñez Ocasio et al. 2020), as well as the location of their origin (Núñez Ocasio et al. 2021), in determining the suitability of an AEW for tropical cyclone formation.

Additionally, AEW literature has advanced to include the role of moisture (Núñez Ocasio and Rios-Berrios 2023; Russell et al. 2020; Rajasree et al. 2023; Núñez Ocasio et al. 2024) and the warming climate (Núñez Ocasio and Dougherty 2024) in the evolution of both AEWs and convection over Africa. This progress has been made possible through the use of convection-permitting modeling, work that builds on the initial guidance and findings established by GATE.

c. Boundary layer. The GATE atmospheric boundary layer subprogram goal was to document the influence of the atmospheric boundary layer (ABL) on meso- and synoptic scales, thus enabling its representation in numerical models. This required reasonably robust samples of vertical transports of heat, moisture, and momentum between the surface and the free atmosphere, a task made possible by carefully planned and executed flights of aircraft equipped with gust probes and inertial-navigation sensors. Up to three gust-probe aircraft combined to obtain vertical profiles of fair-weather ABL mean and flux profiles from 30 m through cloud top. Aircraft films and upward-looking IR data provided additional information on clouds (Zipser et al. 1974). Satellite images also provided context, and radiosondes, shipboard radar, tethered balloon, and surface measurements provided additional information on the boundary layer structure

Eddy-correlation flux estimates require fast and accurate measurements of wind, temperature, and water vapor. By 1974, several groups could measure airflow relative to the ground from sensors on aircraft or tethered balloons, and two methods existed to sample water vapor density at sufficiently high frequencies to estimate vertical fluxes from aircraft (McGavin and Vetter 1965; Buck 1976). However, while GATE could measure clear-air temperature from aircraft, the midlatitude community had not yet appreciated the importance of cleaning salt off the sensors, which sometimes led to artificially high temperatures (due to condensation on the salt) at high relative humidity (e.g., near cloud base). Thanks to the efforts of Steve Nicholls, and previous work by Schmitt et al. (1978), this problem was isolated (Nicholls and LeMone 1980). Similarly, GATE scientists became aware of the ship's impact on heating and airflow (e.g., Goerss and Duchon 1980). Unfortunately, aircraft measurements of temperature and mixing ratio inside clouds were challenging and remain so today.

After rejecting data with the most obvious salt contamination, Nicholls and LeMone (1980) were able to show for fair weather and weak winds that the negative sensible heat flux gets more negative and the positive latent heat flux gets more positive at the top of the subcloud

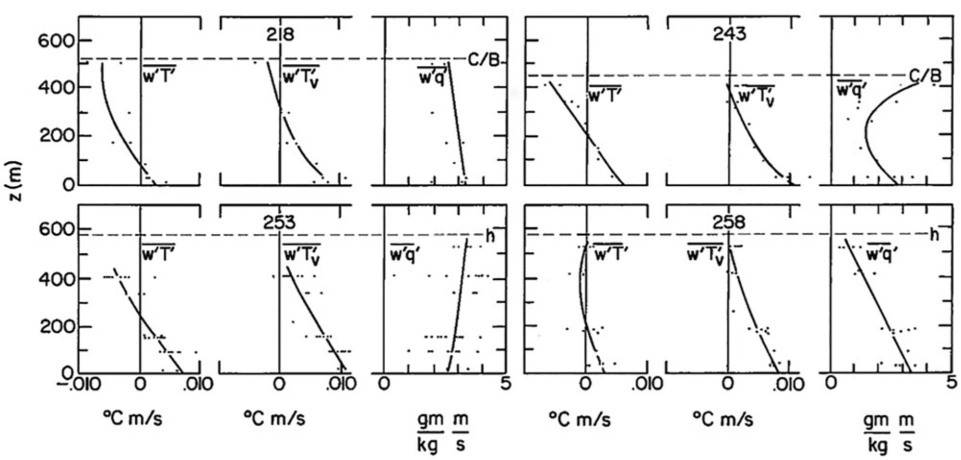

Fig. 4. For four fair-weather days in GATE, fluxes of temperature *T*, virtual temperature T_v, and specific humidity *q*. Equivalent sensible and latent heat (W m^{-1}) can be obtained by multiplying by 1150 and 2800, respectively. Skies were virtually clear on day 258; with cumuli on the other 3 days. From Nicholls and LeMone (1980). Fluxes involving *T* near cloud base on day 253 were clearly affected by salt contamination and thus are not included.

