Response to Comments by W. M. Gray on Science paper: Changes in tropical cyclone, number and duration in a warming environment”

by

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Gray (1: hereafter referred to as Gray) raises a number of issues regarding our study of the global statistics of hurricanes (2: referred to henceforth as WHCC) as compiled for the satellite era (1970-2004). We find all of the issues raised by Gray to be without substance and easily refuted. We show that the WHCC conclusion is robust to an analysis that allows for uncertainty in the discrimination between category 3 and category 4+5 hurricanes and that much of Gray’s analysis is misleading. The issues that Gray raises regarding the treatment of the data during the period prior to 1985 do not introduce any spurious trends or jumps in the data set. The data set that Gray does use for the period 1985-2004 does not agree with the WHCC data set, and he does not document his data set in any way. In spite of his concerns about data between 1970 and 1984 in the WHCC analysis, Gray nevertheless uses data from 1950 to bolster his arguments. Gray presents an alternative hypothesis for variations of hurricane characteristics in the North Atlantic that involves salinity variations; this hypothesis is not substantiated either in his paper or in the published literature. His analysis of the impact of warmer sea surface temperature on the stability of the lower troposphere contains basic errors in thermodynamics. In summary, there is no credence to any of the issues that Gray raises.

In our reply to Gray’s comments, we address the following basic points:

1) The validity of the hurricane data record prior to 1985 and discrepancies in the data used by Gray;
2) The selective use of periods of data and regions by Gray chosen to support his conjectures;
3) Posing of alternative hypotheses that appear *ad hoc* and unfounded and are not discussed in the peer-reviewed literature; and
4) Errors in physical understanding the manner in which a warmer sea-surface would impact the conditional instability of the atmosphere.

Gray states that the data used by WHCC prior to 1985 is inaccurate since category 3 storms cannot be distinguished from category 4 and 5 storms. Even if this is true, we find that including category 3 with the statistics of category 4 and 5 does not change the conclusions of WHCC (Figure 1), although the magnitude of the trend for Category 3+4+5 is not as large as the trend for Category 4+5. This is because of the relatively constant number of category 3 hurricanes throughout the 1970-2004 period (see Figure 4, WHCC).

Nevertheless, it is instructive to clarify the quality of the data for the period between 1970-1984. The problem seems to revolve around the Dvorak (1984) pressure-wind relationship compared to the pressure-wind relationship used earlier. Yet, in the "best-track data" it appears that the wind-pressure relationship has been the same since 1973. But both schemes have been "trained" from aircraft observations so it would appear that errors prior to 1985 would also be in data after 1985. Further, we have consulted with hurricane weather officer's who were responsible for the analysis of the data in the western North Pacific using the suspect relationship. The reality is that their techniques more often relied on other methods than the pressure wind relationship so there is no obvious approach that can be taken to account for this effect, even if it existed. If Gray were correct, we would see spurious trends or jumps in the data set. In fact, inspection of the data in all basins on a year-by-year basis does not show systematic discontinuities in the mid-1980s (not shown).

Gray further justifies rejecting the period prior to 1985 because he states that most of the SST temperature increase has occurred during this period. We note that his statement about the increase of SST is incorrect, which is easily seen from Figure 1 of WHCC; while each basin has some decadal scale variability in SST, overall the global trend in tropical SST has been nearly linear since 1970.

