COMMENTARY

Climate extremes and the role of dynamics

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Thermodynamics Versus Dynamics

One of the most societally important manifestations of climate change is the changing frequency and amplitude of extreme weather and climate events. A simple conceptual picture of why climate change may lead to an increase in weather extremes is that as the atmosphere warms, the specific humidity of the air increases, and in regions of enhanced latent heat release circulation patterns become more intense.

Such arguments, although relevant, are primarily thermodynamic in nature; the effect on the dynamics of the climate system is secondary. However, those with a background in climate dynamics have little doubt that dynamical considerations will play as important a role in our understanding of climate change as the simpler thermodynamic arguments. Unfortunately, our understanding of the dynamical processes that influence such extremes is currently rather poor.

The report by Petoukhov et al. (1), aims at understanding how recent extreme events such as the heat waves in Europe in 2003, Russia in 2010, and North America in 2011, provide a hint at the primacy of dynamics in understanding future changes in weather and climate extremes.

The focus of Petoukhov et al.'s (1) study is the midlatitude atmospheric Rossby wave (e.g., ref. 2). Such atmospheric Rossby waves can be thought of as describing planetary-scale oscillations in the latitude of the jet stream: the "river" of fast moving air that circumnavigates the planet in the upper troposphere in the Northern and Southern Hemispheres. If we know the (east-west, north-south) orientation of the jet stream at some longitude, we pretty much know what the surface weather will be like at this longitude: if the jet stream is flowing from polar latitudes it will be relatively cold at the surface; if it is flowing from subtropical latitudes it will be relatively warm (and, potentially, relatively wet) at the surface.

To understand Rossby waves, one has to understand the subtle noninertial effects that the rotation of the Earth about its axis has on the atmosphere. Most important are the apparent Coriolis "forces" that influence the horizontal movement of an air parcel, for example, in the jet stream. These Coriolis effects are strongest at the poles and weakest at the equator. As a result of this gradient with latitude, the Coriolis effect can act as a restoring force on air parcels that are displaced north or south of their "normal" latitude, and hence lead to an oscillation. The key effects, which can systematically displace such air parcels north or south, are associated with the flow of air over big mountain ranges like the Rockies or Himalaya, or differential heating by continental/ocean temperature contrasts (because these systematic forcing effects are so much stronger in the Northern Hemisphere, so too are quasistationary Rossby wave amplitudes).

Our climate system is not just a static thermodynamic system, it is a fluid dynamical system, and the effects of dynamics (especially on a rotating planet) can often be counterintuitive.

Those who study forced oscillations will know about the phenomenon of resonance. This phenomenon occurs when the forcing excites the unforced or free modes of the system, which brings us back to the Petouhkov study. First of all, Petouhkov et al. (1) show that in the sorts of heat waves mentioned above, which are associated with a type of Northern Hemisphere flow where the amplitudes of zonal wave number is 6–8, components of the quasistationary Rossby wave pattern were unusually large (for example "zonal" wave number 6 defines a mode with six complete sinusoidal oscillations around a line of constant latitude). The authors then provide evidence that although in general it is unlikely that forcing by orography and land/sea thermal contrasts could resonate with the free modes at these particular wave numbers, the "refractive index" properties of the longitudinally averaged flow, during the periods when the extreme events occurred, was such as to favor resonance at these relatively high wave numbers.

The implications of the article are clear: if the conditions that brought about resonance during 2003, 2010, and 2011 become more likely as a result of anthropogenic emissions of greenhouse gases, then Rossby wave resonance will be a key mechanism in accounting for future changes in extremes of weather.

When quasistationary Rossby waves in the upper troposphere reach large amplitudes, then at some longitudes the surface weather will be anomalously warm. However, at other longitudes the surface weather will be anomalously cool. Hence, if climate change leads to an increased likelihood of wave 6–8 resonance, then certain places (and not always the same places from one year to the next) will experience negative temperature anomalies. This finding is something the public (and the "climate sceptic" community) often find hard to understand: How can global warming lead to local cooling? The point is that our climate system is not just a static thermodynamic system, it is a fluid dynamical system, and the effects of dynamics (especially on a rotating planet) can often be counterintuitive. Anyone doubting this should study the humble gyroscope, in particular how it responds to external forcing!

Nonlinear Complications

The Petoukhov et al. (1) study is based on rather idealized, mathematically tractable, dynamics. However, to create quasiresonant conditions requires the formation of appropriate waveguides in the longitudinally averaged flow, and this formation process may involve highly nonlinear dynamics (e.g., associated with precursor periods when the Rossby waves break nonlinearly, like ocean waves on a beach). On top of this, simulating the Rossby wave forcing from the Earth's topography and land/sea thermal contrasts accurately requires a considerable level of detail. For example, recent studies (e.g., ref. 3)

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suggest it may be necessary for climate models to resolve scales down to about 20 km to simulate the large-scale nongaussian structures of the Northern Hemisphere quasistationary Rossby waves accurately. It may indeed be the case that for climate models to be able to represent the effect of tropical diabatic heating anomalies on the Northern Hemisphere Rossby waves, climate models may have to resolve scales associated with deep convective clouds (1 km).

Hence, to study the process of quasiresonance properly requires not only mathematically tractable models that draw out the essential features of the dynamics, but also high-resolution comprehensive models, which can describe all of these dynamical processes ab initio. However, we shouldn't underestimate this challenge; there is no more complex problem in computational science than that of simulating and predicting climate, particularly that of simulating and predicting extremes of climate, from the primitive laws of physics. Currently, national climate institutes do not have the high-performance computing capability to simulate climate with 20-km resolution, let alone 1 km.

This writer, for one, looks forward to the day when governments make the same investment in climate prediction as they have made in finding the Higgs boson. The Pethoukhov et al. (1) study provides yet another reason why this investment is becoming more urgent.

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1 Petoukhov V, Rahmstorf S, Petri S, Schellnhuber HJ (2013) Quasiresonanat amplification of planetary waves and recent Northern Hemisphere weather extremes. *Proc Natl Acad Sci USA* 110:5336–5341.

2 Holton JR (2004) *An Introduction to Dynamic Meteorology* (Elsevier, Burlington, MA), 4th Ed.

3 Dawson A, Palmer TN, Corti S (2012) Simulating regime structures in weather and climate prediction models. *Geophys Res Lett* 39(21):L21805.