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# From Past to Future Warming

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ATMOSPHERIC SCIENCE

# From Past to Future Warming

Analyses of past observations help to predict the human contribution to future climate change.

Gabi Hegerl[1] and Peter Stott[2]

In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change concluded that it is "extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together" (*1*). This conclusion was based on an expert assessment drawing on multiple analyses of observed temperature changes. However, substantial uncertainties remain, especially in estimating the human contribution to regional temperature change and extreme events.

Challenges in CLIMATE SCIENCE

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The physics through which greenhouse gases warm the atmosphere is well understood. However, feedbacks within the atmosphere can enhance or reduce this warming, and the magnitudes of those feedbacks, particularly those associated with clouds, are much more uncertain.

One way to address these uncertainties is to use observations of past climate change and estimate from them the magnitude of "fingerprints" for human and natural influences. The fingerprints themselves are based on climate models and reflect physically robust features (*2*). For example, greenhouse gases cause steadily increasing warming that is stronger over land than ocean; cooling from aerosols is less widespread and has flattened recently in some regions while greenhouse gas levels continued to rise; volcanic eruptions cause short-term cooling; and the sun causes variations that include an 11-year cycle. Variability generated within the climate system also has distinct spatial patterns.

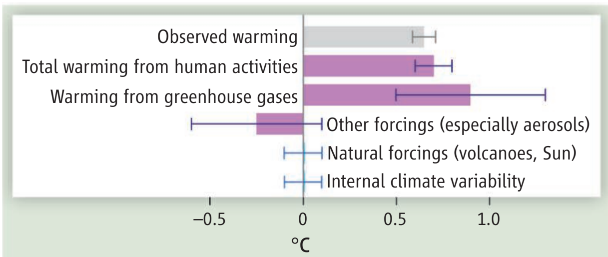
Because observations are used to estimate the magnitude of the fingerprint patterns, the resulting estimates of past temperature changes caused by greenhouse gas increases and other factors (see the first figure) do not depend strongly on models representing uncertain feedbacks correctly, provided that the fingerprint patterns derived from models are reasonably accurate (*2*). These estimates can be used to predict future warming, assuming that any errors in models through under- or overestimating past warming continue into the future. The uncertainty ranges of future warming so derived largely overlap with those directly based on climate models but suggest that a few models may predict too much future warming (*3*).

Despite substantial progress in determining observational constraints for future global-mean warming, the uncertainty range in the estimated contribution of greenhouse gases to the observed global-mean warming is still quite large at 0.5 to 1.3°C (*1*) (see the first figure). A large part of this uncertainty results from difficulties in distinguishing the effects of greenhouse gas-induced warming from other effects, particularly the cooling effect of tropospheric aerosols (*4*). The fingerprints for greenhouse gases and aerosols can be rather similar, and the observations could be explained either by large greenhouse warming counteracted by a large aerosol response, or by smaller greenhouse warming with a smaller aerosol effect. Furthermore, the pattern of aerosol emissions is uncertain (*4*) and cannot always be distinguished from climate variability, particularly regionally (*5*). As a result, uncertainty ranges for the separate contributions by greenhouse gases and other anthropogenic factors remain large (see the first figure) (*6*). In contrast, the pattern of temperature changes expected from all human influences combined is substantially different from that from the combination of volcanic eruptions and changes in the Sun and can thus be estimated more confidently.

Human influence can also be detected in temperature changes over individual continents and many regions (*1*). This is important because the effects of climate change will be felt through regional changes and extremes such as heat waves. Extreme temperatures are often associated with unusual weather patterns, such as blocking high pressure systems (*7*, *8*), but studies suggest that long-term warming from anthropogenic climate change has substantially increased the probability of extremely high temperatures being experienced in some regions (*9*–*11*).

Several factors limit the attribution of regional temperature change and extreme events to climate change. First, data gaps are a problem, particularly in tropical regions and high latitudes (see the second figure). Regional temperature changes caused by human activities are expected to emerge from the range of climate variability in the tropics first (*12*), because climate is least variable there. However, these regional changes can only be observed where long-term data exist. Arctic and Antarctic regions are important because feedbacks to warming are strong there and melting ice contributes to sea level rise. However, in those regions, climate variability is very large and data records are short. Better observational information, including from satellite data and further back in time from digitization of old weather records, will improve understanding of regional climate change and climate variability.

Second, local influences, such as changes in land cover and pollution reducing sunlight, are often poorly known and difficult to distinguish from large natural variability. This makes it difficult to estimate how much regional warming is due to greenhouse gases and how much is due to (or has been offset by) other factors.




