THE SCIENCE OF WILLIAM M. GRAY

His Contributions to the Knowledge of Tropical Meteorology and Tropical Cyclones

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In a career spanning more than 50 years, Professor Gray made extensive contributions to the study of tropical meteorology and tropical cyclones and ushered in a generation of young scientists.

Through a long career from his first paper in 1962 (Gray 1962) to his last paper in 2017 (Klotzbach et al. 2015), William M. Gray was a towering figure in tropical meteorology, particularly for global studies on tropical cyclones (TCs). A major aspect of his legacy is that he is the scientific father of a generation of scientists (Hart and Cossuth 2013), having supervised more than 70 M.S. and Ph.D. students, many of whom have become leaders in research as well as in government, university administration, and weather forecasting.

His most important legacy, however, is his personal contributions to the advancement of knowledge in tropical meteorology in general and in TC science in particular. In this paper, we discuss the scientific advancement in several key areas where Gray was a fundamental contributor: cumulus–convective-scale interactions, observational methodologies and techniques, TC inner-core structure, TC track or motion, tropical cyclogenesis, seasonal TC prediction, and climate change impact on TCs. In each case, we summarize the intellectual contribution of Gray and put it in the context of the current state of knowledge.

TROPICAL CONVECTION–LARGE-SCALE SURROUNDING CIRCULATION.

A primary area of Gray's research in the 1970s was the interaction between cumulonimbus convection and the surrounding circulation. He made three major contributions that stimulated research and left a legacy, described in the following three subsections.

Structure of tropical weather systems. In a series of papers, Gray and his research team documented the structure of oceanic tropical weather systems using radiosonde compositing (as described in the "Tropical cyclone composite studies" section below; Williams and Gray 1973; Gray et al. 1975; Ruprecht and Gray 1976a,b; McBride and Gray 1980). Within a scale of several hundred kilometers, the weather systems identified were cloud clusters as defined by the large areas of upper-level cloud identified through satellite imagery (Williams and Gray 1973). In recent decades, a similar system would be described as a mesoscale convective system (MCS). Modern studies focus on the structure of the embedded squall lines including downdrafts, stratiform regions, and midlevel mesoscale convective vortices [see review of Houze (2004)].

The structure documented by Gray represents the parent synoptic-scale structure, or a "grid-scale average" over the mesoscale components.

The basic dynamic structure documented was a two-layer structure, with inflow (convergence) and cyclonic vorticity from the surface up to approximately 400 hPa, capped by a layer characterized by divergence and anticyclonic vorticity. This had several implications that were revolutionary at the time, including that

1) the boundary layer inflow is a contributing, but not dominant, component of the mass convergence into the weather system;
2) the maximum vertical velocity of the system is in the mid- to upper troposphere; and
3) through the approximate balance between diabatic heating and vertical motion (Frank 1980; Fraedrich and McBride 1989; Sobel et al. 2001), the heating profile also has a maximum in the mid- to upper troposphere.

The implications of this two-layer structure are far reaching and implied in all subsequent dynamical models of large-scale tropical convective structure. In particular, the findings described in points 2 and 3 above influenced the development of cumulus parameterization through the requirement that the cumulus heating profile is at a maximum in the mid- to upper troposphere (Yanai et al. 1973; Arakawa and Schubert 1974; Johnson 1984; Frank and McBride 1989; Houze 1989).

The thermodynamic structure revealed in these studies is weak temperature perturbations (~1°C) that were centered around 300 hPa. The major thermodynamic finding is that the large-scale areas containing tropical convection (the cloud clusters) are significantly more humid through the depth of the troposphere than the surrounding clear areas or regions containing no tropical convection. While seemingly trivial in modern days, this finding had

major implications and still motivates modern research on convection. For example, the introduction to a major work on moisture–convection feedbacks in the tropics (Grabowski and Moncrieff 2004) cites this finding as being the basic observation motivating their theoretical development. A second example is in the developing science of aggregation of convection, where the large relative humidity differences between convective and nonconvective regions play a significant role (Tobin et al. 2012; Wing and Emanuel 2014).

In recent times, the close in situ relationship between column-integrated water vapor and the presence of tropical deep convection is so well established that it is usually implied rather than explicitly cited. Still, as stated by Muller et al. (2009, p. 1), "[a]spects of this relationship are an integral part of theories for explaining tropical phenomena including the MJO, convectively coupled waves and hurricanes."

Documenting and understanding tropical weather systems was an area of activity across several groups at the time. Besides the work described in this subsection by Gray and collaborators at Colorado State University, parallel studies making some of the same findings were carried out at the University of California, Los Angeles (Yanai et al. 1973), and at the University of Washington (Reed and Recker 1971).

Convective mechanisms for heating and drying the large scale. Understanding the interaction between cumulonimbus convection and the large-scale environment was a major research focus in the early 1970s (Betts 1973; Ogura and Cho 1973), with practical applications for cumulus parameterization (Ooyama 1971; Arakawa and Schubert 1974). Gray's work focused on theoretical energy balances in the tropics. The key physical insight is that the observed grid-scale upward vertical motion in regions of convective activity is a residual between a large upward mass flux in protected cumulonimbus cores and a large downward motion (or compensating subsidence) in a larger area between these cores. This is illustrated in Fig. 1, taken from Gray (1973), which

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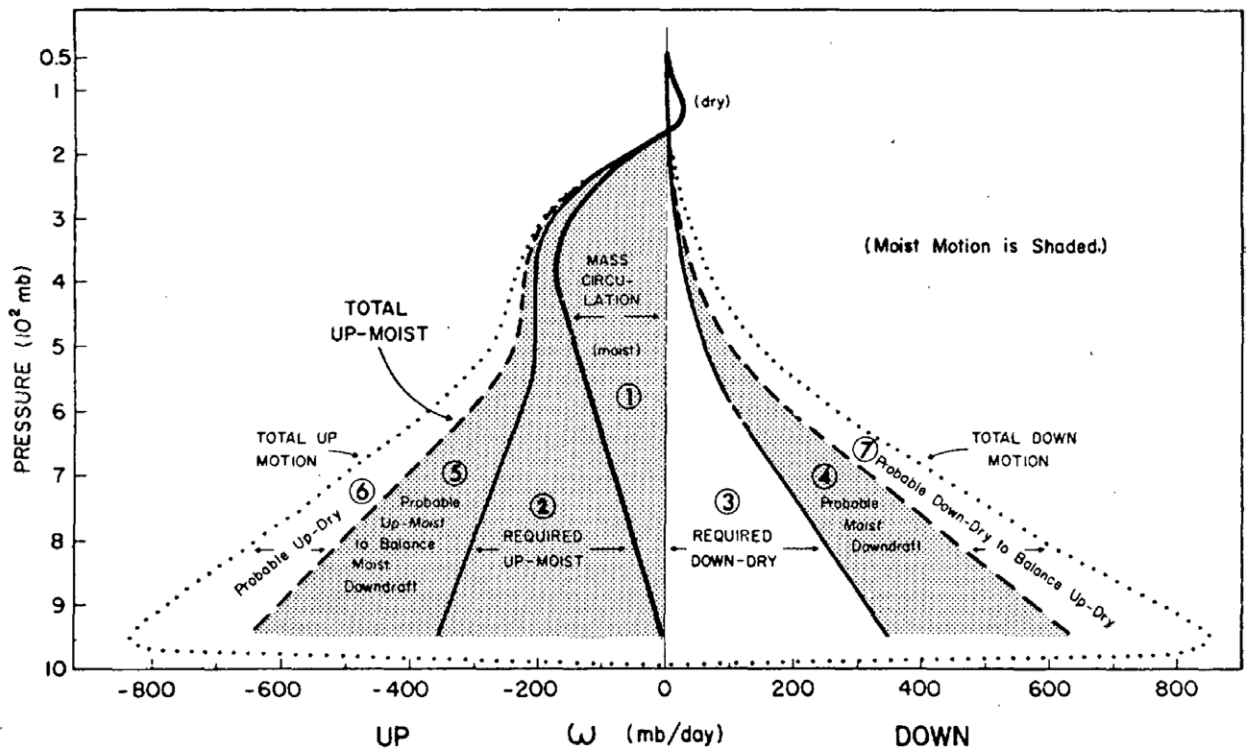
FIG. 1. Gray's original figure showing the requirement for additional (left) upward and (right) downward sub-grid-scale motion necessary to satisfy tropical heat and moisture budgets. The additional upward motion is hypothesized to take place in convective updrafts, while the downward motion includes clear air compensating subsidence, as well as moist downdrafts. From Gray (1973).

was derived from the transport requirements to satisfy the heat and moisture budgets of the large-scale tropics. This concept builds on the earlier "hot tower" hypothesis of Riehl and Malkus (1958). The major advance, made independently[1] by Gray (1972, 1973) and Yanai et al. (1973), was the realization of the mechanisms through which heating and drying of the troposphere occurred. It is succinctly summarized in the following quote from the review paper of Houze and Betts (1981, p. 542):

> Heat and moisture budgets in the vicinities of tropical cloud clusters were determined from rawinsonde data by several investigators in the early 1970s. Gray (1973) suggested that the budgets that were obtained could be explained only if an average cloud affected its large-scale environment through a combination of dry compensating subsidence, which warmed the environment, and detrainment of hydrometeors, which evaporated and thereby cooled the environment.

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[1] This major advance was made independently but in consultation with each other. It is noteworthy that the three major papers where the subsidence heating balancing reevaporation cooling referenced each other when formulating this concept (Gray 1973; Yanai et al. 1973; Arakawa and Schubert 1974).

Forty years later, this basic mechanism is still the paradigm for how cumulonimbus clouds affect the heat and moisture balances of the surrounding troposphere (though, of course, in high-resolution simulations, the mechanisms are resolved rather than parameterized; see, for example, Plant 2010 and Arakawa and Jung 2011). The catchphrase used by Gray to his students and colleagues was that cloud impacts were carried out by a subgrid-scale *up-moist, down-dry circulation*. Figure 2 illustrates this mechanism for temperature balance in a skew *T*–log*p* diagram.

