In-up-and-out: William M. Gray's contributions and legacy to tropical cyclone inner-core characteristics

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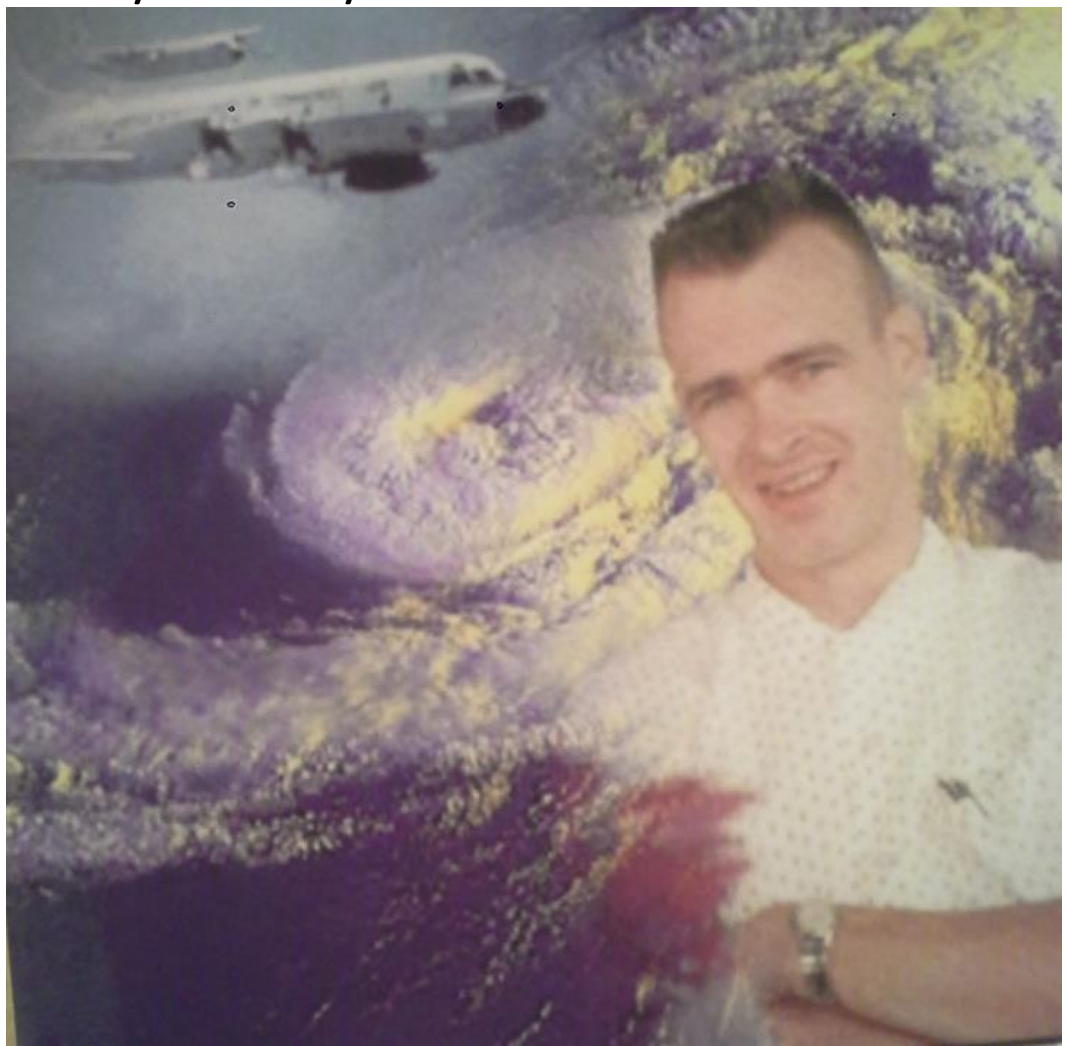
- Started in Air Force (3 yrs forecasting in Azores), continued in graduate school at University of Chicago
- Three examples from BAMS paper
  a) Reconnaissance composites
  b) Wind profile relationship
  c) Landfalling tornadoes
- Legacy and impact

"There are only two types of people in this world. Those who study tropical cyclones, and those who don't."



On the balance of forces and radial accelerations in hurricanes

By W. M. GRAY
Colorado State University, Fort Collins

(Manuscript received 18 July 1961; in revised form 9 April 1962)

"I got right in the nose of the plane. It was plastic and you could look straight down at the angry seas. We flew at 1500 feet in 120-knot winds. It was quite an experience."

- Advisor Herbert Riehl sent Gray to participate in National Hurricane Research Project flights
- Dissertation quantified inner-core budget terms from Carrie (1957), Cleo (1958), Daisy (1958), and Helene (1958), and documented gradient wind imbalance
- Gray actively sent his students to operational centers; many of these students participated in reconnaissance flights

Gray and Shea (1973a,b)

- Storm inflow confined to PBL
- Warmest temperatures from subsidence and inside eyewall cloud edge, not from cloud diffusion
- Supergradient winds; ascent outside of RMW
- Substantial mixing at eyewall cloud edge
- Slope of RMW is small at lower elevations and a function of intensity
- Deepening related to low wind shear

Based on 533 radial reconnaissance data composites

"You have to get down and dirty with the data"