layer with overhead cloudiness, leading to a change from subcloud moistening under clear skies to an increased tendency toward drying with cumulus overhead (Fig. 4). Regardless of cloudiness, these two fluxes combined to produce a buoyancy-flux profile like that associated with a buoyancy-driven cloud-free convective boundary layer in weak winds—namely, decreasing linearly with height to roughly −0.2 times its surface value, a result supported by data summarized in Stull (1976) and large-eddy simulations (e.g., Moeng and Sullivan 1994). This was not surprising, given earlier work by Lilly, Deardorff, and others (Tennekes 1973 and references therein). However, the −0.2 entrainment ratio applies only to near steady-state convective boundary layers with weak winds—making it relatively uncommon, especially over land, so research remains active in this area (LeMone et al. 2019). More importantly, over the tropical oceans, water vapor flux accounts for around half the surface buoyancy flux, consistent with the earlier conclusion by LeMone and Pennell (1976) that all updraft buoyancy in the upper two-thirds of the subcloud layer was due to water vapor. This was expected by earlier researchers, but too-slow water vapor measurements from aircraft delayed documentation until the late 1960s (e.g., BOMEX; Bean et al. 1972).

Disparate fair-weather results based on different analysis approaches or instrumentation presented at the 1977 GATE workshop at NCAR brought conflicting authors together to focus on 1 day, 10 September 1974. They concluded in Barnes et al. (1980) that the fair-weather convective boundary layer could be far more heterogeneous than expected. Both tethered balloons and aircraft revealed organization on roughly 10-km scales. The aircraft maps were made possible by synergistically exploiting the oceanographer-designed sea surface temperature (SST) mapping "grid" pattern to document mesoscale fair-weather convection (LeMone and Meitin 1984). These mesoscale features compromised budget-based fluxes and challenged the statistical representativeness of aircraft fluxes. Despite this, averaged surface flux measurements were close to those extrapolated downward from aircraft profiles. The authors noted that residual cold-air pools from recent precipitation contributed to the heterogeneity. Although not cited as a source of heterogeneity, Gautier (1978) had already pointed out that SSTs in GATE impacted by recent MCSs were cooler than surrounding waters due to rainwater lenses on the ocean surface and enhanced evaporative cooling. The creation and evolution of such lenses remain a large focus of submesoscale oceanography and air–sea interaction research today. The later work by Balaji et al. (1993) suggests that tropospheric gravity waves may have created the 10-km scale subcloud-layer heterogeneity as well.

As observed in the 1965 *Meteor* expedition (Hoeber 1969), the diurnal cycle at the ocean surface sampled in GATE was muted compared to that on the land, with SST variation and order of magnitude less, and correspondingly smaller diurnal variation in surface fluxes (LeMone 1980). The dataset used in LeMone's paper, generated by Katsuyuki Ooyama and J.-H. Chu, is described in Esbensen et al. (1982).

Boundary layer impacts of cold pool air from fully developed MCSs were documented with shipborne acoustic sounders (Houze 1977; Gaynor and Mandics 1978) and by tethered-balloon and ship surface data (e.g., Barnes and Garstang 1982; Addis et al. 1984) as well as occasionally by aircraft. Although Barnes and Garstang (1982, their Figs. 4–6) indicated a smaller boundary layer impact of small-to-intermediate precipitating convection, there were no systematic quantitative studies of boundary layers with smaller precipitating clouds except for an example studied by Frank et al. (1981). Fortunately, recent field campaigns (e.g., EUREC4A; Bony et al. 2017; Stevens et al. 2021) have been investigating such cloud patterns. However, as noted, measuring temperature in clouds remains a challenge.

d. Oceanography. The primary goals of the GATE Oceanographic Program were to establish the temporal and spatial scales of variability of the oceanic circulation in the tropical Atlantic, to understand the dependence of transient features on the mean flow, and to understand the relation of ocean variability to that in the atmosphere (Düing 1974; Philander 1974). The Program sought to use this regional study to better understand the role of certain oceanic processes in the global coupled climate system, including understanding how different ocean basins varied and why. The principal GATE oceanographic measurements were taken in the C-scale hexagon (Fig. 2) with atmospheric measurements between 5° and 10°N close to Africa, downwind of the Equatorial Counter Current, and in the equatorial upwelling zone within the South Equatorial Current (Fig. 5).

