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Advanced Review

Mikhail Budyko's (1920–2001) contributions to Global Climate Science: from heat balances to climate change and global ecology

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Mikhail Ivanovich Budyko (1920–2001) was a Soviet climatologist perhaps best known in the West for his contribution to understandings of climate change. He acted as director of the Main Geophysical Observatory (named after A.I. Voeikov) in Leningrad (St Petersburg) from 1954 and played an active role in advancing Soviet climate agendas within an international context. Three main stages in the development of Budyko's work related to climate systems and global ecology (late 1940s-mid 1980s) are identified. The first period encompasses his early efforts devoted to understanding and quantifying the interrelationship between the lower atmosphere and the earth's surface. This stage of his career was also characterized by a growing interest in regional- and global-scale processes, and was underpinned by collaborative work involving climatologists, physical geographers, and other cognate scientists. The second stage highlights the broadening of his global interest in order to engage more deeply with both natural and anthropogenic climatic and environmental change. The third stage reflects on the development of his expansive and evolutionary approach to the biosphere, and his insight into the formative role of climate with respect to the functioning of physical and biological processes. Furthermore, this later work also exhibited a strong belief in the ability of humankind to reflect wisely on its growing influence on the physical environment and respond appropriately.

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INTRODUCTION

This review explores key areas of work associated with the Soviet climatologist Mikhail Ivanovich Budyko (1920–2001) that emerged over the course of a long and distinguished career. In particular, it examines his substantive contributions to understandings in physical climatology and the development of his ideas to encompass global ecology and associated work related to climate change. There has been limited attention devoted to the work and activities of Soviet climatologists in the English-language literature. Budyko is something of an exception in this regard due to the translation of a number of his texts into English. Nevertheless, Budyko and his compatriots remain subdued voices within the broader published work concerning the science of global climate change. In view of the constraints of space, this review focuses primarily on his main scientific ideas, their historical roots, substance, and development over time.

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The introduction to his *festschrift*, coinciding with his 80th birthday celebrations, suggested that Budyko was 'representative of that rare category of scientist, who comprehends the prospect for the development of science before other specialists, and anticipates its priority tasks…' (Ref 1, p. 4). Allied to this, it stressed that much of his work, including elements of his early initiatives, retained relevance in the contemporary period. The publication also commemorated Budyko's award of the Blue Planet prize by the Asahi Glass Foundation, Japan, in 1998.[2] This award, dating back to the 1992 Rio Conference on Environment and Development, is given to individuals considered to have made outstanding contributions toward solving global environmental issues. In Budyko's case, the award recognized his 'establishment of physical climatology and his quantitative analysis of climate change.' There is little doubt that Budyko made significant contributions to both theoretical and applied branches of climate science. In addition, he also demonstrated an ability to be 'creative' in his approach to scientific method allowing him to reveal insights into the workings of complex natural systems (Ref 3, p. 122 and Ref 4, p. 113). His approach was both quantitative and interdisciplinary in nature and he worked across a range of subdisciplinary areas including hydrology, geophysics, and physical geography in order to strengthen the foundations of a quantitative and physical climatology (e.g., Ref 5, p. 179).

For the purposes of this paper, three main stages in the development of his work are identified. The first period encompasses his early work devoted to understanding and quantifying the interrelationship between the lower atmosphere and the earth's surface. This stage of his career was also characterized by a growing interest in regional- and global-scale processes, and was underpinned by collaborative work involving climatologists, physical geographers, and other cognate scientists. The second stage highlights the broadening of his global interest in order to engage more deeply with both natural and anthropogenic climatic and environmental change. The third stage reflects on the development of his expansive and evolutionary approach to the biosphere, and his insight into the formative role of climate with respect to the functioning of physical and biological processes. Furthermore, this later work also exhibited a strong belief in the ability of humankind to reflect wisely on its growing influence on the physical environment and respond appropriately. Budyko's work demonstrated an awareness of developments in the Western literature and yet was also characterized by clear links with prerevolutionary Russian science, and elements of this intellectual legacy surfaced strongly at various points during his career. In this sense, Budyko's ideas provide a lens through which to discern the long-held interest in understanding large-scale natural systems within Russian science. In particular, he drew from the ideas of individuals such as the biogeochemist and natural scientist V.I. Vernadsky (1863–1945), climatologist A.I. Voeikov (1842–1916), and pedologist V.V. Dokuchaev (1846–1903), and this aspect of his work will be examined in more detail below.

