By Daniel S. Cohan, Associate Professor, Rice University
Nir Y. Krakauer, Associate Professor, City College of New York
James J. Corbett, Professor, University of Delaware
Rui Zhang, Postdoctoral Researcher, Rice University
Anna Ruth Halberstadt, Graduate Student, Rice University
Leah Y. Parks, Associate Editor, Electricity Policy

Reductions in cooling sulfate aerosols may have contributed to recent warmth.

The year 2015 was the warmest in recorded history, and featured an intense El Niño event in the second half of the year. Since global temperatures have been increasing alongside greenhouse gas (GHG) concentrations and also correlate with the El Niño Southern Oscillation (ENSO), both the U.S. National Centers for Environmental Information and the Australian Bureau of Meteorology indicate that El Niño was a major contributor to the 2015 record warmth (NOAA 2016; BoM 2016).

We offer a hypothesis for an additional contributor to the record global warmth in 2015: a reduction in sulfur emissions from the combustion of coal and of petroleum-derived ship fuel. Sulfur emissions have been cut in order to reduce the health impacts of the sulfur dioxide (SO2) pollutant and of the particulate matter (sulfate aerosols) that subsequently forms in the atmosphere. However, sulfate aerosols also provide a cooling veil by scattering sunlight, brightening clouds, and extending cloud size and lifetime (IPCC 2013). Reducing sulfate aerosols could curtail this atmospheric cooling effect (Fiore et al. 2015), and thus contribute to the observed record-breaking 2015 temperatures.

This paper reviews the temperature anomalies of 2015, and presents evidence both consistent with and contradictory to a contributing role of sulfur cuts in recent warming. We suggest the hypothesis presented merits scientific attention in climate models and observations.

Temperature anomalies in 2015

Close examination of the spatial and temporal distribution of record warmth in 2015 reveals key features that do not fit a narrative of causation by El Niño. Specifically:

1. ENSO indices started 2015 at positive levels (i.e., closer to El Niño than La Niña conditions) but below thresholds that typically signify a meaningful El Niño event. The indices rose sharply in mid-2015, and by late 2015 ranked among the three strongest El Niños since 1950 (Climate.gov 2016).
2. Global temperature anomalies rose sharply in early 2015, before El Niño was fully established. On a quarterly basis, they rose 0.09K from September-November 2014 to December 2014-February 2015. February and March 2015 were the largest temperature anomalies on record, later surpassed by each month September 2015-March 2016 (NOAA 2016).
3. Temperature increases from 2014 to 2015 were greater in the Northern Hemisphere (0.22K based on the NASA GISS compilation) than in the Southern Hemisphere (0.03K).
4. Satellites observed record warm sea surface temperatures (SST) off the coasts of North America and Europe throughout 2015 (Figure 1).

These observations from 2015 appear inconsistent with causation exclusively by El Niño. How could an El Niño that began in Q2 2015 and intensified in Q3 and Q4 of 2015 have caused an intense spurt in temperatures that began in the first quarter (Q1) of 2015? Furthermore, El Niño SST anomalies manifest most strongly in the tropical Pacific Ocean, with eastern waters warmer than usual and western waters cooler. Previous El Niño events have not been accompanied by warm SST anomalies in the extratropical waters off the coasts of North America and Europe. The 2015 temperature spurt that occurred almost exclusively in the Northern Hemisphere is also curious, since El Niño is centered over the Equator. However, the El Niño event in 1997-98 also featured more warming in the Northern than Southern Hemisphere.

