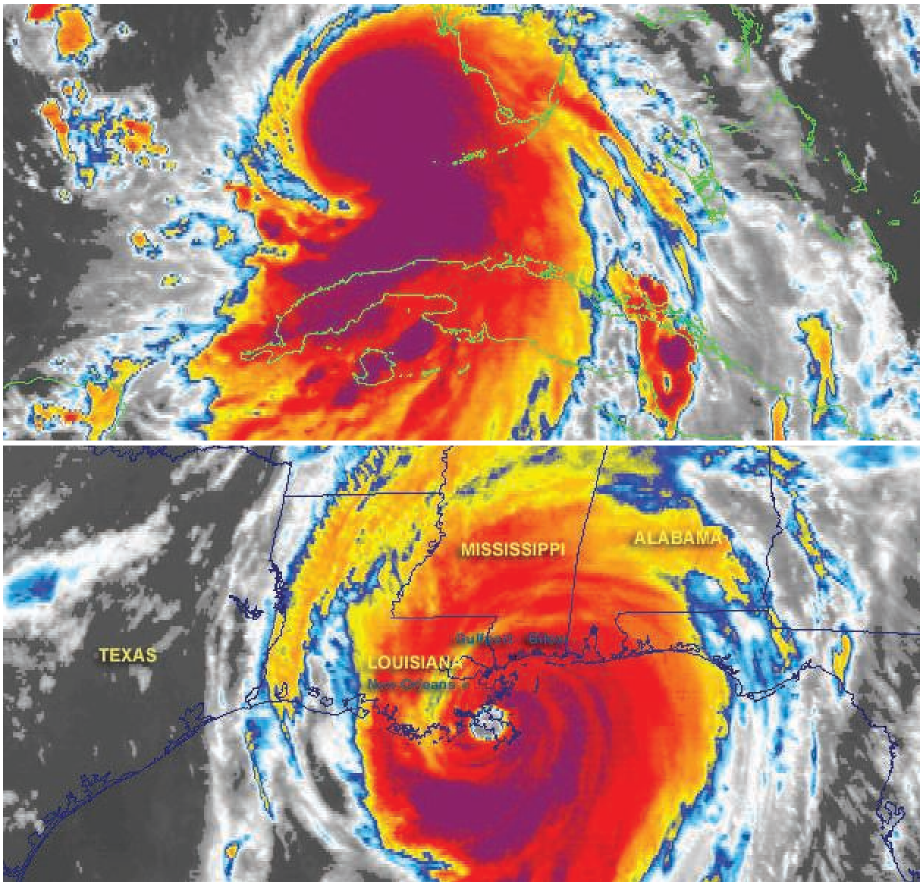
ATMOSPHERIC SCIENCE

Global Warming May Be Homing In on Atlantic Hurricanes



Killer. An analysis of satellite infrared images shows Katrina strengthening from maximum wind speeds of 157 km/h (*top*) to 232 km/h (*bottom*).

CREDIT: NCDC/NOAA

WASHINGTON, D.C.—The idea that increased hurricane activity might be connected to global warming first blew in with Katrina and her cohorts of the horrendous 2005 Atlantic hurricane season. Then two studies reported a striking increase in the number of intense storms around the world. And that increase was suspiciously in step with the warming of tropical waters whose heat fuels tropical cyclones (also called hurricanes or typhoons). But skeptics wondered: Should anyone trust the patchwork records of tropical cyclones compiled over the past century? And couldn't the surge in storms be part of a natural cycle?

New analyses have something to offer both skeptics and proponents. For most of the world's tropical cyclones, existing records should *not* be trusted, according to a new study presented here at a 20 October seminar on Capitol Hill sponsored by the American Meteorological Society (www.ametsoc.org/atmospolicy/environmentalsssarchives.html). The study showed that records of the intensity of most storms around the world have been skewed, producing the impression that tropical cyclones have been getting stronger globally. Records for the Atlantic Ocean, however, do seem to be reliable, and reanalyzed records from the Atlantic going back to 1983 still show a sharp increase in hurricane intensity as tropical Atlantic waters warmed. Other work presented at the seminar suggests that the Atlantic jump was a combination of a long-term increase in the number of storms—possibly under the influence of global warming—and a natural oscillation in storm intensity.

Last year's provocative findings "woke people up," says meteorologist Greg Holland of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, who co-authored a global intensification paper. Now "you're starting to see us make our minds up."

The trouble with tropical cyclone records is that techniques of observation and analysis have changed over the decades. And although observations are now more direct and analyses more objective than before, they still differ from place to place. To create a single, consistent record, tropical meteorologist James Kossin of the University of Wisconsin, Madison, and colleagues altered the satellite records of storm intensity so that they would be uniform from end to end; any trends would reflect trends in the data, not trends induced by changing techniques.

Satellites provide infrared images of storms. Meteorologists can calculate the intensities of those storms from their temperatures: The warmer the eye of a storm and the colder (that is, the higher in altitude) its cloud tops, the stronger the storm. So Kossin and his colleagues altered records to a single spatial resolution of 8 kilometers and a uniform time resolution of 3 hours. They then applied a single algorithm to calculate an objective intensity, as calibrated against Atlantic storms reconnoitered by instrumented aircraft.

Kossin first gave the good news about record reliability. In two regions, the reanalysis was in excellent agreement with previous records. In the Atlantic, the storm energy released in a hurricane season did in fact more than double between the first and second halves of the 1983-to-2005 record. That pattern supports a record that meteorologist and hurricane specialist Kerry Emanuel of the Massachusetts Institute of Technology published in 2005 (*Science*, 16 September 2005, p. 1807). Agreement was also very good in the eastern North Pacific, where energy release declined 60%. These two trends are well-supported, said Kossin.

Then again, there was "not so good news everywhere else," Kossin noted. Where the standard records from the northern Indian Ocean, the southern Indian Ocean, the western North Pacific, and the South Pacific showed rising trends of intensity, the reanalysis showed modest declines or no trend at all. And 85% of the world's tropical cyclones occur in these ocean basins. Outside the Atlantic, Kossin concluded, storms show no signs of intensifying as the underlying waters warm, at least in the past 23 years.

Meteorologist Philip Klotzbach of Colorado State University in Fort Collins says he generally agrees with Kossin's findings. The work "indicates that increases in [tropical cyclone] activity are likely much smaller than some recent papers have claimed," Klotzbach says. Holland, an author of one of those papers, says the work "moves in the direction of what might be the truth. We need to look into this a little bit more."

Holland and tropical meteorologist Peter Webster of the Georgia Institute of Technology in Atlanta have been focusing lately on what many experts consider the most reliable tropical cyclone observations: the number of named tropical cyclones in the North Atlantic and the broad classification of hurricanes as minor or major. At the seminar, Holland reported that the overall number of named Atlantic storms jumped up twice since 1900: in the late 1920s and again in the mid-1990s. That rise was roughly in step with lasting increases in the temperature of waters in the eastern tropical Atlantic, where most storms form. The proportion of those hurricanes classified as "major," however, shows no long-term trend but has oscillated up and down every few decades.

Together, Holland said, the two patterns explain both the lull in hurricane activity in the 1950s and '60s and the surge in the 1990s. The latter was a "double whammy": High storm numbers due to unprecedented tropical warmth coincided with a periodic—and presumably temporary—upswing in the proportion of major hurricanes. Klotzbach isn't so sure. He thinks that the more thorough and precise monitoring of recent decades could well have increased the number of storms rating a name and the number promoted to major status.

Researchers may be edging toward some agreement about how storms respond to warming tropical waters, but they still don't understand why they respond. Modeling studies suggest that greenhouse warming played a substantial role in the recent warming of tropical waters, as climate researcher Thomas Wigley of NCAR and modeler Thomas Delworth of the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, separately reiterated at the seminar. But the best theory and modeling still indicate that ocean temperature has only a minimal direct effect on storms.

As for indirect effects, researchers are just starting to sort them out. One promising step, Delworth said, comes from new work by Thomas Knutson of GFDL and his colleagues, who ran a highly detailed model of the Atlantic region. The model formed realistic tropical cyclones when the modelers fed in the actual ocean and global atmospheric conditions of the past 25 years. The results matched much of the year-to-year variability in actual hurricane numbers, as well as the surge in numbers after the mid-1990s. Now researchers will have to dissect the model's behavior to understand what factors combined to make that happen.