BACKGROUND

Budyko spent much of his academic career in Leningrad (contemporary St Petersburg). He studied at Leningrad Polytechnical Institute graduating from the engineering and physics faculty in 1942. He then moved to the Voeikov Main Geophysical Observatory (GGO) where he worked on his postgraduate Candidate of Science (approximately equivalent to a PhD) on military meteorology, which he subsequently defended in 1944 at the relatively early age of 24 (Ref 4, p. 113). From this point on, his work and intellectual interests became more focused around interdisciplinary concerns of the relationship between the lower atmosphere and natural processes at the earth's surface. As will be highlighted below, this interest provided the basis for his later initiatives regarding the global climate system and the earth's biosphere. In terms of his overall career, Budyko remained at the GGO for the next 30 years, becoming assistant director in 1951 and director in 1954, a position he would hold until 1972. He subsequently acted as chair of the Soviet Scientific Council for the Problem of Climate and Agro-Climatic Resources. From the mid-1970s, he took up a new position leading work on climate change at the State Hydrological Institute. And, from 1989 he became involved with the Research Centre for Interdisciplinary Cooperation, Academy of Sciences (INENKO). Budyko would also pick up a range of domestic and foreign honors during the course of his career including the Lenin Prize (1958) and the Gold Medal of the World Meteorological Organization (WMO) (1987). He was inducted as a full member into the Russian Academy of Sciences in 1992.

As noted, Budyko's name is relatively well-known within the Anglo-US context due to the significant number of his monographs, edited books and papers translated into the English language. Furthermore, he featured on the international stage through conference attendance and his participation in the activities of organizations such as the WMO. Budyko

was involved with a joint US–USSR Agreement on Cooperation in the field of Environmental Protection which emerged in 1972 and he also provided input to the scientific work of the Intergovernmental Panel on Climate Change (IPCC). The specifics of these activities will be returned to at the end of the paper.

RUSSIAN AND SOVIET CLIMATE SCIENCE

Before exploring Budyko's work in more detail, it is useful to reflect upon the institutional and intellectual traditions within which he operated because they provide insight into certain aspects of his overarching scientific approach and agenda.

Budyko was part of a long tradition of climatological and meteorological activity within Russia extending back to the 19th century.[6] James Fleming (Ref 7, pp. 165–169), provides a useful comparative assessment of developments in Russia's observational networks during the 19th century in his book *Meteorology in America 1800–1870*. More specifically, Russian developments, whilst patchy and very limited in their extent, particular in view of the size of the Russian landmass, were at least comparable in certain respects to developments in the United States and elsewhere on the European continent at this time.

A key development for Russia during the 19th century was the establishment of the Main Physical Observatory in 1849.[a] It provided the necessary basis for the development of a regulated system of monitoring activities across the Russian empire. The Observatory was underpinned by the initiative of the physicist A. Ya. Kupfer (1799–1865) and further assisted by the support of Alexander von Humboldt (1769–1859). The activities of the Observatory grew steadily during the second part of the 19th century. Georg Wilhelm Wild (1833–1896) was a key figure, acting as the Observatory's director from 1868 to 1896 and focusing his attention primarily on expanding its meteorological functions (e.g., Ref 8, p. 279). Somewhat inevitably, in spite of such initiatives, the network remained incapable of adequately representing the vast territory of Russia (Ref 9, p. 386).

The Soviet period witnessed a significant physical expansion and reorganization of meteorological and climatological institutions and activities following the disruption of war and revolution in the early part of the 20th century. Understandably, Soviet assessments of such developments post-1917 emphasized the energizing influence of the revolutionary endeavor.[10] At the same time, there was certainly some truth in the hyperbole. The fact that weather and climate concerns were intimately linked to broader economic considerations (e.g., Ref 11, p. 7), and most obviously in the case of agricultural output, ensured state resources were channeled toward improving the existing system. For example, the Main Observatory was able to focus more of its attention on research activities during the 1920s and 1930s as administrative functions were absorbed by newly created entities such as the Hydrometeorological Committee and Central Weather Bureau (Ref 12, p. 2). In general, the early- to mid-Soviet period witnessed the expansion of the physical monitoring system and the focused development of meteorological and hydrometeorological activities (e.g., Ref 13, p. 4). Indeed, a relatively significant number of new research centers was established from the 1930s onwards (e.g., see Ref 14, pp. 660–661).

