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Soviet and Russian perspectives on geoengineering and climate management

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Abstract

Soviet science contributed significantly to our understanding of anthropogenic climate change and, as part of this, played a central role in the emerging science underpinning climate modification and geoengineering initiatives. A key focus of discussion was the use of stratospheric aerosols linked to the innovative ideas of Mikhail Budyko and colleagues. This work had its origins in what has been termed the theory of aerosol climatic catastrophe, which gained prominence in the Soviet context during the early 1970s. Following the breakup of the Soviet Union, the ideas of Budyko concerning the use of stratospheric aerosols were advanced by Yuri Izrael and his collaborators. The associated body of work gained traction during the 2000s and engendered a wider debate concerning the efficacy of geoengineering solutions amongst Russia's climate scientists. The legacies of this scientific discussion are also evident in recent high-level international debates such as those linked to the activities of the IPCC. While significant geopolitical obstacles remain in the way of an international agreement linked to the possible deployment of geoengineering measures, interest continues to grow. The maturity of Russian science in the area of geoengineering and climate modification ensures that it remains an important voice within the broader scientific debate. At the same time, the progressive isolation of Russian science from the international scene due to wider geopolitical events risks deflecting attention away from contemporary popular and political debate in this area and alienating this rich scientific tradition at a critical juncture.

This article is categorized under:

Climate, History, Society, Culture > Ideas and Knowledge
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aerosols, geoengineering, Russia, Soviet Union

1 | INTRODUCTION

Geoengineering has emerged as an area of significant scientific and popular debate during the course of the 21st Century (e.g., Royal Society, 2009; Lawrence et al., 2018; Morton, 2015). Geoengineering solutions, that is "the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming" (Royal Society, 2009, p. ix), have until relatively recently been regarded with skepticism by significant parts of the scientific and policy community due to the unprecedented challenges presented by large-scale manipulation of the Earth's climate system. Concern has embraced environmental, scientific, geopolitical, technical and ethical aspects (e.g., Biermann, 2021; Carlson et al., 2022; Crutzen, 2006; de Coninck et al., 2018; Jones et al., 2017; Marland, 1996; Robock, 2008; Sillmann et al., 2015; Trisos et al., 2018). Nevertheless, the growing urgency of the climate change issue, due to the weakness of global political solutions, continues to drive related scientific activity and interest (Frumhoff & Stephens, 2018). The historical roots of geoengineering science offer a further arena for critical discussion (e.g., Fleming, 2010; Oomen & Meiske, 2021) and linked analysis opens up, amongst other things, the way in which geoengineering ideas are shaped by socio-cultural context. Insight offered by an examination of the intellectual and political framing of geoengineering solutions has been advanced recently by Schubert (2022). In overviewing the place of geoengineering post-1945, Schubert suggests phases during which the interplay between the prevailing science and the state shifted, resulting in different approaches to the broader geoengineering agenda, and culminating in the most recent period where "we can observe how climate engineering is becoming increasingly embedded in a basic research agenda for the atmospheric and oceanographic sciences. It is explored in this context as "just science," concerning mere technicalities, or matters of fact" (Schubert, 2022, p. 10).

Within this area of debate, analysis of the historical contributions of Soviet and Russian science is given short shrift. Russian science has a longstanding interest in the potential of managing climatic processes to effect large-scale change stretching back to the mid-Soviet period. This intellectual legacy remains of significance in the 21st Century not only in terms of the underlying science but also with respect to the broader framing of the discussion. For example, the Soviet case study has the potential to complicate aspects of the broad typology of Schubert's aforementioned longue durée picture of geoengineering due to the particularities of science-state interaction during the mid- to late Soviet period, although a deeper analysis of this aspect is beyond the scope of the current paper. The Putin administration's subdued engagement with the Paris Agreement and climate change agenda (e.g., Poberezhskaya, 2016; Tynkkynen & Tynkkynen, 2018), has undermined assessment of the debate concerning climate mitigation and, by extension geoengineering, within Russia. And, Russia's invasion of Ukraine promises to further reduce engagement with Russian science in this and other areas. Thus, the paper's underlying aim is to provide deeper understanding of Russia's rich scientific tradition with respect to geoengineering, and to provide insight into the shape of recent debate amongst the country's scientific community. It is argued that Soviet scientific work related to climate modification at a global scale was characterized by a considered and wide-ranging discussion that embodied a clear sense of the inherent dangers associated with manipulating complex natural systems (e.g., Oldfield, 2021). Activity in this area was arguably more pronounced than that found in the West due to a deep-seated belief in science and technology. In addition, there was a profound awareness amongst parts of the scientific community of humankind's growing influence within the Earth's biosphere, which was distinct from the cruder versions of society-nature interaction promulgated by the Soviet state and certain areas of Soviet science. A particular focus that emerged from this broad area of interest concerned the use of stratospheric sulfur aerosols to mitigate the excesses of anthropogenic climate change; a focus that continued to play an influential role in the debates around climate change and associated mitigations post-1991. This area of thought intermingled with the work of other Russian scientists which tended to mirror discussion within the wider international climate community. The opening section provides an overview of early Russian and Soviet interest in modifying weather and climate, before moving on to explore the emergence of a focused body of work linked to geoengineering and driven forward by the climate scientist Mikhail Budyko (1920–2001) and his colleagues. The third section examines the post-1991 period and follows the activities of Yuri Izrael and his collaborators in championing the earlier work of Budyko framed by a perceived weakness in the architecture of the Kyoto Protocol and its basic inability to address the challenge of climate change. The associated body of work gained traction during the 2000s and engendered a wider debate concerning the efficacy of the geoengineering solutions amongst Russia's climate scientists. The ensuing debate is assessed in more detail below.

