

Boulders and Superstorms Redux

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In late 2007 I became aware of a paper¹ by Paul Hearty et al. with interesting detail on sea level fluctuations during the prior interglacial period, the Eemian. Most noteworthy was a rapid late-Eemian sea level rise of 3-4 meters to a height 6-9 meters (20-30 feet) above today's sea level.

The paper was based on a body of work, including field work at 15 different sites around the world. The paper led me to many prior papers by Hearty and colleagues, including the one on boulders in the Bahamas.² I was puzzled about why Hearty's work was not mentioned in the IPCC (Intergovernmental Panel on Climate Change) reports.

I have since realized Hearty's extraordinary ability to read the information in geological records. Maureen Raymo describes Hearty, with intended admiration, as "the rock whisperer". That does not mean that there are not alternative interpretations of some aspects of the geologic data; ambiguities arise from reworkings of geologic records over time, dating uncertainties, and so on.

Here, in light of comments on my earlier posts, I clarify some points, as I don't want my attempt to simplify the story for the public to affect its apparent credibility. Also I address why it took so many years to submit our paper on climate simulations started almost 9 years ago.

In late 2006 we initiated climate simulations to test my suspicion that freshwater injected by increasing melt on Greenland and Antarctica, not generally included in IPCC simulations of 21st century climate, was likely to be important. The simulations tended to confirm my suspicion, and raise the question of whether global temperature was an adequate climate diagnostic.

Earth's energy imbalance was in some sense the most fundamental number characterizing the state of global climate. It largely bypasses uncertainties in climate sensitivity and climate forcings. And it can be measured accurately. Efforts to simulate future temperature to define "dangerous" climate change, fraught with these large unmeasured uncertainties, could speak only in terms of broad probability distribution functions – not a very satisfying situation.

Moreover, these probabilities are for some global temperature limit, which itself is arbitrary. The choice, 2°C, seemed to be almost pulled from a hat, without a good scientific basis.

The famous 1992 Framework Convention on Climate Change, on which this all hinged, did not speak to a temperature target. Rather it said that human-made changes of atmospheric composition should be limited so as to avoid dangerous climate change.

Bill McKibben, a practical man, kept asking "what is the limit on CO₂, 450 ppm?" Yikes, no, surely too large. With help of several of the best relevant scientists, we concluded³ that the safe level was no higher than 350 ppm, possibly lower, and we had better get the atmospheric amount back below that level before the ocean has time to equilibrate with the current higher amount. This paper was fairly difficult, requiring more than a year to finish and publish.

¹ Hearty, P.J., J.T. Hollin, A.C. Neumann, M.J. O'Leary & M. McCulloch: Global sea-level fluctuations during the Last Interglaciation (MIS 5e), *Quatern. Sci. Rev.* 26, 2090-2112, 2007.

² Hearty, P.J.: Boulder deposits from large waves during the last interglaciation on North Eleuthera Island, Bahamas, *Quatern. Res.* 48, 326-338, 1997.

³ Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer & J.C. Zachos: Target atmospheric CO₂: where should humanity aim?, *Open Atmos. Sci. Jour.* 2, 217-231, 2008.



Fig. 1. One of the Hearty boulders, with 1.6 m yardstick walking away from her measuring duty.

Governments, especially the legislative and executive branches, were and are largely under the heavy largesse-laden thumb of the fossil fuel industry. The courts provide a way to pressure the other branches of government, but making an effective case would require more than the “Target CO₂” paper.³ The minimum seemed to be better quantification of Earth’s energy imbalance and extraction from paleoclimate data of information on the “dangerous” level of human interference with the climate system, and then combining these in a paper⁴ intended for a lay audience and legal proceedings. The latter paper required two years from first submission to publication, mainly because an anonymous editorial board member of the Proc. Natl. Acad. Sci. refused to accept a paper that included “normative” statements and defined “dangerous” as a normative word. We finally withdrew the paper and started over with a second journal (PLOS One).

Meanwhile, Maxwell Kelley made significant improvements to the GISS ocean model, so in 2012 we initiated new climate simulations. General conclusions from earlier simulations were not altered, as described in our paper⁵ (Ice Melt, Sea Level Rise & Superstorms) submitted to Atmos. Chem. Phys. Disc. (ACPD).

There have been widely-circulated criticisms of submission of the paper to a Discussion journal, some seemingly with intent to make our conclusions seem less credible. In fact, submission to a journal that makes the original paper available to the scientific community and public (after an editor confirms that the paper warrants such publication with formal review by science referees) is common and has multiple advantages. Public access to the reviews (which are often signed)

⁴ Hansen, J., P. Kharecha, M. Sato, V. Masson-Delmotte, F. Ackerman, D.J. Beerling, P.J. Hearty, O. Hoegh-Guldberg, S.L. Hsu, C. Parmesan, J. Rockstrom, E.J. Rohling, J. Sachs, P. Smith, K. Steffen, L. Van Susteren, K. von Schuckmann, J.C. Zacher: Assessing “Dangerous Climate Change”: Required reduction of carbon emissions to protect young people, future generations and nature, PLOS One 8, 1-26, e81648, 2013.

⁵ A 66-page PDF with figures imbedded in the text is available [here](#). The 121 page ACPD version is available [here](#).

and author responses opens the review process to scrutiny. Other scientists are able to submit comments, thus increasing communication and research progress.⁶

ACPD, published by the European Geosciences Union, has an outstanding reputation; indeed, it has received the DOAJ Seal, which recognizes journals with an exceptionally high level of publishing standards and best practices. We published two earlier papers in ACPD/ACP, finding exceptional professional editorial and publishing performance.

