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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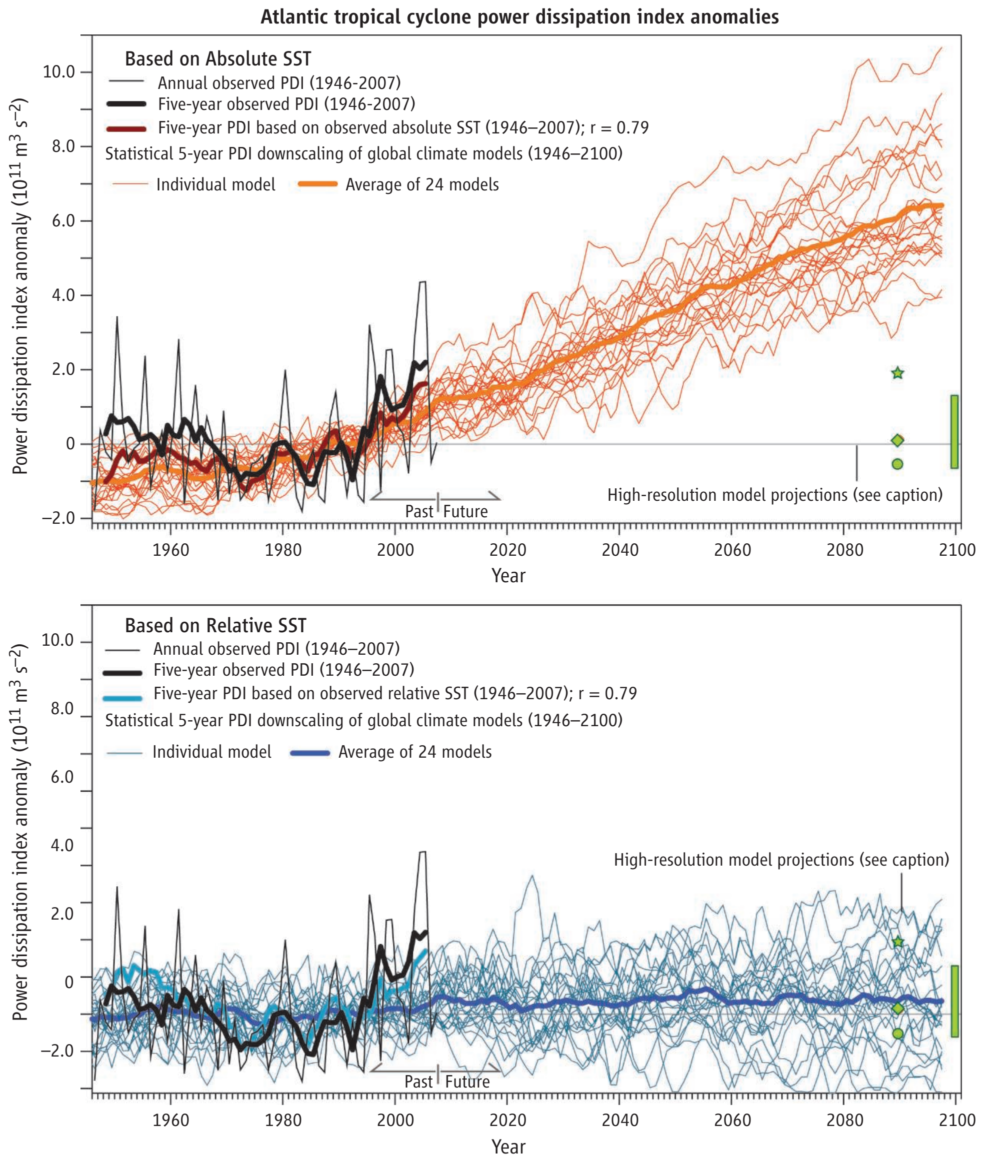

**Past and extrapolated changes in Atlantic hurricane activity.** Observed PDI anomalies are regressed onto observed absolute and relative SST over the period from 1946 to 2007, and these regression models are used to build estimates of PDI from output of global climate models for historical and future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

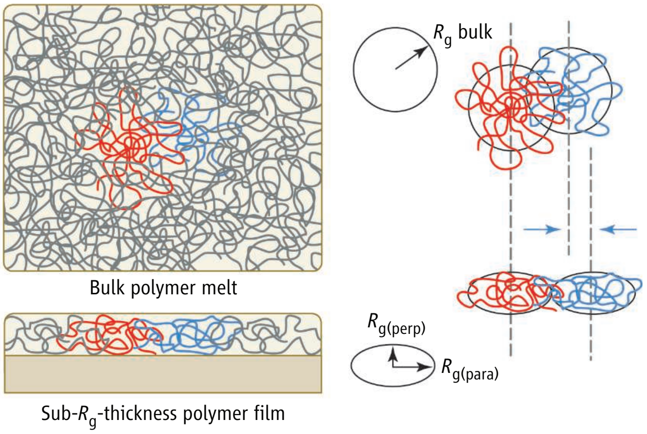
**Christopher L. Soles[1] and Yifu Ding[2]**

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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Science

# Whither Hurricane Activity?

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# Supporting Online Material for

## Whither Hurricane Activity?

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**This PDF file includes:**

Materials and Methods
SOM Text
Figs. S1 to S8
References

# Supplement to "Atlantic hurricanes and climate change: Diverging predictions"

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## Data and Analysis Procedures

Sea surface temperatures (SSTs) are taken from NOAA's Extended reconstructed SST data set, version 3 *(Supp. 1)*. The nomenclature absolute versus relative sea surface temperature (SST) in the main text refers to SST within the so-called "main development region (MDR)," where the bulk of hurricanes in the Atlantic develop, particularly those that become intense. The absolute SST in the Atlantic MDR (henceforth absolute SST) is simply the area-averaged SST over the box 70°W-20°W, 7.5°N-22.5°N; while the precise definition varies from author to author, the results presented here are not sensitive to this definition. The definition of relative SST in the MDR (henceforth relative SST) then follows as simply the difference between the absolute SST and the tropical mean SST, which we take as the area average over 30˚S-30˚N. SSTs are computed for the August-

October season, which is the height of the Atlantic hurricane season. Since the global climate models that we use to make our projections of 21st Century Atlantic basinwide hurricane activity were run with historical forcing through the year 2000, we use the 1981-2000 period to define a climatology from which to compute anomalies.

