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*).

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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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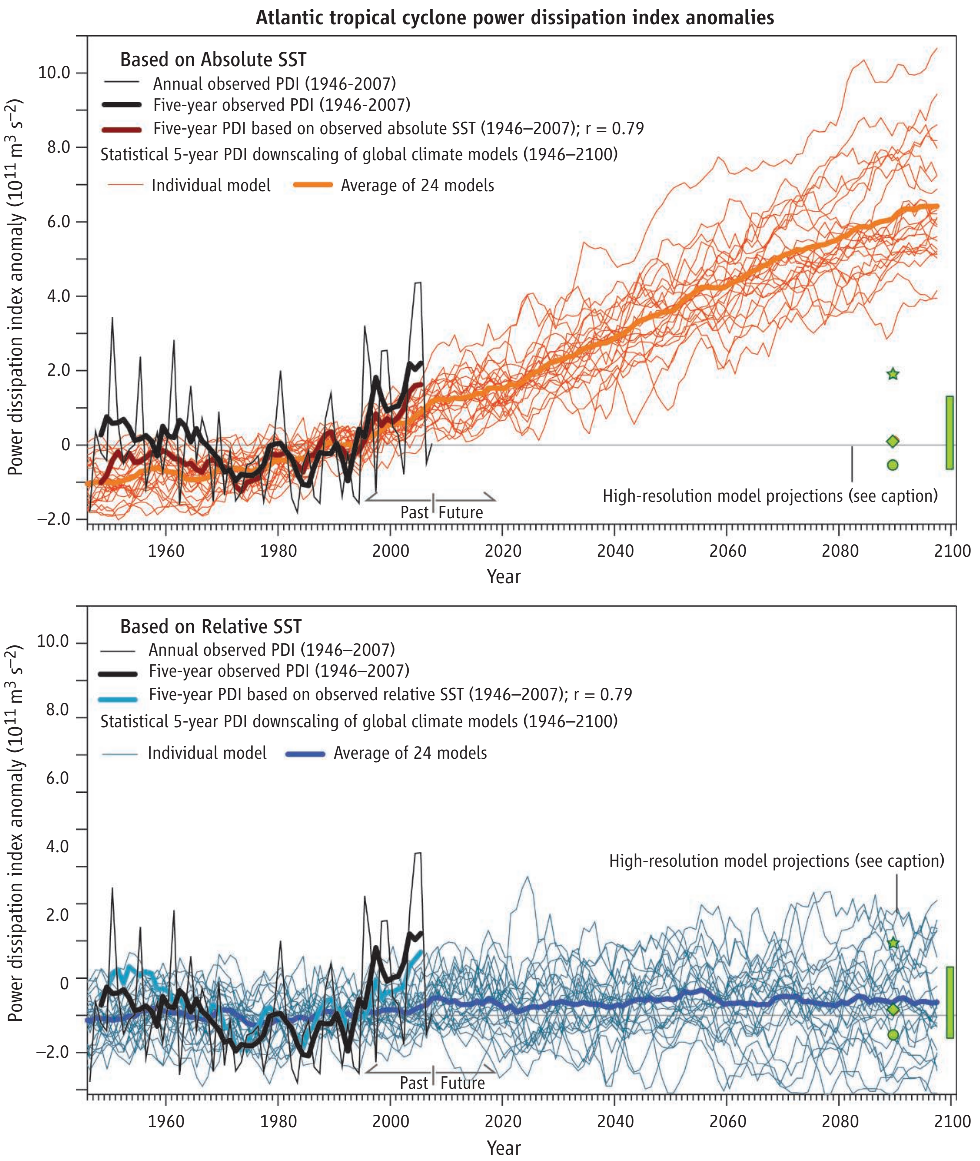

Past and extrapolated changes in Atlantic hurricane activity. Observed PDI anomalies are regressed onto observed absolute and relative SST over the period from 1946 to 2007, and these regression models are used to build estimates of PDI from output of global climate models for historical and future conditions. 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.

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

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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.

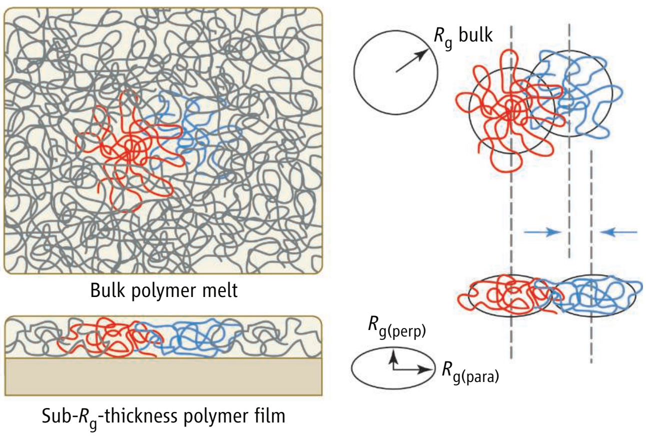
Christopher L. Soles[1] and Yifu Ding[2]

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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