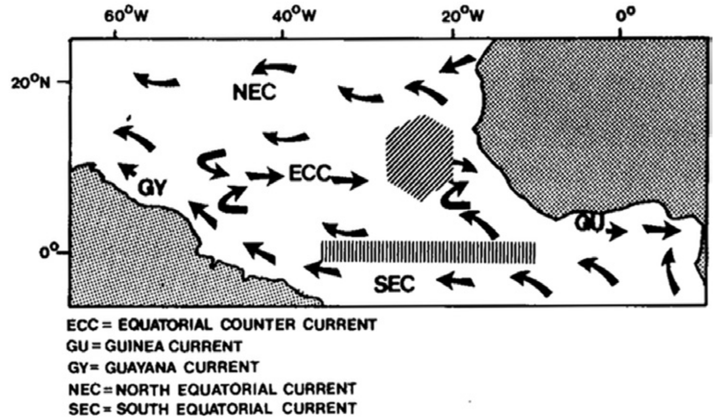

Fig. 5. Primary oceanographic data collection areas during GATE (stippled main A/B-scale array hexagon with coincident atmospheric observations and stippled equatorial elongated rectangle) relative to major Atlantic surface currents (from Philander and Düing 1980). Used with permission from Elsevier.

GATE oceanographic data were limited by significant gaps between sparse moorings and limited ship profiles. Despite this challenge, the equatorial Atlantic current structure and controls on it were inferred from ocean current, temperature, and salinity data, wind data, and geostrophic calculations between direct observations. GATE documented the Equatorial Undercurrent located just above 100-m depth and noted that salinity maximized 20–40 m above that depth (Philander and Düing 1980; Helm et al. 1980). These were some of the earliest salinity data collected in the region (Polavarapu and Austin 1979), as the first salinity sensors were developed in the early 1960s and the technology was not yet widespread.

Because the oceanographic experiment lasted 86 days (three 3-week periods) and the seasonal cycle of the equatorial Atlantic Ocean is so strong, the GATE record sampled a significant portion of seasonal variability. The currents, turbulent mixing, and thermocline tilt were suggested to be responsible for the seasonal cycle of vertical and horizontal heat transport (Philander and Düing 1980). The significance of these findings was that the seasonal cycle of heat transport was found to be impacted largely by internal ocean dynamics and not simply driven by wind variations.

Prior to GATE, knowledge of turbulent mixing from shear or instabilities was limited due to the use of bulky, unwieldy, and slow-to-deploy/slow-to-recover vehicles for vertical microstructure profiling, resulting in small sample sizes (Shroyer et al. 2018; Moum et al. 2022a). GATE revolutionized this process by making measurements from the ship using slimmed down profilers, allowing for more rapid and frequent profiles. This advancement enabled GATE oceanographers to study the minimum SST zone, the Atlantic cold tongue, seasonally varying advection, upwelling, and shear-driven mixing, the latter of which was found during GATE to maximize along the equator, above and extending into the thermocline (Crawford 1976; Crawford and Osborn 1979a,b). This turbulence is generated by shear between the wind-forced westward-flowing current in the ocean mixed layer and the eastward-flowing Equatorial Undercurrent situated above and in the thermocline. Subsurface turbulence's contribution to the surface cooling and downward heat transport through the thermocline remains a key research topic in both the Atlantic and Pacific cold tongues (Moum et al. 2022b; Holmes et al. 2019). In this way, turbulence and upwelling are key regulators of Earth's climate since most net surface cooling and downward transport of heat through the thermocline (i.e., ocean heat uptake) happens in such equatorial cold tongues (Holmes et al. 2019). Better constraining and understanding equatorial ocean processes continues to be one of our biggest climate challenges, demonstrating GATE's enduring influence on coupled climate science.

e. Air–sea interaction. Air–sea interaction, not an official subprogram of GATE, integrated components of the boundary layer and oceanography subprograms. While the technology, ocean observing platforms, and data processing at that time were rudimentary, air–sea observations from GATE were nonetheless part of the long-term efforts to address this critical subject and served as a milestone to mark the advancement in this field through later field observations. Although it is difficult to access articles in the aforementioned early issues of *Deep Sea Research,* limited information from GATE reveals progress made and problems encountered that motivated later studies.

During GATE, surface waves were measured by very large buoys for studies on low-frequency waves (Düing and Hallock 1980; Cardone et al. 1981; Lawson and Long 1983). There was apparently interest at that time to find universal functions or theories for waves. Based on data measured by buoys specifically designed for measuring waves, we know now that waves do not follow just one universal relationship (Donelan et al. 1985).