Diurnal variation of cumulonimbus convection and theory of convective–radiative feedbacks. Gray and Jacobson (1977) wrote a seminal paper documenting that oceanic deep tropical convection experiences a single-cycle diurnal variation, with an early morning maximum and early evening minimum. Fundamental as this observation was, it was unknown at that time because of the masking of the signal by diurnal heating of island convection and out-of-phase contributions from stratiform and shallow convective rainfall. This paper comprehensively drew from global tropical rainfall data for small islands and corroborating information from an extensive literature review. This
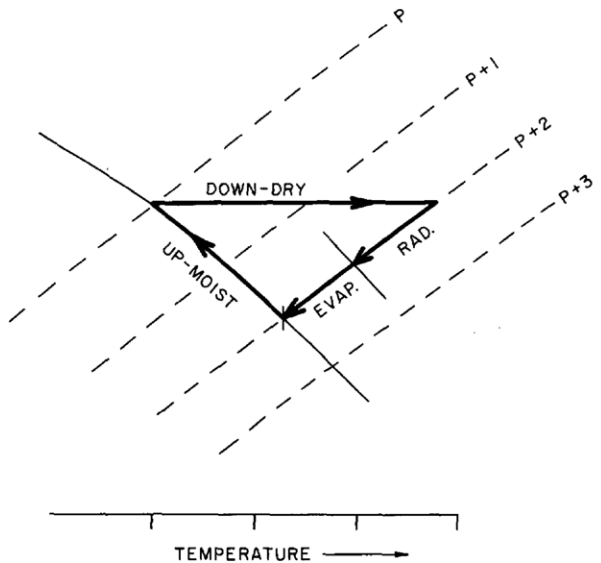
FIG. 2. The "up-moist, down-dry mechanism" whereby clouds transfer heat to the surrounding circulation. The upward motion along a moist adiabat represents the vertical motion within a cumulonimbus cloud. The downward motion along a dry adiabat represents the path of the compensating between-cloud motion. Along this path, the atmosphere is warmed by adiabatic compression. The closing constant-pressure path shows the balancing cooling mechanism of radiative cooling and evaporation of detrained cloud droplets. From Gray (1973).

paper's influence is profound, as illustrated by over 500 citations in the peer-reviewed literature.

Possibly of more lasting importance, however, is the theoretical mechanism proposed by Gray and colleagues to explain the diurnal cycle (Gray and Jacobson 1977; Fingerhut 1978; Foltz and Gray 1979; McBride and Gray 1980). They proposed that deep convection is driven by diurnally varying horizontal pressure gradients that respond to the radiative–convective heating profile differences between cloud-covered and surrounding cloud-free areas. As discussed in many recent reviews (e.g., Nesbitt and Zipser 2003; Ruppert and Johnson 2016), there is still no agreement on the physical cause of the observed diurnal variation of deep convection. However, in all reviews, the Gray and Jacobson (1977) cloud-clear radiative–convective heating differences is one of the major mechanisms evaluated. It is also invoked in ongoing studies of the diurnal cycle of TC upper-level clouds, including the phenomenon of outward-propagating diurnal pulses (Steranka et al. 1984; Kossin 2002; Dunion et al. 2014; Navarro and Hakim 2016).

The Gray–Jacobson mechanism is also important in climate change studies and associated

radiative–convective feedbacks. This is discussed at length in Stephens (2005) and Stephens et al. (2008).

TROPICAL CYCLONE COMPOSITE STUDIES. Development of the global rawinsonde network during World War II provided the first widespread atmospheric measurements of the troposphere. However, tropical rawinsonde stations were much too far apart and irregularly spaced to resolve the three-dimensional structure of individual weather systems. One answer to this problem was to composite the data. This section discusses Gray's development of the rawinsonde compositing approach, its application to analyzing tropical cloud clusters, and its revelation of basic TC structure and dynamics.

By the 1960s, there was general agreement that latent heat release was the dominant energy source realized within the tropical atmosphere and that precipitation occurred primarily within cumulonimbus clouds. Riehl and Malkus (1958) estimated that roughly 1,500 individual thunderstorms would have to be active at all times to explain the observed mean vertical structure of the tropical atmosphere. But as the quantity and quality of satellite data increased, it quickly became obvious that deep convection in the tropics was far more organized and complex than expected. For example, the imagery showed ubiquitous mesoscale clusters of precipitating systems rather than broad fields of single-cell thunderstorms. At the time, these mesoscale areas of deep convection, typically a few hundred kilometers in diameter, were dubbed cloud clusters (see the "Tropical convection—large-scale surrounding circulation" section). Their discovery called into question the tenets of the separation-of-scale arguments and began a healthy, if sometimes fierce, debate on the true nature of tropical weather systems.

Gray believed firmly that while data from the operational rawinsonde network were far too sparse to resolve individual tropical weather systems, one could achieve the necessary data density by compositing data from many similar systems. This approach required enormous quantities of data and adequate computing facilities to analyze them. Gray was the first researcher to assemble a nearly complete dataset of rawinsonde data within the northwestern Pacific, southwestern Pacific, southeastern Indian, and Atlantic basins.

The first problem was data acquisition. Most rawinsonde data were stored as ink on paper at individual weather stations. Gray exerted great effort and solicited considerable funding to accomplish the tedious job of acquiring soundings and surface data from tropical weather stations and digitizing them.
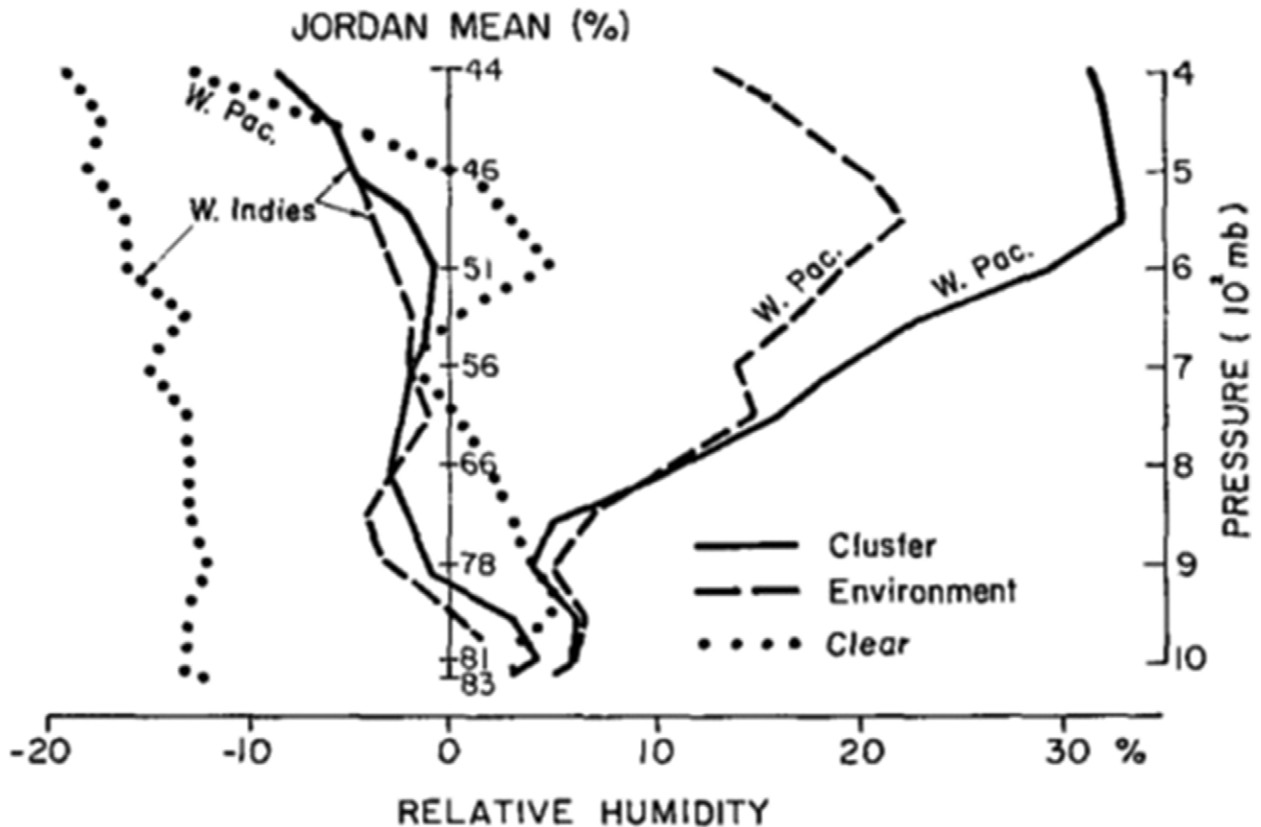
Fig. 3. Composited humidity values from tropical cloud clusters in the northwest Pacific and North Atlantic compared with the humidity profile of the Jordan mean sounding for the West Indies region (from Gray et al. 1975).

He, his students, and several visiting scientists then used these data to produce three-dimensional analyses of cloud clusters and TCs.

Gray's first composite analyses were of the newly discovered tropical cloud clusters. Studies such as Williams and Gray (1973) and Ruprecht and Gray (1976a,b) used a rectangular grid centered on each of many cloud clusters (located using satellite imagery). Rawinsonde data from nearby stations were added to the gridded dataset at their positions relative to the cluster. In this manner, a dense field of data could be obtained that represented the mean, three-dimensional atmospheric state within and around the cloud cluster. This type of compositing had two obvious weaknesses. First, if essential features of the cluster circulation were randomly distributed, they would not be resolved by blending data taken from many different cloud clusters. Second, since the sampled clusters occurred at different locations, the large-scale mean, or background flow, was somewhat distorted. It was then up to the compositor to try and minimize these effects by choosing only weather systems with similar observed characteristics and from limited spatial areas using both subjective and objective criteria. Careful data synthesis elucidated clear comparisons, such as composited humidity values from tropical cloud clusters in the northwest Pacific and North Atlantic contrasted to the humidity profile of the Jordan (1958) mean sounding for the West Indies region as shown in Fig. 3 (Gray et al. 1975). There are striking differences between the humidity values at all levels above the boundary layer. These notable differences between observed air masses and the Jordan mean sounding were confirmed by Dunion and Marron (2008) when investigating Saharan air layer and non-Saharan air layer soundings.

Although instrumented aircraft had probed the cores of TCs since the late 1950s, the datasets were largely confined to small areas of the cores at one or two low levels. Further, the storms could only be sampled for a few hours each day because of the logistical limitations of remotely based aircraft. Several researchers, including Gray, performed a great deal of innovative analyses of TC cores using aircraft data. However, they were unable to perform three-dimensional analyses of the storm core. The larger-scale structure was not observed, and it was impossible to compute budget analyses because of the inability to measure divergence in a vertical column.

The TC was an excellent subject for composite analysis despite the relative lack of observations over the oceans. These storms have a much more stable,
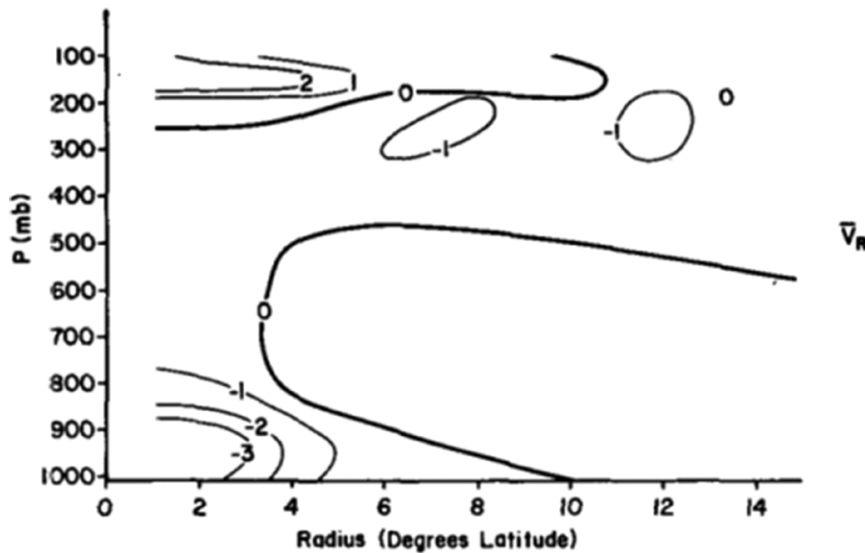
FIG. 4. Radial wind difference (in m s⁻¹) between a mature North Atlantic hurricane and a prestorm cloud cluster in the same region (from Frank 1982).