Tropical cyclone intensities as a function of time are taken from the HURDAT database *(Supp. 2)*, and an empirical correction is applied to correct apparent overestimation of storm intensity prior to 1970 *(Supp. 3)*. To reduce contamination by extratropical cyclones the parts of the cyclone lifetimes that are identified as extratropical in HURDAT (*Supp. 2*) are excluded from the definition of the power dissipation index (PDI). Also, PDI is based on storm records whose intensity exceeds 17 m/s. Annual PDI is defined as the integral of the cube of maximum sustained wind speed over the life of all the cyclones is a season.

Linear least squares regressions are computed, regressing the August-October absolute and relative SSTs against the annual average PDI. Such regressions then provide a "recipe" by which extrapolations of future hurricane activity can be made. Suppl. Fig. 1 shows the regressions, along with the slope and goodness of fit (measured by the square of the correlation coefficient, $r^2$). Again, we use the 1981-2000 period to compute anomalies for the linear fits between SST indices and PDI.

We project PDI into the 21st Century using the observed linear least squares regressions of PDI onto either relative or absolute SST (August-October) anomalies, and applying them to the SST anomalies from the suite of global climate models submitted for the IPCC Fourth

Assessment Report (IPCC-AR4, *Supp. 4*). We use a single ensemble member for each of the 24 models analyzed we explore a single ensemble member of both the historical 20th Century integrations (20c3m) and a mid-range emissions scenario for the 21st Century – known as Scenario A1B or sresa1b. We use only a single ensemble for each model because some models only provided a single ensemble member. References for the climate models used can be found in Supp. Ref. *5* and *6*. We use the base period 1981-2000 from which to define anomalies.

## Further Statistical Analyses:

Global warming has led to increases in absolute SST over the 20th Century, and will likely continue to lead to further increases over the 21st century. This suggests that if PDI follows absolute SST, it will correspondingly increase substantially through the 21st Century. However, an alternative viewpoint is indicated by Supplement Figure 1b, which shows the regression of relative SST against PDI. This regression has an equal goodness of fit, with a higher sensitivity of PDI to relative SST anomalies. An interpretation suggested by the evolution of relative SST in the climate models is that the recent (post-1994) increase in relative SST is due to internal climate variability, and that relative SST may revert to more “normal” values in the future – though one should continue to expect variations of relative SST, the models are not consistent in the sign of the trend in relative SST. If PDI follows this relative SST, it too will revert to more “normal” behavior. The inconsistency of these two viewpoints (a control of hurricanes by absolute SST or relative SST) is the crux of the primary article.

Although our principal argument for the primacy of relative SST is based on the consistency between observations, theory and models that arises within the relative SST framework, there is a statistical basis why one might expect that it is relative rather than absolute SST that controls Atlantic hurricane activity. Supplement Figure 2 shows that for decadal filter time scales, the high level of correlation between absolute SST and hurricane activity weakens somewhat, while that for relative SST strengthens. The top panel in that figure shows the correlation between PDI and absolute/relative SST as a function of the filtering time, where a simple "boxcar" running mean filter is used for ease of comparison. Based on annual data, relative SST "explains" more variance than does absolute SST. On timescales between interannual and decadal, relative and absolute SST exhibit quite equivalent linear relationships to PDI. However, as the averaging time is increased to decadal timescales, the correlation between absolute SST and hurricane activity becomes progressively weaker, while that between relative SST and hurricane activity increases to almost 0.9. This is due to a characteristic "U" shape in the PDI, as shown in Supplement Figure 3, with hurricane activity levels in the 1950's being quite high. The absolute SST is dominated by an increase over this time period, while the relative SST shares a "U" shape with the PDI due to a relative cooling of the tropical Atlantic relative to the tropical mean prior to 1980 and a relative warming since that point in time. The cooling of the Atlantic relative to the rest of the tropics from the 1950s to the 1980s was largely associated with enhanced warming elsewhere in the tropics *(Supp. 5)*, representing a dominantly non-local influence on relative SST, and possibly hurricane activity.

In Supp. Figure 4 we highlight the results of using PDI and SST data filtered with a fifteen-year running average (rather than five-year as in the main text). The principal results from the Figure in the main text are unaltered, except that the correlation between relative SST and PDI is now nominally higher than between absoluted SST and PDI – primarily because relative SST is able to represent the "U-shaped" structure seen in PDI, which is less pronounced in absolute SST. Forward projections of PDI using absolute SST suggest a strong – unprecedented – increase in activity, while those using relative SST suggest a future largely similar to the past, with decadal variations in activity being the dominant signal.