A key goal of the GATE Oceanographic Program (Düing et al. 1980) was to use ship and mooring data to investigate the seasonal energy balance and air–sea interaction across the ocean basin. Simple radiative transfer models were developed to estimate SST only from surface radiation measurements without knowledge or quantification of surface turbulent heat fluxes (Brown et al. 1982a,b). Only a few moorings during GATE collected mean surface meteorological data. Without durable flotation devices, sensors for the harsh air–sea interface, and buoy deployment/recovery procedures not damaging the equipment, meteorological sensors on surface buoys atop the oceanographic moorings were typically 50% successful. Today's gold standard estimates of air–sea fluxes based on eddy covariance did not exist, which require corrections of platform and wave motions and flow distortion around ships that were developed only after GATE (Fujitani 1985). Estimates of heat, moisture, and momentum fluxes from ships and buoys were based on surface-exchange coefficients proposed in the 1977 GATE workshop (NSF/NOAA 1977) by Lutz Hasse and Joost Businger, based on work described in Dittmer (1977), Hasse et al. (1978), and Khalsa and Businger (1977). The surface fluxes thus estimated from buoy/ship were reasonably consistent with those based on aircraft data extrapolated to the surface on a fair-weather day (Barnes et al. 1980) and were best for lowest-level along-wind aircraft measurements, with a correlation of 0.9 (Reinking and Barnes 1981). Although adequate for some applications, improvements were apparently necessary (Friehe and Schmitt 1976). It was not until the Tropical Ocean and Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE) in 1992–93 (Webster and Lukas 1992) that reliable ship estimates of eddy covariance air–sea fluxes were produced, which were used to derive the air–sea bulk flux transfer coefficients. These coefficients revolutionized the computation of bulk air–sea fluxes of momentum, sensible heat, latent heat, and surface buoyancy usable on mean meteorological and SST data from buoys, ships, satellite, and model output (Fairall et al. 1996a,b, 2003; Edson et al. 2013).

f. Radiation. The GATE radiation subprogram emphasized ways to measure and parameterize vertical profiles of radiative heating and their impact, including the effects of clouds [GATE/International Scientific and Management Group (ISMG) 1974]. To this end, Cox and Griffith (1979a,b) estimated 6-hourly radiative flux profiles for the A/B scale array during phase III, from synoptic temperature and humidity and satellite-based cloud structure, benchmarking their calculations using aircraft observations, and discussed the potential role of radiation in reinforcing the Hadley circulation. Atwater and Ball (1983) used hourly

GATE data to test various methods of estimating transmittance through clouds, while Smith et al. (1977) developed a radiative-heating model from the NASA CV-990 seven-channel multispectral scanning radiometer and evaluated the results with GATE data. Griffith et al. (1980) inferred radiative properties of cirrus clouds from aircraft hemispheric radiation data. Davies and Uboegbulam (1979), and Ball et al. (1981) tested models for incoming radiation at the surface using GATE data. Such efforts contributed to the development of modern radiative-transfer codes in numerical models of the weather, climate, and Earth system (Randall et al. 2019).

Radiation data also proved useful for other studies. For example, Nicholls et al. (1982) were able to estimate horizontally averaged net atmospheric heating from aircraft measurements of longwave cooling from Ellingson (1977) and shortwave heating using the method of Cox et al. (1976), enabling the earliest example of an LES of a realistic boundary layer case study with measured net radiation as input. Data from GATE also provided evidence for enhancement of developing MCSs by vertical velocity circulations driven by horizontal differences in radiative flux divergence—an active area of research at the time by Gray, Jacobson, Anthes, and many others (Byrd and Cox 1984 and references therein).

Unfortunately, aerosols were not emphasized in the GATE scientific mission. Opportunistic observations, however, included unique soundings at Dakar with the passage of large dust events (J. Prospero 2024, personal communication). Also, profiles of aerosol size spectra were estimated from GATE multiwavelength radiative flux profiles sampled at several altitudes in Saharan dust (Kondratyev et al. 1981; Welch et al. 1981). Carlson (1979) found horizontal patterns in optical depth for Saharan dust from NOAA 3 VHRR brightness data; and Prospero (1979) used surface-based data in two spectral bands (500 and 880 nm) to estimate turbidity from 5 land and 10 ship sites in the tropical Atlantic. Research on African aerosols later became an emphasis in tropical research (Prospero et al. 2021), especially in relation to AEW and hurricane studies.