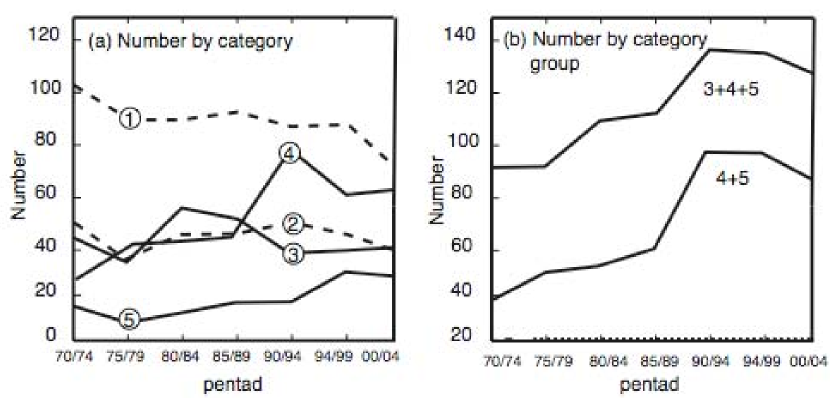

Figure 1: Hurricane characteristics from 1970-2004 in pentad (5-year) bins showing (a) the number of storms in categories 1 to 5, (b) the number of storms globally of category 3 and higher and 4 and higher.

After rejecting the data prior to 1985, Gray then proceeds to use data from 1985-2004 to show that there is no increase in global hurricane intensity if you consider the regions excluding the North Atlantic. Apart from the fact that his analysis is an egregious case of statistical special pleading, Gray's Table 1 appear to be missing approximately 20% of the global hurricanes minus the North Atlantic for each of the two decades he considers. Gray provides no explanation or reference to the data set that he uses. Figure 1 clearly shows how misleading it is to consider only the period from 1985-2005 to assess the trend over the period since 1970 that was addressed in WHCC.

Table 1 further illustrates how Gray's analysis is misleading. To put Gray's analysis into perspective, we examine the data for major hurricanes (category 3 and above) in 3 decadal periods, two of which correspond to the periods that Gray considers. We consider both the number of major hurricanes (column a) and the number of major hurricane days (column b), for each basin and for the entire globe. Table 1 shows that that there was a large increase in the number of major storms between the first and second decades, with the numbers in the second and third decades being roughly constant. It is the constancy during the last two decades that Gray uses as evidence as refuting any increase in the number of major global hurricanes. Gray asks why there are not significant changes in the two decades he considered when the SST was increasing?

	CATEGORIES 3, 4 & 5							
	(a) NUMBER AT CAT 3, 4 & 5				**(b) DAYS AT CAT 3, 4 & 5**			
BASIN	**75-84**	**85-94**	**95-04**	**2005**	**75-84**	**85-94**	**95-04**	**2005**
NATL	18	14	38	6	25	31	99	17
NWPac	71	104	98		166	250	275	
SIO	33	44	53		55	82	101	
NEPac	44	57	36		66	131	94	
SWPac	20	32	22		27	54	36	
GLOBAL	186	251	247		339	548	605	

Table 1: Number of storms of category 3 and above and the number of days storms were at category 3 or above for each basin and for the globe (excluding the North Indian Ocean) for the three decades 1975-1984, 1985-1994 and 1995-2004. The latter two decades were the same as analyzed by Gray. 2005 statistics for the North Atlantic Ocean are also shown.

BASIN	CATEGORIES 4 & 5							
	(a) NUMBER AT CAT 4 & 5				(b) DAYS AT CAT 4 & 5			
	75-84	85-94	95-04	2005	75-84	85-94	95-04	2005
NATL	19	16	23	5	12	16	52	12
NWPac	48	70	73		85	146	177	
SIO	12	25	35		15	35	56	
NEPac	24	37	25		26	58	44	
SWPac	6	14	12		6	21	19	
GLOBAL	109	162	168		144	276	348	

Table 2: Same as Table 1 except for storms category 4 and above.

