COMMENTARY

Water emissions put a damper on the coal-to-gas transition

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Unanticipated environmental and ecological consequences of human decision-making extend back at least as far as the early history of agriculture (1). Activities undertaken with the best of intentions, from biomanipulations (2) to alternative energy technologies (3), have had unexpected side effects leading to problematic, and sometimes long-term, socioecological change. As global momentum toward the adoption of cleaner and more sustainable energy systems grows, there is a need to critically and carefully evaluate the potential indirect consequences of this transition. Work by Xing et al. (4) published in PNAS highlights an under-studied side effect of the ongoing replacement of coal by natural gas: Increased water vapor emissions from combustion of natural gas may drive local increases in air pollution (Fig. 1).

Although water vapor itself has no direct health consequences, moisture is a key contributor to many chemical reactions in the atmosphere that can produce particles that harm human health and well-being. The World Health Organization estimates that ~7 million annual deaths globally are attributable to air pollution (5), but the effects of air pollution extend beyond mortality. Recent research has highlighted links between fine particulate concentrations and metrics as varied as GDP (6) and school attendance by children (7). Although some of these particles are emitted directly to the atmosphere from natural and anthropogenic sources, the majority are usually secondary aerosols produced by chemical reactions in the atmosphere. Here, the concentration of water vapor can be critically important. Many reactions that produce secondary particles are mediated by the presence of heterogeneous aerosols, which contain mixtures of water and other constituents, and the abundance, size, and composition of these aerosols depends strongly on atmospheric humidity (8, 9). In addition, elevated humidity and resulting increases in particulates can themselves affect atmospheric boundary layer optics and structure, potentially producing further aerosol-enhancing feedbacks (10).

Water vapor is a naturally abundant constituent of the atmosphere, present in concentrations that are highly variable in space and time. Although human alteration of water cycling has been substantial, our actions remain absent from most conceptualizations of the water cycle (11). Where human impacts are depicted, they are usually limited to the redistribution of water through processes like groundwater abstraction, irrigation, and impoundment of surface water. This parallels, to some degree, concepts of our species' limited role in the carbon–climate system that were common prior to the widespread recognition of the ongoing secular increase in CO_2 levels (12) (and can still be found reverberating within pseudoscientific climate change discussion groups online).

The same process of fossil fuel burning that underpins much of humankind's now irrefutable influence on the contemporary carbon cycle, however, has also produced locally significant perturbations of the water cycle. Oxygenic photosynthesis, the ultimate source of most fossil fuel, consumes water in the process of producing organic molecules. When these organic compounds are later oxidized, whether through oxidative weathering or natural or human-mediated combustion, new water molecules are produced. In contrast to fossil fuel-derived CO_2 production, global rates of water production via organic matter oxidation are trivial compared to natural fluxes into and out of the atmosphere (13). Water emissions from fossil fuel combustion are highly localized in space and time, however, raising the possibility that combustion may significantly enhance local humidity under certain emissions and atmospheric circulation conditions.

Assessing where and when combustion appreciably alters atmospheric humidity has proven to be a challenge. Spatiotemporal inventories of water vapor emissions from combustion do not yet exist. Moreover, other processes that govern atmospheric water budgets, like evapotranspiration, condensation, and mixing, can be highly dynamic, and their representation in

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Fig. 1. Pollution-induced haze and emission of combustion-derived water vapor over Yantai, China. Image credit: Piqsels.

models is often uncertain. Without a method for directly measuring the amount of combustion-derived water vapor in the atmosphere, and how it varies over time and space, any assessment of the impacts of this process would remain highly speculative.

Writing in PNAS in 2015, our group demonstrated that the amount of atmospheric moisture attributable to combustion could be quantified based on an isotopic signature traceable to the chemical origin of combustion-derived water (13). Most important processes in the water cycle act on intact water molecules, and, as a result, any effect they have on the stable isotope ratios ($^{2}H/^{1}H$ and $^{18}O/^{16}O$) of water leads to parallel changes in H and O isotope ratios. In contrast, water from combustion is produced by a reaction involving nonwater substrates, primarily H from organic molecules and O from atmospheric O_2. The resulting combination of H and O isotope ratios characteristic of combustion-derived water differs from all other "natural" waters, providing a signal with which to quantify water sourced from combustion. Aided by a new generation of water vapor isotope analyzers (14), several groups have used this technique to show that combustion can enhance humidity levels by ~5 to 15% in some urban settings (4, 15, 16).

The research by Xing et al. (4) represents an important advance on these studies in at least two respects. First, after quantifying combustion water concentrations in the northwestern Chinese city of Xi'an, the authors link these results directly to air quality metrics. They demonstrate that periods with low humidity and little enhancement of near-surface humidity by combustion are associated with relatively low fine particulate levels, even when concentrations of the precursors to secondary aerosols are elevated. Moreover, by conducting multiple experiments with a numerical weather model including aerosol chemistry, the authors are able to assess the direct impacts of water vapor emission on particulate concentrations. This work reveals a complex interaction between humidity and particulate precursor compounds, but also suggests that the presence of combustion-derived water increased fine particulate concentrations by several percent across the study period, with larger enhancements during specific events.

Second, in their closing paragraph, Xing et al. (4) propose an important connection between these fundamental atmospheric processes and contemporary energy policy. Despite active debate about the merits of policies that supplant one carbon-based fuel with another, many scholars and governments view the rise of natural gas-powered electrical generation, often at the expense of coal, as a positive (or at least necessary) transitory step toward a clean energy future (17). One side effect of this transition, however, may be increased emission of combustion-derived water vapor to the atmosphere. Despite its much higher energy density, and thus reduced carbon intensity, natural gas is rich in hydrogen, and its combustion emits larger amounts of water than does that of coal (per unit energy produced). To the degree that these emissions promote formation of fine particulates, then, the shift to natural gas may create localized, negative public health outcomes even as it is reducing the global carbon cycle impact of electricity production.

As with any pioneering investigation, many caveats and questions remain. Initial estimates from Xing et al.'s (4) work point to the potential for combustion-induced humidity change to impact particulate production independently of other precursor compounds, but a full assessment of the air quality trade-offs associated with different modes of electrical generation (including the effects of water emissions) is still needed. Many variables such as fuel properties, emission control technologies, and atmospheric conditions will likely come into play, and it is possible that effects associated with water emission would emerge as relatively minor in such an assessment (18). As with other urban air quality work, there is also a need to begin to pursue understanding of water emission impacts at finer spatial and temporal scales. Air quality can vary dramatically over much smaller scales than investigated here, and human health impacts are also highly localized, often raising important environmental justice issues (7). Because emissions of both water vapor and other secondary particulate precursors can be colocalized, for example, along traffic corridors or in the vicinity of industrial zones, their interactions may lead to local, nonlinear enhancement of fine particulate levels. This heterogeneity may be accentuated by the stable atmospheric conditions normally associated with poor air quality events such as those experienced in Xi'an.

As society develops and implements plans for the decarbonization of our energy systems, many potential paths lie before us. Socially responsible decision-making requires that these paths be selected with a full accounting of their direct and indirect implications for human society, our environment, and our planet's ecology. More than ever before, modern environmental science offers us the ability to anticipate unintended consequences of our policy decisions, but we still routinely encounter surprises. The work of Xing et al. (4) identifies and provides an initial assessment of a potential surprise associated with transitions between fossil fuels. Air quality impacts associated with water vapor emissions are only one small part of the picture, but warrant further investigation and inclusion in assessments of the relative merits of natural gas as a bridge fuel.

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