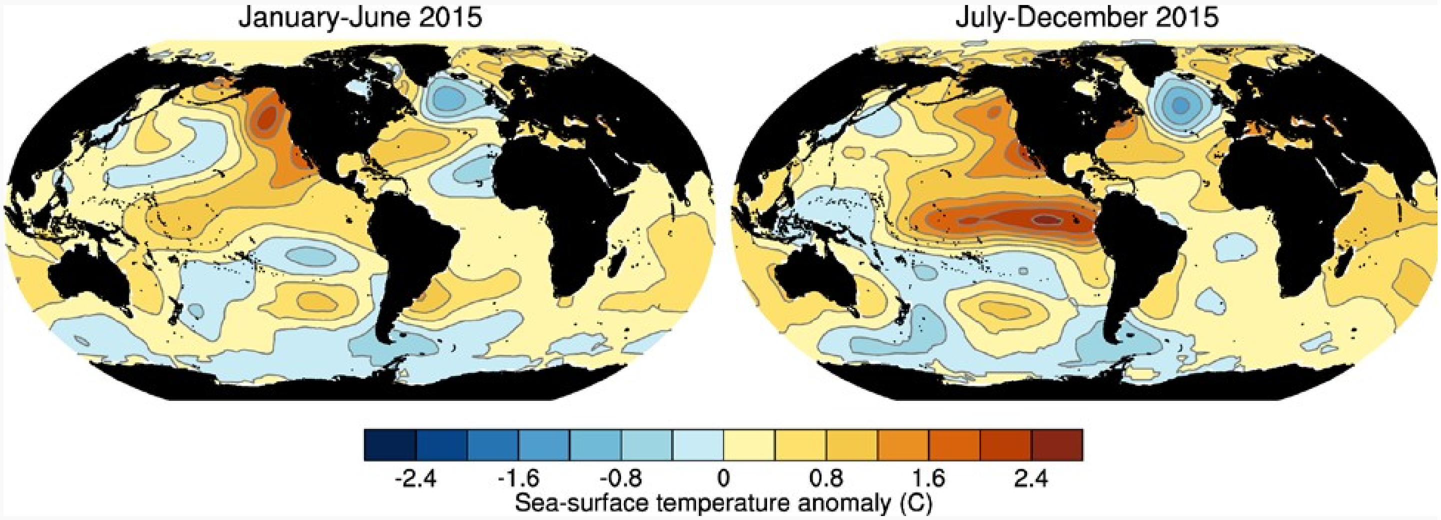

Figure 1. 2015 SST anomalies for Q1 and Q2 compared to the 1981-2010 average. Image Credit: Huang et al. 2014; Liu et al. 2014

Sulfur’s Influence on Climate

Anthropogenic sulfur emissions arise primarily from the burning of coal and fuel oil, and most emissions occur in industrialized regions of the Northern Hemisphere and from ships (Smith et al., 2011). The SO2 is oxidized in the atmosphere, or removed by wet or dry deposition if it comes into contact with a surface or precipitation (Figure 2). The main climate impact of SO2 comes when it is oxidized to form sulfate aerosols (Eatough et al. 1994).

Sulfate aerosols in the atmosphere influence climate in two ways: directly, by scattering solar radiation, and indirectly, by brightening clouds or extending their lifetime or size (Lelieveld and Heintzenberg 1992; Chuang et al. 1997). Both of these effects cause negative radiative forcing (IPCC 2013). Given the lifetime of sulfur in the troposphere (days to weeks), the cooling likely extends hundreds of kilometers from the emissions sources (Fiore et al. 2015).

	1) Sulfur emissions reduced	2a) Decreased SO_2 viewed from space	2b) Decreased SO_4 aerosol in air	2c) Decreased cloudiness & cloud albedo	3a) Temperature anomaly increases	3b) Day vs. night temperature difference enhanced
Coal in China	- Utilities have reduced sulfur content of coal and installed controls	- OMI satellite observes SO_2 reduction over China in the last decade	- Aerosol Optical Thickness measurements decrease over China Sea	- Cloudiness over China and ECAs has not yet been investigated	- No significant change in temperatures over China	- No significant change in Tmax-Tmin over China
Ship fuel in Emission Control Areas (ECAs)	- ECAs reduced ship fuel sulfur limit in January 2015 - Other coastal areas and ports have imposed fuel sulfur limits at various dates	- OMI satellite is insufficiently sensitive to observe changes in ship SO_2	- Aerosol Optical Thickness measurements decrease over most ECAs		- Sea surface temperatures increase over ECAs, especially off west coast of North America	- No significant change in Tmax-Tmin over ECAs

To assess whether sulfur cuts contributed to temperature anomalies in 2015, we assess three lines of evidence (Figure 2):

1. Evidence of sulfur emission reductions, specifically from coal in China and ship fuel in emission control areas (ECAs);
2. Atmospheric observations of SO2 and aerosols; and
3. Temperature trends where sulfur emissions were reduced.