There is another advantage of publication in ACPD. The original submission and the forum (reviews, responses, public comments) are all permanently archived and fully citable. Thus the ACPD paper is available for citation in legal proceedings⁷ and for pre-Paris discussions about actions required to avoid dangerous human-made interference with climate. At this (ACPD) stage, while the paper is undergoing additional peer review, its force and persuasiveness rests largely on the reputation and credibility of the many authors and the initial access peer review.

O.K., now back to the evidence of end-Eemian superstorms in the Bahamas. We posted our response to the first comment on our paper on the ACPD (Atmospheric Chemistry and Physics Discussion) website. Our response is freely available from [ACPD](#) or [here](#).

Hearty's papers discuss three sources of evidence: giant boulders, chevron ridges, and run-up deposits on neighboring hills. The boulders (e.g., Fig. 1) are the most interesting, but may not be the most informative. As Hearty's papers make clear, the boulders do not necessarily have the same explanation as the chevron ridges and run-up deposits, although Ockham's razor would favor the most parsimonious interpretation, as all are indicative of an extreme wave event(s).

The boulders are old rock of "hammer-ringing" hardness sitting on younger softer ("punky") Eemian-era substrate. For the boulders, of age at least 300-400 thousand years, to acquire their hardness, they must have spent most of that time above sea level, which was variable over that period, usually lower than today, by as much as ~130 meters. Based on composition and other characteristics of the boulders, Hearty² suggests that the probable boulder source was the presently exposed adjacent cliff faces, which are middle Pleistocene strata.

The boulders had to be lifted to their present location (on the cliff facing the North Atlantic) in the late Eemian or immediately thereafter before sea level had fallen much from its high Eemian level. It required powerful long-period waves from the Northeast to scour the nearby ocean floor and lift the boulders. The boulders are all located at the apex of a narrowing horseshoe-shaped embayment. Ocean waves funneled into this embayment generate huge surge and splash as they reach the cliffs.

Hearty suggests three possible means by which the boulders could have been thrown up to their present level, where they rest on younger soils: (1) a tsunami, (2) backwash from a major bank

⁶ ACPD describes initial screening by editors as "initial access peer review", summarizing merits of the procedure thusly: "Initial access peer review assures the basic scientific and technical quality of papers published in ACPD (underlining added). Subsequent interactive discussion and public commenting by the referees, authors, and other members of the scientific community is expected to enhance quality control for papers published in ACP beyond the limits of the traditional closed peer review. Also in cases where no additional comments from the scientific community are received, a full peer-review process in the traditional sense, albeit in a more transparent way, is assured before publication of a paper in ACP."

⁷ For example, in [my testimony](#) in a case filed by youth against the U.S. Government and President Obama for not protecting the Constitutional rights of young people and future generations.



Fig. 2. Looking from Glass Window bridge onto dark blue North Atlantic



Fig. 3. Looking the other direction, from the road toward the turquoise Caribbean (the bridge and yardstick are at the extreme right)

margin collapse, thus somewhat analogous to a tsunami, or (3) powerful sustained storms from the northeast, with long-period waves that could scour the coastal ocean bottom. None of these three can be ruled out, but parsimony favors #3, because only it can account for the extensive (V-shaped) “chevron” ridges and run-up deposits (see below).



Fig. 4. Connor and Jake reading Indiana Jones book.

Additional evidence favoring a storm origin of the boulder tossing is the nearby presence of smaller boulders (maximum mass about 10% of the large Eemian-era boulders) deposited during the current (Holocene) interglacial period. These are near the Eemian-era boulders, i.e., at the apex of the funneling embayment.

The suggestion in Revkin's comment on our paper that the boulders were instead remnants of erosion is dismissed readily. The "simple drawing...explaining boulder formation through chemical weathering" can be dismissed by going to Eleuthera and examining the boulders. One of them is shown in Fig. 1. Appearance might be enough, but there is ample scientific evidence. The boulders are much older than the substrate on which they rest. Also the varied orientation of the original bedding planes of the boulders, which can readily be discerned. The bedding planes at time of sedimentation could have been tilted as much as about 30 degrees from the horizontal, but at present these bedding planes are tilted at a variety of angles, some much larger, as would be expected for boulders tossed from the ocean.

The chevron ridges and run-up deposits present other evidence of large scale powerful storms. These are located all along the 900 kilometer eastern front of the Bahamian Islands at places most susceptible to ocean incursion. The power of the storms is indicated by the fact that the chevrons extend as much as several kilometers inland and the run-up deposits on hills immediately adjacent to the chevrons reach heights as great as 30-40 m above today's sea level.

An important characteristic of the chevrons is imbedding of lesser younger chevrons within those deposits that penetrated furthest inland. This is an expected result of storms while sea level was falling, as Earth moved into the post-Eemian ice age. If, instead, the imbedded chevrons were of tsunami origin, a series of tsunamis would be required.

I took the photo in Fig. 1 in January 2011 when Anniek and I visited the place, which is quite remarkable (yikes, 4½ years ago – shows how it took to get to writing this paper). The boulders are near the "Glass Window" bridge (see Fig. 2 in Hearty's 1997 paper). Standing on the bridge and looking northeast you see the dark blue North Atlantic (Fig. 2). Looking southwest you see the turquoise Caribbean (Fig.3). On the same photo chip I found grandsons Connor and Jake (cousins) studying an "Urgent!" pronouncement in an Indiana Jones book (Fig. 4). What is the relevance of that? Come on, you don't need a Ph.D. to figure that out.