Typical example of Gray graphically synthesizing results

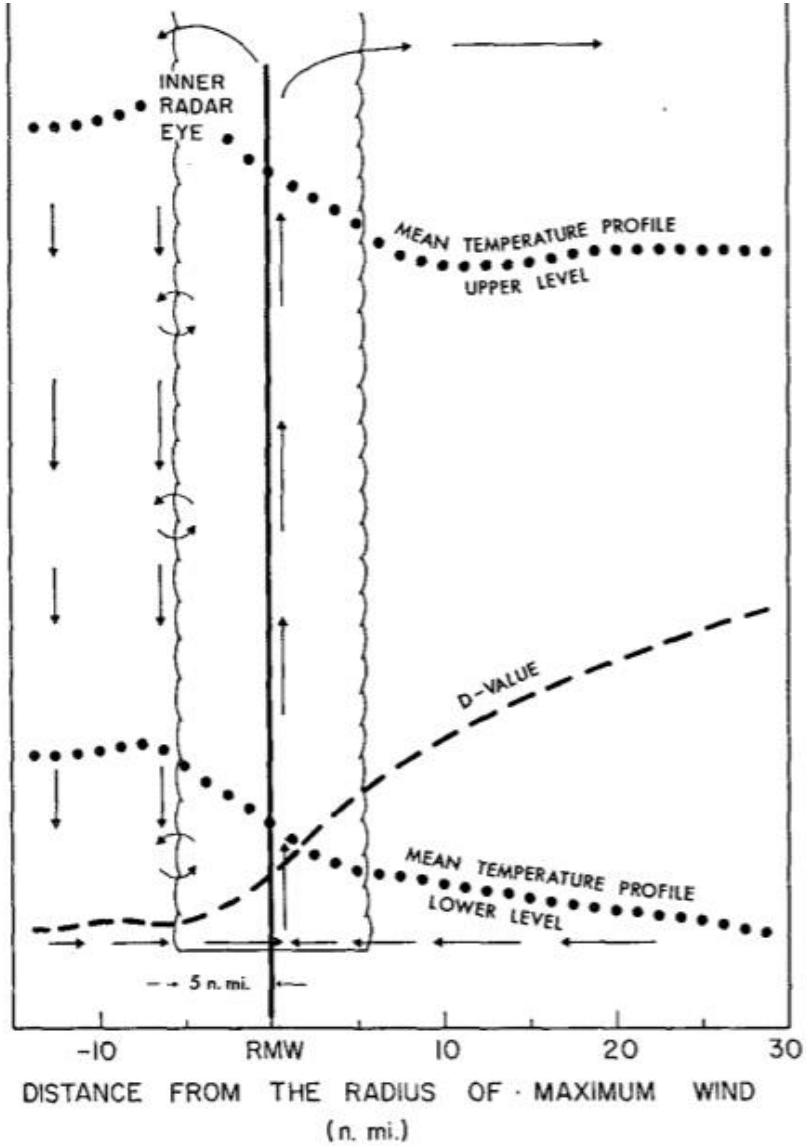


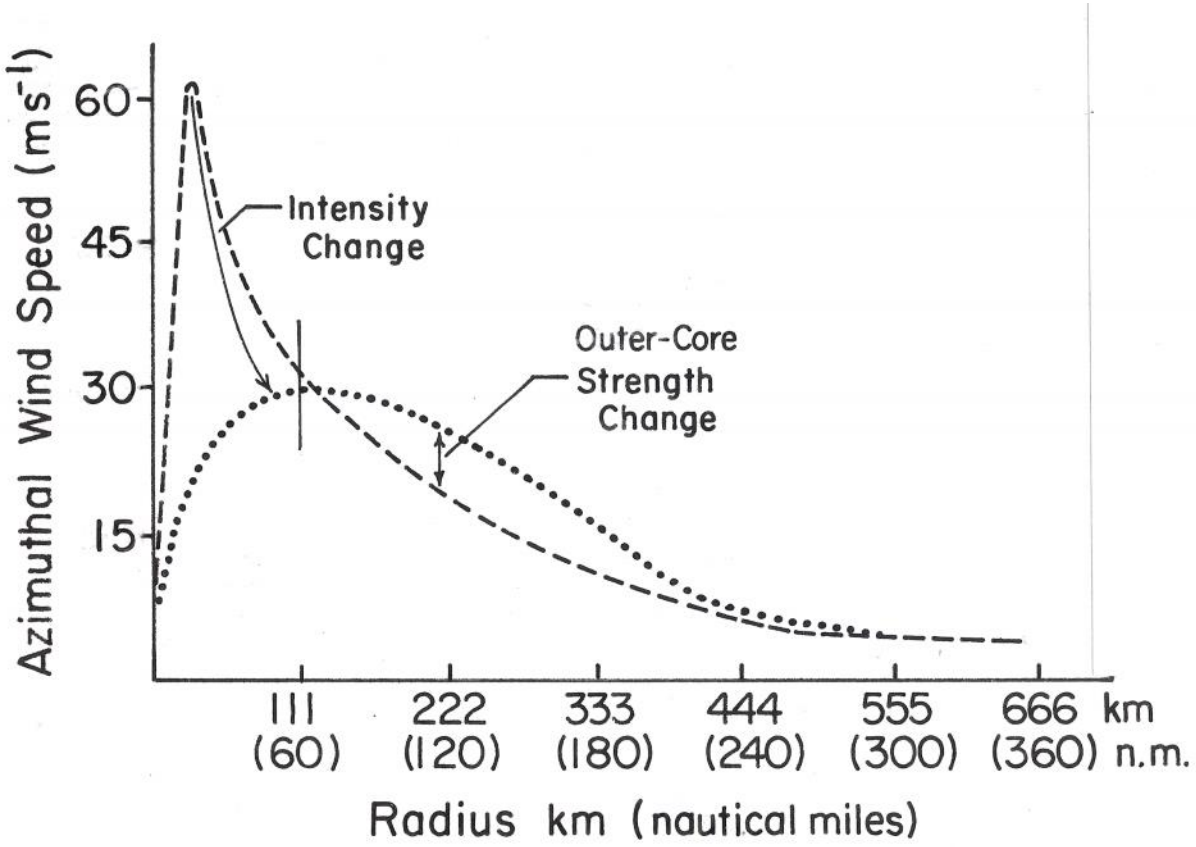
FIG. 19. Portrayal of the mean flow conditions in the hurricane's inner core region. The horizontal and vertical arrows represent the radial and vertical velocities, respectively. The mean *D*-value and temperature profiles are the result of combining all the data for the 900-, 750-, 650- and 525-mb levels.

