Increased Scientific Evidence for the Link of Climate Change to Hurricane Intensity

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Until recently, most scientists would have said that there was no or no clear evidence that global warming has had any effect on the planet's most powerful storms- dubbed hurricanes, typhoons, or cyclones depending on the ocean that spawns them. They would have argued that the changes of the past decade in these metrics are not so large as to clearly indicate that anything is going on other than the multi-decadal variability that has been well documented since at least 1900 (Gray et al. 1997; Landsea et al. 1999; Goldenberg et al. 2001).

2005 a Turning Point of the Debate?

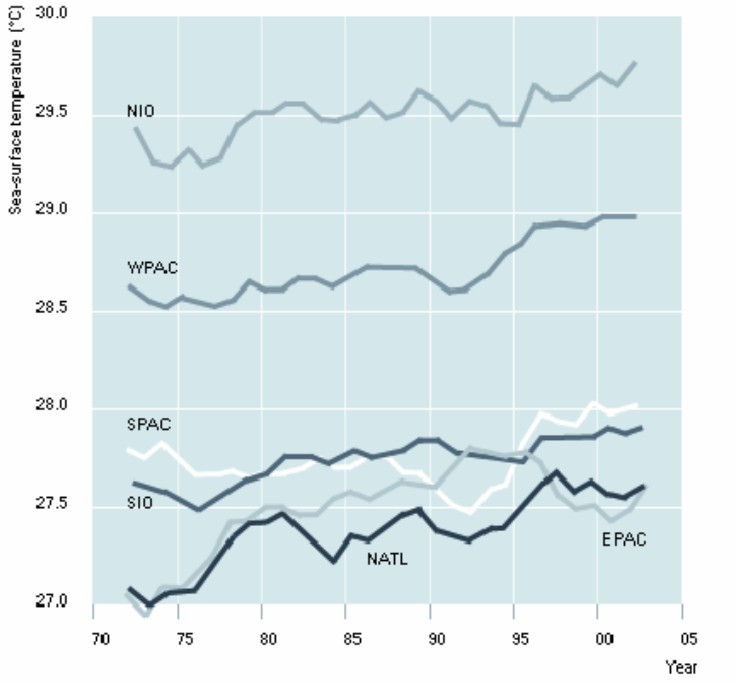
2005 might prove as a turning point of the debate. Two developments came accomponied. First, the two extreme hurricane years 2004 and 2005 increased attention of scientists: At the latest when Wilma's internal pressure hit 882 millibars, beating a record held by 1988's Gilbert, climatologists took notice. It was the first time a single season had produced four Category 5 hurricanes, the highest stage on the 5-step Saffir-Simpson scale of storm intensity. The 28 tropical storms and hurricanes, that the world faced in 2005, crushed the old mark of 21, set in 1933.

Second, a number of new scientific studies provided much more support to the hypotheses by showing that „now … a connection is emerging between warming oceans and severe tropical cyclones " (Kerr, 2005, 1807). Two papers published in Science and Nature in 2005 started a development described as "Birth for Hurricane Climatology" (Kerr, 2006) by identifying the impact of climate change on hurricane intensity, number and regional distribution. Many other interesting papers added new information. The debate is by far not over yet.

Increase in Sea Surface Temperature

One argument is an observed increase in sea surface temperature. Torre and White (2005) could show an increase in sea surface temperature since 1960. The following graph (Faust, 2006) shows the development of surface temperature in relevant ocean basins:

Barnett et al. (2005) compared sea temperatures with model simulations and found a high probabilitiy, that global warming is strongly influencing the increase in sea surface temperature. If this conclusion is accepted, it would mean, that global warming has already now – in its early status – a significant influence on sea surface temperature.