This was most dramatic in the upper-tropospheric outflow layer. Later analyses compared the mean structures of developing tropical depressions to those of mature TCs. Figure 4, taken from Frank (1982), showed the radial wind differences between a mature North Atlantic hurricane and a prestorm cloud cluster in the same region. The increase in the secondary circulation as the storm spins up was confined to within about a 6° radius. At larger radii, the secondary circulation actually became somewhat weaker as the storm intensified. The same compositing technique was applied to study differences between developing and nondeveloping cloud clusters (e.g., McBride and Zehr 1981). These studies showed that while vertical wind shear directly over the circulation center of developing clusters was small, the upper-tropospheric flow exhibited strong anticyclonic shear. In contrast, clusters with weak vertical shear and weak upper-level anticyclonic shear did not develop into TCs. The compositing techniques also were used in studies of TC motion, TC structure analyses using northwest Pacific reconnaissance flight data, and TC-spawned tornados, as discussed in the "Tropical cyclone inner-core structure" and "Tropical cyclone track" sections.

slowly varying structure than do loosely organized convective systems. Further, many of the major structural features are common from one storm to the next. The positions of the circulation centers are relatively well known, and they occur during limited seasons. In recent years, various reanalysis projects have been undertaken to better assess the location and intensity of TCs around the globe (Landsea et al. 2004; Truchelut and Hart 2011; Truchelut et al. 2013).

Most of the TC composites performed by Gray and his students used a cylindrical grid extending to 15° radius (~1,670 km) from the storm center and from the sea surface to about 80 hPa. The grid was centered on the storm circulation center at each rawinsonde observation time. In the northwest Pacific basin, even a grid this large typically had only five rawinsondes at a single time. However, composites performed for 10 years of mature typhoons in the basin could include almost 8,000 soundings. The TC composites resolved their three-dimensional structures, including the wind, moisture, and temperature fields (e.g., Frank 1977a,b). The wind measurements were accurate enough to permit computations of divergence and vorticity and hence vertical velocity. By compositing the products of the radial wind and other quantities (e.g., moisture, tangential wind, temperature), it was possible to estimate horizontal eddy fluxes. Three-dimensional budget analyses allowed computation of difficult-to-resolve quantities, such as sea surface mean fluxes.

The early composites showed that TCs were much larger than commonly thought. Their circulations clearly extended to the limits of the 15° grid boundary.

TROPICAL CYCLONE INNER-CORE
STRUCTURE. By the early 1970s, despite an accumulation of reconnaissance flight data, structural characteristics and variability of the TC inner core remained unexamined in a systematic way. The composite philosophy also proved insightful to deciphering inner-core patterns of TCs. Three examples and their implications toward understanding TC physics and operational implementation will be discussed in this section.

Gray and Shea (1973a,b) utilized 533 radial flight legs executed by the National Hurricane Research Laboratory over a 13-yr period (1957–69) to develop composites of tangential and radial winds, *D*-values (difference between actual altitude above mean sea level and an altitude calibrated to a surface pressure of 1,013 hPa), and adjusted temperatures with respect to the radius of maximum wind (RMW). These were

further stratified by intensity change, intensity, translation speed, and other parameters to identify useful features. Some conclusions were that

1) storm inflow is confined almost exclusively to the boundary layer and occurs from the RMW outwards then converges near the RMW;
2) the warmest TC temperatures result from subsidence and occur just inside the eyewall cloud edge where the sinking is strongest, and inner-core winds are shown to have a natural asymmetry beyond that induced by storm motion;
3) large vertical moist instability is present in the eyewall cloud;
4) supergradient winds are present at the RMW;
5) substantial mixing occurs between the eye and eyewall; and
6) inner-core heating comes from the sinking motion within the eye and not from cumulus updraft diffusion.

Gray and Shea (1973a,b) created spirited debate regarding the flight data navigation positioning accuracy and frame-of-reference gradient balance philosophies (Willoughby 1990; Gray 1991; Willoughby 1991). The composite philosophy of flight measurements encouraged future reconnaissance data to be explored in this fashion, ultimately proving an effective methodology for gleaning thermodynamic and dynamic properties of inner-core physics. In particular, the National Oceanic and Atmospheric Administration/Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division (NOAA/AOML/HRD) flight-level data and Doppler radar archives have generated many studies on kinematic structure (Eastin et al. 2005; Aberson et al. 2006; Rogers et al. 2012). Global positioning system dropwindsondes (Hock and Franklin 1999) showed that a 0.5–1.0-km wind speed maximum is a common feature of the TC boundary layer, from which empirical adjustments for estimating 10-m winds have been developed. These datasets have

spurred discussion and insight into unbalanced flow. As an example, Kepert (2001) proposed a diffusion and advection mechanism for producing the wind maximum, postulating strong inward advection of angular momentum generating the supergradient flow. Schwendike and Kepert (2008) showed that the strength of the supergradient wind flow was related to the inertial stability in an investigation of Hurricane Danielle (1988) and Hurricane Isabel (2003). Northwest Pacific TC case studies in Tse et al. (2014) and Sanger et al. (2014) showed that supergradient flow dominated the TC boundary layer inside the RMW, concluding that the unbalanced dynamics are an important component in determining radial and tangential flow maximum during a storm's evolution.

Boundary layer composites using marine observations have also clarified the quasi-isothermal inflow of TCs (Cione et al. 2000), provided radial flux distributions (Kowaleski and Evans 2015), and clarified quadrant drag coefficient saturation (Powell et al. 2003). Such insight has resulted in adjustments to boundary layer formulations used in the Hurricane Weather Research and Forecasting Model (Gopalakrishnan et al. 2013; Trahan et al. 2016).

A second example highlights the Gray research group's philosophy of compartmentalizing complex structures—such as the TC radial wind field—into conceptual models highlighting distinct features. Merrill (1984) postulated TC wind structure with three characteristics: intensity (maximum sustained 10-m wind), size (extent of the TC vortex from RMW
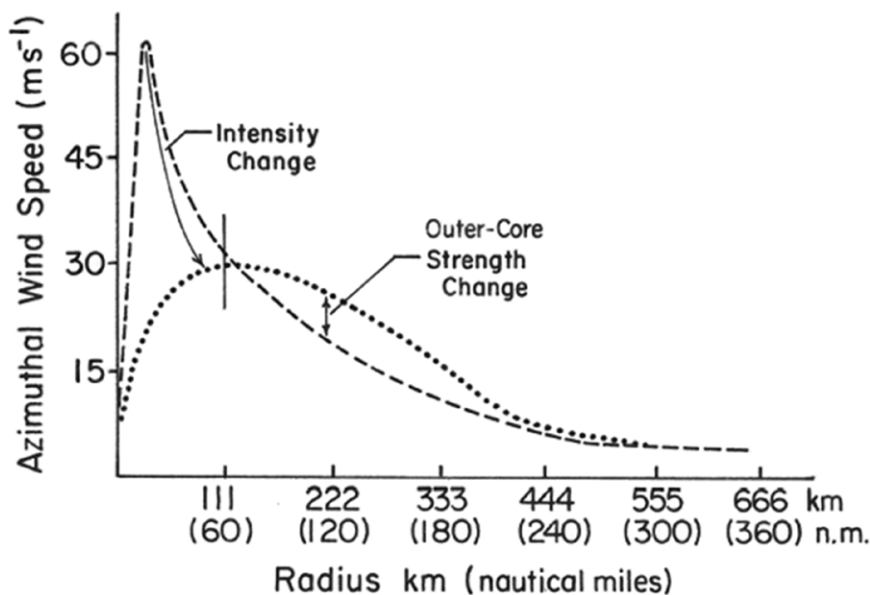
FIG. 5. A conceptualized view of changes in the radial profile of tangential wind in terms of eyewall peak winds and the mean tangential wind within 1°–2.5°, defined as the OCS. From Weatherford and Gray (1988a).

to radius of gale-force wind), and strength (average wind speed of the vortex), motivated by the poor correlation of TC gale-force wind radii to intensity (Fig. 5). From this work, he proposed a metric for size called the radius of outer closed isobar (ROCI). Weatherford and Gray (1988a,b) further defined the mean tangential wind velocity within a 1°–2.5°-latitude radius from the TC center as the outer-core wind strength (OCS) and noted only weak correlations with central pressure. However, the relationship between OCS and central pressure improved when eye size was considered (Fig. 6). A high correlation was also found between OCS and radius of gale-force winds, an important parameter for the U.S. Navy and ship-routing activities, as well as a critical threshold for terminating certain evacuation operations during TC landfall events.

The above research provided motivation that gale-force wind predictions may have skill and spurred further research into multivariate relationships for wind and pressure. Members of the Gray research project and others followed with an operational-oriented focus on empirical gale-force prediction schemes (Cocks and Gray 2002; Knaff et al. 2007; Demuth et al. 2004); analyses from infrared satellite data (Mueller et al. 2006); skill assessments of outer-core

winds in numerical models (Cangialosi and Landsea 2016; Sampson and Knaff 2015); and pressure–wind relationships as a function of size, RMW, latitude, translation speed, and environmental pressure (Knaff and Zehr 2007; Courtney and Knaff 2009). This new wind–pressure relationship is being used operationally by TC warning centers around the world.

Studies of TC structure climatology have also been conducted by Gray project members (Chan and Chan 2012) and by others in the meteorology community (Kimball and Mulekar 2004; Jinnan et al. 2007). From this research has evolved a TC structure dataset known as the "extended best track" used in several studies (e.g., Mohapatra and Sharma 2015; Dolling et al. 2016). The science has evolved using outer-core structure research for improving TC vortex representation in model initialization (Tallapragada et al. 2014) and for parametric models frequently used in storm surge applications (Wood et al. 2013).