–RICHARD A. KERR

ACADEMIC CAREERS

Spain Reconsiders Its University Reform Law

BARCELONA—Eight years ago, astrophysicist Antonio Ferriz sued the University of Salamanca, charging that it violated hiring rules by passing him over for a local candidate. The case, and several similar ones, drew widespread publicity to complaints that Spain's system for appointing professors was flawed and inbred. The government paid heed: It reformed the law in 2001 to open up academic hiring, imposing a national system for vetting candidates. But now a bill being debated in Spain's Parliament would give more leeway to universities in hiring, and the academic community is deeply divided. Some academic leaders are pleased, but critics such as Ferriz say it could be a step backward.

Spanish universities rarely seek talent from afar when they hire professors. "Some people say that the Spanish system is particularly inward-looking," says Ferriz, a professor at the University of Vigo who is currently a visiting scientist at the Max Planck Institute for Solar System Research in Göttingen, Germany. "I think this is a very soft description of reality." Spain's university system "operates like a mafia," he fumes. Under the old system, Ferriz says, advertised positions were sometimes so narrowly defined that "only the preselected candidate fit."

The 2001 law sought to break this grip on academic posts by creating a centralized *habilitation* system to pass judgment on the quality of job applicants. However, the change proved unpopular among professors and administrators. Former education and culture minister Maria Jesús San Segundo and others proposed a model reform plan, which was approved early in September by the Ministerial Council and is now being debated in Parliament.

The proposed law would still require candidates to submit their curriculum vitae for evaluation by "commissions made up of professors with a renowned teaching and research prestige." But universities would be free to pick and choose candidates. The law would also create new posts for assistant professors and postdocs; permit mixed research institutes involving universities, the Higher Research Council, and private companies; and mandate gender equality in university decision-making bodies. It could also lead to academic evaluations like the U.K.'s "research assessment exercise."

Seeking reform. Astrophysicist Antonio Ferriz has campaigned to open up a system that he says promotes favorites "like a mafia."

CREDITS: ANTONIO FERRIZ

Critics such as José Vicente, a professor of inorganic chemistry at the University of Murcia, say the new plan is no reform. It "simply consists of proposing the worst system for contracting with professors," he says, adding that universities will be able to hire accredited researchers "after a pantomime competition before an ad hoc panel." Less than 10% of successful professorial applicants in Spanish universities are outsiders, he says, predicting that "inbreeding will now increase up to 100%."

Others are more optimistic. Eugenio Degroote, a professor of mathematics at the Polytechnic University of Madrid, says that the first accreditation stage will be selective. Unlike in the past, "bad or mediocre researchers will be eliminated," he argues. The parliamentary debate on the new law is expected to conclude with a vote before the end of the year.

–XAVIER BOSCH

Xavier Bosch is a science writer in Barcelona, Spain.

process may not have been so smooth as initially thought, and numerical simulations performed by Tsiganis *et al*. (*4*) show that the passage of Jupiter and Saturn through a 2:1 resonance may have ignited a period of strong chaotic evolution of Uranus and Neptune. In this scenario, the two planets had frequent close encounters and may even have exchanged orbits before their eccentricities finally settled down, allowing a more quiet migration to the present orbits.

The presence of a thick disk of Trojans around Neptune is clearly relevant to understanding the dynamical evolution of the planet. The co-orbital Trojan paths are unstable when Neptune has repeated close approaches with Uranus, and the capture of the present population appears possible either at the time of the last radial jump related to an encounter with Uranus or during the final period of slow migration. In this last case, collisional emplacement—in synergy with the reduction of the libration amplitude attributable to the outward migration and by the mass growth of the planet—is the only viable mechanism for trapping Trojans in this phase, but it does not appear to be so efficient as to capture a large population. Moreover, the only frequent planetesimal collisions are those that are close to the median plane of the disk, and this fact is at odds with the presence of high-inclination Trojans such as the one found by Sheppard and Trujillo. A thick disk of Neptune Trojans seems also to rule out the possibility that Trojans formed in situ from debris of collisions that occurred nearby (*5*).

The chaotic capture invoked to explain the orbital distribution of Jupiter Trojans might have worked out in the same way for Neptune. The planet at present is close to a 2:1 mean-motion resonance with Uranus; however, the resonance crossing has not been reproduced so far in numerical simulations of the migration of the outer planets. Alternatively, some sweeping secular resonance might have provided the right amount of instability for the "freeze-in" trapping to occur. In the near future, after additional Neptune Trojans are detected, an important test would be to look for a possible asymmetry between the trailing and leading clouds. Theoretical studies have shown that the L5 Lagrangian point (the trailing one) is more stable in the presence of outward radial migration and that this asymmetry strongly depends on the migration rate. This finding would have direct implications for the capture mechanism and for the possibility that the outward migration of Neptune was indeed smooth, without fast jumps caused by gravitational encounters with Uranus.

Sheppard and Trujillo also sort out another aspect of the known Neptune Trojans: their optical color distribution. It appears to be homogeneous and similar to that of Jupiter Trojans, irregular satellites, and possibly comets, but is less consistent with the color distribution of KBOs as a group. This finding raises questions about the compositional gradient along the planetesimal disk in the early solar system, the degree of radial mixing caused by planetary stirring, and the origin of the Jupiter and Neptune Trojans. Did Trojans form in a region of the planetesimal disk thermally and compositionally separated from that of the KBOs? How far did the initial solar nebula extend to allow important differences among small-body populations? Additional data are needed to solve the puzzles of the dynamical and physical properties of Neptune Trojans, and the finding by Sheppard and Trujillo is only the first step.

References

1. D. C. Jewitt, C. A. Trujillo, J. X. Luu, *Astron. J.* **120**, 1140 (2000).
2. S. S. Sheppard, C. A. Trujillo, *Science* **313**, 511 (2006); published online 15 June 2006 (10.1126/science.1127173).
3. A. Morbidelli, H. F. Levison, K. Tsiganis, R. Gomes, *Nature* **435**, 462 (2005).
4. K. Tsiganis, R. Gomes, A. Morbidelli, H. F. Levison, *Nature* **435**, 459 (2005).
5. E. I. Chiang, Y. Lithwick, *Astrophys. J.* **628**, L520 (2005).

Published online 15 June 2006;
10.1126/science.1129458
Include this information when citing this paper.

CLIMATE CHANGE

Can We Detect Trends in Extreme Tropical Cyclones?

Subjective measurements and variable procedures make existing tropical cyclone databases insufficiently reliable to detect trends in the frequency of extreme cyclones.

Christopher W. Landsea, Bruce A. Harper, Karl Hoarau, John A. Knaff

Recent studies have found a large, sudden increase in observed tropical cyclone intensities, linked to warming sea surface temperatures that may be associated with global warming (*1*–*3*). Yet modeling and theoretical studies suggest only small anthropogenic changes to tropical cyclone intensity several decades into the future [an increase on the order of ~5% near the end of the 21st century (*4*, *5*)]. Several comments and replies (*6*–*10*) have been published regarding the new results, but one key question remains: Are the global tropical cyclone databases sufficiently reliable to ascertain long-term trends in tropical cyclone intensity, particularly in the frequency of extreme tropical cyclones (categories 4 and 5 on the Saffir-Simpson Hurricane Scale)?

Tropical cyclone intensity is defined by the maximum sustained surface wind, which occurs in the eyewall of a tropical cyclone over an area of just a few dozen square kilometers. The main method globally for estimating tropical cyclone intensity derives from a satellite-based pattern recognition scheme known as the Dvorak Technique (*11*–*13*). The Atlantic basin has had routine aircraft reconnaissance since the 1940s, but even here, satellite images are heavily relied upon for intensity estimates, because aircraft can monitor only about half of the basin and are not available continuously. However, the Dvorak Technique does not directly measure maximum sustained surface wind. Even today, application of this technique is subjective, and it is common for different forecasters and agencies to estimate significantly different intensities on the basis of identical information.

The Dvorak Technique was invented in 1972 and was soon used by U.S. forecast offices, but the rest of the world did not use it routinely until the early 1980s (*11*, *13*). Until then, there was no systematic way to estimate the maximum sustained surface wind for most tropical cyclones. The Dvorak Technique was first developed for visible imagery (*11*), which precluded obtaining tropical cyclone intensity estimates at night and limited the sampling of maximum sustained surface wind. In 1984, a quantitative infrared method (*12*) was published, based on the observation that the temperature contrast between the warm eye of the cyclone and the cold cloud tops of the eyewall was a reasonable proxy for the maximum sustained surface wind.