1973a paper had 48 figures!

Merrill (1984)
Weatherford and Gray (1988a,b)

A second example highlighting Gray's philosophy of compartmentalizing complex structures into conceptual models

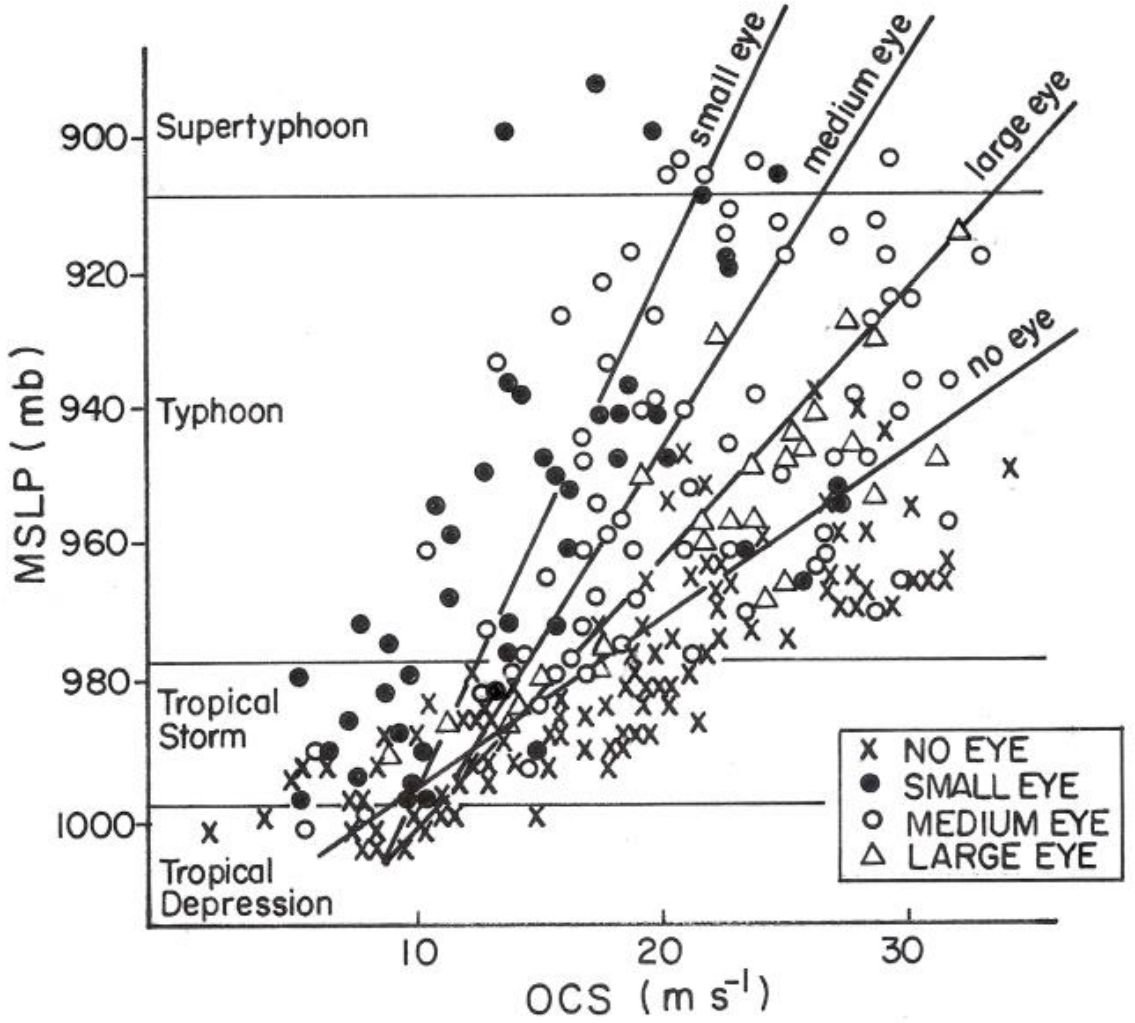
- Labeled wind structure with three characteristics: intensity (maximum sustained 10-m wind), size (extent of the TC vortex from RMW to radius of gale-force wind), and strength (average wind speed of the vortex)
- Proposed size metric radius of outer closed isobar (ROCI)
- Defined the mean tangential wind velocity within a 1°–2.5°-latitude radius as the outer-core wind strength (OCS)



"I am the Last of the Mohicans"

Merrill (1984)
Weatherford and Gray (1988a,b)
continued

- Noted weak correlations with central pressure.
- However, the relationship between OCS and central pressure improved when eye size was considered.
- A high correlation was also found between OCS and radius of gale-force winds.
- Motivated gale-force wind prediction schemes