2 | SOVIET SCIENCE, SOCIETY-NATURE INTERACTION, AND CLIMATE MODIFICATION

Soviet science has contributed significantly to our understanding of anthropogenic climate change (e.g., Doose & Oldfield, 2019; Oldfield, 2018) and, as part of this, played a central role in the emerging science underpinning weather and climate modification which in time morphed into large-scale geoengineering initiatives (e.g., Oldfield, 2013). For Soviet science, the desire to understand complex weather and climate systems provided a key impetus for related activity during much of the post-1945 period linked to a state-led drive to utilize natural resources as efficiently and effectively as possible for the betterment of society. The broad debate around geoengineering in the West has been characterized by enduring concerns linked to the consequences of such activity (e.g., Jamieson, 1996), and aspects of this debate were also evident within analogous Soviet and Russian scientific discussions at least with respect to the need for a cautious approach and international agreement (e.g., Izrael & Ryaboshapko, 2011). More specifically, the main proponents of large-scale climate modification within Soviet climate science were careful not to advocate a cavalier approach to such activity, and their work consistently flagged the need for concerted scientific appraisal before any attempt to modify natural processes at scale. This approach was rooted firmly in an appreciation of the complexity of natural systems and the likelihood that any substantive intervention would result in unforeseen and potentially deleterious consequences. As such, this scientific work can be contrasted with the often-reckless actions of other scientists and the Soviet state with respect to society-nature interaction (see Josephson et al., 2013). Something of the triumphalist and populist exhortations of Soviet Marxist rhetoric in this area is captured by the 1959 publication by Adabashev which was also disseminated in English via Progress publishers and entitled "Global-engineering." The original title in Russian captured the sense of humankind repairing the planet (*Chelovek ispravlyaet planetu*), and as such conveyed the rather crude but nonetheless influential notion of remolding the physical and natural environment to suit the needs of society.

While certain areas of Soviet science displayed a more considered approach to society-nature than those evidenced within political rhetoric, there was nevertheless a broad appreciation of the growing role and importance of society (and human activity) with respect to the natural world, and an associated effort to conceptualize this shifting relationship to ensure a carefully managed interaction between society and the wider environment in the future. An influential strand of thought in this area was promulgated by the Cosmist movement, which had its roots in the 19th Century, and the work of assorted scholars and intellectuals (e.g., Hagemeister, 1997; Oldfield, 2021; Young, 2012). The scope of the movement is difficult to capture in brief. It drew from diverse intellectual sources in order to emphasize the evolutionary character of humankind's growing environmental reach framed by scientific and technical developments.

For the purposes of this paper, two individuals from within this movement are worth highlighting. First, the nominal founder of the movement, Nikolai Fedorov (1829–1903), was a philosopher of influence, and in line with his futurist thinking he pursued the end of death and the attainment of immortality for humankind together with the associated mastery and regulation of both bodily and natural processes. As part of a 1995 edition of his collected works, a range of articles and writings linked to the regulation of nature was outlined and this included the 1892 essay "Karazan: meteorologist or meteorurge." This short piece encompasses both philosophical and science fiction elements. Writing in the introduction to *Red Star Tales: A Century of Russian and Soviet Science Fiction*, Yvonne Howell notes that Fedorov uses the essay to draw attention to the "expectation of spiritual salvation that was indivisible from the Russian thinker's scientific rationalism" (Howell, 2015, p. 10). At its heart, Fedorov's essay contrasts the meteorologist and the meteorurge, the former being concerned with predicting weather and the latter with managing weather patterns and processes (Fedorov, 1995, p. 260). The essay contains various allusions to the ability of humankind to manage and control the processes of the atmosphere. It is also framed by the latent potential Fedorov perceived in Russia as a country. In particular, he argued that Russia's varied landscapes and attendant extremes of climate ensured that greater emphasis was placed on the need for effective climate control than was evident amongst the leading maritime powers of the period (Fedorov, 1995, p. 263).