It is vital to note the impact of empirical corrections to hurricane intensities, which attempt to correct different intensity estimation procedures that occurred in the early part of the record (prior to 1970) *(*supp. *3)*. While these corrections appear subtle when viewed graphically *(*supp. *7,8)*, the impact of such corrections on the relationship between absolute SST and hurricane activity are profound. The bottom panel in Supplement Figure 2 shows the identical analysis as the top panel, but without the empirical correction used in Supp. Ref. 3. The correlation between absolute SST and hurricane activity is significantly reduced at all time scales, while that between relative SST and hurricane activity is similar to that found in the corrected HURDAT data used in the primary manuscript. However, comparison between the top and bottom panels reveal that the empirical correction produces roughly 70% of the variance explained by a linear regression of absolute SST and hurricanes on decadal averaging time scales.

The impact of the intensity correction on the filtered time series is shown in Supplement Figure 5; the uncorrected PDI series has a much stronger "U" shape over the 1946-2007 period, and now more closely resembles the relative SST. A similar analysis to that in the primary manuscript figure but using the uncorrected HURDAT data is shown in Figure 6; the superiority of relative to absolute SST is apparent. This is even more so for longer averaging periods, as Figure 7 shows that the "U" shape in the uncorrected PDI is qualitatively quite different from the roughly linear increase in model absolute SST for each model over the 1946-2007 time period. However, the principal results, that a projection of Atlantic activity into the 21st Century using absolute SST indicates an increase, while a projection using relative SST shows a future largely like the past is unaltered by this analysis. While the sensitivity to the intensity correlation of the strength of the statistical relationships between PDI and relative/absolute SST highlights the need for a thorough and systematic evaluation of the necessary corrections for HURDAT intensities, for projections of future activity it is more essential to distinguish between relative and absolute SST as the causal predictor of PDI, and to improve regional projections of SST.

Even when time averaging is removed from the analysis, the enhanced explanatory power of relative SST compared to absolute SST emerges. Supplement Figure 8 shows the tracks of intense Atlantic hurricanes (category 4 and 5 on the Saffir-Simpson scale; max wind > 58 $ms^{-1}$) that occurred during the 10 years with the highest/lowest absolute and relative MDR SSTs, respectively. A much larger disparity in the number of such intense storms is found when the data are classified by the relative SST, with 23 events/decade occurring when relative MDR SST is anomalously large, and 6 events/decade when relative MDR

SST is small. In contrast, the difference between years when absolute MDR SST is anomalously large (18 events/decade) and small (9 events/decade) is more subdued. This again hints that it is relative SST that governs Atlantic hurricane activity.

## Model interpretation

Finally, a few words are appropriate about the methods used in comparing model downscaling of hurricane activity to the statistical regression-based projections described above. It is well understood that at their current stage of development, many of the dynamical models used to explore the response of hurricane activity to climate change have difficulty capturing the dynamics of the most intense storms *(e.g.,* Supp. *9)*. Hence, all dynamical results presented in the primary paper were interpreted in terms of their *relative* increase in PDI when comparing the period 2001-2020 and 2081-2100. This relative increase is then multiplied by the *observed* climatological value of PDI over the period 1981-2000 to yield the symbols shown in the Figure. For consistency of comparison, a similar analysis was applied to the statistical-dynamical results of supplement ref. 10, even though that approach captures aspects of the behavior of the most intense storms and represents the response at the end of the 22nd Century.

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# Figure Captions

**Supplement Figure 1:** The regression of hurricane activity in the Atlantic as measured by the PDI against (a) absolute Atlantic main development region August-October SST anomalies from the 1981-2007 mean; and (b) Atlantic main development regions August-October SST anomalies relative to the tropical mean SST. Goodness of fit (*r*) and the slope in terms of PDI per Kelvin are as indicated.

**Supplement Figure 2:** The top panel is the correlation between the absolute and relative SST time series and the hurricane activity PDI time series based upon HURDAT intensity data corrected as in Supplement Reference 3. The abscissa marks the averaging time applied to each time series before the correlation is taken. The bottom panel is the same, but for hurricane intensities from HURDAT without the intensity correction of Supplement Reference 3.

**Supplement Figure 3:** Power dissipation index (PDI) versus absolute and relative SST for 1, 5, and 15 year boxcar filtered timescales using the HURDAT intensity data corrected as in Supplement Reference 3. Note the "U" shape centered about 1980 for both PDI and relative SST, while the absolute SST is quite constant prior to 1980.

**Supplement Figure 4:** As in the primary manuscript, but with a 15-year averaging period. Note the significant departure of the predicted PDI from the model envelope for the absolute SST case (top panel) around 1980. Anomalies are computed from the 1981-2000 climatology.