As part of a special 1957 issue of the disciplinary journal *Meteorology and Hydrology* which reflected on the relative successes of Soviet meteorological and climate sciences, Budyko (Ref 11, pp. 14–15) highlighted a number of areas of climate science which had been advanced since 1917 and these included: (1) understandings of different climates at the earth's surface, (2) atmospheric circulation, (3) the heat and water balance, (4) palaeoclimates, (5) ameliorative measures typically aimed at agricultural practices, and (6) the influence of climate on other physical processes.

While Budyko was deeply embedded in the Soviet Union's hydrometeorological activities, he was also part of a distinct intellectual heritage which found expression in various aspects of his own work. A key figure in this regard was the Russian climatologist Alexander I. Voeikov. One of Voeikov's major publications was his 1884 monograph entitled *Climates of the Globe, particularly Russia*. This outlined his efforts to provide leadership in the development of climatology to rival achievements within the related field of meteorology (Ref 15, p. iii). Indeed, according to Soviet climatologists such as F.F. Davitaya, Voeikov was considered a key figure in helping to establish the discipline of climatology (Ref 16, p. 8). As will be discussed in more detail below, his ideas would provide a stimulus to key aspects of Budyko's own research agenda. In addition to Voeikov's work concerning fundamental aspects of the climate system (e.g., temperature, evaporation, precipitation etc.) at regional and global scales, advances were also made in applied meteorology during the late 19th century via individuals such as Petr Ivanovich Brounov (1852–1927). His work on the influence of meteorological factors on

agriculture saw him credited with founding agricultural meteorology (agrometeorology) and would provide the basis for later initiatives during the Soviet period (e.g., Ref 17, p. 3 and Ref 18, p. 5). He also helped advance understandings of synoptic (large-scale) meteorology (e.g., Ref 19, p. 3). Brounov's scientific work was shaped to a large extent by the 1891 famine in the European steppe region and associated failure of key crops (Ref 17, p. 3). While Budyko's core work moved beyond agro-meteorological concerns during the course of his career, he would nevertheless retain an interest in the applied aspects of his work.

A further intellectual strand evident in the work of Budyko, and which emerged particularly strongly during the course of the 1970s and 1980s, is associated with the activities of the abovementioned pedologist V.V. Dokuchaev and his student the biogeochemist V.I. Vernadsky. Both Dokuchaev and Vernadsky were interested, amongst other things, in the relationship between the physical environment and living matter. For example, Dokuchaev famously highlighted the intimate connections between soil formation and a range of 'soil-forming' factors of which climate was central, noting the consequent latitudinal regularity of soil type and natural regions more generally (Ref 20, pp. 48–77 and Ref 21). Vernadsky developed this general theme through his work on the biosphere in order to advance an understanding of the various ways in which living matter, understood as the totality of all life on earth acting in unison, shaped the physical world.[22,23] The later work of Vernadsky acknowledged the growing ability of collective human activity to influence the state of the biosphere. He utilized the concept of the noosphere in order to try and capture the nature of this transformative process, identifying human intellectual and scientific abilities as key driving forces behind the noted changes.[24] This combination of environmental concern allied to a belief in the ability of society to address the emergent issues via a sound understanding of the physical processes at work would find a strong echo in Budyko's later publications.

UNDERSTANDING THE HEAT AND WATER BALANCE AT THE EARTH'S SURFACE

Budyko's early years at the Leningrad Polytechnical Institute and the GGO were influenced by the twin pressures of war and late Stalinism, both of which encouraged an applied focus to his work. During the immediate postwar period, the situation for Soviet scientists changed rapidly. The relative openness of the war years was replaced by a period of marked uncertainty framed by a renewed emphasis on ideological conformity led by Stalin's lieutenant Andrei Zhdanov.[25,26]

As a result of this, during the late 1940s and early 1950s, an emphasis was placed on indigenous science as well as the need for applied science that could contribute to the advancement of Soviet society. This phase of Soviet history was a traumatic one for many scientists across a range of disciplines. In the case of Budyko, Dando (Ref 5, p. 179) alludes to an altercation with the local city branch of the Communist Party during the early 1950s resulting in a brief period away from his post. However, in general, it would appear that Budyko was able to navigate the difficulties, at least with respect to his scientific endeavors, relatively successfully. This can be attributed to the aforementioned applied nature of his work and perhaps also to his intellectual links to pre-revolutionary Russian scientists such as Voeikov and Dokuchaev.