The biogeochemist Vladimir Vernadsky (1863–1945) was also linked strongly to the Cosmist movement, and he was influential in advancing a belief in the ability of humankind to ensure a scientifically managed biosphere. More specifically, Vernadsky had developed his ideas pertaining to the biosphere and noosphere (sphere of reason) during the first half of the 20th Century (Vernadsky, 1926, 1945, 1997, 2001). The latter concept embodied the idea that humankind's growing presence within the biosphere would culminate in a new evolutionary stage framed by scientific and technical progress, and this would present humankind with a moral imperative to ensure the careful management of the Earth's biosphere in its entirety. The work of Vernadsky in this area proved significant for a number of leading Soviet scientists interested in the large-scale functioning of the biosphere and the relationship between the biosphere and society (e.g., Oldfield, 2021; Rindzevičiūtė, 2020). In this respect, the aforementioned climate scientist Mikhail Budyko (1920–2001), who would play a leading role in advancing geoengineering thought, engaged deeply with Vernadsky's ideas around the biosphere and noosphere and the linked evolutionary framing. For example, in his monograph *Evolution of the Biosphere* (1984), Budyko drew from the interpretive work of Yanshin and suggested that the emergence of the noosphere was a long-term process that demanded large-scale shifts in the functioning and organization of society and, importantly from our perspective, Budyko envisaged an associated "radical transformation of the natural environment" grounded on new sources of energy (Budyko, 1984, pp. 338–339). Within the context of a broader discussion around the future of the biosphere, Budyko went on to suggest that:

> … the creation of the noosphere will be completed following the formation of a system of control for the state of the biosphere, and after the realization of methods for the regulation of large-scale biospheric processes… Amongst the problems that creating the noosphere should solve is climate control: the development of methods for controlling climate and optimizing climatic change in the interests of [humankind] as a whole… this problem in its simplest form is accessible even to modern technology (1984, p. 431).

This underlying belief in science and technology, and its potential role in controlling climate amongst other natural processes, facilitated a relatively open discussion around climate modification and associated management ideas within areas of the Soviet scientific literature, which contrasted with the more muted debate in the West at this time.

3 | SOVIET CLIMATE SCIENCE AND THE EMERGENCE OF GEOENGINEERING

The ideas of Budyko are typically acknowledged as some of the earliest interventions in the geoengineering debate (e.g., Lawrence et al., 2018). Much of the early Soviet focus in this general area was directed towards the country's Arctic region and involved consideration of solar radiation management techniques (e.g., management of ocean surface evaporation rates, ice removal etc.) during the early 1960s (e.g., Budyko, 1962a; Rakipova, 1962). This scientific debate existed in conjunction with a range of more aggressive initiatives to transform the natural environment for socioeconomic benefit, many of which had implications for regional climates. These included infamous large-scale engineering schemes to reverse-engineer the flow of Siberian rivers as well as influence the temperature of the water flowing through the Arctic Ocean. With regard to the latter, the Soviet engineer Borisov advanced one of the most influential projects (his ideas were translated into English and widely circulated) in which he outlined a mechanism to alter the flow of waters within the Arctic Basin in order to melt the sea ice and warm the regional climate (Borisov, 1969, 1973, 2003). While similar dramatic engineering schemes to modify natural processes and associated regional climate systems have received a high level of attention and critique in the English-language literature (e.g., Pryde, 1991), the more involved scientific debate has been largely ignored due to Cold War framing, language barriers and related issues. Nevertheless, key elements of Budyko's work were translated into English during the 1970s and 1980s (see Oldfield, 2016).

Soviet science had a longstanding interest in weather and climate modification (Oldfield, 2013). Historians of science including James Fleming (2010) and Jacob Hamblin (2013) have drawn attention to the activities of Soviet scientists in this area within the context of Cold War tensions and highlighted the connection with broader discussions around environmental modification and climate management during this period (see also Hamblin, 2010; Harper & Doel, 2010). Soviet work in this area pre-dated the Cold War period, driven by domestic needs in agriculture as well as a state-led agenda aimed at understanding the complexities of physical systems to assist the effective utilization and management of natural resources. This initiative underpinned a range of activities linked to the ill-fated Stalin Plan for the Transformation of Nature. While much has been written about the involvement of Trofim Lysenko in the science shaping key aspects of the initiative, the Stalin Plan also involved cadres of credible scientists concerned with understanding and influencing moisture levels, air turbulence, evaporation rates, and so on (e.g., Oldfield & Shaw, 2015; Pogosyana, 1952). Budyko was involved in this early work linked to aspects of atmospheric science investigating the process of evaporation (Budyko, 1948) and the complexities of the heat–water balance at the Earth's surface (Budyko, 1956). Writing in the preface to his highly influential 1956 publication, which would be translated into English within 2 years, Budyko noted that a deeper understanding of regional meteorological and hydrological regimes would permit the more effective prognosis of hydrometeorological processes and linked activity to manage regional climatic conditions (Budyko, 1956, p. 1; see also Shaw, 2015).

The polar explorer and geophysicist, Fedorov, authored an article in the journal *Philosophical Questions* (Voprosy Filosofii) in 1958 exploring the "influence of humankind on meteorological processes." Framed by the activities of the International Geophysical Year (1957–1958), Fedorov discussed the potential of the geophysical sciences to provide society with the means to understand and influence key elemental processes including those concerning the atmosphere. He noted the growing volume of CO2 from industrial activity and underlined that, "[i]t is well known that CO2 powerfully absorbs infrared radiation and its presence in the atmosphere significantly changes the balance of radiant energy" (Fedorov, 1958, p. 143). He went on to highlight the potential for the hydrogen bomb to result in significant changes to the electrical characteristics of the atmosphere in addition to other large-scale consequences. Such observations led him to conclude that "society is already an involuntary climatological factor" (Fedorov, 1958, p. 144).