In 1975, two geostationary satellites were available for global monitoring, both with 9-km resolution for infrared imagery. Today, eight

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satellites are available with typically 4-km resolution in the infrared spectrum. The resulting higher resolution images and more direct overhead views of tropical cyclones result in greater and more accurate intensity estimates in recent years when using the infrared Dvorak Technique. For example (*13*), Atlantic Hurricane Hugo was estimated to have a maximum sustained surface wind of 59 m s^{-1} on 15 September 1989, based on use of the Dvorak Technique from an oblique observational angle. But in situ aircraft reconnaissance data obtained at the same time revealed that the hurricane was much stronger (72 m/s) than estimated by satellite. This type of underestimate was probably quite common in the 1970s and 1980s in all tropical cyclone basins because of application of the Dvorak Technique in an era of few satellites with low spatial resolution.

Operational changes at the various tropical cyclone warning centers probably also contributed to discontinuities in tropical cyclone intensity estimates and to more frequent identification of extreme tropical cyclones (along with a shift to stronger maximum sustained surface wind in general) by 1990. These operational changes include (*13*–*17*) the advent of advanced analysis and display systems for visualizing satellite images, changes in the pressure-wind relationships used for wind estimation from observed pressures, relocation of some tropical cyclone warning centers, termination of aircraft reconnaissance in the Northwest Pacific in August 1987, and the establishment of specialized tropical cyclone warning centers.

Therefore, tropical cyclone databases in regions primarily dependent on satellite imagery for monitoring are inhomogeneous and likely to have artificial upward trends in intensity. Data from the only two basins that have had regular aircraft reconnaissance—the Atlantic and Northwest Pacific—show that no significant trends exist in tropical cyclone activity when records back to at least 1960 are examined (*7*, *9*). However, differing results are obtained if large bias corrections are used on the best track databases (*1*), although such strong adjustments to the tropical cyclone intensities may not be warranted (*7*). In both basins, monitoring and operational changes complicate the identification of true climate trends. Tropical cyclone "best track" data sets are finalized annually by operational meteorologists, not by climate researchers, and none of the data sets have been quality controlled to account for changes in physical understanding, new or modified methods for analyzing intensity, and aircraft/satellite data changes (*18*–*21*).

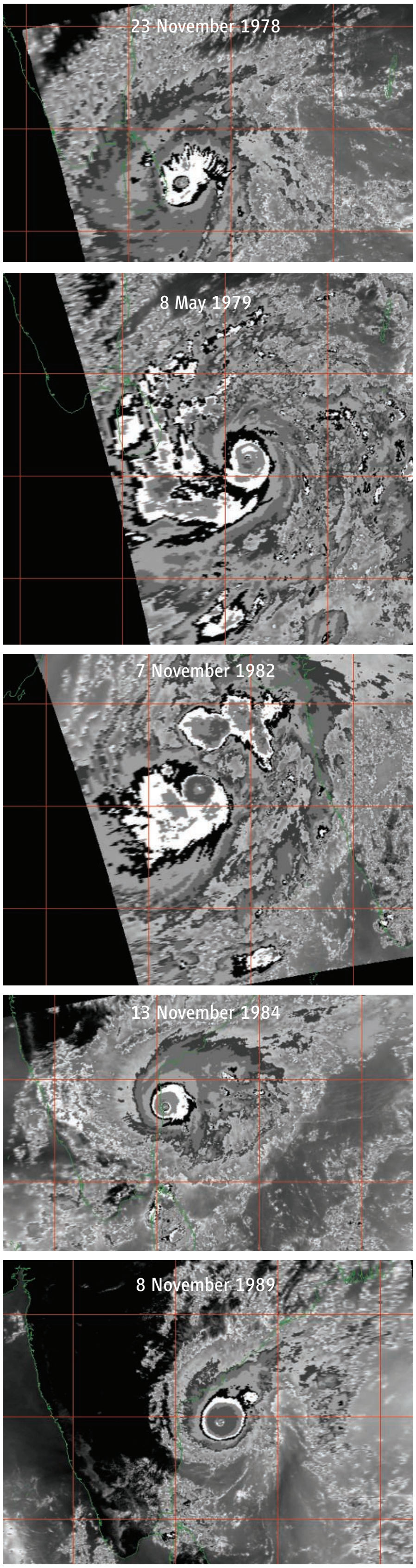
To illustrate our point, the figure presents satellite images of five tropical cyclones listed in the North Indian basin database for the period 1977 to 1989 as category 3 or weaker. Today, these storms would likely be considered extreme tropical cyclones based on retrospective application of the infrared Dvorak Technique. Another major tropical cyclone, the 1970 Bangladesh cyclone—the world's worst tropical-cyclone disaster, with 300,000 to 500,000 people killed—does not even have an official intensity estimate, despite indications that it was extremely intense (*22*). Inclusion of these storms as extreme tropical cyclones would boost the frequency of such events in the 1970s and 1980s to numbers indistinguishable from the past 15 years, suggesting no systematic increase in extreme tropical cyclones for the North Indian basin.

These examples are not likely to be isolated exceptions. Ongoing Dvorak reanalyses of satellite images in the Eastern Hemisphere basins by the third author suggest that there are at least 70 additional, previously unrecognized category 4 and 5 cyclones during the period 1978–1990. The pre-1990 tropical cyclone data for all basins are replete with large uncertainties, gaps, and biases. Trend analyses for extreme tropical cyclones are unreliable because of operational changes that have artificially resulted in more intense tropical cyclones being recorded, casting severe doubts on any such trend linkages to global warming.

There may indeed be real trends in tropical cyclone intensity. Theoretical considerations based on sea surface temperature increases suggest an increase of ~4% in maximum sustained surface wind per degree Celsius (*4*, *5*). But such trends are very likely to be much smaller (or even negligible) than those found in the recent studies (*1*–*3*). Indeed, Klotzbach has shown (*23*) that extreme tropical cyclones and overall tropical cyclone activity have globally been flat from 1986 until 2005, despite a sea surface temperature warming of 0.25°C. The large, step-like increases in the 1970s and 1980s reported in (*1*–*3*) occurred while operational improvements were ongoing. An actual increase in global extreme tropical cyclones due to warming sea surface temperatures should have continued during the past two decades.

Efforts under way by climate researchers—including reanalyses of existing tropical cyclone databases (*20*, *21*)—may mitigate the problems in applying the present observational tropical cyclone databases to trend analyses to answer the important question of how humankind may (or may not) be changing the frequency of extreme tropical cyclones.

Previously unrecognized category 4 and 5 tropical cyclones in the North Indian Ocean, 1978–1989



Underestimated storm intensity. The North Indian basin tropical cyclones shown here are listed in the best track data set as category 3 or weaker, but were probably category 4 or 5. Similar underestimates may have been common in all ocean basins in the 1970s and 1980s. Trend analyses for tropical cyclones intensities are therefore highly problematic.

References and Notes

1. K. Emanuel, *Nature* **436**, 686 (2005).
2. P. J. Webster, G. J. Holland, J. A. Curry, H.-R. Chang, *Science* **309**, 1844 (2005).
3. C. D. Hoyos, P. A. Agudelo, P. J. Webster, J. A. Curry,