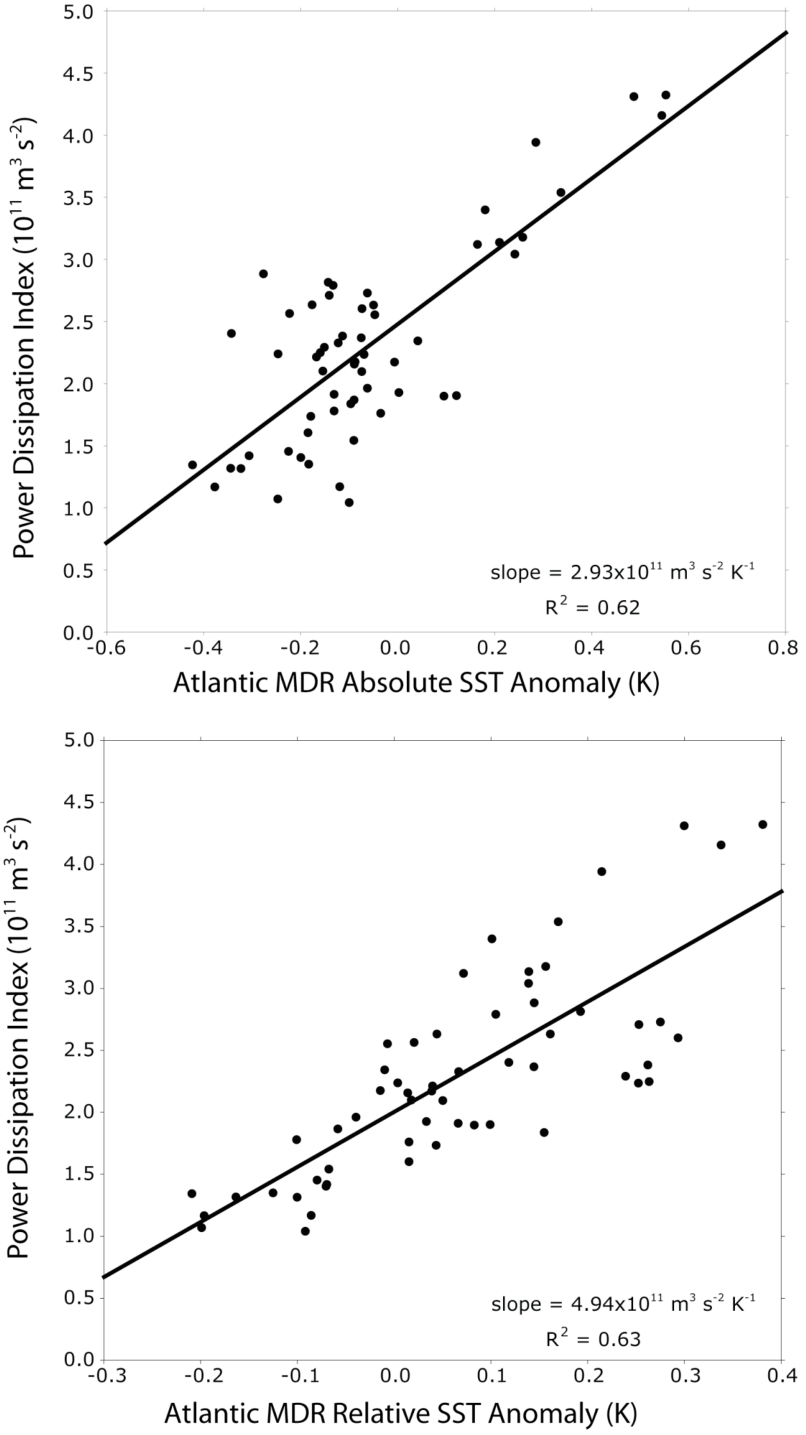
**Supplement Figure 5:** As in Supplement Figure 3, but using HURDAT data without the intensity correction of Supplement Ref. 3. Note that the corrected PDI is exhibits a more pronounced "U" shape, as the intensity correction that was removed acted to reduce intensities of pre-1970 tropical cyclones pre-1970 compared to the raw HURDAT data.

**Supplement Figure 6:** As in the primary manuscript, but for PDI computed using the uncorrected HURDAT data. Anomalies are computed from the 1981-2000 climatology.

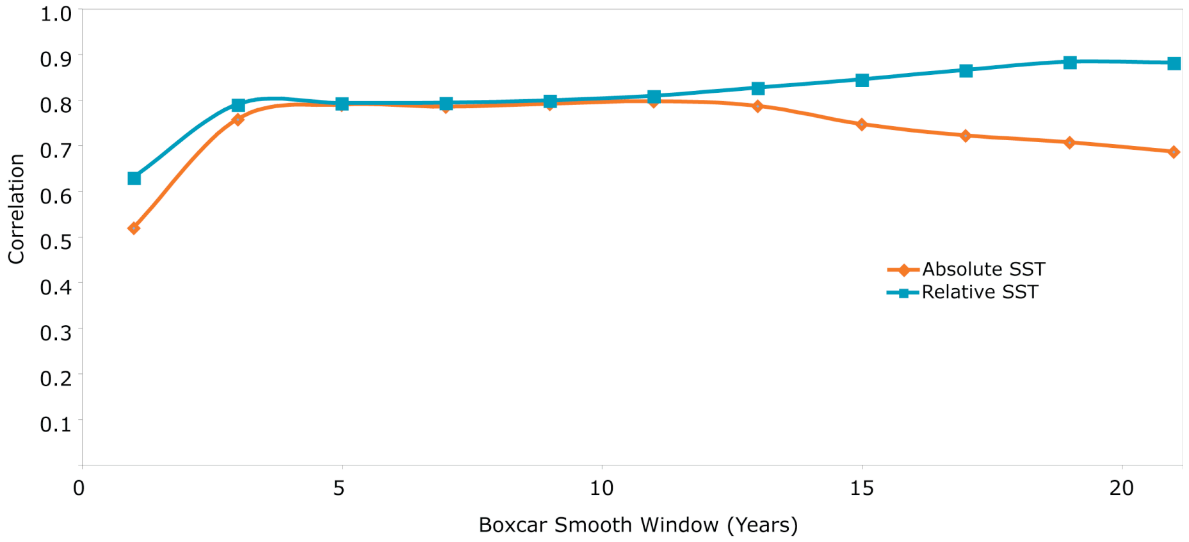
**Supplement Figure 7:** As in Supplement Figure 6, except for a 15-year averaging period. Anomalies are computed from the 1981-2000 climatology.