Our analyses show strong evidence of point 1, but conflicting evidence for points 2 and 3. We begin by presenting evidence that emissions from coal and ship fuel oil declined in 2015 in distinct regions of the Northern Hemisphere.

Coal Sulfur in China and Elsewhere

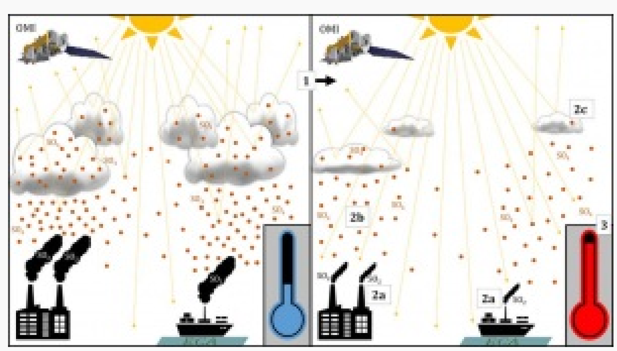

Figure 2. Hypothesis for how reductions in SO2 emissions from ships and coal could lead to warmer temperatures. Numbering in the schematic aligns with the table above. Image Credit: Anna Ruth Halberstadt

Dramatic reductions underway in China coal use have been recognized only recently. China consumes as much coal as the rest of the world combined (EIA 2014; Buckley & Sanzillo 2015), and coal consumption grew at an annual rate of 7.8 percent between 2000 and 2012 (Hao et al. 2015). Most forecasts by the Intergovernmental Panel on Climate Change projected growth in coal in China and worldwide (IPCC 2014). However, the Chinese government in December 2015 announced that it was banning new coal mines for three years to alleviate growing stockpiles of coal. A January 2016 announcement from the National Energy Administration (NEA) outlined plans to shutter 4,300 existing small and inefficient coal mines and cut outdated production capacity of 700 million tonnes in the coming three years (Xinhua Net 2016). Together, these developments strongly indicate that Chinese coal combustion is in ongoing decline. China's National Bureau of Statistics confirmed in February 2016 that China's coal use has fallen for a second year in a row, dropping roughly 3.7 percent in 2015.

Sulfur emissions associated with China's coal combustion have fallen faster than the declining coal usage. The national average sulfur content of coal used by the power sector in China was 1.01 percent in 2005, ranging between 0.25 and 3.24percent for different source regions (Wang and Li 2001; Zhao et al. 2008; You and Xu 2010). China has explicitly targeted sulfur emission reductions to mitigate unhealthy levels of particulates in eastern cities. A Chinese government plan issued in September 2013 aims to increase coal washing rates to 70percent by 2017 and to accelerate construction of scrubbers for flue gas desulfurization (Chinese Environmental Protection Ministry 2013).

In addition to China, declines in coal consumption have also been reported in the United States, Japan, the European Union, South Korea, and South Africa (Buckley & Sanzillo 2015). In the United States, for example, power plant consumption of coal fell 12percent in 2015 (EIA 2016). Only two of the major coal-consuming countries, India and Australia, showed growth in 2015 (Buckley and Sanzillo 2015). Although the International Energy Agency expects India to lead global growth in coal demand (IEA 2015), growing stockpiles and lagging demand for coal (Cohan 2016) have led to moves to scale back coal mining and imports in India (Kanungo 2016; Das 2016).

Ship combustion of fuel oil is estimated to emit 13percent to 15percent of global SO2 from anthropogenic sources (Klimont et al 2013, Smith et al 2014), ranking behind the power sector and industrial coal combustion but producing eight times more SO2 than other transport sources. Ships burn residual fuel oil, which contains orders of magnitude more sulfur than highway diesel and gasoline, and they typically do not control their SO2 emissions. Emission Control Areas (ECAs) for shipping were established by the 1997 MARPOL Protocol that originally took effect in May 2005. ECAs extend 200 nautical miles from the U.S., Canada, and portions of Europe. Ship fuel sulfur limits within ECAs were tightened to 1.0percent in July 2010, and to 0.1percent in January 2015. Elsewhere, the International Maritime Organization (IMO) began limiting ship fuel to 3.5percent sulfur in January 2012, and plans to set a 0.5percent limit in 2020 or 2025 (IMO 2008).