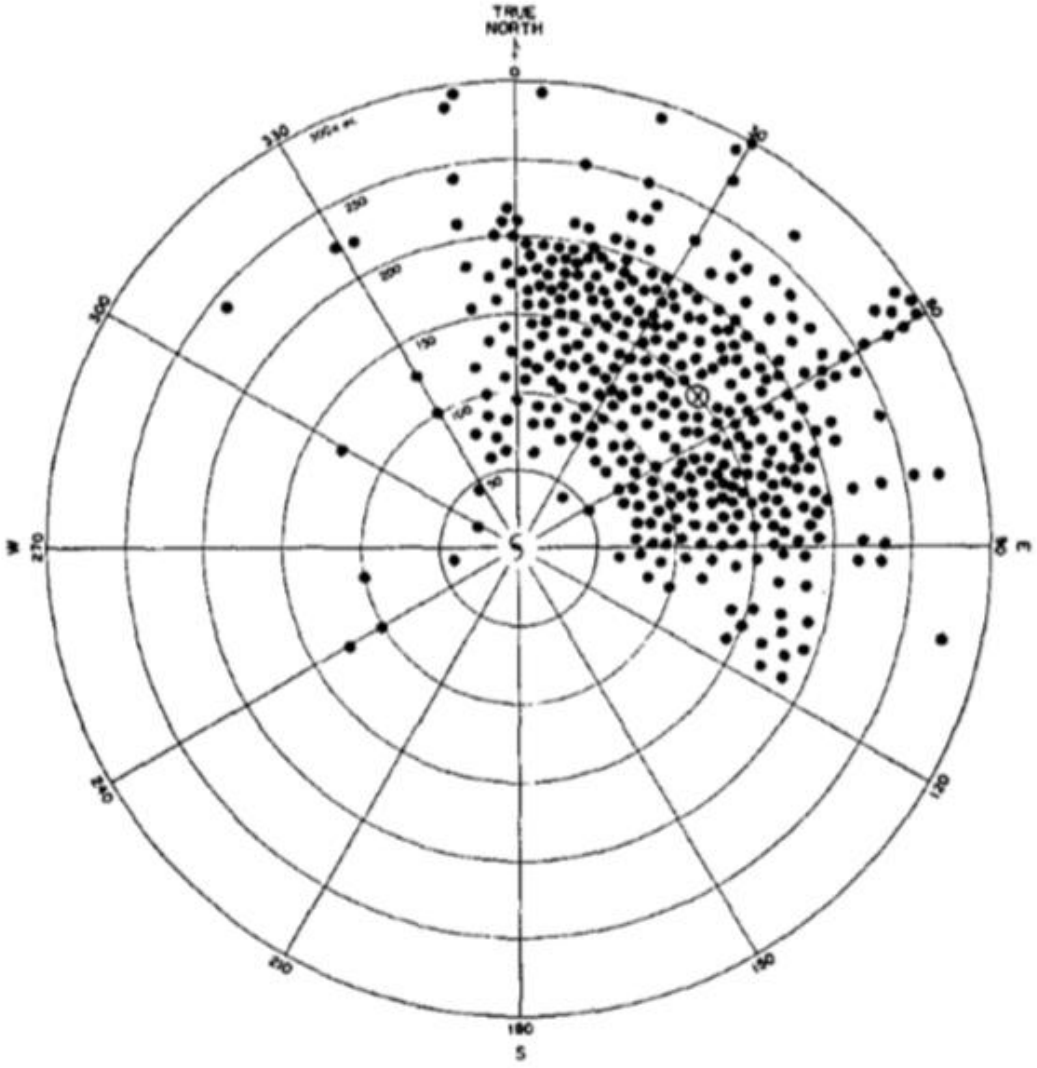


"Why study tropical cyclones in Colorado? The storm surge can't get you at 5000 feet!"

Novlan and Gray (1974)

Composite of tornado location relative to storm center at landfall

- Identified the importance of the land interface in generating tornadoes due to increased low-level vertical shear and maximum low-level convergence
- Confirmed tornadoes concentrated in the right-front quadrant from 100 to 400 n mi
- Primary findings true today. Later work showed:
  a) Higher concentrations in the outer bands
  b) Hurricanes produce more tornadoes than tropical storms
  c) Diurnal influence
- Tornado prediction today a coordinated effort between the SPC, NHC, and local NWS office staged as outlooks, watches, and warnings



"Do hurricanes suck or blow?"