BASIN	DURATION OF CAT 3+ (DAYS)				DURATION OF CAT 4+ (DAYS)			
	75-84	85-94	95-04	2005	75-84	85-94	95-04	2005
NATL	1.3	2.2	2.6	2.8	0.6	1.0	2.3	2.4
NWPac	2.3	2.4	2.8		1.8	2.1	2.4	
SIO	1.7	1.9	1.9		1.3	1.4	1.6	
NEPac	1.5	2.3	2.6		1.1	1.6	1.8	
SWPac	1.4	1.6	1.6		1.0	1.5	1.6	
GLOBAL	1.8	2.2	2.5		1.3	1.7	2.1	

Table 3: Average duration of a storm at category 3 and above (left) and category 4 and above (right). Calculated from Tables 1 and 2 by dividing the number of days at which a storm was in the category range with the number of storms in that category range. Note the monotonic increase of the duration of major hurricanes in all basins.

However, considering just the number of major storms is far from the complete story that was told by WHCC. Column b of Table 1 shows the total number of days that hurricanes existed as category 3 storms or higher. Even though the number of major hurricanes remained much the same for both the second and third decades, the number of major hurricane days increased by 11% during this period (with a 26% increase for category 4 storms and above). Between the first and second decades the number of major hurricane days increased by 61% (with a 92% increase for category 4 storms and above). It is easily inferred from the data in Table 1 that the average duration of major hurricanes has increased substantially, not only prior to 1985 but also over the last two decades. We have shown that there are substantial changes in hurricane characteristics between the two decades especially in terms of the number of days that severe hurricanes exist and their duration. Table 3 summarized the duration of storms category 3 and above, and category 4 and above the three decades. Duration is computed by dividing the number of days of storms by the number of storms from Table 1. In each basin and across the globe, and in each category bin, the average duration of major storms has increased substantially. In summary, the data shows clear evidence that not only has there been an increase in the number of intense hurricanes, they have also been lasting longer.

Gray did not include the North Atlantic data in his global statistics, and apparently considers the North Atlantic to be a special case with a different explanation from the rest of the globe. Changes in the North Atlantic are "explained" by Gray using a completely unsupported hypothesis involving surface salinity that is stated without evidence or without reference to the peer reviewed literature. Gray further dismisses the large amount of literature that attributes warming in the tropical oceans to greenhouse warming (as summarized by Barnett et al. 2005).

Finally, Gray concludes with a discussion of the physics of hurricanes and why they are independent of changes in the SST. He states that "*…there is no physical basis for assuming global intensity or frequency is related to global mean surface temperature changes of less than ±0.5C….*". Does this mean that outside this range that there is a physical relationship? This is coupled to the statement that "*…as the surface temperature warms, so does the upper air temperatures rise to maintain conditionally unstable lapse-rates at their required values…*", although what the "required" values are is not stated. Gray makes the mistake of assuming that conditional instability will remain the same as the surface temperature increases. However, the Clausius-Clapeyron relationship stipulates that saturated vapor pressure at the ocean surface increases exponentially with temperature. Thus, the surface θ_e over the ocean increases at a greater rate than does the surface temperature and the saturated lapse rate decreases, rendering the tropical atmosphere more conditionally unstable.

In summary, we find Gray's comments without merit.

Endnotes:

(1) Gray, W. M., 2005: Technical comments. Submitted to *Science*.

(2) WHCC: Webster, P. J., Holland G. H., Curry J. A., and Chang H-.R, *Science*, Vol. 309, 1844-1846 (2005)

(3) K. E. Trenberth, *Science, 308,* 1753 (2005).

(4) The global data set is catalogued and available at: http://www.eas.gatech.edu/research/data.htm

(5) In this analysis, we omit the North Indian Ocean due to some uncertainty in cataloguing in the 1970s. We are currently attempting to update the data for this area. In any event, North Indian Ocean storms constitute only 6% of global storms.

(6) The logical fallacy of "statistical special pleading" occurs when the interpretation of the relevant statistic is "massaged" by looking for ways to reclassify or requantify data from one portion of results, but not applying the same scrutiny to other categories.

(7) Curry, J. A. and P. J. Webster, 1998: *Thermodynamics of Atmospheres and Oceans*. International Geophysics Series, Academic press, Volume 65, 471 pp.