Despite their limited geographical extent, ECAs substantially influence shipping SO2 emissions overall since ships spend much of their time in and near ports, and approximately 70percent of their operating time within 200 nautical miles of land (Corbett and Fischbeck, 1997). Assuming full compliance, the ECA regulations would imply a 90percent reduction in ship SO2 emissions in those areas beginning January 2015. Because fuel with a higher sulfur content is cheaper, it is likely that ships would resume their use of high-sulfur fuel oil upon leaving the ECAs. The North American ECAs are expected to have reduced SO2 emissions by 834,000 tonnes per year (Marine Environment Protection Committee, 2009), and the European ECA by 150,000 tonnes per year (Kalli et al. 2013). Together, that would represent about a 9percent reduction in shipping SO2 emissions in the Northern Hemisphere. In terms of radiative forcing, Lauer et al (2009) estimate that a 0.1percent sulfur cap on ship fuel within 200 nautical miles of coasts (akin to the 2015 ECAs, but also applied to other coasts) would increase radiative forcing globally by 0.12 W/m2 (Watts per square meter), largely via interactions of the sulfate with marine clouds. While this radiative forcing is smaller than needed to explain the rise in Northern Hemisphere temperatures in 2015, it could have played a contributing role regionally.

The ECAs complement a growing array of strict regulations of ship sulfur. For example, China implemented a 0.5percent fuel sulfur cap effective July 2015 in Hong Kong and January 2016 in the Pearl River Delta, Yangtze Delta, and Bohai Bay rim. European Parliament Directive 2005/33/EC limited ship fuel sulfur in inland waterways and ports to 0.1 percent, effective January 2010. The Port of Long Beach, California, offered a Green Ship Incentive Program for ships that met 2016 emission standards early.

Satellite Observations of SO2

Though in situ measurements of SO2 are not readily available over the oceans or beyond urban regions of China, NASA provides daily and monthly averaged measurements of SO2 from the polar-orbiting Ozone Monitoring Instrument (OMI) that can be used to evaluate point 2a of our hypothesis. A recent study used OMI to identify trends in SO2 over the last decade (Krotkov et al 2015; Figure 3). Though China tops the world in SO2 emissions, OMI observed a 50percent drop in SO2 concentrations over China from 2011 to 2014 (Krotkov et al. 2015). OMI also observed large reductions in SO2 columns over the U.S. and Eastern Europe from 2005 to 2014. Meanwhile, OMI observed SO_2 increases over India over what time frame.

Our examination of OMI satellite Level 3 monthly data for 2015 shows an acceleration of the downward trend in SO_2 over China. However, SO_2 from ships is too diffuse for the trends to be observed by OMI (Iolanda Ialongo, Finnish Meteorological Institute, and Nickolay Krotkov, NASA, personal communication).

Aerosol Anomalies and Diurnal Temperature Range in 2015

To evaluate whether aerosols responded to the emissions changes (Point 2b of our hypothesis), we consider weekly values of over-ocean aerosol optical thickness (AOT), available on a 1-degree grid from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (AVHRR) aboard polarorbiting satellites (Tragou and Lascaratos 2003). The mean AOT from this AERO100 dataset was stable globally from 2010-2015.

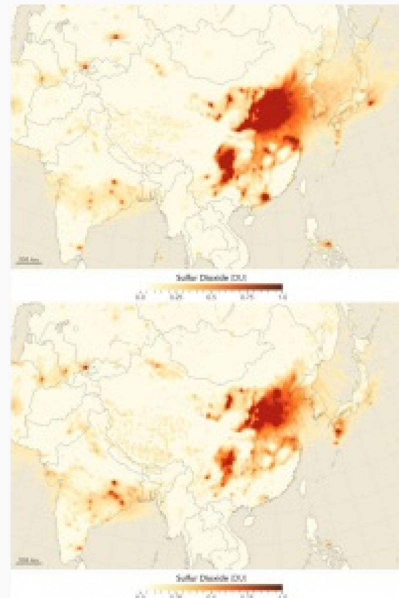

Figure 3: SO_2 over China observed by OMI satellite, averaged over 2005-2007 (top) and 2011-2014 (bottom). Image Credit: NASA