Legacy and impact

Bill's Commitment to the front lines and furthering knowledge

Bill went on a WMO, NSF, Navy and CSU sponsored operational center survey trip

11 April – 3 June 1978

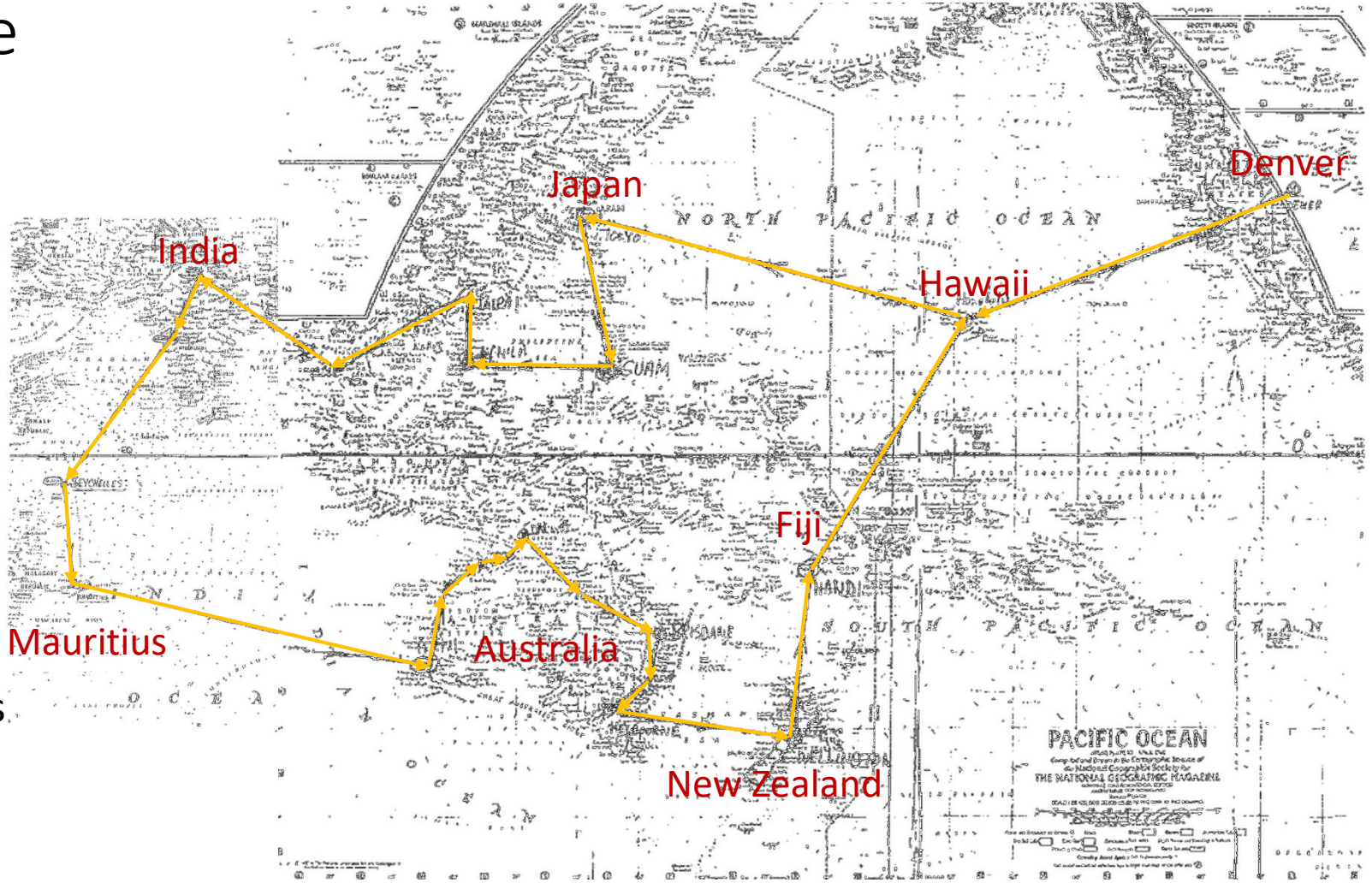
28 facilities, 20 operational, were visited

Early philosophy of data fusion to address TC research

Barriers to improving tropical cyclone knowledge were presented and solutions offered.

The resulting recommendations, in part, lead to the formal establishment of the WMO's Tropical Cyclone Working Committees and the International Workshop on Tropical Cyclones

"Better to rule in hell than serve in heaven"



Gray (1978) Prepared for Presentation to
The WMO Working Group on Tropical Meteorology
Geneva, 14-18 August, 1978

Always looking ahead

"Of particular interest is the relationship between cyclone size, strength and intensity - growth seems explainable as a direct result of increased angular momentum fluxes into the cyclone, while strength and intensity changes are controlled by other factors as well. A later research paper will attempt to address intensification directly. Additional work planned on tropical cyclone size will be efforts to develop information of operational use, such as a pressure-wind relationship including the effects of size, detailed statistics of the radius of gales around cyclones of different sizes, and a survey of the effect of cyclone size on hurricane surge and rainfall. Efforts will also be made to determine whether the increased momentum fluxes can be consistently related to growth as has been hypothesized, and in exactly what ways the increased fluxes occur." Merrill and Gray (1984)

BLUE BOOKS… Communication to the unwashed masses

- Size, Strength, & Intensity – Weatherford (1989)
- Intensification – Dropco (1981) , Merrill (1985), Fitzpatrick (1995), Mundell (1990)
- Wind Pressure Relationships – Vilpers (2001)
- Gales/ROCI/TC growth – Cocks (2002), Cocks and Gray (2002), Weatherford (1985)

Bill's Influence… led to practical applications

Bill's students were, in general, from an observational background

- Air Force students
- International students with forecasting backgrounds

Bill encouraged work that not only increased understanding, but solved practical problems

Work of his students have provided applied solutions to many TC problems throughout the world and both hemisphere

"I can tell I'm in the Southern Hemisphere. Don't you feel the pull to the left?"