At the heart of Budyko's applied work was his interest in understanding the interrelationship between the lower levels of the atmosphere and the earth's surface. His first two major monographs reflected this emphasis. The first, entitled *Evaporation under natural conditions* (*Isparenie v estestvennykh usloviyakh*), was published in 1948 when Budyko was just 28 years old. The second was his highly regarded 1956 publication *Heat balance at the earth's surface* (*Teplovoi balans zemnoi poverkhnosti*). The 1948 monograph aimed 'to work out physical methods for calculating evaporation rates from the earth's surface' and simultaneously address the gap that existed between the hydrological and meteorological sciences (Ref 27, p. 1). In retrospect, the monograph was deemed to be an innovative contribution to work in this area. Amongst other things, it helped to develop general laws for such phenomena as the rate of evaporation from soil, insight which would lay the basis for his later more developed work on the heat and water balance (Ref 3, p. 122 and Ref 4, p. 113).

His 1956 publication was the culmination of several years of collaborative work with colleagues from the GGO as well as individuals such as A.A. Grigor'ev at the Institute of Geography.[28,29] Interest in the heat balance at the earth's surface has a long history in both Russia and the West. For example, writing in 1965, Miller (Ref 30, p. 176) noted the earlier work of Voeikov as well as that of the 19th century American environmentalist George Perkins Marsh (1801–1882) in this regard. Both

scientists had drawn attention to the potential importance of determining the energy budget at the earth's surface in recognition of the fundamental importance of heat energy and associated transformation processes for understandings of the climate system. While both scientists were able to articulate the problem, they lacked the necessary data and methods with which to advance insight into the issue. These lacunae were addressed during the course of the early to mid 20th century. Budyko was certainly aware of this intellectual heritage and in reviewing work in the field he made explicit reference to the pioneering efforts of Voeikov and particularly his aforementioned 1884 publication *Climates of the Globe* (Ref 31, p. 16 and Ref 32, p 123). Furthermore, Budyko, as well as his colleagues at the GGO involved in heat balance work, were also abreast of relevant work carried out in the West during the first half of the 20th century.[31,33]

At the beginning of his 1956 publication, Budyko outlined the significance of the work from his perspective:

> Investigations of the heat balance at the earth's surface are now occupying an important place in all hydrometeorological disciplines…. The main purpose of these investigations is the study of the causal principles which determine the meteorological and hydrological regimes in various geographical regions which could be used for the forecasting and calculation of important hydrometeorological processes and phenomena. (Ref 31, p. 3)

This work garnered favorable attention for Budyko both within the Soviet Union and beyond. Aided by a relatively rapid translation into English, much of this positive reception was linked to its emphasis on a quantitative approach and accompanying efforts to understand global-level characteristics (Ref 1, p. 4 and Ref 34). For example, writing in the preface to Budyko's 1974 English-language edition of *Climate and Life*, the US climatologist, David Miller noted:

> In many areas of geophysics in North America (including climatology, hydrology, and meteorology) energy-mass budget work then under way was powerfully strengthened by the methods and the global-scale data published in [the English translation of] 'The Heat Balance of the Earth's Surface,' Washington, 1958. It has since repeatedly served as the base level on which further investigations have built—some at the micro- and mesoscales, others at the world scale. (Ref 33, p. vii)

In reviewing English-language works on physical climatology during this period, the 1956 work of Budyko looms large. For example, in the introductory comments to his 1965 book *Physical Climatology*, the US climatologist William D. Sellers noted the early importance of Budyko's monograph, although at the same time bemoaning the difficulties of following up his ideas in the Russian language.[35]

Within the Soviet Union, the research agenda advanced by Budyko's publication would have a substantial influence on the subsequent development of Soviet climate studies. Indeed, in reviewing the state of Soviet climatology in 1971, the American geographer Paul Lydolph noted that '[m]odern Soviet climatology is probably better known for its heat balance studies than for any other single branch of climate' (Ref 14, p. 640).

The work of Budyko and his colleagues at the GGO in this area was complemented by the publication of an accompanying *Atlas of the heat balance of the Earth's surface* in 1955, with a second edition published in 1963, under the general editorship of Budyko. The later publication benefitted greatly from additional data generated through the activities of the International Geophysical Year (1957–1958) and the expansion of the global actinometric monitoring system, allowing for a more accurate and expansive atlas. In particular, the second edition provided more detailed information related to the continental landmasses whereas the 1955 edition tended to focus on oceanic regions (Ref 36, p. 1).