5. GATE's legacy

a. Publications. A fundamental measure of a project's legacy is its publication record, and GATE's publication record is monumental. NSF NCAR maintains an online GATE bibliography, previously described by Zhang and Moore (2023). We have updated and expanded the bibliography to include journals not previously examined. Most new additions are from oceanography because some important publications are difficult to access via typical online searches. Notably, *Deep Sea Research* included a two-volume supplement on GATE results published (Siedler and Woods 1980; Düing 1980). Papers in the AMS *Journal of Physical Oceanography* (JPO) and the AGU *Journal of Geophysical Research-Oceans* (JGR-Oceans) were also missing from the NCAR database as were journals covering other topics, such as *Water Resources Research*. Finally, some early papers in the *Bulletin* of the AMS that had not been scanned for internet access were missing as were some publications in non-English journals. For example, 104 articles in Russian produced by USSR scientists in a two-volume set called *TROPEX-74* (Soviet National GARP Committee 1976a,b) were not included in the updated NCAR bibliography. Today, both the NCAR bibliography and a list of the articles from *TROPEX-74* are available on the NCAR-GATE website (https://www.eol.ucar.edu/field_projects/gate). These two sets of references have only a modest overlap with this article's references, which include

Table 1. Refereed papers for the first 15 years after field campaign. The first four rows are from Fig. 7 of Zhang and Moore (2023).

Field campaign	No. of papers
GATE (old NSF NCAR database)	95
TOGA COARE	210
AMMA (13 years)	178
DYNAMO	214
GATE (updated NSF NCAR database)	338

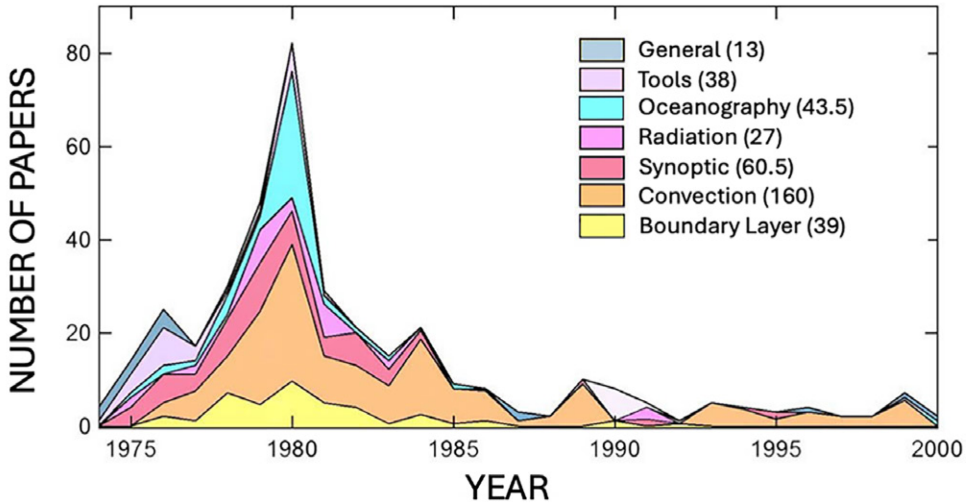

Fig. 6. Contribution of different topics to the total GATE publications in referred literature by year. Papers corresponding to more than one subprogram are assigned 0.5 for each of the two most significant ones.

both GATE articles and later studies inspired by GATE. For further details on the online bibliographies, see the online supplemental material.

The results, in Table 1, indicate that GATE papers 15 years after the field phase greatly exceeded those from the other field campaigns listed. The large number of GATE papers despite far fewer total scientific publications globally compared to today reflects the value of the GATE observations and the large number of scientists involved in GATE research.

Figure 6 shows GATE publications by year and topic, including the five GATE subprograms, boundary layer, convection, synoptic, radiation, and oceanography. In sorting, each publication was assigned a 1 for the subprogram that it best fit or a ½ for each of the top two subprograms that provided the best fit if it was more interdisciplinary. As documented earlier by LeMone (1983, 2003) and Zhang and Moore (2023), the number of papers peaked in 1980. GATE convection articles, peaking the same year, were the most common, consistent with most GATE talks at the GATE 50th anniversary being on atmospheric convection. The 6-yr lag of boundary layer papers as well as convection papers often reflected collaborations that combined data of different types from different platforms and sometimes different countries, with delays due to communication by post and the need to validate the data. Specialized boundary layer and radar data required extensive processing and detailed analysis. Also some GATE investigators depended on graduate student and postdoc researchers to analyze GATE data, and 4–6 years is the typical time for them to complete their programs of study. Evaluation of aircraft and radar data continued into the early 1980s. GATE oceanographic papers also peaked in 1980, owing partly to the time frame of the two volumes published as a special supplement to *Deep Sea Research*. Synoptic-scale papers had an earlier and shallower peak, in 1979, likely resulting from easier-to-access sounding data. It is not surprising that instrument descriptions peaked early.