One final example is the composite study of Novlan and Gray (1974) regarding tornadoes in landfalling TCs, with more details on quadrant methodology in Novlan and Gray (1975). Before this study, smaller-sampled studies had been conducted in shorter time frames (e.g., Smith 1965). However, Novlan and Gray (1974) utilized rawinsonde and pibal datasets from 1948 to 1972 for the United States and 1950–71 for Japan, the largest scope at that time. More crucially, it identified the importance of the land interface in generating tornadoes due to increased low-level vertical shear and found that one important difference between TC-generating tornadoes and tornado-free TCs was a vertical shear of 20 m s^{-1} between the surface and 1.5 km. As originally postulated by Smith's limited dataset, Novlan and Gray also confirmed tornadoes concentrated in the right-front quadrant from 100 to 400 n mi (1 n mi = 1.852 km) radially from the storm center, establishing an additional hazard of concern during landfalling events. Novlan (1973) argued that two primary reasons why tornadoes concentrated in
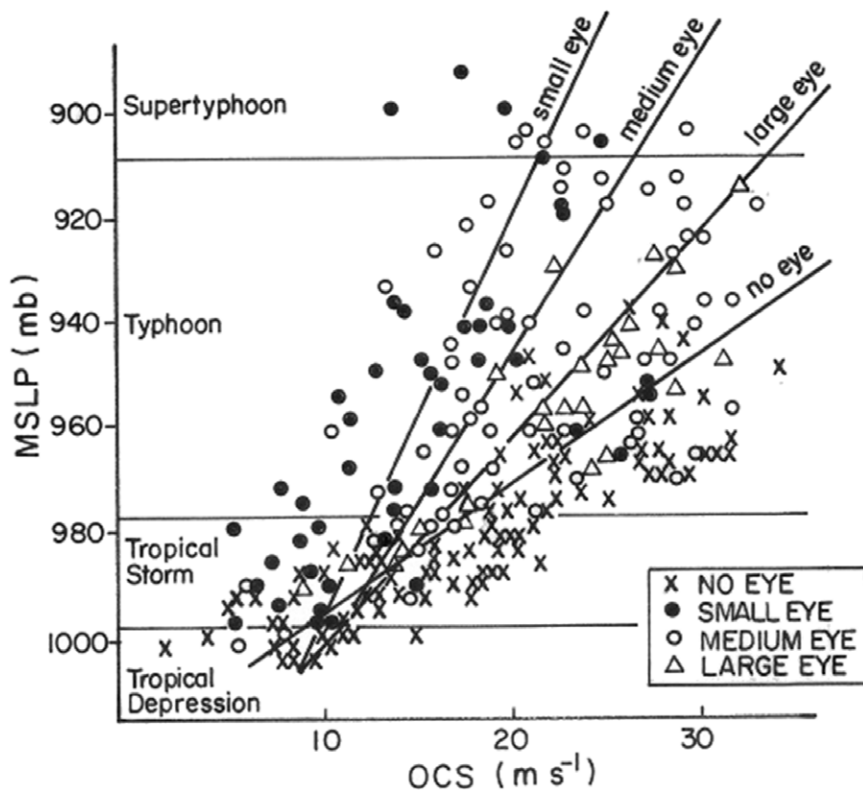
FIG. 6. Mean sea level pressure (MSLP) vs OCS by eye-size class. From Weatherford and Gray (1988b).

that quadrant were that it contained the strongest vertical wind shears as well as the maximum values of low-level convergence.

The primary findings of Novlan and Gray (1974) have changed little with time, even with larger and more modern datasets (e.g., McCaul 1991). However, nuances in tornado patterns have emerged, summarized by Edwards (2012, and references cited therein). These studies have established that higher concentrations occur in the outer bands because of increased low-level vertical shear, continuous banding with supercellular structure, larger convective available potential energy values, and a more pronounced diurnal cycle than in the central region. The peak time period for TC tornadoes is just prior to landfall to 24 h after landfall because of early inland spiral bands. The most productive tornadic TCs are of hurricane strength as opposed to tropical storm strength.

Later climatological research showed that typically 10–30 EF0 or EF1 tornadoes, on the enhanced Fujita (EF) scale, will occur in the spiral bands, with an occasional EF2 or EF3, indicating that special forecast attention is necessary during landfalling events. In the United States, TC tornado prediction today is a coordinated effort between the Storm Prediction Center, the National Hurricane Center, and the local National Weather Service office staged as outlooks, watches, and warnings [see details in Edwards (2012)]. However, not all landfalling TCs produce tornadoes, and the geographic coverage varies, so forecast challenges remain, requiring further research.

TROPICAL CYCLONE TRACK. Riehl (1954, p. 345) stated that "in the mean, tropical storms move in the direction and with the speed of the steering current, which is defined as the pressure-weighted mean flow from the surface to 300 mb over a band 8° latitude in width and centered on the storm." Based on this statement, many schemes have since been developed to predict a TC track using the "steering flow" at different levels and over different regions around the TC (e.g., Sanders and Burpee 1968; Velden
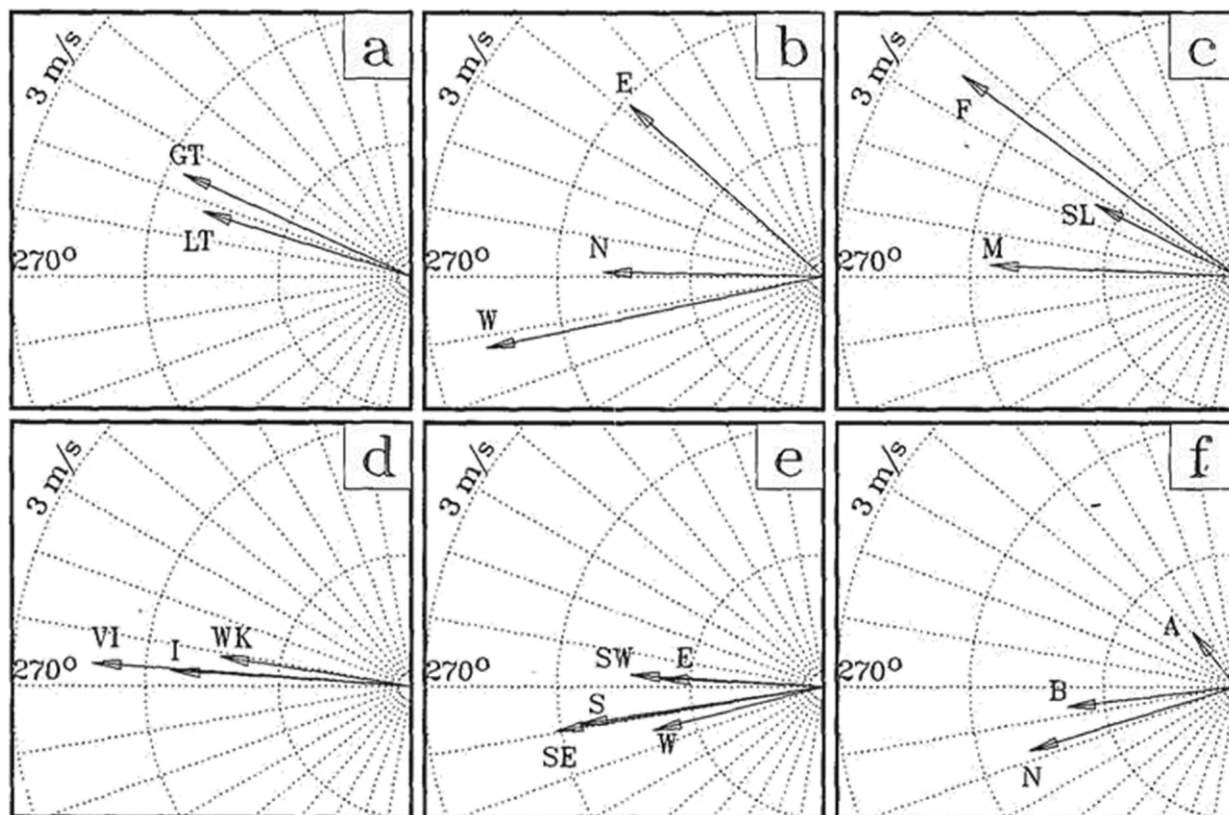
FIG. 7. (a)–(d) Difference vectors of composite TC motion minus the steering flow for various categories of TC characteristics in the western North Pacific based on the data from Chan and Gray (1982): (a) latitude [north (GT) and south (LT) of 20°N], (b) direction of TC motion, (c) speed of TC motion [fast (F), medium (M), and slow (SL)], and (d) TC intensity [very intense (VI), intense (I), weak (WK)]. (e),(f) As in (a)–(d), but for TCs in the Southern Hemisphere based on the data from Holland (1984): (e) direction of TC motion, and (f) before (B), no (N), or after (A) recurvature (from Carr and Elsberry 1990).
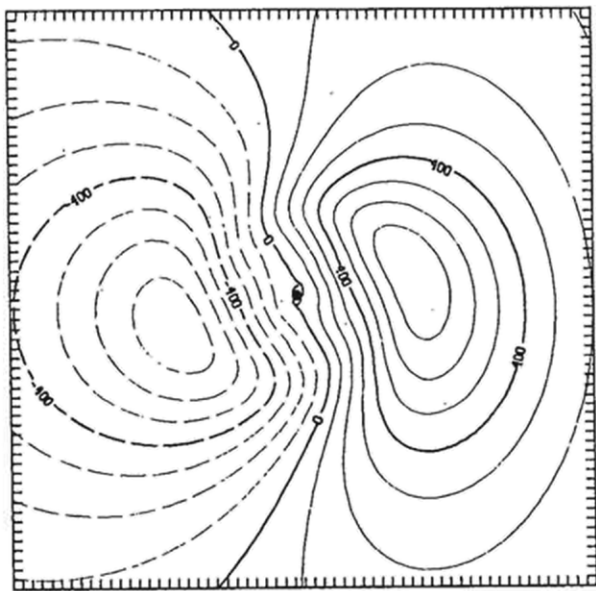
Fig. 8. Asymmetric streamfunction (10^4 m^2 s^{-1}) associated with the beta effect in a barotropic model. Solid and dashed contours indicate positive and negative values of streamfunction, respectively (from Fiorino and Elsberry 1989).

and Leslie 1991). These differences resulted from the limited cases used for each of the studies.

In an attempt to find a "universal" scheme for track prediction based on this steering concept, Gray proposed that one should apply a compositing technique to study the flow surrounding many TCs. George and Gray (1976) therefore composited 10 years of rawinsonde data over the western North Pacific for TCs with different characteristics, including direction and speed of motion, intensity, and intensity change. In all the categories, the same general conclusion was made: the 1°–7° latitude azimuthally averaged winds have the best correlations with TC motion, with the 700-hPa flow having the highest correlation for speed and that at 500 hPa for the direction of motion. This was the first time such a systematic documentation of the relationship between TC motion and its surrounding flow was made. A similar conclusion was drawn by Gray for the Atlantic using a similar methodology (Gray 1977).