**Supplement Figure 8:** Tracks of intense hurricanes (Saffir-Simpson Category 4 and 5; max wind > 58 $ms^{-1}$) during the years with the 10 highest/lowest SST anomalies. Panels (a) and (b) indicate absolute SST, and panels (c) and (d) indicate relative SST. There is a higher level of implied sensitivity on relative SST by this measure.

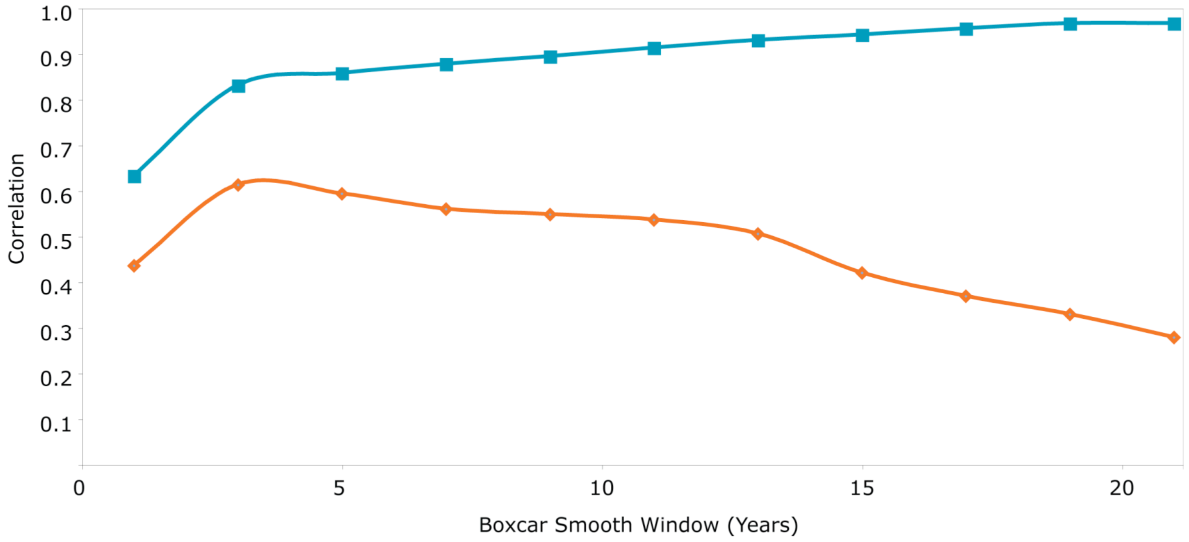