- Wind models - Holland (1980, 2008)
- Intensity change – Merrill (1987), Fitzpatrick (1997), Knaff et al. (2005)
- Wind-Pressure Relationships – Knaff and Zehr (2007), Courtney and Knaff (2009)
- Wind Structure estimation – Demuth et al. (2006), Knaff et al. (2011), Knaff et al. (2014) Knaff et al. (2016)
- Wind Structure change – Cocks and Gray (2002), Knaff et al. (2017), Chan and Chan (2013), Sampson and Knaff (2015)

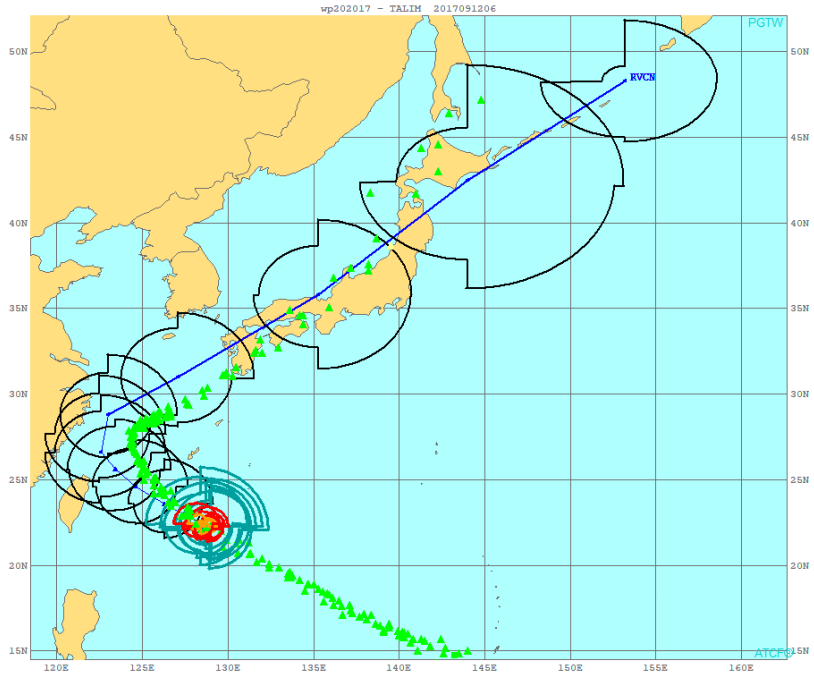
Toward analysis and forecast of the 2-D wind fields

Great progress has been made in the last decade.

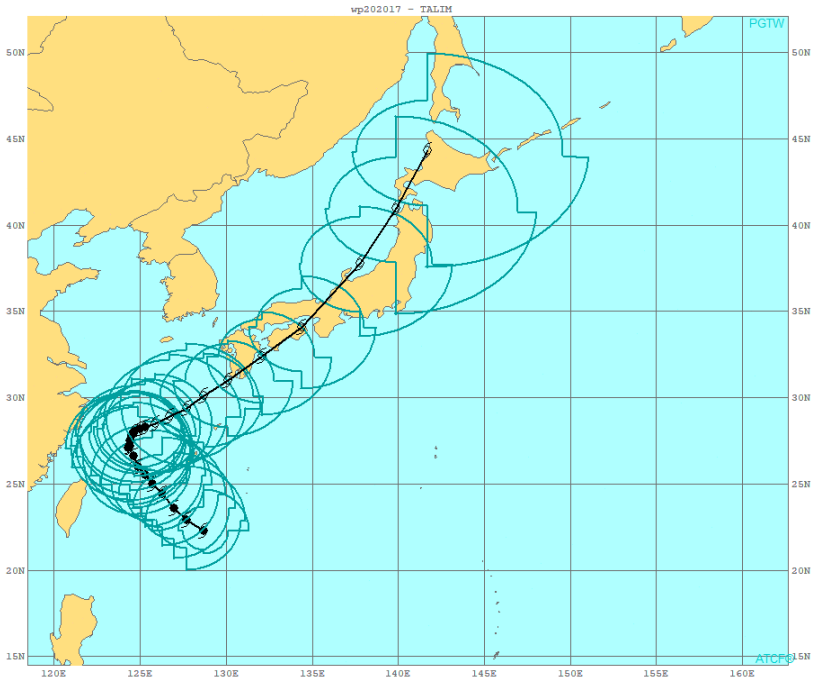
- Initial wind fields can be estimated by satellite from multiple methods
- Models are more numerous and skillful
- Consensus approaches provide forecasters initial and forecast wind fields

Gray loved quoting others. Arago's Admonition:

"Never, no matter what may be the progress of science, will honest scientific men with regard for their reputation venture to predict the weather."



Wind radii fixes
&
RVCN (consensus)