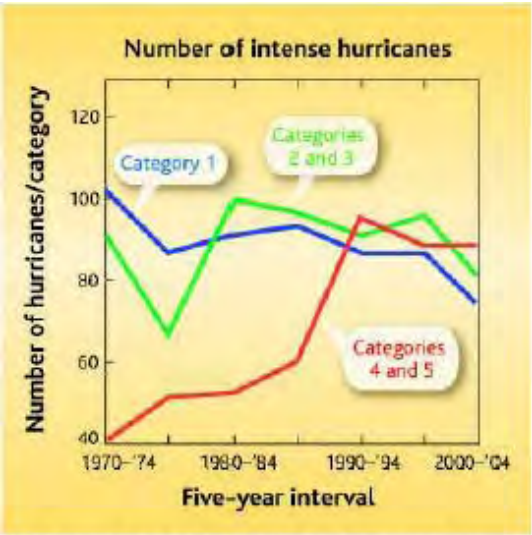
Development of sea surface temperatures in ocean basins with cyclone activity since 1970.
Source: according to Webster et al. (2005), Science Vol. 309.

NATL = North Atlantic
NIO = North Indian Ocean
WPAC = West Pacific
SIO = South Indian Ocean
SPAC = South Pacific
EPAC = East Pacific

Increase in Most Intense Hurricanes

The next argument is based on the observation that the most intense hurricanes increased over time. Alone in 2004 and 2005 four of the ten strongest hurricanes ever have been registered (Faust, 2006, 1). Kerry Emanuel (MIT) showed for the first time that major tropical storms, both in the Atlantic and the Pacific region, have already increased since the 1970s in duration and intensity by about 50 percent (Emanuel, 2005). He concluded: "My results suggest that future warming may lead to an upward trend in tropical cyclone destructive potential." In the years before Emanuel had asserted often that no firm link had been established between warming and the intensity and frequency of hurricanes. But then in August 2005, just two weeks before Hurricane Katrina struck the Gulf Coast, Emanuels article in 'Nature' was published, pointing out, that he had discovered statistical evidence that hurricanes were indeed affected by global warming. He linked the increased intensity of storms to the heating of the oceans.

Peter Webster (Georgia Institute of Technology, Atlanta) and his colleagues examined in another study satellite records of storms around the tropics, a history which started 35 years ago. They haven't found a long-term trend in the number of storms per year, only natural ups and downs, even as summer tropical sea surface temperatures rose 0.5°C. In the North Atlantic, where hurricane numbers have surged since 1995, such variability arises from changes in the strength of warm ocean currents (*Science*, 1 July 2005, p. 41). But more relevant is another part of the results: "The researchers did find a sharp increase during the past 35 years in the intensity of storms: The number of category 4 and 5 tropical cyclones, the most intense storms that cause most of the damage on landfall" (Kerr, 2005, 1807.) Globally, category 4 and 5 storms increased regarding to his calculation by 57 percent from the first half of the period to the second.



Bad trend rising. The number of the most intense tropical cyclones is increasing worldwide.