In the wake of the work highlighted above aimed at influencing regional climate allied to an appreciation of the ability of humankind to effect large-scale change on the climate, there followed two landmark meetings in 1961 and 1962 organized jointly by the Main Geophysical Observatory, the Institute of Applied Geophysics, and the Institute of Geography, which aimed to initiate focused discussion around "climate change in the past and possible paths for its artificial transformation in the future" (Gal'tsov, 1961, p. 128; Gal'ltsov & Cheplygina, 1962). Animating the meetings was an acceptance that large-scale climate and weather modification was in reach technologically speaking. Indeed, confidence was high in this regard during the early 1960s, with Budyko highlighting society's ability to influence cloud, rain, and fog conditions as part of an interview published in the national state newspaper *Pravda* in February of 1962 (Pravda, 1962, p. 6). The conclusion of the second meeting underlined the need for further research into areas such as general atmospheric circulation, natural and anthropogenic change of climate, regional conditions for the transformation of climate and weather modification, and the theoretical foundations for the artificial manipulation of key climatic processes (Gal'ltsov & Cheplygina, 1962, p. 187).

As noted, one of the key areas that attracted significant Soviet interest was that of the link between climate change and ice cover. The climate scientist Rakipova captured this interest in her 1962 article, opening with the following statement:

> Of all the possible means for the artificial change of climate, one of the most effective to consider is the melting of Arctic ice as a result of the implementation of corresponding scientific and technically based measures. The changes that will result in this case in the state of the atmosphere will have an effect on the general circulation, that is they will have a planetary scale (Rakipova, 1962, p. 28).

The importance of the Arctic region, and its ice cover, for regional and global climate gained traction during the course of the 1960s and would emerge as an area of focus for Budyko and colleagues at the Main Geophysical Observatory in Leningrad (e.g., Budyko, 1962a). For Budyko, a main feature of the Arctic region with respect to the broader climate change debate, was its ability to effect global shifts in climate regimes due to relatively small changes in the level of incoming solar radiation. And, he went on to suggest:

> There is significant interest in the question concerning the possibility of the artificial destruction of long-term ice. The expediency of such measures is currently unclear, however if… it is recognized as useful, then the destruction of ice could be technically feasible in the near future. (Budyko, 1962a, p. 10; see also Budyko, 1969).

In the same year, he published an article in the interdisciplinary journal *Meteorology and Hydrology* exploring "the different ways of influencing climate," which developed several themes in this general area. The paper embodied the noted optimism in the potential of science and technology to effect beneficial changes to the climate to support economic activity (Budyko, 1962b, p. 3). In the paper, Budyko discussed several areas including the impact of human-produced heat on local climates, potential climate impacts of nuclear technology, and the manipulation of the heat and water balance at the Earth's surface. The final part of the paper moved onto "one of the most interesting problems of climate transformation" concerning the impact of the Arctic Ocean on ice formation in view of its importance as a climate-forming factor (Budyko, 1962b, pp. 5–6). Budyko acknowledged the complex nature of the removal of ice from the Arctic region in terms of the potential climatic consequences and the need for detailed research to determine the character and range of such consequences. Several possible means for reducing the ice cover were outlined including the application of dark powder scattered on the ice surface, and action to reduce the evaporation rate from the open ocean to alter the thermal regime of the adjacent water and air.

This interest in the Arctic region was part of a scientific exchange across the Iron Curtain. An agenda-setting international symposium, which brought together the Soviet scientists Budyko (1966) with a host of Western scientists, took place in January 1966 in California. Organized by the RAND corporation, which had been established in the late 1940s to buttress the public welfare and security of the United States, the symposium was intended to explore the Arctic heat budget and atmospheric circulation (Fletcher, 1966, p. v). The symposium consisted of four main thematic sections: the interaction of climate and the Arctic heat budget, quantitative evaluation of the Arctic heat budget, models of atmospheric circulation, and ocean–atmosphere interactions and models of oceanic circulation. Budyko's intervention entitled "Polar ice and climate" rehearsed the main arguments of his earlier work referenced above.