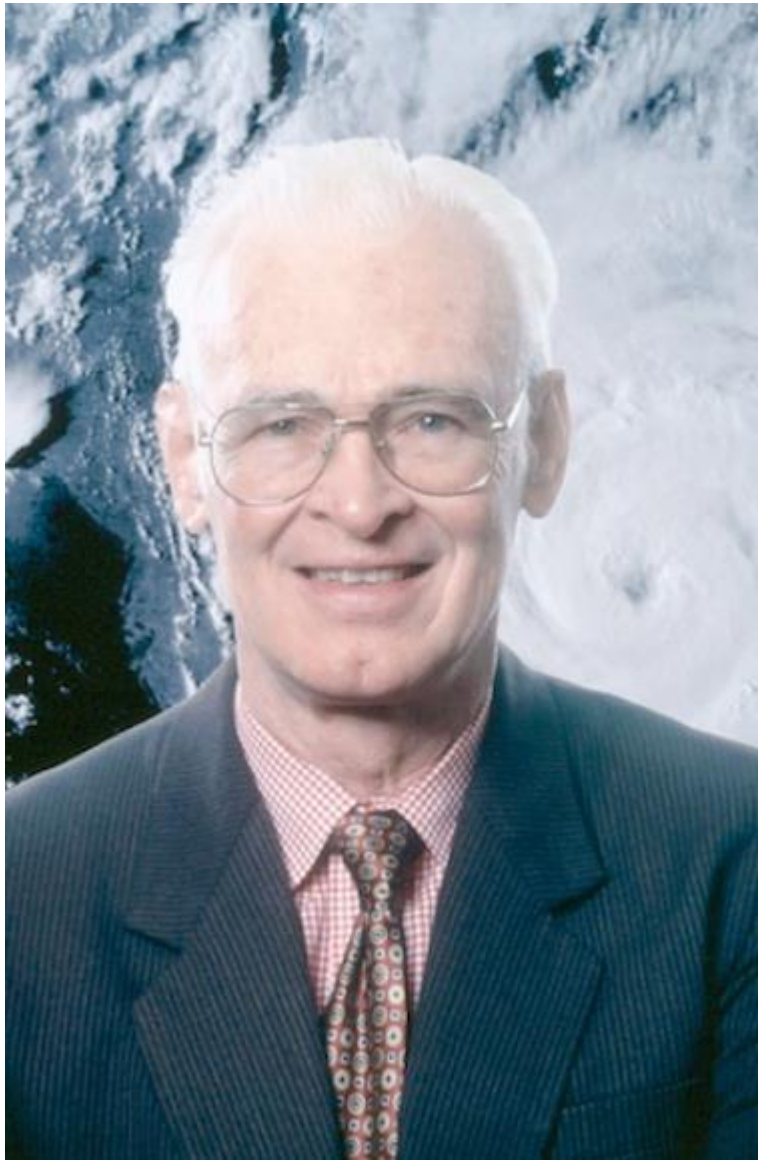
WP202017
Talim

Best Track
&
34-kt Wind Radii

Conclusion - Bill Gray's Research Ideal

As stated in his invited lecture to the 12th World Meteorological Organization Congress:

"There is much to be learned about tropical cyclones from the wide variety of observational data sets that are now available. Although each type of data is inadequate in itself, an improved underlying synthesis of the cyclone's internal physics and its environment becomes possible if one is able to piece together the interlocking association between the many different data sources. We need to better integrate the satellite, radar, aircraft, surface buoys, surface ships, rawindsondes and related data sets."

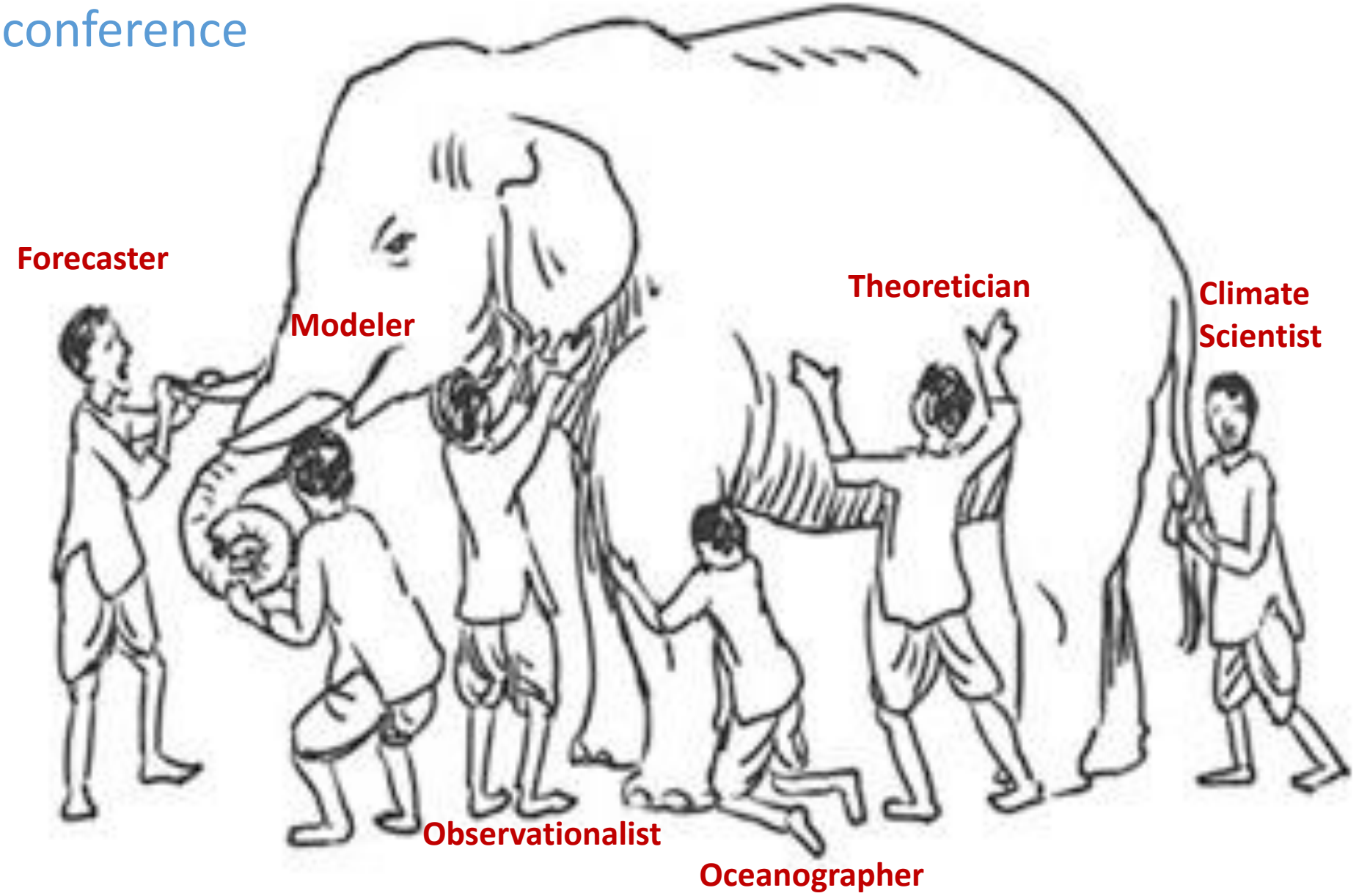


But he would have stated it like this at the AMS hurricane conference

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right
And all were in the wrong!