While the insight of Budyko and his colleagues linked to the global variation in the earth's heat-water balance was of great significance, their collective work and associated insight held practical value at the regional scale too. More specifically, the interplay between heat and water balances at the earth's surface was shown to assist in determining the broadly latitudinal shift in natural zones (e.g., see Ref 20, pp. 78–108). Work in this area lay at the heart of a productive relationship between Budyko and the geographer A.A. Grigor'ev (1883–1968) (Ref 29, p. 517 and Refs 20 and 37). Furthermore, as a key mechanism for determining '…the intensity and character of all other forms of energy and matter between the basic components of the geographical environment…' (Ref 38, p. 4), a deeper understanding of regional heat and water balance dynamics also promised to assist in efforts to raise levels of agricultural activity. This potential was to put to the test, albeit inadequately, as part of the ill-fated Great Stalin Plan for the Transformation of Nature.[39]

The Stalin Plan was a large-scale effort to alter the regional climate regime of Russia's southern

European steppe and semiarid regions. It was ushered in by a 1948 decree and aimed to address the periodic drought characterizing this important agricultural region through the construction of large-scale shelter belts, reservoirs, and the imposition of new land-use management practices. The initiative is typically used as an example of the Soviet Union's crude engagement with the wider environment and noted for the damaging involvement of Trofim Lysenko and his erroneous understanding of genetics.[40] Furthermore, the scheme failed to achieve its ultimate aim and faded away with the death of Stalin in 1953. Nevertheless, central aspects of the science underpinning the initiative drew from discussions around the heat and water balance at the earth's surface. Budyko contributed to the associated debate. In particular, he questioned the influence of the earlier work of the German climatologist Eduard Brückner concerning the extent to which regional alterations in moisture content through tree planting was able to impact the level of regional precipitation. Budyko, together with colleagues from the GGO, downplayed the significance of tree planting as a main factor whilst flagging the importance of large-scale atmospheric circulation patterns.[41,42]

NATURAL AND ANTHROPOGENIC CLIMATE CHANGE

From the early to mid 1960s, Budyko began to develop further lines of work drawing from his energy budget research and linked to understandings of global climate change and the role of humankind in such changes (Ref 1, p. 5). This included, amongst other things, a number of focused papers on historical climate change, the relationship between polar ice and the global climate, and the relative instability of the current global climate regime.

In terms of the causal mechanisms behind historical shifts in global climate regimes, and particularly those in the recent past, he drew attention to natural factors including fluctuations in solar radiation as well as changes in levels of atmospheric transparency linked to natural events such as volcanic eruptions.[43] With respect to human influence, Budyko reflected on the extent to which humankind's growing technological capabilities and collective ability to produce large quantities of heat promised to play a role in modifying local and regional climates in the near future (e.g., Ref 44, pp. 35–36 and Ref 45). In order to gain a feel for his general work as it developed during the 1960s, it is instructive to reflect on the content of his concise 1969 semipopular publication entitled *Climate Change* (*Izmeneniya klimata*). It was divided into four main sections covering: contemporary climate change, quaternary glaciations, pre-quaternary climates, and climates of the future. He opened with a consideration of the lessons to be drawn from empirical work on climates of the past and in doing so noted the relative instability of the earth's climate over both long- and short- (last 100 years) time periods. In considering climate change evident during the late 19th and 20th centuries, and particularly within the mid and high latitudes, Budyko made reference to theories of varying atmospheric transparency in addition to changing levels of carbon dioxide, solar fluctuations, and so on, while simultaneously noting the difficulties of verifying such hypotheses (Ref 46, p. 8). Budyko then moved on to consider the links between climate and glaciation processes. He rehearsed his earlier findings in which he concluded that full glaciation of the earth did not necessarily require a significant change in the current level of incoming solar radiation, an insight that we will return to in the next section (Ref 46, p. 22). With respect to future climates, Budyko opened by acknowledging the need to take into account both natural and anthropogenic influences (Ref 46, p. 30). He then highlighted humankind's varied and growing influence on climate regimes through construction activities as well as ameliorative work such as afforestation, before moving on to focus on the possible consequences of a marked increase in artificial energy and heat production for meteorological processes. Budyko ended by highlighting once again the importance of humankind's emergence as a major climate player:

> …the contemporary stage of biological evolution, linked with the appearance of humankind, is a significant factor for the future development of climate in so far as the activity of humankind opens up the prospect of substantial climate change in the near future. Thus, in our time, natural changes of climate are to be gradually replaced by changes created and regulated by humankind. (Ref 46, p. 35).