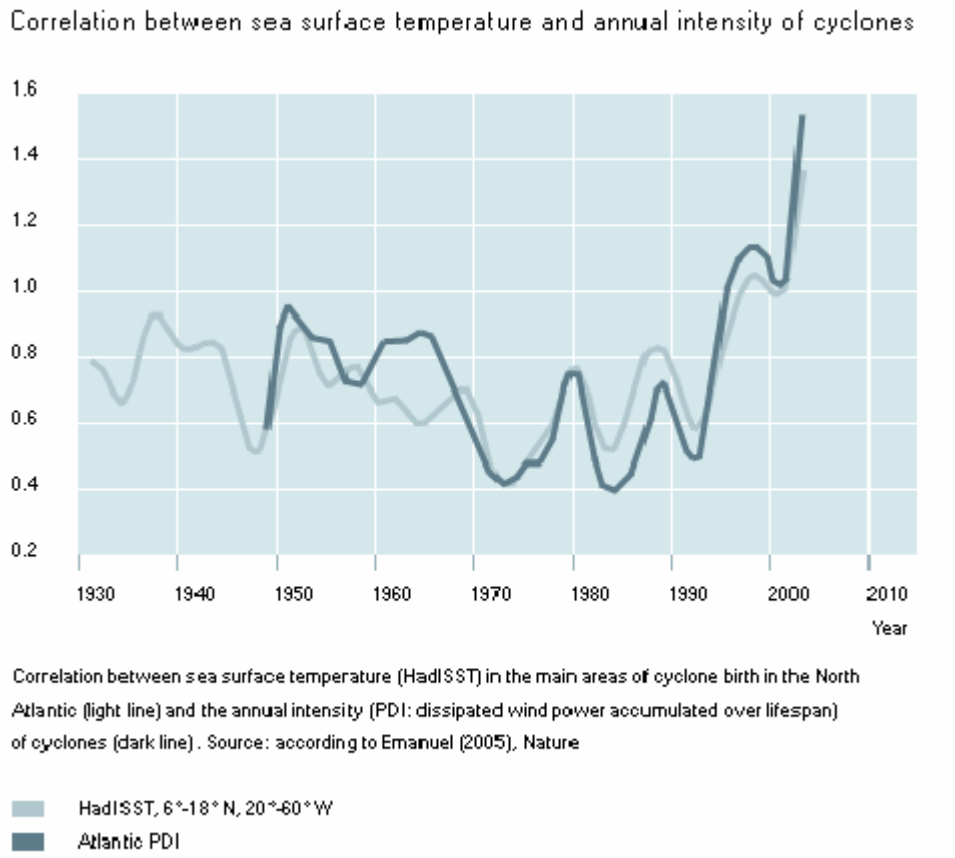
Source: Kerr, 2005, Science, p. 1807

At this point the main criticism of opponents starts. They have suggested that the upward trend of storm intensity might be artificially produced by the insufficient state of tropical cyclone intensity measurements. And two groups – led by John Knauf of CSU and Bruce Harper of Systems Engineering Australia Proprietary Limited in Brisbane – attempted to correct intensity records from parts of the Pacific Ocean for now-obvious errors. Both reanalyses reduced upward trend of storm intensity (See Kerr, 2006). Therefore it seems to make sense to check the reliability of the data base used by Emanuel and Webster. On the other hand, it also has to be noted, that both reanalyses did not eliminate the trend (Kerr, 2006). Webster agrees, that "the data's not very good". But he also adds: "However, to say it's all artificial is an exaggeration. We would have had to have misidentified 160 to 180 category 4's and 5's" (Kerr, 2006).

And a new study by Ryan Sriver and Matthew Huber, which soon will be released in Geophysical Research Letters, supports the results of Emanuel and Webster with a different set of data. It uses a compilation of the world's weather data developed at the European Centre for Medium-Range Weather Forecasting in Reading, UK. They found a 25% increase in storm power between the first half of the 45-year record and the second, consistent with Emanuel's analyses (Kerr, 2006).

Strong Correlation between Sea Surface Temperature and Hurricane Intensity in the North Atlantic

A further aspect of the argument is based on the validity of the datas. In his article, Emanuel displays (Emanuel 2005) that there is a strong correlation between sea surface temperature and hurricane intensity in the relevant part of North Atlantic. In the area just north of the equator in the Atlantic Ocean, where most hurricanes get their start, the power released during their lifetimes is "spectacularly well correlated with sea surface temperature", (Emanuel in Kerr 2006). It is interesting to note that this correlation has been strongest since 1970. This is the periode where the best data exist. Only since the 1970s researchers had satellites that allow them to look directly at hurricanes. However, even for this modern era record, there is some controversy in the wind speed estimates (Landsea, 2005). Based on this strong correlation Emanuel expects that the trend of more intense hurricanes, induced by global warming, will continue in the future, if sea surface temperature is to be further increased.