Science **312**, 94 (2006); published online 15 March 2006 (10.1126/science.1123560).
4. T. R. Knutson, R. E. Tuleya, *J. Clim.* **17**, 3477 (2004).
5. K. Emanuel, in *Hurricanes and Typhoons: Past, Present and Future*, R. J. Murnane, K.-B. Liu, Eds. (Columbia Univ. Press, New York, 2004), pp. 395–407.
6. R. A. Pielke Jr., *Nature* **438**, E11 (2005).
7. C. W. Landsea, *Nature* **438**, E11 (2005).
8. K. Emanuel, *Nature* **438**, E13 (2005).
9. J. C. L. Chan, *Science* **311**, 1713b (2006).
10. P. J. Webster, J. A. Curry, J. Liu, G. J. Holland, *Science* **311**, 1713c (2006).
11. V. F. Dvorak, *Mon. Weather Rev.* **103**, 420 (1975).
12. V. F. Dvorak, *NOAA Tech. Rep. NESDIS 11* (1984).
13. C. Velden *et al.*, *Bull. Am. Meteorol. Soc.*, in press.
14. J. A. Knaff, R. M. Zehr, *Weather Forecast.*, in press.
15. C. Neumann, *in Storms Volume 1*, R. Pielke Jr., R. Pielke Sr., Eds. (Routledge, New York, 2000), pp. 164–195.
16. R. J. Murnane, in *Hurricanes and Typhoons: Past, Present and Future*, R. J. Murnane, K.-B. Liu, Eds. (Columbia Univ. Press, New York, 2004), pp. 249–266.
17. J.-H. Chu, C. R. Sampson, A. S. Levine, E. Fukada, *The Joint Typhoon Warning Center Tropical Cyclone Best-Tracks, 1945–2000*, Naval Research Laboratory Reference Number NRL/MR/7540-02-16 (2002).
18. C. W. Landsea, *Mon. Weather Rev.* **121**, 1703 (1993).
19. J. L. Franklin, M. L. Black, K. Valde, *Weather Forecast.* **18**, 32 (2003).
20. C. W. Landsea *et al.*, *Bull. Am. Meteorol. Soc.* **85**, 1699 (2004).
21. C. W. Landsea *et al.*, in *Hurricanes and Typhoons: Past, Present and Future*, R. J. Murnane, K.-B. Liu, Eds. (Columbia Univ. Press, New York, 2004), pp. 177–221.
22. K. Emanuel, *Divine Wind—The History and Science of Hurricanes* (Oxford Univ. Press, Oxford, 2005).
23. P. J. Klotzbach, *Geophys. Res. Lett.* **33**, 10.1029/2006GL025881 (2006).
24. This work was sponsored by a grant from the NOAA Climate and Global Change Program on the Atlantic Hurricane Database Re-analysis Project. Helpful comments and suggestions were provided by L. Avila, J. Beven, E. Blake, J. Callaghan, J. Kossin, T. Knutson, M. Mayfield, A. Mestas-Nunez, R. Pasch, and M. Turk.

10.1126/science.1128448

COMPUTER SCIENCE

New Life for Neural Networks

With the help of neural networks, data sets with many dimensions can be analyzed to find lower dimensional structures within them.

Garrison W. Cottrell

As many researchers have found, the data they have to deal with are often high-dimensional—that is, expressed by many variables—but may contain a great deal of latent structure. Discovering that structure, however, is nontrivial. To illustrate the point, consider a case in the relatively low dimension of three. Suppose you are handed a large number of three-dimensional points in random order (where each point is denoted by its coordinates along the x, y, and z axes): {(–7.4000, –0.8987, 0.4385), (3.6000, –0.4425, –0.8968), (–5.0000, 0.9589, 0.2837), …}. Is there a more compact, lower dimensional description of these data? In this case, the answer is yes, which one would quickly discover by plotting the points, as shown in the left panel of the figure. Thus, although the data exist in three dimensions, they really lie along a one-dimensional curve that is embedded in three-dimensional space. This curve can be represented by three functions of x, as $(x, y, z) = [x, \sin(x), \cos(x)]$. This immediately reveals the inherently one-dimensional nature of these data. An important feature of this description is that the natural distance between two points is not the Euclidean, straight line distance; rather, it is the distance along this curve. As Hinton and Salakhutdinov report on page 504 of this issue (*1*), the discovery of such low-dimensional encodings of very high-dimensional data (and the inverse transformation back to high dimensions) can now be efficiently carried out with standard neural network techniques. The trick is to use networks initialized to be near a solution, using unsupervised methods that were recently developed by Hinton's group.

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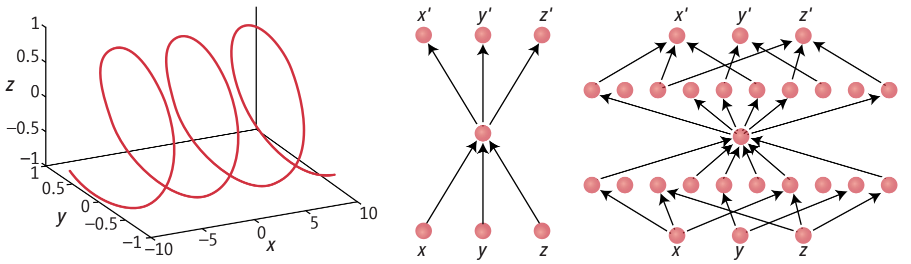


Searching for structure. (Left) Three-dimensional data that are inherently one-dimensional. **(Middle)** A simple "autoencoder" network that is designed to compress three dimensions to one, through the narrow hidden layer of one unit. The inputs are labeled x, y, z, with outputs x', y', and z'. **(Right)** A more complex autoencoder network that can represent highly nonlinear mappings from three dimensions to one, and from one dimension back out to three dimensions.

This low-dimensional structure is not uncommon; in many domains, what initially appears to be high-dimensional data actually lies upon a much lower dimensional manifold (or surface). The issue to be addressed is how to find such lower dimensional descriptions when the form of the data is unknown in advance, and is of much higher dimension than three. For example, digitized images of faces taken with a 3-megapixel camera exist in a very high dimensional space. If each pixel is represented by a gray-scale value between 0 and 255 (leaving out color), the faces are points in a 3-million-dimensional hypercube that also contains all gray-scale pictures of that resolution. Not every point in that hypercube is a face, however, and indeed, most of the points are not faces. We would like to discover a lower dimensional manifold that corresponds to "face space," the space that contains all face images and only face images. The dimensions of face space will correspond to the important ways that faces differ from one another, and not to the ways that other images differ.

This problem is an example of unsupervised learning, where the goal is to find underlying regularities in the data, rather than the standard supervised learning task where the learner must classify data into categories supplied by a teacher. There are many approaches to this problem, some of which have been reported in this journal (*2*, *3*). Most previous systems learn the local structure among the points—that is, they can essentially give a neighborhood structure around a point, such that one can measure distances between points within the manifold. A major limitation of these approaches, however, is that one cannot take a new point and decide where it goes on the underlying manifold (*4*). That is, these approaches only learn the underlying low-dimensional structure of a given set of data, but they do not provide a mapping from new data points in the high-dimensional space into the structure that they have found (an encoder), or, for that matter, a mapping back out again into the original space (a decoder). This is an important feature because without it, the method can only be applied to the original data set, and cannot be used on novel data. Hinton and Salakhutdinov address the issue of finding an invertible mapping by making a known but previously impractical plexity. The rapidity of the diversification and the ecological interactions between species suggests that, as in the plants and insects of the Hawaiian and Canary islands, species begat species. In terms of MacArthur and Wilson's model, these macroevolutionary events should be limited by the extent to which new resources increased the carrying capacity of the environment. But if there is feedback between diversifying species, and a total potential diversity that is not limited by resources, then we may need a class of models in which future diversity is a function of current diversity.

Diversity cannot continue to increase forever, and ultimately resource availability must play a role, but perhaps a smaller one over evolutionary time than has been thought. Paleontologists, taking their cue from ecologists, have generally assumed that resource limitation controls the diversity of a community, but some have wondered whether changes in diversity might come from periodic disturbance. There have been few explicit considerations of this possibility, but Stanley (*11*) suggested that the apparent periodicity of mass extinctions and biotic crises reflected prolonged environmental disturbance and lengthy rediversification, not a periodic external forcing factor (such as periodic meteor bombardment). If periodic disturbance does provide a major control on diversity, then niche generation may be an ongoing process, more rapid during macroevolutionary transitions, but providing a regular source of new adaptive possibility until the next crisis occurs.

References
1. R. H. MacArthur, E. O. Wilson, *The Theory of Island Biogeography* (Princeton Univ. Press, Princeton, NJ, 1967).
2. B. C. Emerson, N. Kolm, *Nature* **434**, 1015 (2005).
3. F. J. Odling-Smee, K. N. Laland, M. W. Feldman, *Niche Construction: The Neglected Process in Evolution* (Princeton Univ. Press, Princeton, NJ, 2003).
4. C. G. Jones, J. H. Lawton, M. Shachak, *Oikos* **69**, 373 (1994).
5. C. G. Jones, J. H. Lawton, M. Shachak, *Ecology* **78**, 1946 (1997).
6. R. Dawkins, *The Extended Phenotype* (Oxford Univ. Press, Oxford, 1982).
7. R. C. Lewontin, in *Evolution from Molecules to Men*, D. S. Bendall, Ed. (Cambridge Univ. Press, Cambridge, 1983), pp. 273–285.
8. R. Dawkins, *Biol. Philos.* **19**, 377 (2004).
9. B. D. Webby, F. Paris, M. L. Droser, I. G. Percival, *The Great Ordovician Biodiversification Event* (Columbia Univ. Press, New York, 2004).
10. P. W. Signor, G. J. Vermeij, *Paleobiology* **20**, 297 (1994).
11. S. M. Stanley, *Paleobiology* **16**, 401 (1990).