Chan and Gray (1982) refined such a documentation by examining only the 5°–7° latitude azimuthally averaged winds, postulating this band average would eliminate most of the TC circulation and thus be more representative of the surrounding flow. They also composited the flow based on latitude and size and included TCs in the Southern Hemisphere. In addition to the flow at individual levels, they also examined the mean tropospheric flow between 850

and 300 hPa. In all the ocean basins, similar results to those of George and Gray (1976) were found.

A more important conclusion from both studies is that although the tropospheric flow around the TC correlates very well with TC motion, contrary to Riehl's (1954) statement, TCs very often move at an angle to their "steering" flow, as summarized by Carr and Elsberry (1990) using the results from Chan and Gray (1982) and Holland (1984; Fig. 7). Irrespective of the characteristics of the TCs, the difference vector of TC motion minus the composite steering flow is generally nonzero and points westward and poleward. In other words, in addition to steering, some other mechanism(s) must be present to cause the TC to move. Indeed, theoretical studies starting with Rossby (1948) had proposed the Coriolis force as being a mechanism for TC movement, but no observational evidence had been shown.

Chan (1984) for the first time composited rawinsonde observations to demonstrate that the vorticity budget can be used to diagnose TC movement. A TC tends to move toward the area of maximum relative vorticity tendency, which within most of the troposphere (850–300 hPa) is mainly contributed by the advection of absolute vorticity. The advection of relative vorticity is essentially steering. The advection of planetary vorticity is the component that was not considered. It is apparently this component that causes the TC to move differently from that of steering.

Holland (1983) showed that in the Northern Hemisphere, advection of planetary vorticity by the tangential winds of the TC gives a positive (negative) vorticity tendency to the west (east) of the TC. This sets up a secondary circulation with cyclonic (anticyclonic) flow, which then drives the TC northward. Combining this movement with the relative vorticity tendency being positive to the west causes the TC to move toward the northwest. Chan (1982) discussed this concept to explain the results of George and Gray (1976) and Chan and Gray (1982) in terms of the deviation of TC motion from the steering flow.

Chan and Williams (1987) ran a barotropic numerical model to study the concept proposed by Holland (1983) further. They found that inclusion of the nonlinear advection of relative vorticity was crucial in causing the TC to move toward the northwest. This northwestward movement of a TC caused by the variation of the Coriolis parameter has been known as the beta effect. Fiorino and Elsberry (1989) showed that the asymmetric flow associated with the beta effect is in the form of a pair of counter-rotating gyres, which have since been known as "beta gyres" (Fig. 8).
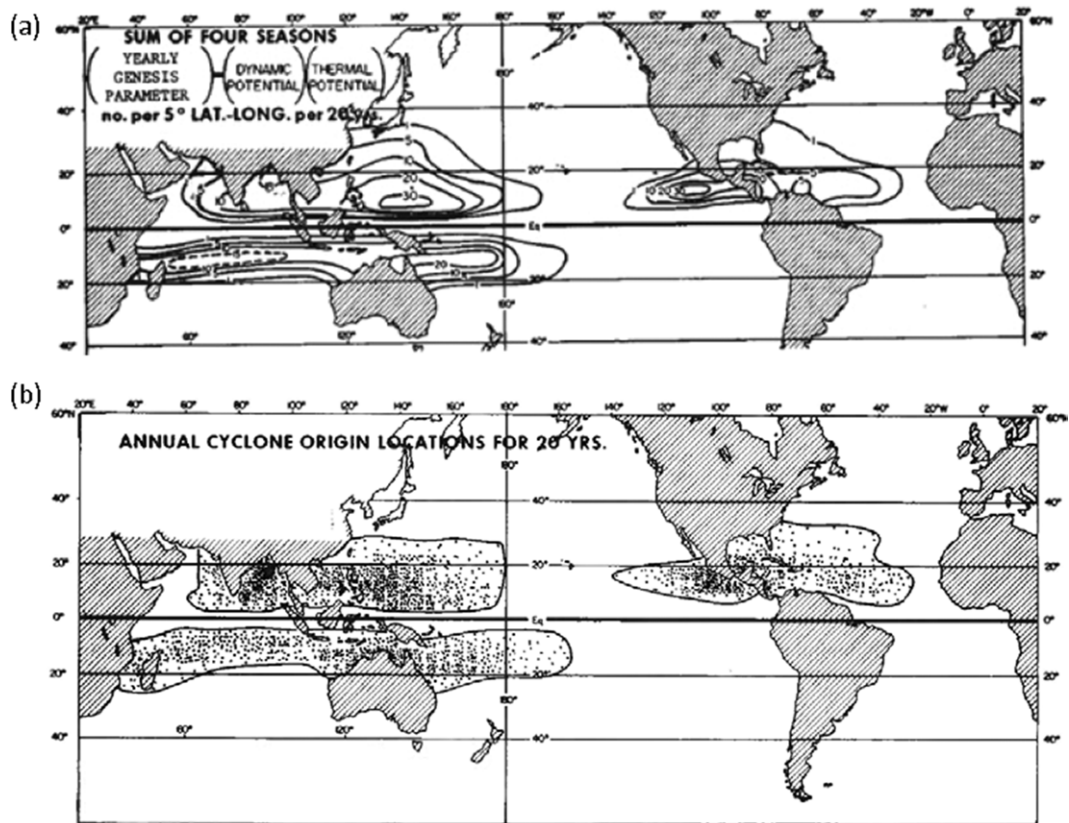
FIG. 9. Portrayal of (a) four-season sum of the original genesis parameter and (b) TC origin locations for a 20-yr climatology from 1958 to 1977. Both figures taken from Gray (1979).

This new concept that TC motion equals steering plus the beta effect, together with their nonlinear interaction, proposed by Gray and his students triggered many subsequent theoretical and observational studies [see review by Chan (2005)]. These concepts have also been used to explain why numerical weather prediction (NWP) models for TC track prediction at the time all tended to have a slow bias in the first 24–36 h. A symmetric vortex was generally inserted into the model, but because of the beta effect, the vortex should be asymmetric. Carr and Elsberry (1992) used a barotropic model to obtain improvements in track forecasting by explicitly including the beta propagation. Following this idea, Heming et al. (1995) inserted an asymmetric vortex in the Met Office operational forecast model to simulate the beta effect and reduced the TC track forecast errors for all time periods by up to 50%. Since then, many operational NWP models for TC track predictions have also included asymmetric vortices in their initial conditions, until the last decade, when many more observations have become available to be assimilated into the model so that the initial vortex could be better represented, especially with the improved assimilation techniques.

With advances in computational capability, TC motion studies evolved from barotropic to fully baroclinic models, and the use of vorticity budgets to diagnose TC motion were replaced by potential vorticity budgets to take into account the diabatic heating in a baroclinic atmosphere (Wu and Emanuel 1995a,b; Wu and Wang 2000; Chan et al. 2002). With these studies, it may be concluded that the physical mechanisms responsible for TC motion over the ocean are largely understood (Chan 2005).

Thus, the pioneering effort of Gray and his students in initiating a composite study to relate TC motion to its environmental flow has led to a relatively complete understanding of TC motion and contributed to a substantial improvement in operational forecasting of TC tracks for close to two decades.

TROPICAL CYCLOGENESIS. Gray's research often focused upon understanding the physical mechanisms and controls of tropical cyclogenesis: the formation of a coherent convectively forced, synoptic-scale vortex. Gray wrote a seminal paper on tropical cyclogenesis (Gray 1968), which today is still one of the most widely cited papers in all of tropical meteorology. This foundational paper explained the observed geographic

and annual cycle climatology of tropical cyclogenesis with the key environmental factors that determine these distributions. One of the most important factors was tropospheric vertical shear. Previously, the importance of vertical shear for genesis (and intensification) was not fully appreciated in either the peer-reviewed literature or by operational forecasters, though earlier work (e.g., Riehl 1954; Palmen 1956; Ramage 1959) did make some linkages. The paper also provided a clear differentiation between basins in which the monsoon trough (termed "doldrum equatorial trough" in the paper) is present and helped promote genesis versus basins in which the intertropical convergence zone (termed "trade winds equatorial trough" in the paper) dominates and is less conducive to tropical cyclogenesis. Gray further elucidated the necessary factors for genesis in Gray (1979), where he formulated the occurrence of tropical cyclogenesis to be a combination of dynamic and thermodynamic potentials (Fig. 9). Here is where he first specifically related genesis to the following factors:

1) cyclonic low-level vorticity (from a preexisting easterly wave, the monsoon trough, or an upper-level low/frontal boundary),
2) moist midtroposphere,
3) conditional instability through a deep tropospheric layer,
4) warm and deep oceanic mixed layer,
5) weak tropospheric vertical shear of the horizontal wind, and
6) location of disturbance a few degrees poleward of the equator (i.e., a significant value of Coriolis force).

These six "ingredients" in the TC "recipe" for genesis are still widely accepted today, though modified some. For example, newer formulations use subsets of these factors and obtain more variability explained, while others have combined factors together (such as 1 and 6 together as absolute vorticity) or have replaced ingredients with a more physically based factor (such as substituting in potential intensity for 4; Emanuel and Nolan 2004; Camargo et al. 2007c).