Correlation between sea surface temperature (HadISST) in the main areas of cyclone birth in the North Atlantic (light line) and the annual intensity (PDI: dissipated wind power accumulated over lifespan) of cyclones (dark line). Source: according to Emanuel (2005), Nature

Faust, 2006 based on Emanuel, 2005

Only Climate Change can Explain this Correllation

Carlos Hoyos and colleagues from *Georgia Institute of Technology* (GIT) in Atlanta et al. (2006) have shown in an additional study based on statistical models and data from six ocean basins in the last 35 years, that all other known factors – as humidity in the lower troposphere, vertical wind shear and the changes in "zonal" winds with longitude - which might potentially be able to explain the increase in intense hurricanes don't show a stable trend over the last 35 years. The new Georgia Tech study has now clarified this issue, showing that while hurricane intensity may be

substantially influenced by these other factors for an individual storm or storm season, only an increase in sea surface temperatures can account for the long term increase in hurricane strength. The results show that the trend of increasing numbers of category 4 and 5 hurricanes for the period 1970–2004 is directly linked to the trend in sea-surface temperature; other aspects of the tropical environment, although they influence shorter-term variations in hurricane intensity, do not contribute substantially to the observed global trend.

If this conclusion is accepted as well, it would be clear that global warming has an impact on the intensity of hurricanes.

Wrong Observations or wrong Theory?

The debate doesn't seem to be, whether there exists a link between global warming and hurricane intensity at all, but whether it is really so unexpected strong as the observations from Emanuel, Webster, Sriver and Huver suggest.

Doubtlessly, theory and computer models so far didn't support such a strong connection between global warming and hurricane intensity. The sensitivity of hurricane intensity to sea surface warming implied in the Emanuel (2005) results exceeds by a factor of 6 the sensitivity inferred from Knutson and Tueleya's (2004) idealized hurricane modeling study, which found a sensitivity of about 4% per degree Celsius SST increase. In a recent examiniation of Atlantic potential intensity data since about 1980, the discrepancy with Knutson's modelling work appears to be a factor of 4, and the discrepancy might be partly attributable to a general reduction of surface wind speeds in the basin over time (Emanuel 2006, Knutson 2006). Pielke argues that the global modelling studies suggest the potential for only relatively small changes in tropical cyclone intensities related to global warming. And as Landsea stated, according to theory and computer models the intensification by now should be only a sixth of what Webster and Emanuel have reported. Consequently, the current question is: are the observations, which support an anomalous strengthening trend of hurricane intensity wrong and a fiction, based on a deeply flawed hurricane record? Or are the theory and modelling wrong? As Emanuel puts it: „They tend to count [the anomalous strengthening] against observations. I count it against the theory, although I helped develop the theory." (Kerry, 2006).

A new simulation from Kazuyoshi Oouchi et al. of the Advanced Earth Science and Technology Organisation in Yokohoma, Japan, runs on Japan's Earth Simulator, the world's most powerful supercomputer devoted to earth sciences. The result supports the idea, that improved modells could reconcile ones with the observations. Global climate models typically calculate climate at points of 200 kilometers or more apart. The resulting pictures of climate are to fuzzy to pick up anything as small as a tropical cyclone. But the Japanese group simulated the present climate and the warming climate near the end of the century at a resolution of just 20 kilometers, thanks to the Earth Simulator's power. That was detailed enough for tropical cyclones to appear in the model, allowing the researchers to roughly gauge their intensities. In fact, in the warmer world, the total number of storms over the globe had actually decreased by 30%. „But the number of the rarer category 3 and 4 storms had increased substantially, not unlike observational results" (Kerr, 2006).