10.1126/science.1113416

CLIMATE

Uncertainty in Hurricanes and Global Warming

Kevin Trenberth

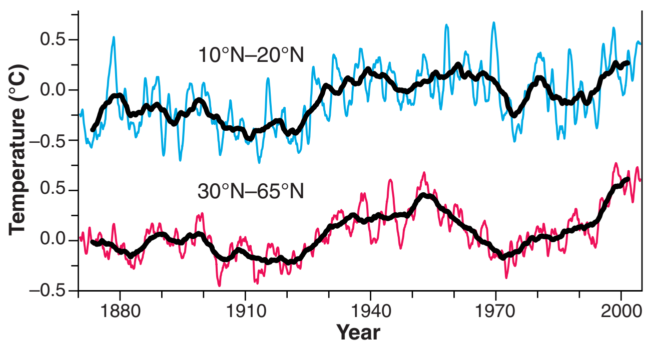
During the 2004 hurricane season in the North Atlantic, an unprecedented four hurricanes hit Florida; during the same season in the Pacific, 10 tropical cyclones or typhoons hit Japan (the previous record was six) (*1*). Some scientists say that this increase is related to global warming; others say that it is not. Can a trend in hurricane activity in the North Atlantic be detected? Can any such trend be attributed to human activity? Are we even asking the right questions?

In statistics, a null hypothesis—such as "there is no trend in hurricane activity"—may be formed, and it is common to reject the null hypothesis based on a 5% significance level. But accepting the null hypothesis does not mean that there is no trend, only that it cannot be proven from the particular sample and that more data may be required. This is frequently the case when the signal being sought is masked by large variability. If one instead formulates the inverse null hypothesis—"there is a trend in hurricane activity"—then the 5% significance level may bias results in favor of this hypothesis being accepted, given the variability. Acceptance of a false hypothesis (a "type II" error) is a common mistake. Rather than accept the hypothesis, one may be better off reserving judgment. Because of the weakness associated with statistical tests, it is vital to also gain a physical understanding of the changes in hurricane activity and their origins.

Hurricane activity generally occurs over the oceans in regions where sea surface temperatures (SSTs) exceed 26°C (*2*). In the Atlantic, SSTs and hurricane activity (see both figures) vary widely on interannual and multidecadal time scales. One factor in the year-to-year variability is El Niño: Atlantic hurricanes are suppressed when an El Niño is under way in the Pacific (*3*, *4*). The decadal variability is thought to be associated with the thermohaline circulation and is referred to as the Atlantic multidecadal oscillation. It affects the number of hurricanes and major hurricanes that form from tropical storms first named in the tropical Atlantic and the Caribbean Sea (*5*–*7*).

In addition to interannual and multidecadal variability, there is a nonlinear upward trend in SSTs over the 20th century. This trend is most pronounced in the past 35 years in the extratropical North Atlantic (see the first figure). It is associated with global warming and has been attributed to human activity (*8*). In the tropical North Atlantic—the region of most relevance to hurricane formation—multidecadal variability dominates SSTs (see the first figure), but the 1995–2004 decadal average is nonetheless the highest on record by >0.1°C. Hence, although the warming in the tropical North Atlantic is not as pronounced, it is probably related to that in the extratropical North Atlantic.

SSTs are not the only important variable affecting hurricanes (*2*, *9*, *10*). Other factors that have influenced the increase in hurricane activity in the past decade (*11*) include an amplified high-pressure ridge in the upper troposphere across the central and eastern North Atlantic; reduced vertical wind shear over the central North Atlantic [wind shear tends to inhibit the vortex from forming (*2*)]; and African easterly lower atmospheric winds that favor the development of hurricanes from tropical disturbances moving westward from the African coast. Atmospheric stability is also important (*4*).



Getting warmer. Annual mean SST anomalies relative to 1961 to 1990 (*23*) for 1870 to 2004, averaged over the tropical Atlantic (10°N to 20°N, excluding the Caribbean west of 80°W) (**top**) and the extratropical North Atlantic (30°N to 65°N) (**bottom**). Heavy lines are 10-year running means.

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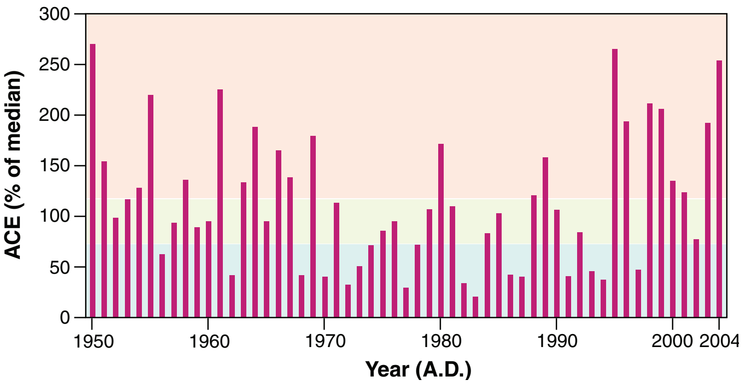
Higher SSTs are associated with increased water vapor in the lower troposphere. Since 1988, the amount of total column water vapor over the global oceans has increased by 1.3% per decade (*12*); the variability and trends in water vapor are strongly related to SST anomalies. This behavior is similar to that expected theoretically (*13*) and supports model projections (*14*) suggesting that relative humidity remains about the same as temperatures increase. Both higher SSTs and increased water vapor tend to increase the energy available for atmospheric convection, such as thunderstorms, and for the development of tropical cyclones (*9*, *15*). However, the convective available potential energy (*15*) is also affected by large-scale subsiding air that increases the stability and dryness of the atmosphere, and is often associated with wind shear throughout the troposphere (*16*). The convective available potential energy appears to have increased in the tropics from 1958 to 1997 (*17*, *18*), which should increase the potential for enhanced moist convection, and thus—conceivably—for more hurricanes.



A measure of regional storm activity. The ACE index reflects the collective intensity and duration of tropical storms and hurricanes during a given hurricane season. Values are given as percentage of the median from 1951 to 2000; the white band indicates normal conditions, the blue is below normal, and the pink is above normal, according to NOAA. [Adapted from (*1*)]

An important measure of regional storm activity is the Accumulated Cyclone Energy (ACE) index (see the second figure) (*1*). Since 1995, the ACE indexes for all but two Atlantic hurricane seasons have been above normal; the exceptions are the El Niño years of 1997 and 2002. According to the National Oceanic and Atmospheric Administration (NOAA), the hurricane seasons from 1995 to 2004 averaged 13.6 tropical storms, 7.8 hurricanes, and 3.8 major hurricanes, and the ACE index was 169% of the median. In contrast, the hurricane seasons during the previous 25-year period (1970 to 1994) averaged 8.6 tropical storms, five hurricanes, and 1.5 major hurricanes, and the ACE index was 70% of the median. In 2004, ACE reached the third-highest value since 1950 (*1*); there were 15 named storms, including nine hurricanes.

Despite this enhanced activity, there is no sound theoretical basis for drawing any conclusions about how anthropogenic climate change affects hurricane numbers or tracks, and thus how many hit land. The environmental changes that are under way favor enhanced convection and thus more thunderstorms. But to get a hurricane, these thunderstorms must first be organized into a tropical storm (which is essentially a collection of thunderstorms that develops a vortex). Model projections of how wind shear in the hurricane region responds to global warming caused by increased carbon dioxide in the atmosphere tend to differ (*14*), and it is not yet possible to say how El Niño and other factors affecting hurricane formation may change as the world warms.