In the 1980s and early 1990s, Gray's contributions to TC genesis were in conjunction with many of his graduate students at Colorado State University: McBride and Gray (1980), McBride (1981a,b), McBride and Zehr (1981), Frank (1982), Love (1985), Lee (1989a,b), and Zehr (1992). Much of this work demonstrated that while the thermodynamic components in the tropical cyclogenesis recipe (2, 3, and 4) were often satisfied for much of the cyclone season, it was the variability in the dynamical factors (1 and 5) that determined whether a disturbance would undergo genesis or not. Such differentiation allowed for better understanding of the physical causes between the very active TC basins (such as the northwest and northeast Pacific), the "marginal" basins (such as the North Atlantic), and basins that are generally free of TC activity (such as the southeast Pacific and South Atlantic). Zehr's work in particular identified a two-stage process (Fig. 10) for genesis when the synoptic conditions were fulfilled. Stage one is when a convective maximum occurs within the circulation of a synoptic-scale tropical
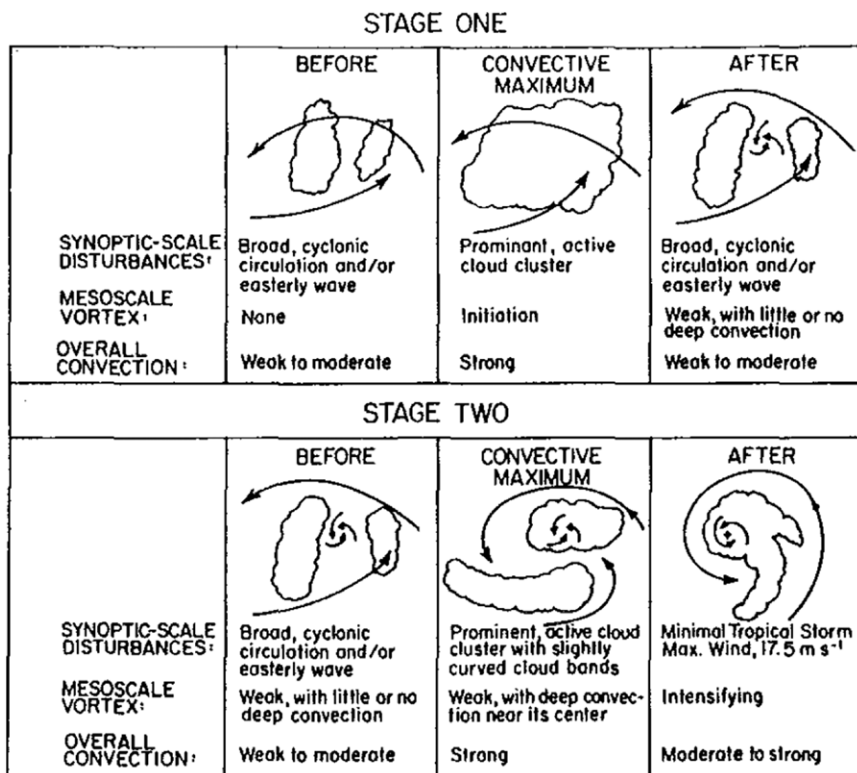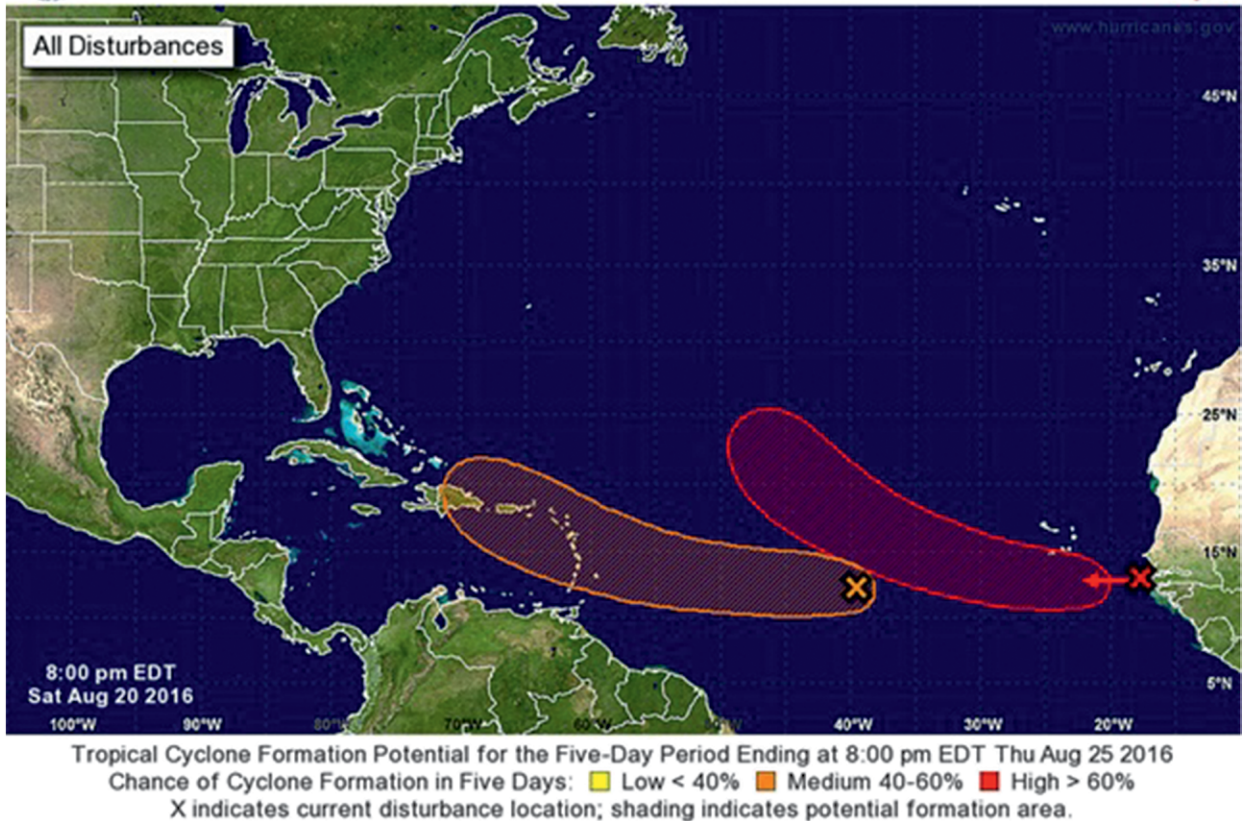

Fig. 10. Conceptual model of tropical cyclogenesis with illustrations and descriptions of characteristics that are observable using satellite imagery (from Zehr 1992).

Five-Day Graphical Tropical Weather Outlook
National Hurricane Center Miami, Florida

All Disturbances

8:00 pm EDT
Sat Aug 20 2016

Tropical Cyclone Formation Potential for the Five-Day Period Ending at 8:00 pm EDT Thu Aug 25 2016
Chance of Cyclone Formation in Five Days: ☐ Low < 40% ☐ Medium 40-60% ☐ High > 60%
X indicates current disturbance location; shading indicates potential formation area.

Fɪɢ. 11. The five-day graphical tropical weather outlook issued by the National Hurricane Center at 0000 UTC 20 Aug 2016. The x indicates current disturbance location, and the shading indicates potential formation area.

disturbance. This initiates a midlevel mesoscale vortex. Stage two occurs one day to a few days later with a second convective burst, which then develops the mesoscale vortex to the surface and thus genesis. Gray's last direct contribution to the field (Gray 1998) was an overview of Gray and his students' 30 years of research toward understanding the physics of genesis.

Despite these accomplishments, as Frank (1987, p. 78) described, "[a]ttempts to apply these criteria to daily forecasting of cyclone genesis have met [at that time] with little success." It was not until the advent of high-resolution global weather forecast models in the late 1990s that predictions of genesis were possible. The first methods with some forecast skill were those that used the synoptic-scale output of the global models to make genesis predictions (e.g., Hennon and Hobgood 2003). More recent work is in using the explicit genesis predictions from global models after accounting for various models' biases either in being over- or undercyclogenetic (Halperin et al. 2013). These improved capabilities have allowed operational TC forecasting centers such as the National Hurricane

Center[2] to begin issuing quantitative, probabilistic-based genesis predictions—48-h graphical tropical weather outlooks (GTWO) beginning in 2008 and 5-day GTWO starting in 2013 (Fig. 11). The success of these genesis predictions would not be possible without the foundation for understanding tropical cyclogenesis that Gray and his students provided over the last few decades.

SEASONAL ATLANTIC HURRICANE PREDICTIONS. Gray was best known among the general public for his groundbreaking contributions to Atlantic basin seasonal TC prediction. Prior to his development of these forecasts, not only were there were no publicly issued predictions for overall

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[2] Five of Gray's former graduate students are currently forecasters at the National Hurricane Center and are active in making tropical cyclogenesis (and other TC-related) predictions on a daily basis. They are Eric Blake, Todd Kimberlain, Chris Landsea, Carl McElroy, and Dan Mundell. They represent about one-fifth of the current forecast staff at NHC.
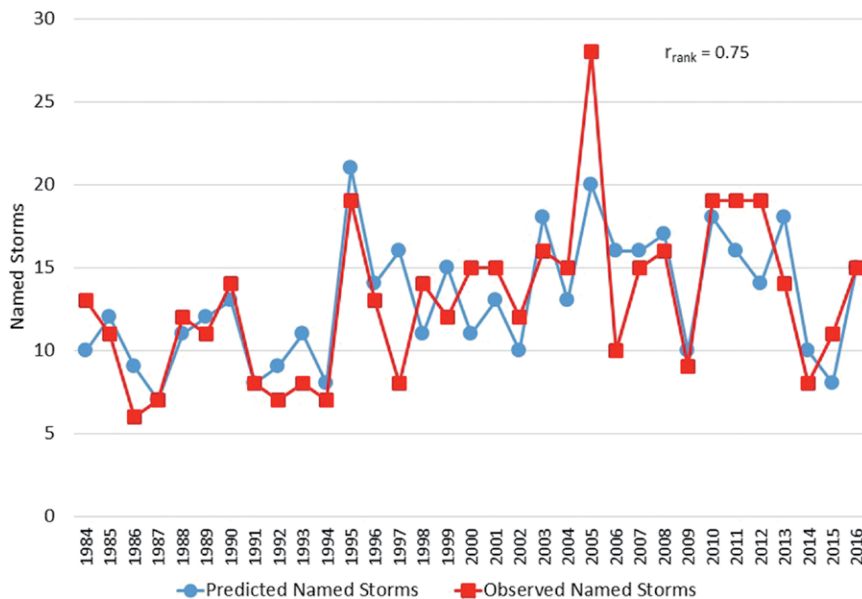
FIG. 12. Observed vs predicted Atlantic basin named storms by year from 1984 to 2016 from the early Aug seasonal forecast. The rank correlation between prediction and observation is 0.75 over the 33-yr forecast period.

Atlantic basinwide activity, but Atlantic TC teleconnection patterns had only been rudimentarily investigated (Ballenzweig 1959). In a series of two papers (Gray 1984a,b), Gray noted statistically significant relationships between El Niño–Southern Oscillation (ENSO), Caribbean sea level pressures, and the phase of the quasi-biennial oscillation (QBO) with Atlantic hurricane activity over the period from 1950 to 1982. Warm ENSO conditions, high Caribbean sea level pressures in June–July, and an east phase of the QBO were all associated with below-normal hurricane seasons, with opposite conditions being associated with above-normal hurricane seasons. Gray's hypothesized link was that El Niño–forced increased convection in the central tropical Pacific reduced Atlantic hurricane activity through increases in upper-level westerly winds that increase vertical wind shear. Gray's forecasts at Colorado State University began in 1984 and continue to the present day (available at http://tropical.colostate.edu), now being issued regularly by his final Ph.D. student, Phil Klotzbach. These initial seasonal forecasts were issued in early June and then updated in early August.

Atlantic seasonal hurricane forecasts have changed significantly since the early 1980s. Through the mid-1990s, CSU was the only entity consistently issuing seasonal hurricane forecasts. Gray's team was the first to note the relationship between West African rainfall and Atlantic basin hurricane activity as well as major U.S. landfalling hurricanes (Landsea and Gray 1992; Landsea et al. 1992). CSU began issuing an early December forecast in 1991 for the 1992 Atlantic hurricane season (Gray et al. 1992) but suspended these forecasts in 2012 following the failure to demonstrate real-time skill. CSU also has issued early April forecasts since 1995. The failure of CSU's seasonal hurricane forecast in 1997 because of a stronger-than-anticipated El Niño along with the degradation of several other previously strong predictive signals motivated other entities to begin issuing predictions. NOAA began formal forecasts in 1998, with Tropical Storm Risk (TSR), based at the University College London, beginning to issue forecasts in 1999. These three longest-running prediction efforts have all shown modest levels of skill in early June and moderate skill in early August when compared with a variety of no-skill metrics over the period from 2003 to 2014 when each group's methodologies have remained fairly constant (Klotzbach et al. 2017). Figure 12 displays the skill of the Atlantic basin seasonal hurricane forecasts from CSU for a 1 August prediction of named storms. The rank correlation between observed and predicted named storms is 0.75, explaining over 50% of the variance for this parameter.