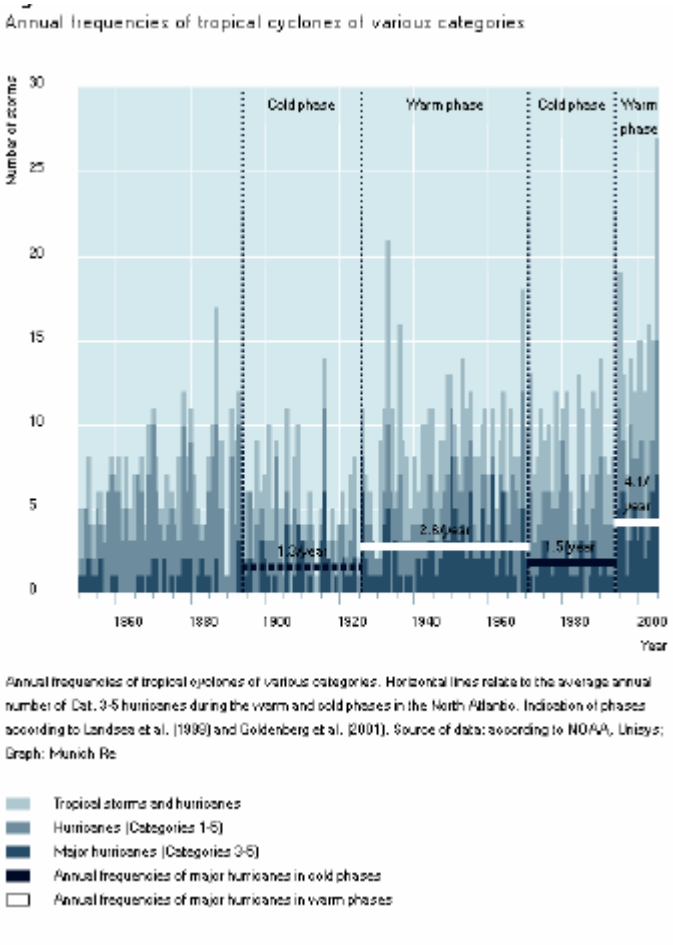
How Big is the Impact of Global Warming in Relation to the Natural Cycle?

Although there is concern about the quality of intensity data prior to the late 1960s on account of changes in observational techniques we take it as given that there was another period of high activity before the period with lower activities started about 1970.

Pielke argues that the relevance of global warming is exceedingly small in the context of, for example, the more than doubling in numbers of major hurricanes between quiet and active decadal periods in the Atlantic (Pielke, 2005, based on Goldenberg et al. 2001). Also the U.S. National Oceanic and Atmospheric Administration (NOAA) stated 2005 in press releases, that „longer-term climate change appears to be a minor factor" in „the most devastating hurricane season the country has experienced in modern times". The surge in Atlantic hurricane activity since 1995 is the latest upswing in a natural cycle, the releases said: As the Atlantic Ocean warms and wind patterns shift, hurricanes increase for a

decade or two until a lull sets in again (see Kerry, 2006). Christopher Landsea of the Hurricane Center in Miami, Florida, recently claimed that NOAA public affairs staff members writing the press releases had overstated the case for natural cycle. The warming may well be largely human-induced, cited Kerr Landsea. (Kerr, 2006). As all ocean basins show a warming of sea water surface, it seems very likely that it also plays a significant role in this case.

Faust (2006) used the data provided from NOAA to show a remarkable increase of strong hurricanes over time both in cold and warm phases since 1860. The new warm phase shows more intense hurricanes than former the warm phase. The last cold phase showed more intense hurricanes than the former one:



Because of lack on reliable data only four time periods have been compared. Length of time series and data quality don't allow to base a strong argument, about to what extent anthropogenic global warming contributes to the actual increase of intense hurricanes. But at least they demonstrate, that the existing data better support the claim, that climate change is a relevant co-driver of record hurricane intensity than its opposite claim, that the natural cycle is the only driver.

Are Category 4 and 5 Storms also Stronger after Land Fall?

There is still a debate, whether category 4 and 5 storms are not only stronger at sea, but also at the time of landfall (Kerry, Emanuel in Dreifus, 2006). However, Faust has shown, again based on NOAA-data, that between the last (1926 until ca. 1970) and the actual warm period (since ca. 1995) also the number of landfalls has dramatically increased:

category 3-5 hurricanes: +67 %

category 1-5 hurricanes: + 28%

tropical storms and category 1-5 hurricanes: +47.

Faust does consider global warming as the main driver for this difference (Faust, 2006).

Faust, 2006

On the other hand only during 2004 and 2005 did the U.S. landfalling PDI reach or exceed the strong levels that occurred several times in the first half of the 20th century.