However, once a tropical storm has formed, the changing environmental conditions provide more energy to fuel the storm, which suggests that it will be more intense than it would otherwise have been, and that it will be associated with heavier rainfalls (*14*). Groisman *et al.* (*19*) found no statistically significant evidence that precipitation associated with hurricanes increased along the southeastern coast of the contiguous United States during the 20th century; however, their analysis did not include years after 2000, and there was a distinct increase in hurricane precipitation after 1995. Groisman *et al.* found a linear upward trend in precipitation amount by 7% in the 20th century in the contiguous United States; the increases in heavy precipitation (the heaviest 5%) and very heavy precipitation (the heaviest 1%) were much greater at 14% and 20%, respectively (*19*). Such trends are likely to continue (*20*).

Thus, although variability is large, trends associated with human influences are evident in the environment in which hurricanes form, and our physical understanding suggests that the intensity of and rainfalls from hurricanes are probably increasing (*8*), even if this increase cannot yet be proven with a formal statistical test. Model results (*14*) suggest a shift in hurricane intensities toward extreme hurricanes.

The fact that the numbers of hurricanes have increased in the Atlantic is no guarantee that this trend will continue, owing to the need for favorable conditions to allow a vortex to form while limiting stabilization of the atmosphere by convection. The ability to predict these aspects requires improved understanding and projections of regional climate change. In particular, the tropical ocean basins appear to compete to be most favorable for hurricanes to develop; more activity in the Pacific associated with El Niño is a recipe for less activity in the Atlantic. Moreover, the thermohaline circulation and other climate factors will continue to vary naturally.

Trends in human-influenced environmental changes are now evident in hurricane regions. These changes are expected to affect hurricane intensity and rainfall, but the effect on hurricane numbers remains unclear. The key scientific question is not whether there is a trend in hurricane numbers and tracks, but rather how hurricanes are changing.

References and Notes

1. D. H. Levinson, Ed., special issue on State of the Climate in 2004, *Bull. Am. Meteorol. Soc.* **86 (suppl.)** (2005).
2. A. Henderson-Sellers *et al.*, *Bull. Am. Meteorol. Soc.* **79**, 19 (1998).
3. W. M. Gray, *Mon. Weather Rev.* **112**, 1649 (1984).
4. B. H. Tang, J. D. Neelin, *Geophys. Res. Lett.* **31**, L24204 (2004).
5. M. E. Schlesinger, N. Ramankutty, *Nature* **367**, 723 (1994).
6. T. L. Delworth, M. E. Mann, *Clim. Dyn.* **16**, 661 (2000).
7. S. B. Goldenberg *et al.*, *Science* **293**, 474 (2001).
8. Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001).
9. G. J. Holland, *J. Atmos. Sci.* **54**, 2519 (1997).
10. K. A. Emanuel, *Nature* **401**, 665 (1999).
11. M. Chelliah, G. D. Bell, *J. Clim.* **17**, 1777 (2004).
12. K. E. Trenberth, J. Fasullo, L. Smith, *Clim. Dyn.*, 10.1007/s00382-005-0017-4 (25 March 2005).
13. The water-holding capacity of the atmosphere increases by ~7% per °C (*20*).
14. T. R. Knutson, R. E. Tuleya, *J. Clim.* **17**, 3477 (2004).
15. The convective available potential energy (CAPE) depends on the vertical profile of moist static energy (the combination of sensible heat, which is related to temperature, and potential and latent energy) and thus on moisture and temperature profiles.
16. J. C. L. Chan, K. S. Liu, *J. Clim.* **17**, 4590 (2004).
17. A. Gettelman *et al.*, *J. Geophys. Res.* **107**, 10.1029/2001JD001082 (2002).
18. Results based on more stations (*21*) may be compromised by uncertainties in changing instrumentation and adjustments to the data that were flawed (*22*).
19. P. Ya. Groisman *et al.*, *J. Hydrometeorol.* **5**, 64 (2004).
20. K. E. Trenberth, A. Dai, R. M. Rasmussen, D. B. Parsons, *Bull. Am. Meteorol. Soc.* **84**, 1205 (2003).
21. C. A. DeMott, D. A. Randall, *J. Geophys. Res.* **109**, D02102 (2004).
22. I. Durre, T. C. Peterson, R. S. Vose, *J. Clim.* **15**, 1335 (2002).
23. N. A. Rayner *et al.*, *J. Geophys. Res.* **108**, 10.1029/2002JD002670 (2003).
24. I thank J. Fasullo for generating the first figure, and R. Anthes, G. Holland, and S. Solomon for comments. NCAR is sponsored by the National Science Foundation.

10.1126/science.1112551

These observations of nonlinear wave propagation need to be modeled successfully in order to have practical engineering implications. Currently, the integrated physical processes of earthquake rupture and wave propagation are separated into simpler substructure analyses. To make the computations feasible, empirical ground-motion prediction equations (*18*) or the large-scale physics of earthquake rupture and wave propagation are used to obtain linear free-surface ground shaking (*1*, *19*, *20*) that omits the soil component (see the figure, panel D). The linear ground motions are then used as inputs to calculate surface and embedded motions in a model that accounts for nonlinear soil responses (see the figure, panel C). Finally, the ground-motion outputs are used to conduct soil-structure interaction (SSI) analyses (*21*) that include both the foundation and the engineered structure (see the figure, panel B).

It is not clear that the anomalous large vertical accelerations observed by Aoi *et al.* could occur in the foundation of a structure at a site that has been compacted and had a foundation emplaced, particularly because large structures impose considerable confining pressures on a soil. Specifically, can these new large accelerations occur at the foundation level of buildings and critical structures?

Answers to this question will require a much larger-scale deployment of strong motion sensors at the foundation level of buildings. In this regard, the volunteer-based Quake-Catcher Network (QCN) links triaxial accelerometers internal to many laptops and low-cost USB-port accelerometers connected to desktops to a network of servers (*22*, *23*). The USB sensors are typically set to record up to 2*g*, but can record up to 6*g* with reduced resolution. Currently, the network has roughly 500 users globally, but within the next 6 to 9 months 1100 USB sensors will be installed in schools, firehouses, and community buildings. The QCN could record many thousands of ground motions at the foundation level of buildings from a single earthquake, vastly exceeding the scope of single-earthquake ground-motion recordings that have been obtained to date. The data obtained will provide valuable constraints on the practical limits on ground-shaking amplitudes imposed on buildings and critical structures, an issue that is currently far from resolved (*24*, *25*).

References and Notes

1. A. D. Frankel, *Science* **283**, 2032 (1999).
2. L. F. Bonilla *et al.*, *Bull. Seismol. Soc. Am*. **95**, 2373 (2005).
3. E. H. Field *et al.*, *J. Geophys. Res.* **103**, 26869 (1998).
4. D. R. H. O'Connell, *Science* **283**, 2045 (1999).
5. S. Hartzell *et al.*, *Bull. Seismol. Soc. Am*. **95**, 614 (2005).
6. H. Fujiwara *et al.*, *Technical Note of the National Research Institute for Earth Science and Disaster Prevention* **264**, 91 (2005).
7. S. Aoi, T. Kunugi, H. Fujiwara, *Science* **322**, 727 (2008).
8. H. B. Seed, I. M. Idriss, *Bull. Seismol. Soc. Am*. **60**, 125 (1970).
9. I. A. Beresnev *et al.*, *Bull. Seismol. Soc. Am.* **85**, 496 (1995).
10. B. O. Hardin, V. P. Drnevich, *J. Soil Mech. Found. Div. ASCE* **98**, 603 (1972).
11. B. O. Hardin, V. P. Drnevich, *J. Soil Mech. Found. Div. ASCE* **98**, 667 (1972).
12. M. Vucetic, *Can. Geotech. J.* **27**, 29 (1990).
13. I. A. Beresnev *et al.*, *Bull. Seismol. Soc. Am*. **92**, 3152 (2002).
14. S. Iai *et al.*, *Soils Found.* **35**, 115 (1995).
15. D. H. Weichert *et al.*, *Bull. Seismol. Soc. Am.* **76**, 1473 (1986).
16. D. Howell *et al.*, *Phys. Rev. Lett.* **82**, 5241 (1999).
17. Animations are available online at www.phy.duke.edu/~dhowell/research.html.
18. Next Generation of Ground-Motion Attenuation Models, *Earthquake Spectra* **24**, 1, (2008).
19. S. Hartzell *et al.*, *Bull. Seismol. Soc. Am*. **92**, 831 (2005).
20. Southern California Earthquake Center (SCEC) PetaSHA/PetaShake Project, http://scecdata.usc.edu/petasha.
21. C. B. Crouse, J. C. Ramirez, *Bull. Seismol. Soc. Am*. **923**, 546 (2003).
22. E. S. Cochran *et al.*, *SCEC Ann. Meet. Proc. Abs.* **18**, 85 (2008).
23. For more information on QCN, see qcn.stanford.edu.
24. T. C. Hanks *et al.*, in *Directions in Strong Motion Instrumentation*, P. Gülkan, J. G. Anderson, Eds., (Springer Netherlands, Dorcrecht, 2005), vol. 58, pp. 55–59.
25. 2008 SCEC Etreme Ground Motion Workshop http://scec.org/meetings/2008am/exgmworkshop.html

26. Research supported by USGS award no. 08HQGR0068.

10.1126/science.1166149

CLIMATE CHANGE

Whither Hurricane Activity?