Here, we analyze AERO100 data over regions most likely to be affected by the sulfur cuts from China coal and the shipping ECAs (Figure 4). For China, we define a region over the China Sea bounded by the Korean Peninsula, Japan, the Philippines, and Vietnam (Figure 4). Over this region, AOT was 6percent lower in 2015 than the 2008-2014 average (Table 1). The AOT drop in 2015 was greatest near the China coast, consistent a reduction of SO_2 from inland sources. Over the North American and European ECAs, AERO100 data show AOT declined 2.7 to 8.0percent in 2015 relative to the prior seven-year average (Table 1). The exception is the Hawaiian ECA, which showed a slight increase in AOT in 2015.

We had hypothesized that the lower AOT would increase sunlight reaching the regions, leading to daytime warming and a wider gap between maximum and minimum daily temperatures (Figure 2, point 3b). However, 1-degree gridded temperatures from the Berkeley Earth Surface Temperature project (BEST) based on land weather stations, do not show a statistically significant change in the daily temperature range over China or near the ECAs.

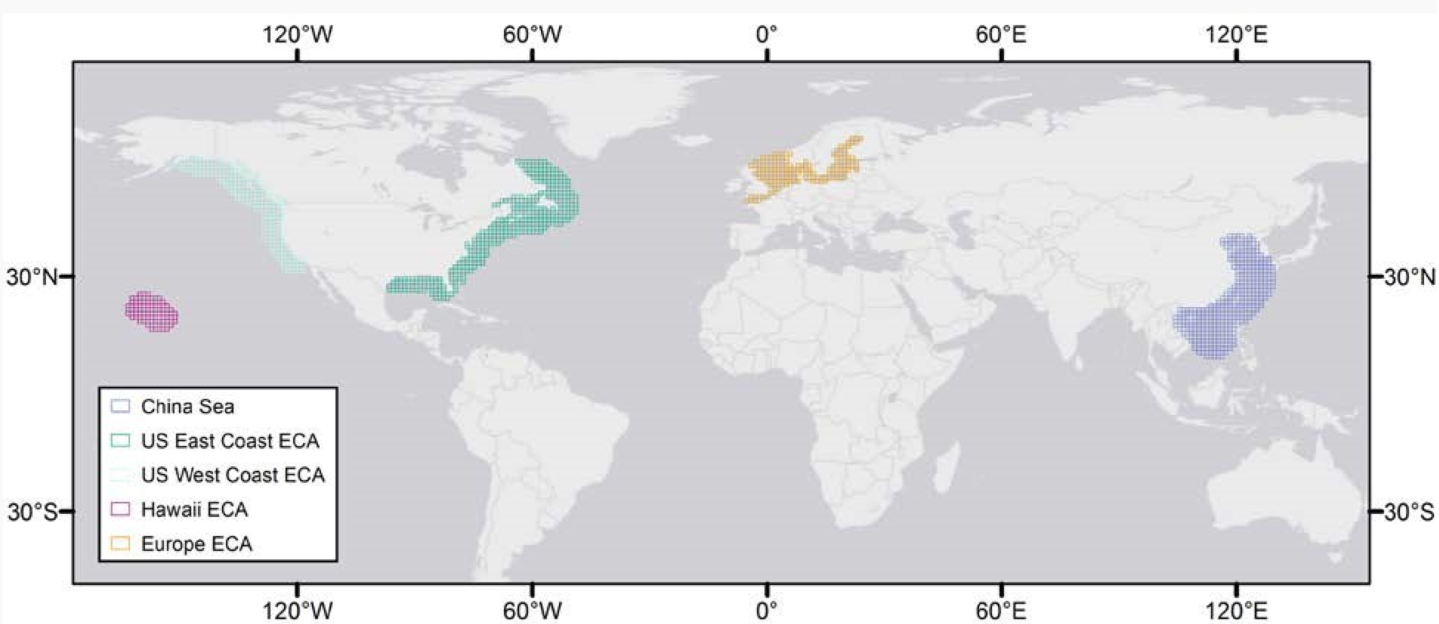

Figure 4. Regions over which aerosol optical thickness was assessed. Image Credit: Basemap: ESRI, DeLorme, HERE, MapMyIndia