**Getting warmer.** The observed global temperature change between 1951 and 2010 (gray bar; whisker: observational uncertainty) is compared to the warming from human activities (purple bars), both combined and split into greenhouse gas and other forcings. The blue bars show the estimated contributions by natural forcings and by variability generated by the climate system. Bars give best estimates, and whiskers indicate the assessed uncertainty range within which the contribution is likely to lie (>66% probability). [Adapted from (*1*)]

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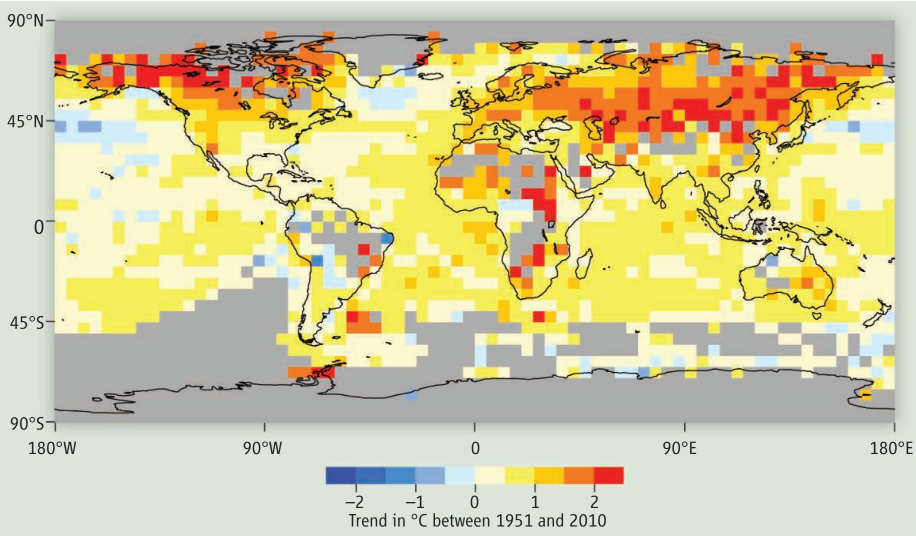


**A mixed regional picture.** In this map of observed local surface temperature changes from 1951 to 2010, areas without adequate observational coverage (shown in gray) are mostly found in the tropics and at high latitudes. [Adapted from (*1*)]

Third, systematic changes in weather systems would influence local weather and the incidence of extremes. Understanding and predicting such changes is much harder than predicting changes in mean temperatures. In observations, changes in circulation are difficult to identify among large random variability. Climate models struggle to simulate some circulation changes reliably (*8*). Increasingly, climate models have finer spatial resolution and better resolve processes relevant to regional climate variability. This will eventually improve confidence in attribution results on regional scales.

In the aftermath of damaging extreme events, it is important to be able to address the question to what extent human-induced climate change is to blame. Therefore, reliable information is needed to determine whether human influence has changed the risk of the occurrence of extreme climate events. Where regional changes appear to buck the long-term expected trend, scientists must determine whether this is because climate variability masks climate change or because observations and models disagree as a result of model deficiencies. This information can then be used to improve future climate models. There is little doubt that human activities were the main cause of global warming over the past 60 years, but work to better understand the causes of changes in regional climate, and thereby better understand our vulnerability to climate extremes, is far from done.


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MATERIALS SCIENCE

# Fibers Do the Twist

Twisted fibers provide a simple, low-cost route to high-energy artificial muscles.

**Jinkai Yuan and Philippe Poulin**

In a rubber band–powered airplane, a pretwisted band untwists when the hook used to initially balance its torque is released (see the figure). Such an actuation is based on the elastic recovery of the stretched polymer chains. The material has to be mechanically retwisted to operate but the method is simple and efficient, because the rubber band delivers almost as much energy as needed to twist it. Unfortunately, soft rubber cannot easily provide large stress and cannot be used in modern applications such as robotics, artificial muscles, smart textiles, and new medical devices. But as Haines *et al*. show on page 868 of this issue (*1*), the concept of twisted fibers can nevertheless be useful in demanding actuator applications.

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Twisted carbon nanotube yarns can act as highly efficient torsional and tensile actuators. Actuation in these yarns is not based on the entropic elasticity of polymer chains (as in a rubber band) but instead involves ionic swelling in a liquid electrolyte (*2*), electromagnetic effects (*3*), or the thermal expansion of an infiltrated paraffin wax (*4*). However, carbon nanotube yarns are expensive and difficult to make. Also, their energy density is low compared to that of competing materials such as shape memory alloys, considered to be the highest–energy density materials in the field of actuators (*5*).

Haines *et al*. now report artificial muscles made of twisted polymer fibers that deform in response to thermal expansion. Thermal expansion has long been used for thermal actuators—for example, in the "solar muscle," which converts solar heat into mechanical energy (*6*). These systems are simple, robust, and cheap, but have low thermal efficiency and provide lateral deformations of only a few percent. The strain can be amplified into large stroke by combining different materials, but this makes the actuators heavier and less efficient. By contrast, Haines *et al*. use a single material and a basic design. This single material can, for example, be commercial polyamide fibers used for fishing lines.

Polyamide is a semicrystalline polymer with a large stiffness over a wide temperature range. Its deformations involve not only entropic elasticity but also strong interac-



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