Statistically based seasonal hurricane forecasts underwent significant changes with the development of globally gridded reanalysis products such as the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kistler et al. 2001). These types of products and easily available online resources allowed for plotting of a wide variety of atmospheric–oceanic predictors and helped elucidate relationships that may have been harder to ascertain using station data. Important statistical seasonal connections that have refined statistical models in more recent years include the relationship between hurricanes and Caribbean and tropical Atlantic trade wind strength (Saunders and Lea 2008; Klotzbach 2011), as well as between hurricanes and tropical and subtropical Atlantic sea surface temperatures (Saunders and Harris 1997; Klotzbach 2007; Saunders and Lea 2008; Klotzbach 2011). The strength of the Atlantic multidecadal oscillation

(Goldenberg et al. 2001; Bell and Chelliah 2006; Klotzbach et al. 2015) and the Atlantic meridional mode (Kossin and Vimont 2007; Vimont and Kossin 2007) are also frequently referenced in seasonal hurricane forecasts being issued today.

In addition to statistically based outlooks, as their physics and resolution have improved, dynamical models have also provided Atlantic seasonal hurricane predictions. The European Centre for Medium-Range Weather Forecasts (ECMWF) demonstrated skill in using a GCM to predict seasonal levels of hurricane activity in 2001 (Vitart and Stockdale 2001) and have issued operational seasonal hurricane forecasts to their member states since 2002. Both the International Research Institute (IRI; Camargo and Zebiak 2002) and Florida State University (FSU; LaRow et al. 2010 issued operational seasonal hurricane forecasts for a time during the period from 2002 to 2014, but neither of these groups continue to issue dynamically based forecasts. The Met Office has issued dynamically based seasonal hurricane forecasts since 2007 (Camp et al. 2015). These dynamically based seasonal hurricane forecasts have shown comparable skill to the statistically based schemes (Klotzbach et al. 2017). Camargo et al. (2007a) documented all known formal seasonal TC forecasts from universities and government agencies at that time. The Barcelona Supercomputing Centre and CSU have recently finished a website (located online at www.seasonalhurricanepredictions.org) that displays over 20 publicly available Atlantic seasonal hurricane forecasts.

The future of Atlantic seasonal hurricane prediction is bright, as higher-resolution and more advanced data assimilation techniques continue to improve reanalysis products. The ECMWF is in the final stages of completing a full four-dimensional variational data assimilation reanalysis extending back to 1900 [Coupled ECMWF Reanalysis of the 20th Century (CERA-20C)]. This reanalysis will also include historical pibals from the 1920s to the 1940s, which should help provide at least a crude estimate of upper-level wind data prior to the mid-1950s. Being able to build statistical models on longer periods of data should help prevent chance statistical relationships between atmospheric–oceanic predictors and Atlantic hurricane activity (DelSole and Shukla 2009).

The ability of dynamical models to better predict ENSO and other large-scale conditions will improve so-called hybrid models (Vecchi et al. 2011). These hybrid models utilize dynamical model forecasts of atmospheric–oceanic conditions that are known to impact Atlantic hurricane activity through modulations of Gray's genesis parameters (Gray 1979).

Hybrid forecast techniques are utilized by many forecasting groups today, including CSU and NOAA.

Dynamical model predictions should continue to advance with more upgrades to model physics and data assimilation schemes. The potential of being able to predict predominant TC tracks is closer to reality (Vecchi et al. 2014). If these forecasts can demonstrate real-time regional forecast skill, the utility of seasonal hurricane forecasts will become more strategic than predicting the Atlantic basin as a whole. The Atlantic seasonal hurricane predictions that Gray founded in the early 1980s are likely to flourish as technology and meteorological understanding continue to improve.

Gray's influence on seasonal hurricane prediction also extends beyond the Atlantic basin. One of his Ph.D. students, Johnny Chan, pioneered the seasonal typhoon forecast for the northwest Pacific basin. These predictions, based at the City University of Hong Kong, began in 2000 and continued until 2012, utilizing a variety of predictors related to ENSO and the strength of the west Pacific subtropical ridge as well as the West Pacific Index (Chan et al. 1998; Chan 2000). After a brief hiatus, the City University of Hong Kong resumed issuing forecasts for basinwide activity as well as landfall across East Asia, using dynamically down-scaled models as the basis for its forecasts (Huang and Chan 2014). A considerable number of other forecast groups now issue forecasts for the northwest Pacific as well as other TC basins around the globe, using a variety of dynamical, statistical–dynamical, and statistical models (Camargo et al. 2007a).

CLIMATE CHANGE AND ITS IMPACTS ON TROPICAL CYCLONE ACTIVITY. In the later decades of Gray's life, he was a prominent "skeptic," or critic of the prevailing view on climate change science. He had a well-known distrust of climate models and believed that the water vapor feedback from increasing CO_2 was negative, not positive. He argued that the recent increase in global temperature was primarily due to a long-term weakening in the strength of the Atlantic thermohaline circulation (Gray 2012). While his thoughts on climate change were well-known among his students and presented at several conferences, they were never published in the peer-reviewed literature.

His primary contribution to the peer-reviewed literature was with regards to the impact of climate change on TCs. His contributions to the relationship between climate change (as well as climate variability) and TCs were fourfold:

1) Gray (1990) and Gray et al. (1997) noted multiyear swings in Atlantic basin hurricane activity that
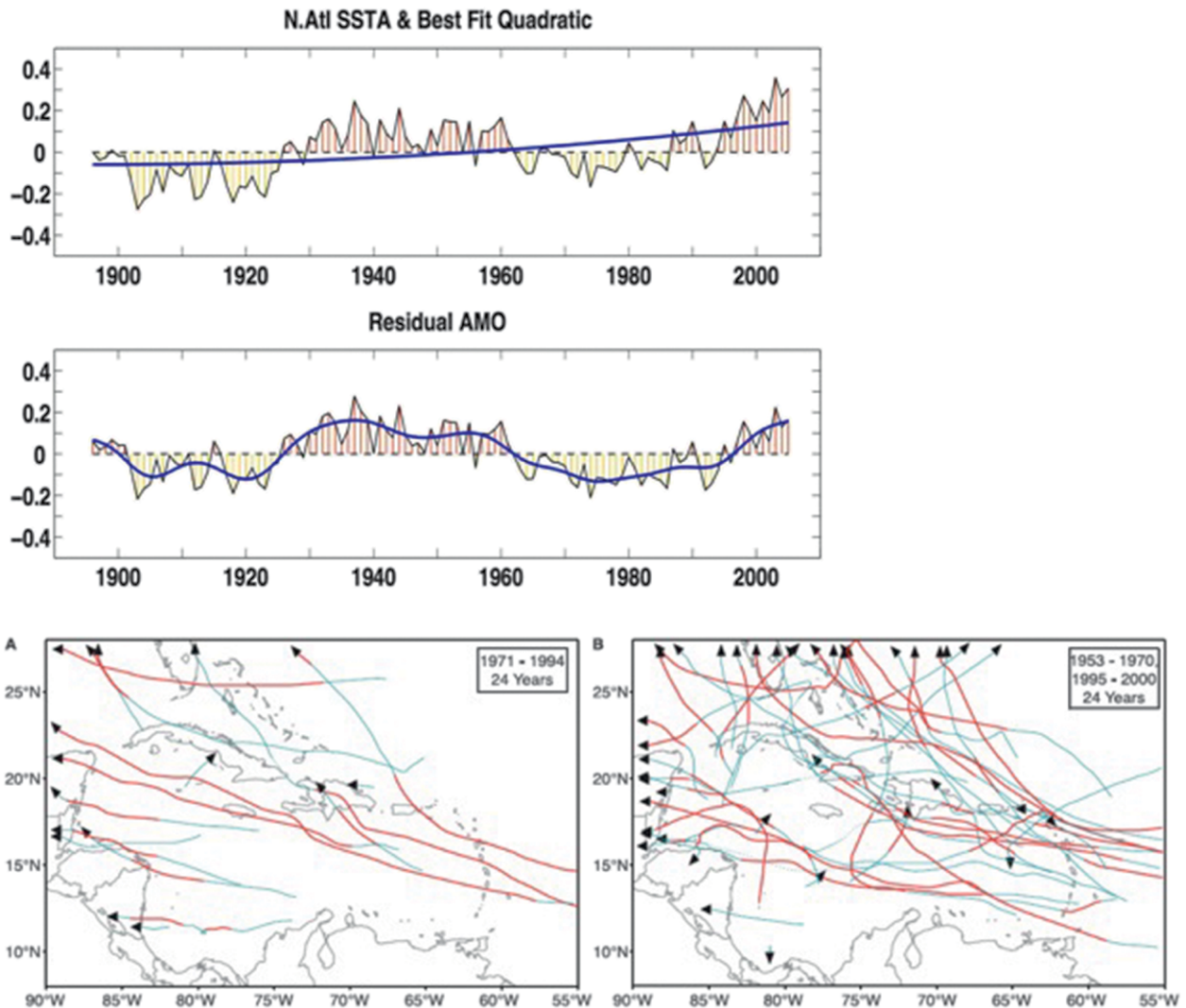
Fɪɢ. 13. (top) Annual averages for Aug–Oct North Atlantic sea surface temperature anomalies from 1856 to 2005 with a least squares quadratic trend fit superimposed. **(middle)** The difference between the sea surface temperatures and the quadratic fix with a decadal-scale smoothing superimposed (from Enfield and Cid-Serrano 2010). Contrast of Caribbean hurricanes between 24 seasons during **(a)** the AMO cold period (1971–94) and **(b)** the AMO warm period (1953–70 and 1995–2000). The solid thin blue and thick red lines indicate where the hurricanes were at nonmajor and major hurricane intensity, respectively (from Goldenberg et al. 2001).

were linked to variability in SST patterns in the Atlantic Ocean and in the overlying atmosphere, including the strength of the West African monsoon. This variability was noted to occur on time scales of approximately 25–40 years. Gray related these differences to the Atlantic multidecadal oscillation (AMO; Goldenberg et al. 2001; the low-frequency component of the now more generalized Atlantic meridional mode; Kossin and Vimont 2007), which has been argued to be a primarily natural fluctuation driven by the Atlantic Ocean. The Atlantic experiences distinct warm and cool periods independent of the long-term global warming signal (Fig. 13; Enfield and

Cid-Serrano 2010). However, others have argued that the AMO is primarily driven by sulfate aerosols (Evan et al. 2009; Booth et al. 2012). When the Atlantic is in a warm phase, the tropical Atlantic may only be warmer by ~0.25°C, but the atmosphere has more moisture, substantially less tropospheric vertical wind shear, and more vigorous and plentiful deep convection. Conversely, in the cool phase of the AMO, the waters are slightly cooler and the atmosphere is drier, has more inhibiting vertical wind shear, and cannot sustain the deep convection as readily. Gray was part of a team (Goldenberg et al. 2001) that concluded that the AMO had switched from the cool to the warm

phase beginning in 1995. Klotzbach and Gray (2008) defined warm AMO phases from 1878 to 1899, 1926 to 1969, and 1995 to the near present, with cold AMO phases from 1900 to 1925 and 1970 to 1994. More recently, Gray and colleagues (Klotzbach et al. 2015) hypothesized that the AMO switched back again in the mid-2010s to a cool phase. When stratified by AMO phase, there is a doubling in the number of major hurricanes, a 50% increase in the frequency of U.S. landfalling major hurricanes, and over 3 times as many Caribbean hurricane strikes between the warm and cool phases (Goldenberg et al. 2001).