Conclusions and Implications

The analysis and discussion above provide mixed evidence about whether reduced sulfur emissions contributed to 2015 Northern Hemisphere warming. The temperature anomaly distribution (Figure 1) suggests that El Niño alone cannot explain several of the key features of 2015 Northern Hemisphere warming. Regulatory changes and economic statistics are consistent with declines in sulfur emissions from coal in China and the U.S. and from ships in the ECAs (Figure 2, point 1). OMI observations confirm SO2 reductions over China (Figure 3, point 2a), but cannot detect changes over the ECAs, while another satellite confirms reductions in aerosols over the ECAs (Table 1; point 2b). Warm SST anomalies are observed over the ECAs (Figure 1; point 3a), but air temperature data do not show an increased gap between maximum and minimum temperatures (point 3b).

	AOT average 2008-2014	AOT average 2015	Avg2015 - AvgPre2015	percent Difference (Dif/Avg * 100)
East Coast ECA	0.108	0.105	-0.003	-2.7
West Coast ECA	0.100	0.092	-0.008	-8.0
Europe ECA	0.103	0.096	-0.007	-6.7
Hawaii ECA	0.111	0.114	0.003	+2.3
China Sea	0.098	0.0924	-0.006	-6.0

Table 1. Aerosol optical thickness over the ECA regions of North America and Europe, in 2015 and averaged over the prior 7 years in AERO100 data.

IPCC forecasts predict that SO2 and sulfate aerosols will decline sharply in the coming decades; accelerating those reductions is a boon to public health. However, CO2 and other long-lived gases accumulate in the atmosphere, whereas sulfur is short-lived. Thus, reducing CO2 and other greenhouse gases must remain a primary target of climate change mitigation, even if sulfur reduction drives short-term regional warming.

The possibility that a cut in ship sulfur emissions could dramatically impact temperatures in ECAs raises important policy questions. In particular, is it wise for the IMO to follow through with plans to cut ship fuel sulfur globally in 2020 and 2025? This question was recently raised in the context of Arctic shipping by Lindstad et al (2016). Creating new ECAs near coasts, especially near the heavily populated coastal mega-cities of Asia and beyond, would reduce population exposure to harmful particulate matter. However, sulfur released over the open oceans is more likely to enter clouds than human lungs. In remote marine areas where baseline particulate matter and cloud condensation are typically low, sulfate aerosols derived from ship sulfur emissions may be especially impactful on clouds (Lauer et al. 2009). After decades of ships emitting cooling sulfur over the open oceans, imposition of a global cut in fuel sulfur content could bring a sudden change to the little noticed climate “geoengineering” that ships provide in remote marine areas. Observations and modeling studies should be deployed to better quantify the climate, health, and ecosystem impacts of ship emissions in the open ocean and to help guide the timing and sequence of regulations to reduce shipping fossil fuel use and pollution as part of the global transition away from reliance on fossil fuels.

Ultimately, our speculations and hypotheses raise as many questions as answers. It is our hope that future work by our team and other scientists will better elucidate the roles of sulfur and other factors in driving recent atmospheric and ocean warming, and its impact on the weather and climate variability.

Acknowledgments: This manuscript benefitted from a review by Tracy Volz of Rice University, discussions with Nickolay Krotkov (NASA) and Iolanda Ialongo (Finnish Meteorological Institute), and the comments of two anonymous reviewers. Funding for D. Cohan, R. Zhang, and A.R. Halberstadt was provided by NASA Air Quality Applied Sciences Team.

Daniel Cohan is associate professor of environmental engineering at Rice University, a member of the NASA Air Quality Applied Sciences Team, and a contributing author for The Hill, The Conversation, and The Houston Chronicle.

Nir Krakauer is associate professor of Civil Engineering at City College of New York.

James Corbett is professor of Earth, ocean, and environment at University of Delaware.

Rui Zhang is a postdoctoral researcher.

Anna Ruth Halberstadt received her M.S. in Earth Sciences at Rice University.

Leah Y. Parks is associate editor of Electricity Policy and author of All Electric America.