-John Godfrey Saxe

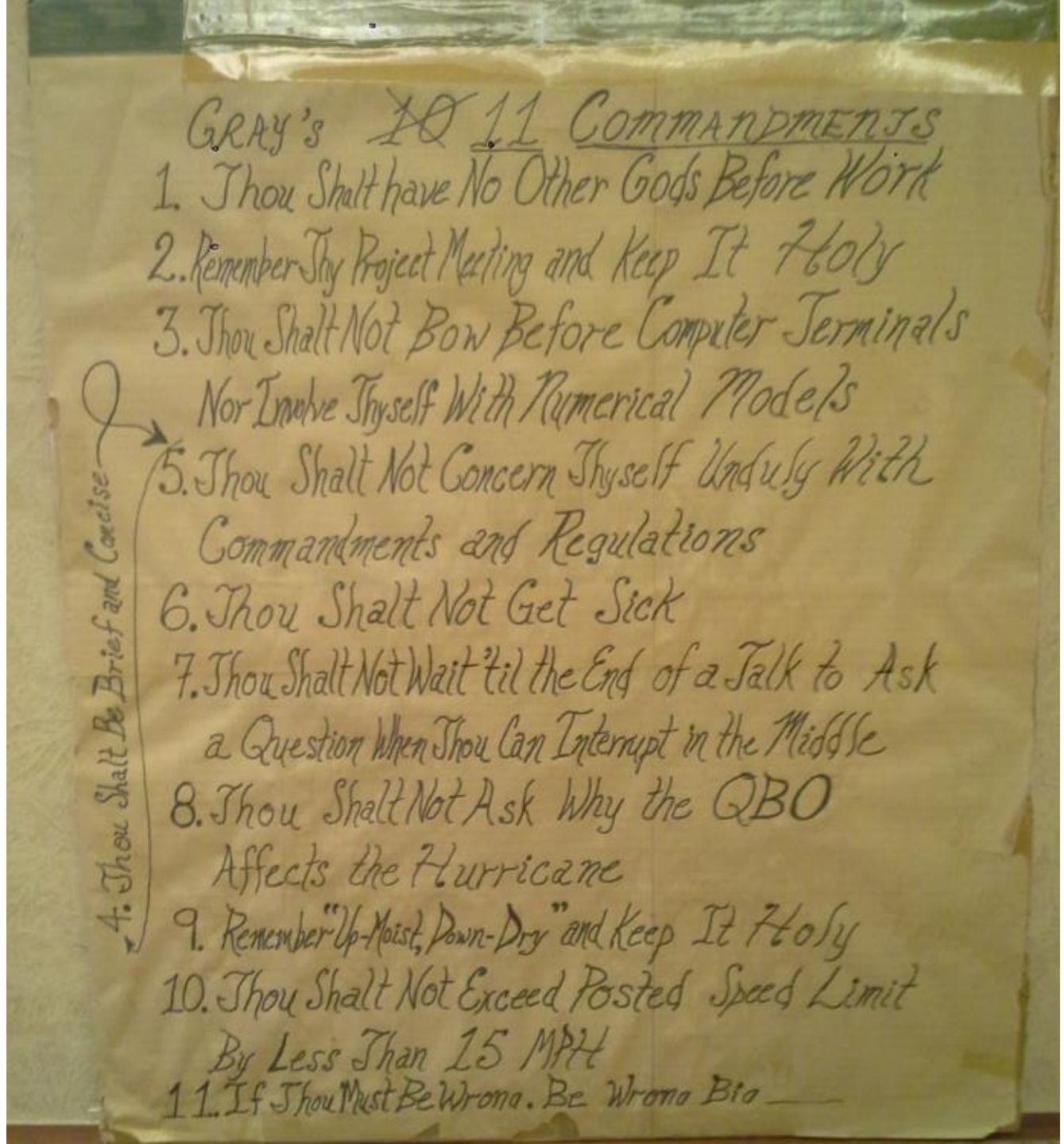
(From *The Blind Men and the Elephant*)



Extra slides

BAMS reference

Klotzbach, P. J., J. C. L. Chan, P. J. Fitzpatrick, W. M. Frank, C. W. Landsea, and J. L. McBride, 2017: The science of William M. Gray – his contributions to the knowledge of tropical meteorology and tropical cyclones. *Bull. Amer. Meteor. Soc.*, **98**, 2311-2336.



GRAY'S ~~10~~ 11 COMMANDMENTS

1. Thou Shalt have No Other Gods Before Work
2. Remember Thy Project Meeting and Keep It Holy
3. Thou Shalt Not Bow Before Computer Terminals Nor Involve Thyself With Numerical Models
4. Thou Shalt Be Brief and Concise
5. Thou Shalt Not Concern Thyself Unduly With Commandments and Regulations
6. Thou Shalt Not Get Sick
7. Thou Shalt Not Wait 'til the End of a Talk to Ask a Question When Thou Can Interrupt in the Middle
8. Thou Shalt Not Ask Why the QBO Affects the Hurricane
9. Remember "Up-Moist, Down-Dry" and Keep It Holy
10. Thou Shalt Not Exceed Posted Speed Limit By Less Than 15 MPH
11. If Thou Must Be Wrong, Be Wrong Big ___