Alternative interpretations of the relationship between sea surface temperature and hurricane activity imply vastly different future Atlantic hurricane activity.

Gabriel A. Vecchi,[1] Kyle L. Swanson,[2] Brian J. Soden[3]

A key question in the study of near-term climate change is whether there is a causal connection between warming tropical sea surface temperatures (SSTs) and Atlantic hurricane activity (*1*–*3*). Such a connection would imply that the marked increase in Atlantic hurricane activity since the early 1990s is a harbinger of larger changes to come and that part of that increase could be attributed to human actions (*3*). However, the increase could also be a result of the warming of the Atlantic relative to other ocean basins (*4*), which is not expected to continue in the long term (*5*). On current evidence, can we decide which interpretation is likely to be correct?

To appreciate the problem, consider the observed relation between hurricane activity [power dissipation index (PDI)] (*6*) and SST in the main development region of Atlantic hurricanes (hereafter "absolute SST"). Between 1946 and 2007, this relation can be defined by a simple linear regression between the two quantities (see Supporting Online Material). This observed relation can be extrapolated into the 21st century using absolute SSTs calculated from global climate model projections (see the figure, top panel) (*7*). By 2100, the model projections' lower bound on 5-year averaged Atlantic hurricane activity is comparable to the PDI level of 2005, when four major hurricanes (sustained winds of over 100 knots) struck the continental United States, causing more than $100 billion in damage. The upper bound of the projected 5-year average exceeds 2005 levels by more than a factor of two. This is a sobering outlook that, combined with rising sea levels, would have dramatic implications for residents of regions impacted by Atlantic hurricanes.

However, there is an alternate future, equally consistent with observed links between SST and Atlantic hurricane activity. Observational relationships (*4*), theories that provide an upper limit to hurricane intensity (*5*), and high-resolution model studies (*8*) suggest that it is the SST in the tropical Atlantic main development region relative to the tropical mean SST that controls fluctuations in Atlantic hurricane activity. Between 1946 and 2007, this "relative SST" (see the figure, bottom panel) is as well correlated with Atlantic hurricane activity as the absolute SST. However, relative SST does not experience a substantial

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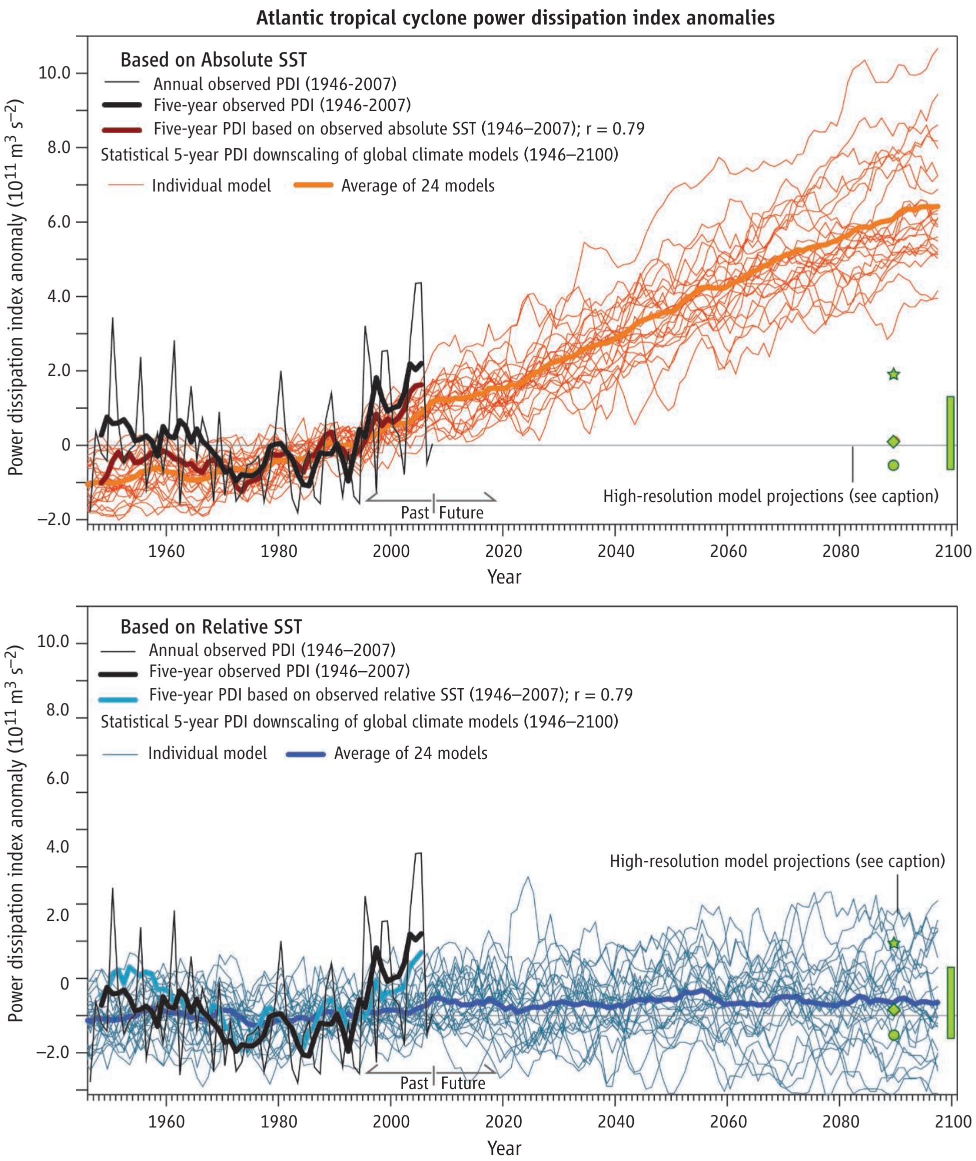


Past and extrapolated changes in Atlantic hurricane activity. Observed PDI anomalies are regressed onto observed absolute and relative SST over the period from 1946 to 2007, and these regression models are used to build estimates of PDI from output of global climate models for historical and future conditions. Anomalies are shown relative to the 1981 to 2000 average (2.13 x 10^{11} m^3 s^{-2}). The green bar denotes the approximate range of PDI anomaly predicted by the statistical/dynamical calculations of (*12*). The other green symbols denote the approximate values suggested by high-resolution dynamical models: circle (*8*), star (*13*), and diamond (*15*). SST indices are computed over the region 70°W-20°W, 7.5°N-22.5°N, and the zero-line indicates the average over the period from 1981 to 2000. See Supporting Online Material for details.

trend in 21st-century projections. Hence, a future where relative SST controls Atlantic hurricane activity is a future similar to the recent past, with periods of higher and lower hurricane activity relative to present-day conditions due to natural climate variability, but with little long-term trend.

From the perspective of correlation and inferred causality, this analysis suggests that we are presently at an impasse. Additional empirical studies are unlikely to resolve this conflict in the near future: Many years of data will be required to reject one hypothesis in favor of the other, and the climate model projections of hurricane activity using the two statistical models do not diverge completely until the mid-2020s.Thus, it is both necessary and desirable to appeal to nonempirical evidence to evaluate which future is more likely.

Physical arguments suggest that hurricane activity depends partly on atmospheric instability (*2*), which increases with local warming but is not determined by Atlantic SSTs alone (*5*). Warming of remote ocean basins warms the upper troposphere and stabilizes the atmosphere (*5*). Furthermore, relative Atlantic SST warming is associated with atmospheric circulation changes that make the environment more favorable to hurricane development and intensification (*9*–*11*).