Much will depend, whether 2004 and 2005 are interpreted as extreme outliers or as the start of a new trend, which has been masked since 1995 by the fact that U.S. landfalling storms are only a small fraction of all Atlantic hurricanes. Future will show.

he record years 2004 and 2005 could support this assumption of a new trend. But for really seeing a new trend rather than just some extreme years, the timeline from 1995 to 2005 alone is by far too short to show this. If we see from now on an increase of 70 % or (with increasing sea surface temperature) even more 3-5 hurricane landfalls, in all warm phases, then this would be extremely significant. The record numbers of the last years could support such an expectation. Still, there is also the possibility that we have only experienced some extreme landfall years and the rest of the decade will be more like past warm phases. Until 2003 statistics gave little support for other expectations.

Is Climate Change a Significant Factor for Increased Hurricane Impacts on Society?

So far there has been a broad consensus that *for the past* the most significant factor underlying trends and projections associated with hurricane impacts on society is societal vulnerability to those impacts and not the trends or variation in the storms themselves (sea Pielke and Landsea 1998; Pielke 2005). Consensus seems to be that growing population and wealth in exposed coastal locations guarantee increased economic damage in coming years, regardless of the details of future patterns of intensity or frequency (Pielke et al. 2000). "In the past (centennial time scales) variability of natural

geophysical hazards (including possible trends) has been orders of magnitude smaller than trend implied by economic or population growth." (Grenier, 2006).

But whether already in the past the impact of climate change – not as the primary but as a secondary factor – on societal impacts can be shown; and whether climate change is becoming an increasingly significant factor for the increase of hurricane impacts on soceity up to now constitutes an open debate. And it has to been noted, that non-detecting does not enable to conclude regarding the existence (Trenberth, 2005).

A further question is, whether the methodology of Pielke really can support his strong hypothesis that „long-term records of economic damages show no upward trend, once the data are normalized to remove the effects of societal changes" (Pielke, 2006; Pielke et al., 2005).

An additional debate of interest could be, whether other methodologies would be more appropriate, to look at the impact of hurricanes on society. One example: As we know, the poor and marginalised population is most affected from weather extremes. Only 11 percent of the people exposed to natural disasters lived in countries classified, according to the UNDP Human Development Index (HDI), as those with a low HDI. But still, these countries account for more than 53 percent of the total recorded deaths (see UNDP 2003). Even more striking is the fact, that over 96 percent of disaster-related deaths in recent years have taken place in developing countries (World Bank 2001). Also the data for weather-related disasters in 2004 show, that countries with a low ranking on the Human Development Index and people living there are more vulnerable:

It is questionable whether Pielke's methodology would adequately reflect significant effects of increased hurricane intensity for the poorest and marginalised part of the population. Such a change might not be relevant in economic terms but most relevant for many people.

Even more relevant might be, whether the conclusion of Pielke (2005) regarding *the future* can be defended. He not only sees no trend identified in various metrics of hurricane damage over the 20th century. While he accepts, that scientists may identify discernible changes in storm behavior, he also argues regarding the future, that it is „exceedingly unlikely that scientists will identify large changes in historical storm behavior that have significant societal implications". (Pielke, 2005).

Rahmstorf et al. (2005) come to a different conclusion: "The current evidence strongly suggests that:

(a) hurricanes tend to become more destructive as ocean temperatures rise, and

(b) an unchecked rise in greenhouse gas concentrations will very likely increase ocean temperatures further, ultimately overwhelming any natural oscillations. Scenarios for future global warming show tropical SST rising by a few degrees, not just tenths of a degree." (Rahmstorf et al. 2005)

SST increases in the Atlantic during 21st century are likely to be much more substantial than seen so far, perhaps by a factor of four (Knutson and Tuleya 2004).

As windstorm damages are exponentially related to wind speed (see for example Dlugolecki et al. 1996, in IPCC WG2 SAR), even small changes could have some effect. The force of increased velocity is proportional to the cube of the velocity. So it is not a linear function. So if we see a significant increase in 4-5 hurricanes and in related landfalls the impact on damage will even be more compelling.