## Supplement Figure 1



## Supplement Figure 2

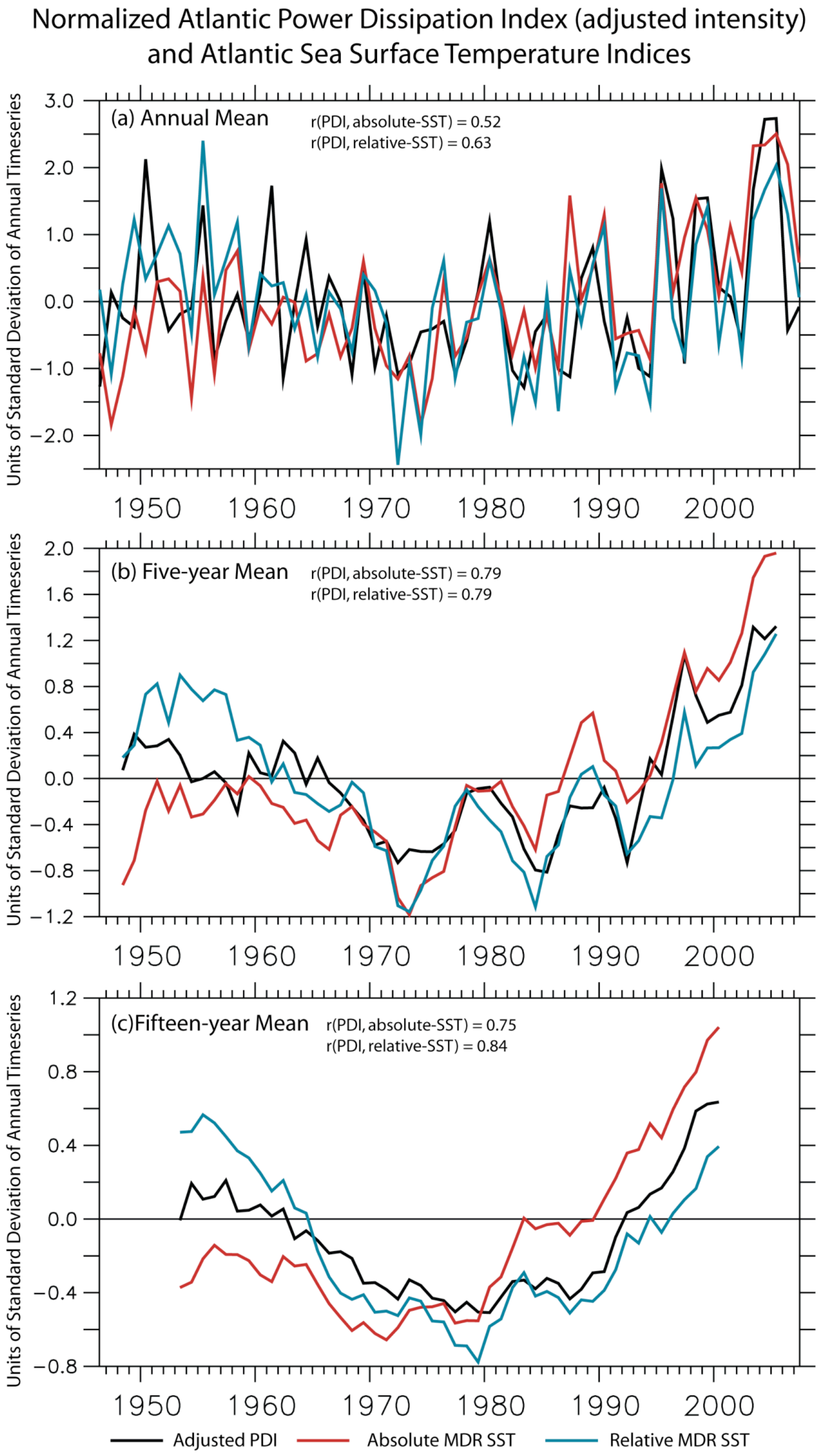


(a) Correlation PDI to SST-Index as Function of Smoothing Window - Corrected PDI

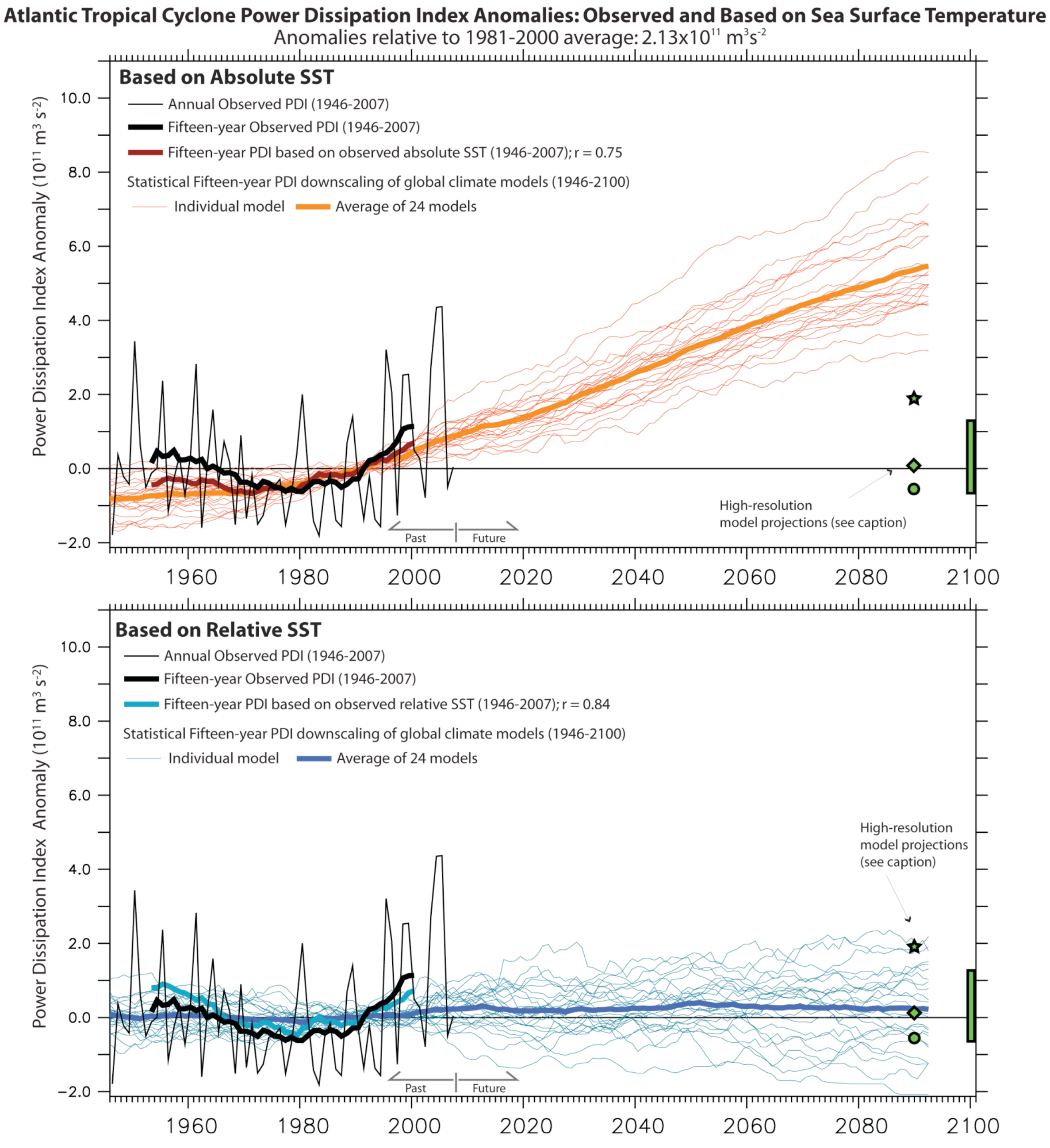


(b) Correlation PDI to SST-Index as Function of Smoothing Window - Uncorrected PDI