3.1 | Deployment of stratospheric aerosols

Budyko published further work related to climate modification during the mid-1970s. In 1974, he collaborated with colleagues from the Main Geophysical Observatory in Leningrad (Gandin, Drozdov, Karol', and Pivovarova) to reflect on the use of aerosols in the stratosphere and their potential influence on global climate. The starting point for the paper was an acknowledgement that increasing levels of CO2 from industry and transport had the potential to elevate global temperature, and that there was much to be gained from maintaining the current climatic conditions at the Earth's surface to avoid socio-economic upheaval. This emphasis on the status quo can be contrasted with Budyko's later accent on the potential benefits of climate change for certain regions (see Oldfield, 2018). The paper worked through existing knowledge linked to the influence of aerosols in the stratosphere on both temperature and moisture, before moving on to consider methods for engineering change through the delivery of aerosols into the lower stratosphere via aircraft. The basic idea was relatively straightforward. Drawing on the observed cooling effect of aerosols ejected by volcanic eruptions and industrial activity, the aim was to mimic the consequences via the deliberate injection of aerosols into the lower stratosphere. This aerosol layer would act to reflect incoming sunlight and regulate the temperature at the Earth's surface. This paper ended on a cautionary note, underlining that shifts in the aerosol content of the stratosphere had the potential to lead to a range of uncertain ("undirected") climatic consequences for different countries (Budyko et al., 1974, p. 22).

Aspects of this work also appeared in a monograph by Budyko that same year entitled *Climatic Changes* (published in English several years later in 1977). The final chapter of this monograph examined the theme of climate modification based on the premise that it was not possible to prevent rising levels of CO2 and energy use in the short- to medium-term. This emphasis on the potential short-term value of geoengineering interventions would emerge consistently in later work. Budyko considered the modification of aerosol content in the lower stratosphere to effect global climate change as one of the most realistic methods to mitigate climate change at that time (Budyko, 1977, p. 239). More specifically, he focused on the use of sulfate particles and the conversion of SO2 into sulfuric acid. Approximate calculations were suggestive of the potential for a relatively modest number of aircraft to be effective in delivering the necessary quantities of sulfur to the lower atmosphere to affect a relatively significant shift in mean temperature at the Earth's surface (Budyko, 1977, p. 240). Developing the discussion, and drawing from the work of US climate scientists, Budyko proceeded to note that:

> …the prospect of climate modification by varying the type of fuel used by stratospheric aviation becomes promising… [and] …stratospheric flights can be considered a promising element in a system of global climate modification (Budyko, 1977, p. 243).

Budyko's concluding comments highlighted his belief in science and technology and the imperative to advance climate management methods if feasible:

> If we agree that it is theoretically possible to produce a noticeable change in the global climate by using a comparatively simple and economical method, it becomes incumbent on us to develop a plan for climate modification that will maintain existing climatic conditions, in spite of the tendency towards a temperature increase due to [humankind's] economic activity (Budyko, 1977, p. 244).

Related work by Budyko and colleagues emerged in subsequent years. For example, a 1976 article with Drozdov in the *Herald* of Leningrad University reflected on the scope for artificial increases in aerosols in the lower atmosphere to retard anticipated anthropogenic increases in temperature during the 21st Century. The authors complemented the general discussion with a consideration of the scale of human activity required to address modest warming trends, and restated Budyko's earlier conclusion that a relatively small number of high-altitude aircraft would be capable of delivering necessary loads of sulfur (to be burned in the atmosphere to produce droplets of sulfuric acid) in the lower stratosphere (Budyko & Drozdov, 1976, p. 39). Looking ahead to the likely stronger warming trends in the 21st Century driven by human activity, the authors accepted the possibility of technical capabilities being developed to address such trends (Budyko & Drozdov, 1976, p. 40). Nevertheless, the paper concluded with a recognition of the need for careful assessment of the impact of any increase in aerosol particles in the lower atmosphere.

The work of Budyko and his collaborators linked to stratospheric aerosols had its roots in broader scientific activity and appears to have been driven, at least in part, by a deepening interest in anthropogenic climate change. The ambition embedded in notions of geoengineering also had clear overlap with the broader technocractic aims of the Soviet state in regard to managing nature for the good of society and to buttress political control (e.g., Josephson et al., 2013). In addition, the broader debate around weather and climate modification developed into a topic of marked sensitivity with respect to US-Soviet relations (see Hamblin, 2013, pp. 204–216). Associated political debate between the two governments prepared the ground for the United Nations Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (1978), which was subsequently renamed the Environmental Modification Convention.

3.2 | Aerosols and catastrophic climate change

Towards the end of the Soviet period, Budyko pursued his twin interests in the relative instability of the global climate system and the role of both natural and anthropogenic factors influencing the climate system in a catastrophic manner. These interests were tied together via the earlier work on aerosols. He pursued these interests in collaboration with the physicist Golitsyn and the then head of the Soviet Union's hydrometeorological service, Izrael (Budyko et al., 1988). According to the authors:

> The theory of the initiation of global catastrophes, both in the present and the geological past, by the climatic effects of certain external factors arose in the late 1960s, when a new scientific discipline – physical climatology – began to develop (Budyko et al., 1988, p. v).