References

Australian Bureau of Meteorology (2016). Annual Climate Statement 2015. http://www.bom.gov.au/climate/current/annual/aus/.

Buckley and T. Sanzillo. (Nov 2015). Past Peak Coal In China, Institute for Energy Economics and Financial Analysis Report, Available: http://ieefa.org/wpcontent/uploads/2015/11/IEEFA_Peak-Coal_November-2015.pdf

Chinese Environmental Protection Ministry (2013). The State Council issues action plan on prevention and control of air pollution introducing ten measures to improve air quality. Available: http://english.mep.gov.cn/News_service/infocus/201309/t20130924_260707.htm-minister-says/

C.C. Chuang et al., “An assessment of the radiative effects of anthropogenic sulfate,” J. Geophys. Res. Atmos., vol. 102, pp. 3761-3778, 1997.

D.S. Cohan (Feb 17, 2016), “Plummeting coal use and peaking stockpiles” The Hill. Available: http://thehill.com/blogs/pundits-blog/energy-environment/269684-plummeting-coal-use-andpeaking-stockpiles

D.S. Cohan and L.Y. Parks (Feb 26, 2016), “Achieving Clean Power Plan targets well ahead of schedule,” The Hill. Available: http://thehill.com/blogs/pundits-blog/energy-environment/270544achieving-clean-power-plan-targets-well-ahead-of

Corbett, J. J. and P. Fischbeck (1997). “Emissions from ships.” Science 278(5339): 823-824.

A.K. Das (Feb 2016), “Coal of India may scale back production to deal with 40Mt stockpile,” Mining Weekly. Available: http://www.miningweekly.com/article/coal-of-india-may-scale-backproduction-to-deal-with-40mt-stockpile-2016-02-22

D.J. Eatough et al., “The conversion of SO2 to sulfate in the atmosphere,” Isr. J. Chem., vol 34, no. pp. 301-314, 1994.

Energy Information Administration (EIA), (2014). Today in Energy. Available: http://www.eia.gov/todayinenergy/detail.cfm?id=16271

Energy Information Administration (EIA), (2016). Short Term Energy Outlook, Coal. Available: https://www.eia.gov/forecasts/steo/report/coal.cfm

A.M. Fiore et al., “Air Quality and Climate Connections,” J Air Waste Mgmt Assoc, vol. 65, pp. 645-685, doi: 10.1080/10962247.2015.1040526, 2015.

Hao et al, “China’s farewell to coal: A forecast of coal consumption through 2020,” Energy Policy, vol. 86, pp. 444-455, 2015.

Huang et al., “Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4): Part I. Upgrades and intercomparisons,” J. Climate, vol. 28, pp. 911–930, 2014.

International Energy Agency (IEA) (2015). Coal medium-term market report: market trends and projections to 2020. Available: http://www.iea.org/bookshop/712-MediumTerm_Coal_Market_Report_2015

Intergovernmental Panel on Climate Change (IPCC), Climate Change 2013: The Physical

Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Intergovernmental Panel on Climate Change (IPCC), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

International Maritime Organization (2008). Revised MARPOL Annex VI: Amendments to the

Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution From Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto. International Maritime Organization. London, UK, International Maritime Organization. MARPOL Annex VI:

Kalli, J.-P. Jalkanen, L. Johansson, and S. Repka. “Atmospheric emissions of European SECA shipping: long-term projections,” WMU Journal of Maritime Affairs, vol. 12(2), pp. 129145, 2013.

Kanungo (Jan 29, 2016), “Coal India likely to scale back production as stock piles: Piyush Goyal,” Live Mint. Available: http://www.livemint.com/Industry/e5apwEUsVytgLGq0EbAsRP/Coal-India-likely-to-scale-backproduction-as-stock-piles-P.html

Klimont et al. (2013). The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions. Available: http://iopscience.iop.org/17489326/8/1/014003/media/erl441620suppdata.pdf

A. Krotkov et al., “Aura OMI observations of regional SO2 and NO2 pollution changes from

2005 to 2014,” Atmos. Chem. Phys. Discuss., vol. 15, pp. 26555-26607, doi:10.5194/acpd-1526555-2015, 2015.