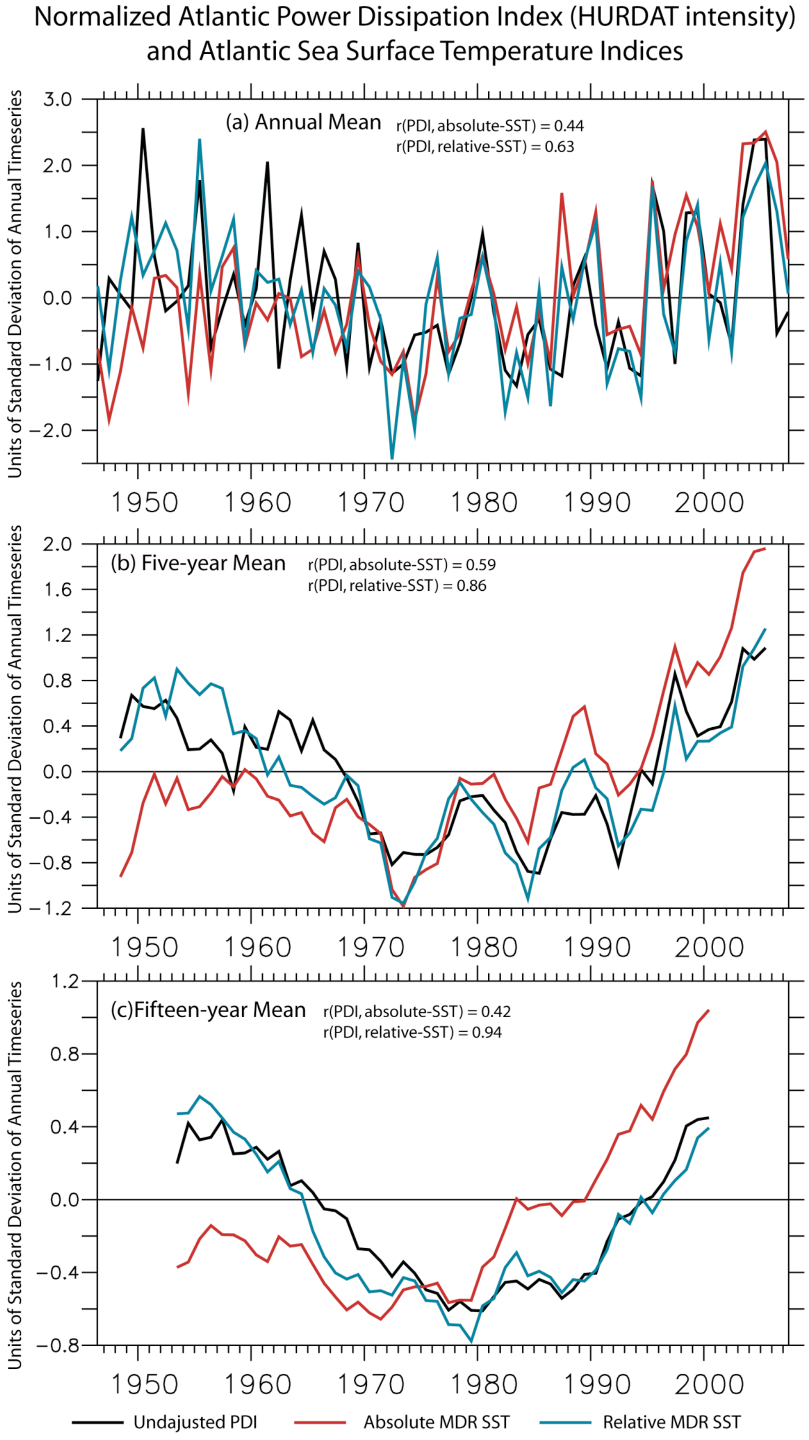
## Supplement Figure 3



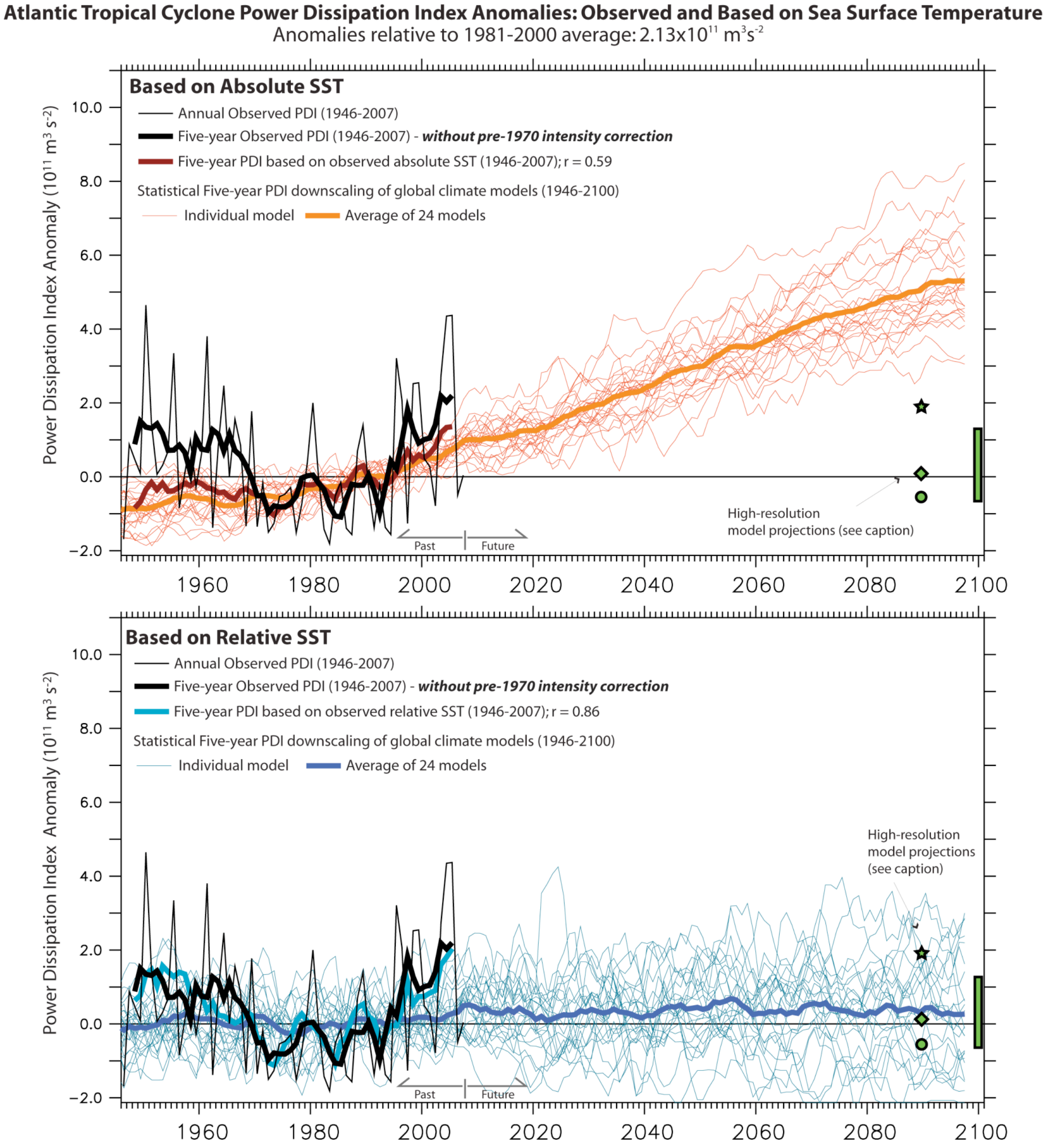
## Supplement Figure 4