Furthermore, they suggested that developments were led primarily by Soviet scientists and specifically that "the theory of *aerosol climatic catastrophe* appeared in studies by Soviet scientists more than 10 years earlier than similar conclusions in other countries" (Budyko et al., 1988, p. vi, *italics not in the original*). By referencing "aerosol climate catastrophe" they made a case for the importance of long-standing efforts to theorize the environmental consequences of large-scale aerosol injection into the atmosphere. The authors worked through several natural and anthropogenic causal factors capable of generating large volumes of aerosols, and as part of this spent some time reflecting on the role of volcanic eruptions on aerosol climatic catastrophes. Other natural causal factors considered included "falling celestial bodies", dust storms, and forest fires. Nuclear conflict formed the central focus with respect to anthropogenic causation. Reflecting on the earlier work of Budyko and others concerning the potential cooling influence of anthropogenic aerosol production due to modern technological practices, it was suggested that an expected intensification of this trend would assist in blunting some of the warming attributable to the build-up of CO2 (Budyko et al., 1988, p. 41). In moving beyond this scenario to consider the consequences of a large-scale nuclear exchange, Budyko et al. (1988, pp. 41–44) advanced a bleak assessment of the effects on the biosphere linked to the cooling effect of a large aerosol mass propelled into the stratosphere. In short, they were keen to stress the catastrophic nature of any meaningful nuclear exchange between the superpowers for the biosphere. A similar stance was taken by the atmospheric scientist Kondratyev in his exploration of *Climate Shocks* Kondratyev (1988). Kondratyev was also interested in utilizing natural analogues to gain insight into the scope and extent of possible climate change events driven by nuclear war. In addition to volcanic activity, he spent some time considering the impact of the Tunguska meteor fall on both the ozone layer and climate during the early 20th Century (Kondratyev, 1988, pp. 220–255).

4 | GEOENGINEERING DEBATES POST-1991

The fall of the Soviet Union and the associated societal dislocation across the region had an understandable subduing influence on scientific activity. Discussion around geoengineering was reinvigorated within Russia during the early part of the 21st Century, animated by the modern realities of climate change science, political negotiations of the period, and the carbon demands of national economies. The debate involved strong proponents of geoengineering techniques as well as those advancing a more cautious position. The first official assessment report on climate change and its consequences for the Russian Federation was published under the auspices of the Federal Hydrometeorological and Environmental Monitoring Service (Rosgidromet) in 2008. A second report followed in 2014 (Rosgidromet, 2014). The first report acknowledged the importance of the climate change challenge and the range of potential outcomes (both positive and negative) for Russian society and the wider environment (Rosgidromet, 2008a, 2008b). While focusing primarily on the science of climate change, it was accepted that the development of technology helping to mitigate climate change and increase energy efficiency would be a key area of activity moving forward (Rosgidromet, 2008c, p. 27).

Arguably the most ardent supporter of geoengineering solutions to climate change during this period was the aforementioned Yuri Izrael. Izrael had played a dominant role advancing the Soviet Union's position on anthropogenic climate change during the late 1980s and acted as chair of the Intergovernmental Panel on Climate Change (IPCC) Working Group II in the lead up to publication of the panel's first report in 1990 (Oldfield, 2018). As part of this activity, Izrael worked closely with Budyko and the two of them co-authored a number of publications linked to the mechanisms of climate change and the role of humankind (e.g., Budyko & Izrael, 1991). In view of this, it is of little surprise that Izrael emerged as a key conduit for the work of Budyko post-1991.

4.1 | Yuri Izrael and the promotion of geoengineering methods

While Izrael remained a significant national voice in view of his earlier government positions (which included a prolonged period as head of the Soviet Hydrometeorological Service), his political presence was less prominent post-2000. More generally, the early 2000s were characterized by a political debate around Russia's ratification of the Kyoto Protocol, which became enmeshed with broader geopolitical and geoeconomic considerations. Izrael's support for geoengineering was framed in part by his strong opposition to the Kyoto Protocol and its attempt to reduce CO2 emissions, an opposition that extended back to the period before its formal ratification in 2005 (e.g., Izrael et al., 2002). Together with others in the Russian scientific community, Izrael and his co-authors believed that the instrument's core measures lacked a clear scientific basis or the necessary scale and ambition to ensure an effective reduction in CO2 (e.g., Izrael, Ryaboshapko, & Petrov, 2009, p. 5). This conclusion only strengthened over time as the relative ineffectiveness of the Protocol and its antecedents was recognized. In this context, geoengineering methods, and the use of stratospheric aerosols in particular, were posited as an efficient and cost-effective means of addressing the climate issue in the short- to medium-term (Izrael, 2008; Izrael et al., 2007). Izrael utilized his standing in both Russian and international scientific circles to advance an agenda for geoengineering methods to mitigate against the worst excesses of the projected global climate change. This included pushing for recognition of this approach as part of a declaration made by 13 national scientific academies (including the UK's Royal Society) in Japan during March 2008 (Izrael, 2008; JSA, 2008). The Joint Science Academies' Statement on Climate Change Adaptation and the Transition to a Low Carbon Society included the following paragraph:

> There is also an opportunity to promote research on approaches which may contribute towards maintaining a stable climate (including so-called geo-engineering technologies and reforestation), which would complement our greenhouse gas reduction strategies (JSA, 2008, p. 2).