2) Gray was one of a group of international researchers who published early assessments on the impact of climate change on TCs (Lighthill et al. 1994; Henderson-Sellers et al. 1998). In the years since, this aspect of climate change science has evolved considerably, as per the recent reviews by Knutson et al. (2010) and Walsh et al. (2015). However, at the time, the Lighthill and Henderson-Sellers papers were definitive statements, laying an important foundation for later research on the topic.

3) The seasonal genesis parameter (SGP) described in the "Tropical cyclogenesis" section above related TC frequency to large-scale monthly mean variables that can be resolved by climate models (Gray 1979). The SGP was first used as a downscaling method to diagnose TC activity in future climates by Ryan et al. (1992). Since then, the method has been modified by subsequent authors (Emanuel and Nolan 2004; Holland and Bruyère 2014; Tang and Camargo 2014) and is now a standard tool in the study of TC activity in future climates (e.g., Camargo et al. 2007b,c; Vecchi and Soden 2007).

4) Gray and colleagues have carried out a number of studies of trends in TC activity (Landsea et al. 1997; Gray et al. 1997; Goldenberg et al. 2001; Landsea et al. 2006; Klotzbach and Landsea 2015) and in particular carried out "attribution" studies for particular years and decades of extreme TC activity (Landsea et al. 1998; Klotzbach and Gray 2006; Collins et al. 2016). His students and others have also attempted to estimate potential missing TCs from earlier in the data record, primarily during the presatellite era (Landsea 2007; Vecchi and Knutson 2008; Truchelut and Hart 2011; Truchelut et al. 2013). These efforts have helped to better put into context the current era's TC activity levels compared to the long-term climatology.

CLOSING REMARKS. Here, we have described the ideas generated by William Gray during 54 years of active research, shown the impact of these ideas on the development of thought in tropical meteorology, and discussed the relevance of his concepts to current research. Gray made fundamental contributions across a wide breadth of topics, including tropical convection, tropical cyclogenesis, TC inner-core structure, and seasonal TC prediction. For example, his groundbreaking global TC climatology paper (Gray 1968) has been cited over 1,500 times according to Google Scholar. Many of his other papers have also been cited several hundred times and have helped focus research directions in tropical meteorology for the past several decades.

As described above, Gray's primary scientific contributions include the following:

- documenting the structure of tropical weather systems, including the existence of a vertical velocity maximum in the upper troposphere and the existence of large deep tropospheric relative humidity gradients between convective areas and clear areas;
- developing the theoretical paradigm by which tropical convection heats and dries the larger scale through adiabatic subsidence and reevaporation of cloud droplets;
- proposing the Gray–Jacobson mechanism for the dynamical effects of different radiative–convective heating profiles between convective versus cloud-free regions;
- compiling large radiosonde datasets to carry out composite studies, allowing the first structural and budget studies of tropical weather systems, in particular typhoons and hurricanes;
- documenting and analyzing the core structures and dynamics of TCs using aircraft data in both case study and composite analyses;
- developing a conceptual framework whereby the outer-core structure is added to inner-core intensity to characterize TCs;
- documenting the relationship between TC landfalls and tornadoes and proposing the formation mechanism for their right-front quadrant concentration at landfall;
- describing the steering relationship between TC motion and the azimuthally averaged surrounding wind flow;
- authoring the seminal paper on tropical cyclogenesis, including the discovery of the large-scale climatological variables that account for seasonal and geographical distributions of TCs;
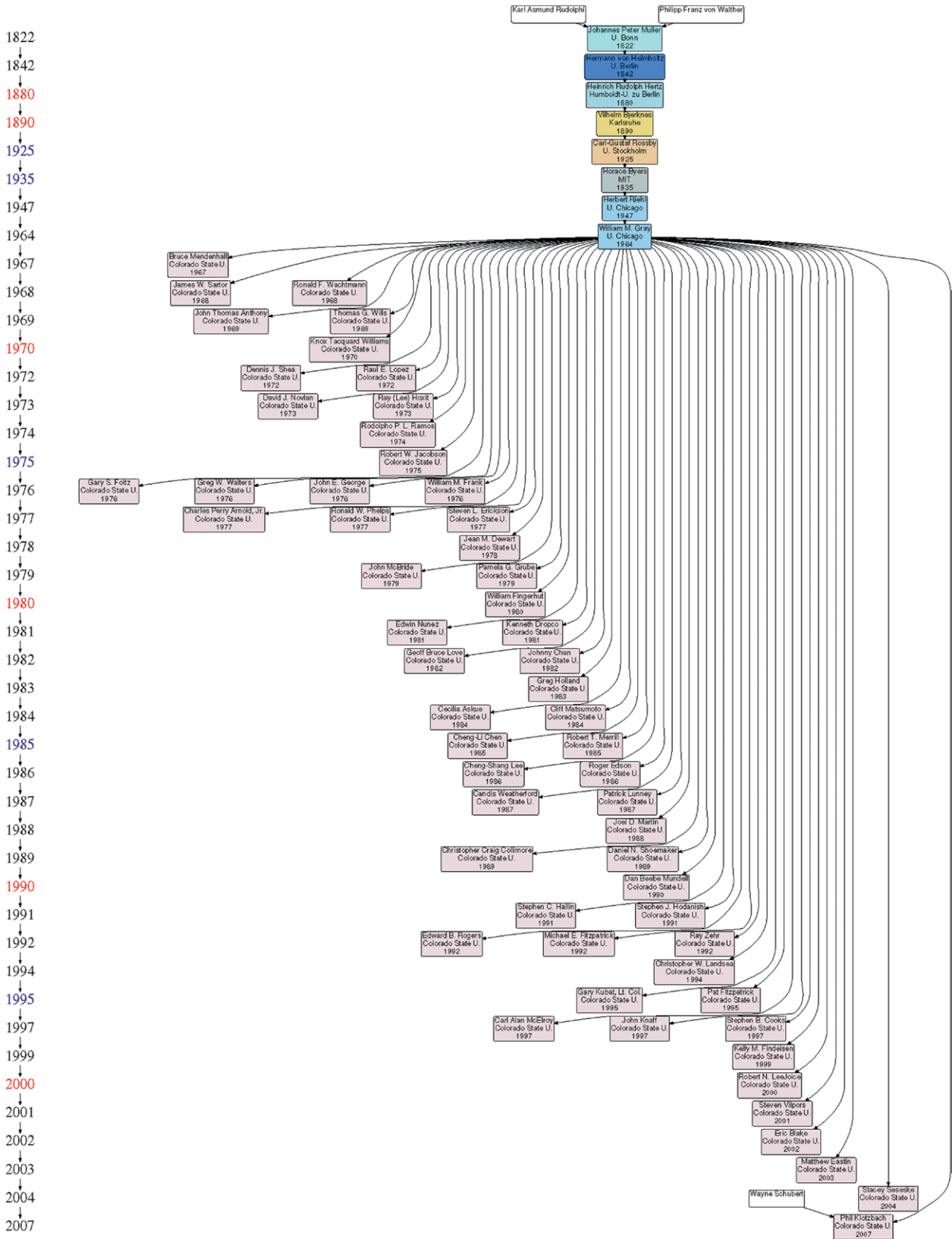
Fig. 14. The William Gray portion of the family tree of tropical meteorology listing all of his students who received degrees. The year listed is when each student received their terminal degree. The full tropical meteorology family tree is available at http://moe.met.fsu.edu/familytree/.

- developing the science of seasonal forecasting of Atlantic hurricane activity through statistical models, with predictor sets derived from physical mechanisms;
- issuing the first operational seasonal TC forecast in 1984;
- discovering the relationships between multiyear variations in hurricane activity and variability in Atlantic Ocean SST patterns; and
- contributing to the early multiauthor, multiagency scientific assessments of the relationships between global warming and TC activity.

In addition to his research contributions, he also was an advisor to over 20 Ph.D. recipients and 50 masters recipients. Many of these students became leaders in the field and have since trained students of their own. Gray's portion of the tropical meteorology family tree (Fig. 14; Hart and Cossuth 2013) is very extensive, and that was one of the things that he was most proud of later in life. He was frequently overheard stating that "your only immortality is through your graduate students."

Gray also spearheaded the development of the quadrennial International Workshop on Tropical Cyclones sponsored by the World Meteorological Organization, which brings together researchers and forecasters from around the world to discuss fundamental research developments as well as critical forecasting challenges. Gray strongly believed that research should be tailored to improve forecasts of TCs on time scales ranging from the daily to the multidecadal.

The authors of this paper are six scientists who received their Ph.D. degrees under the supervision of Professor Gray. To us, the papers written by Gray are part of our heritage or personal culture. We receive both an intellectual and emotional thrill at the mention of his classic papers such as the Gray and Shea (1973a,b) hurricane structure composites, the Gray and Jacobson (1977) diurnal variation paper, the early seasonal forecasts, the 1973 up-moist, down-dry paper (Gray 1973), the 1997 book chapter discussing the multidecadal nature of Atlantic hurricanes (Gray et al. 1997), and of course the 1968 global climatology paper (Gray 1968).

Through describing these ideas and their influence on the field, we hope we have conveyed some of the joys of research—and the joys of working over the years—under the tutelage of Professor Gray. We have included a video of a speech that Dr. Gray gave at an informal research project meeting at the 31st AMS Conference on Hurricanes and Tropical Meteorology in 2014 (http://dx.doi.org/10.1175/BAMS-D-16-0116.2). This clip highlights Dr. Gray's enthusiasm and sense of humor. Both of these traits were endearing characteristics that helped make working under Dr. Gray such a pleasure.

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