b. Influences on later field campaigns. Another measure of GATE's legacy is how strongly it influenced subsequent field campaigns. GATE was the first of four similar field programs carried out in different parts of the equatorial oceans. These programs all used shipborne and land-based rawinsonde networks in combination with meteorological radars, boundary layer, air–sea interaction, ocean measurements, and research aircraft to better understand how energy from the ocean is transferred to the upper troposphere and affects atmospheric convection and large-scale dynamics.

In 1978, three of the Soviet ships that participated in GATE participated in the subsequent GARP field experiment, the Winter Monsoon Experiment (W-MONEX) (Johnson and Chang 2007). The ships formed a triangular rawinsonde network off the north coast of Borneo. A quantitative radar was positioned on the north coast to coordinate with the ship network, and the NOAA *WP3D* aircraft collected radar data over the network. W-MONEX began to show the universality of GATE results on the nature of tropical oceanic convection. In 1992–93, the international TOGA COARE (Webster and Lukas 1992) deployed nine ships and seven aircraft over the western Pacific warm pool. Again inspired by GATE, the ships formed a sounding network. Radars, now Dopplerized, were used and measured air motions consistent with those inferred indirectly from GATE data. The sounding network further led to the discovery of the trimodal nature of the oceanic tropical cloud population (Johnson et al. 1999). In 2011–12, DYNAMO (Yoneyama et al. 2013), conducted with ships, aircraft and land-based radars, rawinsondes, and other instruments over the tropical Indian Ocean, showed how convection like that in GATE contributed to the initiation of the Madden–Julian oscillation (MJO).

The GATE experimental design of a large network, and subnetworks within, also initiated a trend in oceanography to use supersites (Clayson et al. 2021, 2023) and overlapping platforms to obtain distributed, long-term observation sites, which are key to surmounting the sampling variability issues of observing atmospheric convection and the marine atmospheric boundary layer, as well as the submesoscale and lateral variability in the ocean.

Over the last half century, many other tropical field programs have followed the field program designs of the type pioneered by GATE (Johnson et al. 2012; Zhang and Moore 2023). A recent example is the EUREC4A project (Stevens et al. 2021).

c. DATA availability. The collection, processing, and storage of data are described in the GATE Report No. 13, the GATE International Data Management plan (de la Moriniere 1974), with details provided in the subprogram GATE reports, all archived at NSF NCAR, as described on the GATE/EOL website. The United States and USSR were named "World Data Centers," which archived data evaluated by subprogram data centers and organized according to the platform. As part of the U.S. GATE World Data Center, NSF NCAR still houses much of the GATE data, in either microfilm, hard copy, or digital form. For example, aircraft data were evaluated at NCAR and are still available in microfilm and digital form, and aircraft notes, films, and other metadata are also available through the website, which is still being refined.

6. Conclusions

GATE represented a significant step in our learning about the behavior of the tropical atmosphere, ocean, and their interaction. The experiment was designed to document phenomena on scales ranging from cumulus to synoptic. It produced a vast dataset that is accessible today (at https://www.eol.ucar.edu/field_projects/gate). Although the planning of GATE had envisioned cumulus and synoptic to be widely separated scales of motion, the field experiment showed that mesoscale convective systems were a major component of the cloud population, lying in the gap between cumulus and synoptic scales. Mesoscale convective systems are now widely recognized as major contributors to weather and climate. Other GATE findings about easterly waves, the tropical ocean boundary layer, and the oceanography of the tropics have led to decades of ongoing research.

Among the thousands of people in the field in GATE were young scientists, and for some of them, GATE launched their careers. Among the young participants were women, marking the beginning of a new era of atmospheric science in which women would become leaders in atmospheric science. Some of the younger GATE participants are still alive, and at the GATE celebration, they described their unique experiences half a century ago. GATE enabled people on the two sides of the Cold War not only to do something productive together but also to get to know one another. Finally, we would like to remember and dedicate this paper to those no longer living, from all the participating countries, who made GATE—the planning, the field phase, the data, and the discoveries that resulted—the grandest meteorological field program of all time.

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