The need for international involvement, collaboration and coordination was returned to on several occasions by Izrael in subsequent publications. Furthermore, Izrael and Ryaboshapko (2011, p. 20) noted the growing traction of geoengineering as a viable response to the climate issue amongst scientists and this included activities of the US Meteorological Society and the UK's Royal Society. They proceeded to underline the need to ensure a thorough scientific and economic analysis of likely consequences linked to the application of geoengineering methods together with the establishment of international agreements and a suggested geoengineering protocol attached to the UN Framework Convention on Climate Change (Izrael & Ryaboshapko, 2011, p. 21).

4.1.1 | Aerosol deployment in the lower stratosphere

In advancing their argument, Izrael and his collaborators picked up on the early work of Budyko devoted to the deployment of aerosols in the lower stratosphere (e.g., Izrael, Ryaboshapko, & Petrov, 2009). Furthermore, they maintained the Soviet emphasis with respect to utilizing the natural analogue of volcanic eruptions to advance their point, noting the potential for ejected sulfate aerosols to have a significant influence on the level of direct solar radiation at a global scale (Izrael et al., 2007). Izrael and colleagues pushed their interest in the sulfate aerosol method, and this included a critical reflection on the precise methodology to be utilized (Izrael, Ryaboshapko, & Petrov, 2009, p. 8). They also provided a detailed assessment of other methods for addressing the climate change challenge. This embraced afforestation in addition to more ambitious schemes such as the creation of cosmic reflectors, the manipulation of the ocean surface albedo, and changes in the level of cloud cover. In terms of the various methods considered, the authors concluded that the use of stratospheric sulfate aerosols provided the most promising combination of high probable effectiveness and relatively limited negative effects (Izrael, Ryaboshapko, & Petrov, 2009, p. 20).

Their associated analysis considered the delivery of approximately 1 million tonnes of sulfate to the stratosphere and the suggestion that the overall costs would be far less than those embedded in the architecture of the Kyoto Protocol (Izrael, Ryaboshapko, & Petrov, 2009, p. 8). The question of the potential side effects of the proposed geoengineering methods emerged repeatedly in the work of Izrael and his co-authors. Beyond the broad conclusions drawn from natural analogues, it was determined that the use of sulfate aerosols would not lead to a significant acidification of precipitation or have a substantive impact on the level of ozone concentration in the stratosphere (Izrael, Ryaboshapko, & Petrov, 2009; see also Izrael et al., 2007, p. 6). With the successful deployment of aerosols and associated mitigation of CO2's warming influence, additional arguments were advanced suggesting that elevated level of CO2 may have a potential beneficial influence on activities such as agricultural production (Izrael & Ryaboshapko, 2011, p. 16).

Izrael, together with a team of scientists from the Institute of Global Climate and Ecology (Russian Academy of Sciences), the state Hydrometeorological Service, the Central Aerological Observatory, and the industrial association "Taifun", advanced a series of field experiments which explored the theoretical possibility of reducing solar radiation levels at the Earth's surface with an artificial aerosol layer. As part of the experiments, aerosol was sprayed directly into the troposphere by helicopter, and aerosol generators were also attached to vehicles on the ground (Izrael, Zakharov, et al., 2009a, 2009b). The results were considered successful in demonstrating the potential of the method in helping to manage levels of incoming solar radiation.

4.1.2 | Resistance to geoengineering methods

Running parallel to the work of Izrael and his team was a more cautious debate driven forward by senior scientists from the Main Geophysical Observatory (GGO) in St Petersburg. The Director of the GGO (Kattsov) had worked with Izrael as part of the scientific-coordination committee for preparation of the Rosgidromet assessment reports concerning climate change (Rosgidromet, 2008b, 2014), and the ensuing discussion around geoengineering responses can be seen as part of this broader response by Russian scientists to the climate change challenge. Furthermore, this response mirrored similar developments in the English-language literature aimed at evaluating the efficacy of stratospheric sulfate aerosols (e.g., Pope et al., 2012; Rasch et al., 2008). Discussions internal to Russia concerning the technical viability of geoengineering techniques gained pace following the focused intervention of Izrael and colleagues (e.g., Frolkis & Karol, 2011). A vigorous debate played out within the journal *Meteorology and Hydrology*. The scientific issues under discussion revolved around the unintended consequences of aerosol deployment and the complexity of the climate system, which it was argued militated against clearcut responses (Meleshko et al., 2011; see also Meleshko et al., 2008). For example, Chernokul'skii, Eliseev, and Mokhov (2010, p. 17) warned of the emergence of arid conditions over large areas, ozone depletion and possible acidification of the ocean. Similar concerns were echoed within the same volume by Meleshko et al:

> Most of the world's community is deeply concerned about the possible large-scale, deliberate influence on the climate system....It is clear that the intention to mitigate climate warming through the scattering of aerosols in the stratosphere will not prevent all of the negative consequences linked with the increased concentration of CO2 in the atmosphere (Meleshko et al., 2010, pp. 14–15).