Further evidence comes from high-resolution dynamical techniques that attempt to represent the finer spatial and temporal scales essential to hurricanes, which century-scale global climate models cannot capture due to computational constraints. High-resolution dynamical calculations under climate change scenarios (*8*, *12*–*14*) (green symbols in the figure) are consistent with the dominance of relative SSTs as a control on hurricane activity. Even the dynamical simulation showing the most marked increase in Atlantic hurricane activity under climate change (*13*) is within the projected range for relative SST but outside the projected range for absolute SST.

Whether the physical connections between hurricane activity and SST are more accurately captured by absolute or relative SST also has fundamental implications for our interpretation of the past. If the correlation of activity with absolute SST represents a causal relation, then at least part of the recent increase in activity in the Atlantic can be connected to tropical Atlantic warming driven by human-induced increases in greenhouse gases and, possibly, recent reductions in Atlantic aerosol loading (*3*, *15*, *16*). In contrast, if relative SST contains the causal link, an attribution of the recent increase in hurricane activity to human activities is not appropriate, because the recent changes in relative SST in the Atlantic are not yet distinct from natural climate variability.

We stand on the cusp of potentially large changes to Atlantic hurricane activity. The issue is not whether SST is a predictor of this activity but how it is a predictor. Given the evidence suggesting that relative SST controls hurricane activity, efforts to link changes in hurricane activity to absolute SST must not be based solely on statistical relationships but must also offer alternative theories and models that can be used to test the physical arguments underlying this premise. In either case, continuing to move beyond empirical statistical relationships into a fuller, dynamically based understanding of the tropical atmosphere must be of the highest priority, including assessing and improving the quality of regional SST projections in global climate models.

References and Notes

1. C. D. Hoyos, P. A. Agudelo, P. J. Webster, J. A. Curry, *Science* **312**, 94 (2006).
2. K. Emanuel, *J. Climate* **20,** 5497 (2007).
3. U.S. Climate Change Science Program, *Weather and Climate Extremes in a Changing Climate*, T. R. Karl *et al.*, Eds. (Department of Commerce, NOAA's National Climatic Data Center, Washington, DC, 2008).
4. K. L. Swanson, *Geochem. Geophys. Geosys.* **9**, Q04V01; 10.1029/2007GC001844 (2008).
5. G. A. Vecchi, B. J. Soden, *Nature* **450**, 1066 (2007).
6. PDI is the cube of the instantaneous tropical cyclone wind speed integrated over the life of all storms in a given season; more intense and frequent basinwide hurricane activity lead to higher PDI values.
7. We use 24 different global climate models run in support of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4) (*17*). See Supporting Online Material for details.
8. T. R. Knutson *et al.*, *Nature Geosci.* **1**, 359 (2008).
9. R. Zhang, T. L. Delworth, *Geophys. Res. Lett.* **33**, L17712 (2006).
10. D. J. Vimont, J. P. Kossin, *Geophys. Res. Lett.* **34**, L07709 (2007).
11. M. Latif, N. Keenlyside, J. Bader, *Geophys. Res. Lett.* **34**, L01710 (2007).
12. K. A. Emanuel, R. Sundararajan, J. Williams, *Bull. Am. Met. Soc.* **89**, 347 (2008).
13. K. Oouchi *et al.*, *J. Met. Soc. Japan* **84,** 259 (2006).
14. L. Bengtsson *et al.*, *Tellus* **59A**, 539 (2007).
15. B. Santer *et al.*, *Proc. Natl. Acad. Sci. U.S.A.*; 10.1073/pnas.0602861103 (2008).
16. T. R. Knutson *et al.*, *J. Climate* **19**, 1624 (2006).
17. G. A. Meehl *et al.*, *Bull. Am. Meteorol. Soc.* **88**, 1549 (2007).

18. We are grateful for comments from T. Delworth, I. Held, S. Ilcane, A. Johansson, T. Knutson, D. E. Harrison, and M. Vecchi. This work was partly supported by NOAA/OGP.

Supporting Online Material
www.sciencemag.org/cgi/content/full/322/5902/687/DC1
Materials and Methods
SOM Text
Figs. S1 to S8
References

10.1126/science.1164396

MATERIALS SCIENCE

Nanoscale Polymer Processing

The established rules for fabricating plastics now require a rethink as feature sizes of the products head toward the nanoscale.

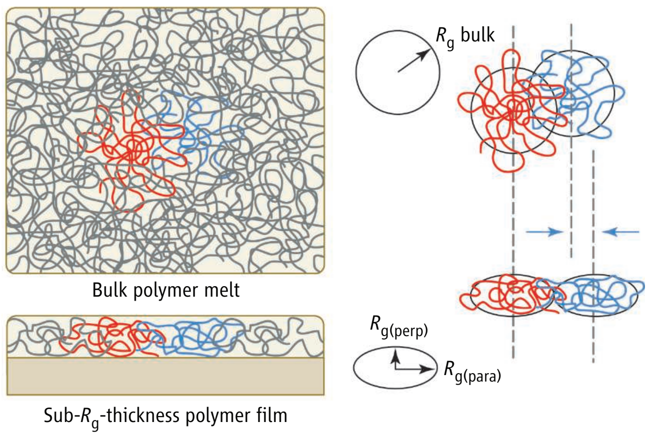
Christopher L. Soles[1] and Yifu Ding[2]

It is difficult to find a manufactured object that does not contain at least some polymeric (plastic) components. This ubiquity reflects the ease with which polymers can be formed into arbitrary shapes through processes that induce flow of a viscous polymer melt into the cavity of a mold or die. The equations that quantify the rheological response of viscous polymer melts under large-scale deformations have been developed over the past 60 years, providing the paradigms by which forming processes are optimized to produce well-controlled, high-quality, robust polymeric parts (*1*). These paradigms, however, are poised to change as polymer processing approaches the nanoscale. On page 720 of this issue, Rowland *et al.* present evidence suggesting that the relationships that govern the viscous flow of polymers in highly confined geometries are dramatically different from those of the bulk (*2*).

Nanoimprint lithography (NIL) can be used to manufacture polymeric features with dimensions of 10 nm or smaller (*3*). The thermal embossing form of NIL relies on a melt squeeze-flow process to transform a smooth polymer film into a patterned surface. Nanoscale features that have been etched into silicon, quartz, or some other hard template material can be inexpensively replicated by stamping the template into a thin polymeric film. Even roll-to-roll NIL tools capable of continuous, high-throughput patterning are now available (*4*). However, optimizing such NIL processes will require knowledge of the rheological response of the polymer being squeezed into a nanoscale cavity, as well as the effect of this response on the properties of the imprinted structure (*5*).

The large-strain deformation properties of a polymer melt are dominated by the topological entanglement of the transient network established by the sea of interpenetrating polymer coils (see the figure). The volume pervaded by a single molecule (proportional to R_g^3, where R_g is the radius of gyration of a single coil) is nearly an order of magnitude larger than the sum of the hard-core volumes of the atoms that constitute the macromolecular chain. The degree of interpenetration or entanglement between neighboring coils is determined by the pervaded volume of a single macromolecular coil and the packing density of the individual chain segments. The large-scale rheological response of a polymer melt is then determined by the response of this entangled network to an applied load. Both the pervaded volume and the extent of entanglement increase with molecular mass, thereby making the flow of the high-molecular-mass melts more viscous. The rheological consequences of squeezing a polymer into a cavity or dimension that is smaller than the pervaded volume of the molecule itself are not obvious.

Because quantitative rheological measurements in NIL are complicated, Rowland *et al.* designed a simplified method that mimics the large-strain deformation fields encountered. An instrumented indenter records the force and displacement as a well-defined flat punch



Processing polymers. (**Upper left**) A sea of interpenetrating macromolecular coils in a polymer melt. (**Right**) An arbitrary pair of nearest-neighbor coils, highlighted in red and blue, is lifted from the melt to illustrate their radius of gyration (R_g) and the fact that interpenetration or entanglement between the coils exists; the separation between the centers of mass between the two coils is less than $2R_g$. (**Lower left**) For thin films with total thickness below R_g, the coils do not appear to spread laterally, and $R_{g(para)} \approx R_g > R_{g(perp)}$. This implies that the interpenetration of the coils decreases, and as argued by Rowland *et al.,* suggests a loss of entanglement and a decreased resistance to flow in a thin-film polymer melt.

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