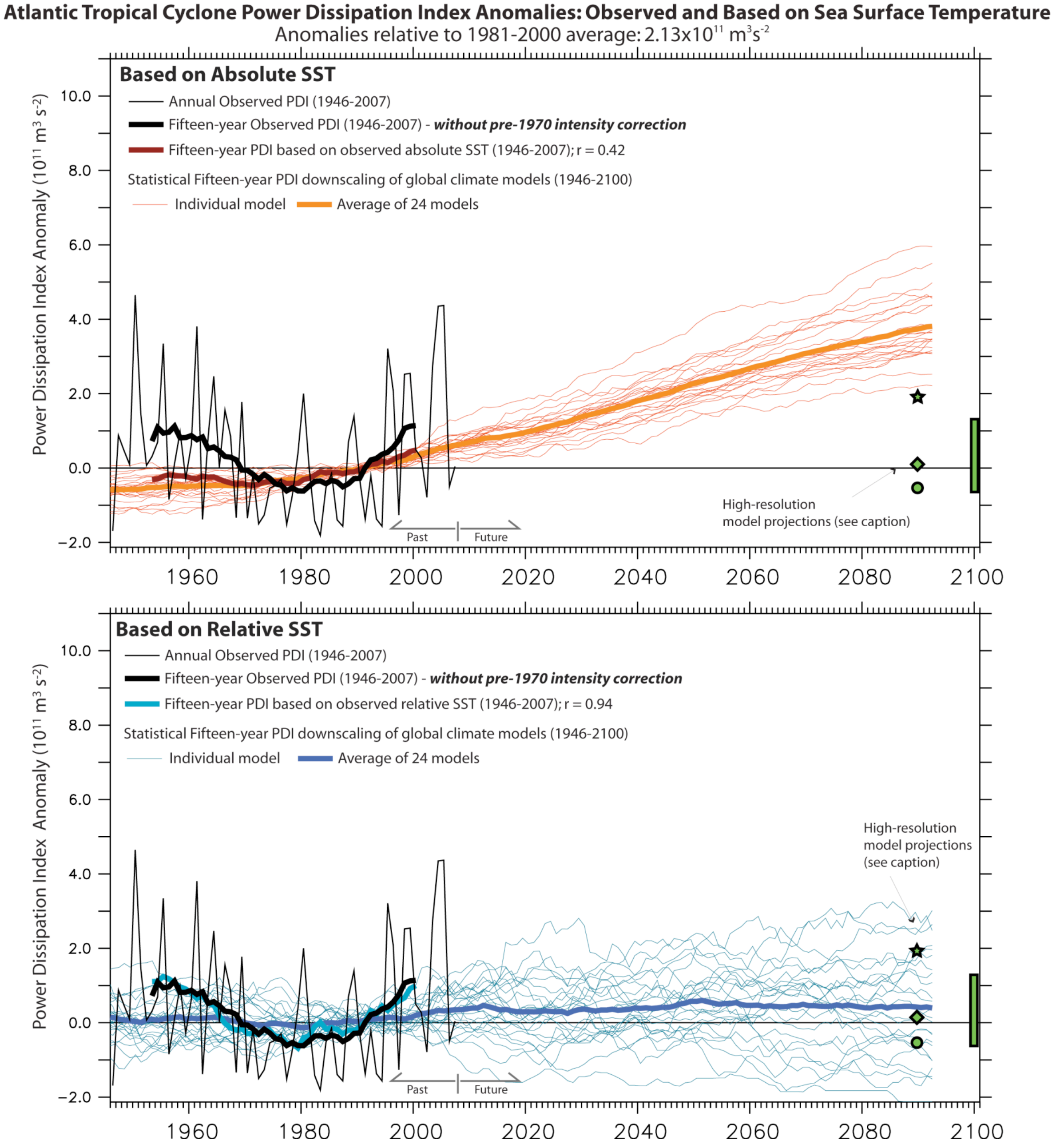
## Supplement Figure 5



Supplement Figure 6



# Supplement Figure 7



## Supplement Figure 8