New Regions, New Risks

Another risk for societies, not acknowledged in Pielke's hypotheses regarding the future, is that societies which so far didn't have to expect hurricanes could face this risk in future.

For most tropical meteorologists the most astonishing storm of 2004 took place in March 2004. Hurricane Catarina --

so named because it made landfall in the southern Brazilian state of Santa Catarina -- was the first recorded south Atlantic hurricane in history. Textbook orthodoxy had long excluded the possibility of such an event; sea temperatures, experts claimed until then, were too low and wind shear too powerful to allow tropical depressions to evolve into cyclones south of the Atlantic Equator.

Two other extremely unusual, as far as we know unique, hurricanes emerged in 2005. Hurricane Vince developed in the eastern North Atlantic, a region not previously affected by hurricanes. It passed Madeira as a full-blooded hurricane and even reached the European mainland in southern Spain, but only caused minor damage.

At the end of November 2005, the Canary Islands were hit by Hurricane Delta, the first such storm there since the recording of tropical cyclones in the Atlantic began. This regional extension is one of the strongest arguments, that we might have experienced during the last two years the emergence of a new pattern of hurricane activity.

Sea Level Rise Increases Risk

Global warming also makes hurricanes more destructive by raising the sea level. So even if we wouldn't see any increase in number, intensity and regional distribution of hurricanes, they will become more destructive because of rising sea level, unless substantial damage mitigation steps are undertaken: Assuming current trends of development practice continue, a FEMA study (1991) found that an increase in the expected annual flood damage in the US by the year 2100 for a representative NFIP insured property subject to sea level rise is estimated to increase by 36-58 percent for a 1-foot rise, and by 102-200 percent for a 3-foot rise in sea level. IPCC 2001 expected an increase of 9 to 88 cm during this century. But using the altimetry satellites TOPEX/Poseidon and Jason, a global mean sea-level rise of 2.8 $\pm$ 0.4mma was estimated (Cazenave & Nerem, 2004). If this is the actual rate of sea level increase it would be at the upper range of the IPCC 2001 expactations (see Summary for Policy Makers, figure 5; sea also Rahmstorf and Schellnhuber, 2006: 63f) and a 3-foot rise this century seems possible. Also the newest scientific evidence from an unexpected melting dynamic in greenland and west antarctis points in a direction, that even the extreme scenarios of IPCC 2001 (88 cm this century) might now be a very realistic one. As future sea level rise has a very long equlibration time scale – centuries to millenia – further temperature increase will over time further exacerbate more and more coastal flooding problems from a given hurricane.

Ready to Agree on Rules of the Game to Test the Different Hypotheses?

Pielke et al. have given some criteria, under which circumstances they would be ready to accept that climate change increases significantly the hurricane risk for society. „Looking to the future, until scientists conclude (a) that there will be changes to storms that are significantly larger than observed in the past, (b) that such changes are correlated to measures of societal impact, and (c) that the effects of such changes are significant in the context of inexorable growth in population and property at risk, then it is reasonable to conclude that the significance of any connection of human-caused climate change to hurricane impacts necessarily has been and will continue to be exceedingly small." (Pielke et al., 2005). It would be very interesting if different parties of this debate could agree about similar criteria, which are able to shift evidence to one side or the other.

It is to expect, that for many debates we shouldn't expect quick decisive results. Data still can be used to support different hypotheses. Politics, insurance, investment sector and others nevertheless have to act under uncertainty. It would be very interesting to use Bayesian Logic as a means of quantifying uncertainty. E.g. Carlo Jäger and his team from PIK, Potsdam, work with this method.

Based on probability theory, the Bayesian theorem defines a rule for refining a hypothesis by factoring in additional evidence and background information, and leads to a number representing the degree of probability that the hypothesis is true. Each year we could then see how reality changes the probability of different hypotheses. This would be a suggestion for the next constructive steps in this important debate.

The balance of evidence has been shifted. Strong arguments now point in direction of a hypotheses, which had few supporters only two years ago: that global warming has an increasing effect on the planet's most devastating storms. But there might be much more left to say.

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