Lauer, V. Eyring, J.J. Corbett, C. Wang, and J.J. Winebrake. “Assessment of Near-Future Policy Instruments for Oceangoing Shipping: Impact on Atmospheric Aerosol Burdens and the

Earth’s Radiation Budget,” Environmental Science and Technology, vol. 43, pp. 5592-5598, 2009.

Leber (Feb 29, 2016). “Coal use is down in the U.S. and China — and it’s not a blip”, Grist. Available: http://grist.org/news/coal-use-is-down-in-the-u-s-and-china-and-its-not-a-blip/

Lelieveld and J. Heintzenberg, “Sulfate cooling effect on climate through in-cloud oxidation of anthropogenic SO2,” Science, vol. 258, pp. 117-120, 1992.

Lindstad, H., R. M. Bright and A. H. Strømman (2016). “Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation.” Transport Policy 45: 24-30.

Liu et al., “Extended Reconstructed Sea Surface Temperature version 4 (ERSST.v4): Part II. Parametric and structural uncertainty estimations,” J. Climate, vol. 28, pp. 931–951, 2014.

Marine Environment Protection Committee, “ Proposal to Designate an Emission Control Area for Nitrogen Oxides, Sulphur Oxides and Particulate Matter," MEPC 59/6/5, available at https://www3.epa.gov/nonroad/marine/ci/mepc-59-eca-proposal.pdf, 2009.

National Bureau of Statistics of China (NBS) (Feb 29, 2016), Statistical Communiqué of the People's Republic of China on the 2015 National Economic and Social Development, Available: http://www.stats.gov.cn/english/PressRelease/201602/t20160229_1324019.html

NOAA National Centers for Environmental Information (2016). State of the Climate: Global Analysis for Annual 2015, published online January 2016, retrieved on April 26, 2016 from http://www.ncdc.noaa.gov/sotc/global/201513.

Parkinson (Jan 2016), "Solar Power Now Cheaper Than Coal In India, Says Energy Minister," CleanTechnica, Available at, http://cleantechnica.com/2016/01/22/solar-power-nowcheaper-than-coal-in-india-says-energy-minister/

Shah (Feb 2016), "Why India Has Become The Sunniest Land For Solar Opportunities," SeekingAlpha, Available at, http://seekingalpha.com/article/3883056-india-become-sunniestland-solar-opportunities

Wang and R. Li, R., 2011, "Typical kinds of coal in China and some special coals with their fly ash difficult to precipitate by ESP". in 8th International conference on Electrostatic Precipitation, Available: http://www.isesp.org/icesp%20viii%20papers/VIII-ICESP%20PC4-2.pdf

Rife, et al. (Mar 2016) " A New Kind of Drought: U.S. Record Low Windiness in 2015." Submitted to Earthzine.

Robert et al., "Berkeley earth temperature averaging process," Geoinfor. Geostat.: An Overview, vol. 1, pp. 1-13, 2013.

J. Smith, J. van Aardenne, Z. Klimont, R. J. Andres, A. Volke, and S. Delgado Arias, " Global and regional anthropogenic sulfur dioxide emissions: 1850-2005", Atmos. Chem. Phys., 11, 1101-1116, doi:10.5194/acp-11-1101-2011, 2011.

Smith, T. W. P., J. P. Jalkanen, B. A. Anderson, J. J. Corbett, J. Faber, S. Hanayama, E.

O'Keeffe, S. Parker, L. Johansson, L. Aldous, C. Raucci, M. Traut, S. Ettinger, D. Nelissen, D.

Lee, S. Ng, A. Agrawal, J. J. Winebrake, M. Hoen, S. Chesworth and A. Pandey (2014). Third IMO GHG Study 2014. London, International Maritime Organisation (IMO).

Tragou and A. Lascaratos, "Role of aerosols on the Mediterranean solar radiation," J. Geophys. Res. Ocean, vol. 108, C2, 2003.

Xinhua Net (Jan 21, 2016). "China to further cut coal capacity." Available: http://news.xinhuanet.com/english/2016-01/21/c_135031210.htm

F. You and X. C. Xu, "Coal combustion and its pollution control in China," Energy, vol. 35, pp. 4467-4472, 2010.

Zhao et al., "Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction," Atmos. Environ., vol. 42, pp. 8442-8452, 2008.