This group of scientists also doubted the wide applicability of the experimental work referenced above, in view of its relatively small scale and focus on the troposphere (Meleshko et al., 2010, p. 15; Meleshko et al., 2011, p. 101). They concluded with the suggestion that the focus of activity should be on the root causes of climate change, a purposeful shift away from hydrocarbons, and the search for new types of energy sources (Meleshko et al., 2010, p. 15). The response from proponents of a geoengineering approach focused on the perceived taboo surrounding research on geoengineering methods and techniques (Ryaboshapko, 2010), the generally positive results of modeling activity (e.g., Volodin et al., 2011), and the need to be realistic about the likely consequences of not addressing the climate change issue. In short, the suggestion was that the possible side-effects of large-scale climate intervention were in fact less problematic than the issues posed by global warming (Ryaboshapko, 2010, p. 101; see also Izrael et al., 2013, p. 147).

The work of Izrael and his collaborators was undermined by the passing of Yuril Izrael in 2014. Nevertheless, the intellectual legacy of the group's activity remains evident in Russian scientific debate concerning geoengineering (e.g., Izrael, 2019; Revokatova & Ryaboshapko, 2015). Furthermore, published output from the broader team concerning the feasibility of solar radiation management continues to feed into high-level international scientific debates, and most notably those linked to the activities of the IPCC (e.g., de Coninck et al., 2018, pp. 347–351). Izrael's team pulled their collaborative work together in the year's following Izrael's death to provide a clear statement of the main findings (Izrael, 2019). The resulting edited volume covered the science behind climate change, natural and artificial aerosol formation, comparative assessment of other geoengineering techniques, as well as reflections on issues of ecological security. Writing in the foreword to the collection, Romanovskaya (Director of the Institute for Global Climate & Ecology), overviewed the development of the team's activity since the early 2000s. She posited the weakness of the framing Kyoto Process and the relative importance of a geoengineering approach. She also acknowledged the criticisms leveled at the use of stratospheric aerosols outlined in the Fifth report of the IPCC which echoed aspects of the earlier domestic Russian debates noted above. In conclusion, she stressed that the geoengineering methods advanced by Izrael and his team should be understood as "an additional means helping to buy time for the implementation of measures assisting the shift to a low carbon world economy" (Romanovskaya, 2019, p. 13).

5 | CONCLUSION

The work of Soviet and Russian scholars linked to geoengineering has made significant contributions to the broader science over the course of the last 70 years. This activity has been framed by an appreciation of humankind's growing significance with respect to the biosphere and an associated belief in the ability of science and technology to offer a solution to the pressures surrounding society-nature interaction. In addition, Soviet and Russian science has a longstanding interest in managing weather and climate as well as the mechanics of global climate change. A key focus of activity has been the use of stratospheric aerosols which built on the innovative work of Budyko and colleagues during the early 1970s. This work had its origins in what has been termed the theory of aerosol climatic catastrophe, which gained prominence in the Soviet Union during the 1970s.

The stance of Budyko and, more recently, Izrael and his colleagues, with regard to the possibilities of certain types of geoengineering solutions finds at least some reflection in the ongoing work of the IPCC. Its special report of 2018 concerning *Global Warming of 1.5 °C* spent some time discussing the state of the art with respect to both Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM) (see de Coninck et al., 2018). The ongoing contested nature of the debate surrounding the employment of SRM is evident in the report:

> SRM could reduce some of the global risks of climate change related to temperature rise, rate of sea level rise, sea-ice loss and frequency of extreme storms in the North Atlantic and heatwaves in Europe. SRM also holds risks of changing precipitation and ozone concentrations and potentially reductions in biodiversity… (de Coninck et al., 2018, p. 347).

Earlier IPCC reports had made direct, albeit brief, reference to the work of Budyko concerning SRM techniques (e.g., IPCC, 2014, p. 486). The most recent IPCC Reports (2021, 2022) engage with both CDR and SRM methods for mitigating climate change, although uncertainty around the efficacy of the technology in addition to ethical and governance issues are highlighted as ongoing areas of concern (IPCC, 2022, p. 1–26).

The ideas advanced by Budyko and others concerning the use of stratospheric aerosols during the 1970s were shaped by long-standing domestic scientific debates over society-nature interaction and growing interest in anthropogenic climate change. The more recent support for geoengineering solutions to climate change associated with Izrael and colleagues has been accompanied by a broader debate, both at home and abroad, concerning the pros and cons of specific methods, with particular attention paid to the use of stratospheric aerosols. While significant geopolitical obstacles remain in the way of an international agreement linked to the possible deployment of such measures, interest continues to grow. The maturity of Russian science in respect of geoengineering ensures that it remains an important voice in this broader scientific debate. At the same time, the progressive isolation of Russian science from the international scene due to wider geopolitical events risks deflecting attention away from popular and political debate in this area (e.g., Losev, 2022), and alienating this rich scientific tradition at a critical juncture.

AUTHOR CONTRIBUTIONS

Jonathan Oldfield: Conceptualization (equal); formal analysis (equal); writing – original draft (equal); writing – review and editing (equal). **Marianna Poberezhskaya:** Conceptualization (equal); formal analysis (equal); writing – original draft (equal); writing – review and editing (equal).

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The authors declare no conflict of interest.

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