As an extension of his interest in mechanisms behind noted historical shifts in climate, Budyko also developed abstract energy balance models to help understand the potential consequences of changes in the extent of incoming solar radiation on climate (Ref 47, p. 305). He published an influential article in the English-language journal *Tellus* in 1969 (Ref 48) which advanced a simple energy balance model highlighting the sensitive nature of the earth's contemporary climate. The model suggested that

relatively small variations in the level of incoming solar radiation could have marked consequences for the earth's heat balance leading to periods of significant cooling or warming via its effect on sea ice. His ideas displayed overlap with the work of the US physicist, William D. Sellers who was based at the University of Arizona. While more complex than Budyko's approach, Seller's energy balance model (Ref 49) was similar in many respects, and their shared emphasis on the possibility of a 'runaway positive feedback' linked to the global climate system attracted a great deal of attention (Ref 50, pp. 506–507).

EVOLUTIONARY UNDERSTANDINGS OF THE BIOSPHERE

During the course of the 1970s and 1980s, Budyko published a series of more developed pieces of work, many of which were subsequently translated in to English. Common themes underpinning these publications included an interest in contemporary climate change (both natural and anthropogenic), and an effort to place climate change within a broader framework of global ecological change. With reference to the former, Dando (Ref 5, p. 179) refers to his 1973 publication 'Atmospheric carbon dioxide and climate' as a significant piece of work in view of its attempt to consider the extent to which relatively small changes in atmospheric carbon dioxide levels might trigger significant shifts in global climate regimes.[51]

In order to provide some sense of the main features of his work during this period, the following section focuses on three influential publications. First, in 1971, he published Climate and Life (*Klimat i zhizn'*), which was translated into English in 1974. This book explored the relationship between climate and a range of natural processes and drew explicitly on the work and inspiration of individuals such as the aforementioned geographer A.A. Grigor'ev, as well as Voeikov and Dokuchaev. For David Miller, writing in the preface to the English-language edition, the book's value resided in two specific areas: as 'an authoritative statement of the new concepts of climatic analysis that are based on the laws of conservation of mass and of energy…' and in its application of 'energy-budget concepts to important questions in the biology of the planet' (Ref 33, pp. vii). He went on to highlight the effective way in which Budyko combined 'small-scale biological and large-scale geophysical phenomena' (Ref 33, p. viii). The book represented an attempt to imbue the relationship between climate and a range of global physical and biological processes with greater precision, building in particular on the earlier work of Grigor'ev and his notion of a single physical–geographical complex. It might be added, that Grigor'ev's ideas in this regard had met with significant levels of criticism from within Soviet geography during the early 1950s due to their purported lack of clarity.[20] In concluding the book, Budyko reflected on humankind's growing influence on climate formation through energy production and pollution emissions (and this included carbon dioxide production) picking up on a range of themes advanced in earlier publications. This particular area of discussion would be developed purposefully in following years, as will be discussed below. In general, his analysis was mindful of the complexities of the climate system and the need for greater understanding. At the same time, it was also imbued with a technocratic belief in the ability of humankind to manage the global climate system effectively in due course (Ref 52, p. 493).

Budyko's 1977 (English edition 1980) publication *Global Ecology* (*Global'naya ekologiya*) engaged purposefully with what he termed the 'distinct scientific discipline' of global ecology (Ref 53, p. 5). Writing in the preface, he noted the relative immaturity of the discipline and yet underlined its importance for addressing the growing influence of humankind on natural processes. For Budyko, the focus on global ecology was a natural progression of his earlier work on energy flows at the earth's surface and developed many of the themes advanced in his monograph *Climate and Life*. The approaches and insights of both Dokuchaev (soil and natural historical zones) and Vernadsky (biosphere concept) loomed large in this particular work. A key conclusion of the work concerned the relative instability of the global ecological system and, linked to this, the rapid growth of humankind's influence on the system and particularly its atmospheric processes (Ref 53, pp. 310–11). As with his earlier work, Budyko emphasized the need to ensure effective management of humankind's activities and on this occasion highlighted the Soviet Union's proactive stance both domestically and internationally in this regard.

In 1984 he published a further monograph, *Evolution of the Biosphere* (*Evolyutsiya biosfery*). This extended his discussion of the future of the biosphere in view of humankind's growing influence. It also drew heavily on Vernadsky's intellectual legacy and his earlier work on the biosphere. This included a more developed discussion of his noosphere concept which, as noted above, envisaged a qualitative shift in the nature of the biosphere underpinned by humankind's intellectual and scientific capabilities

(Ref 22 and Ref 54, pp. 338–339). In keeping with his earlier emphasis on humankind's collective potential to manage effectively the state of the biosphere in the future, Budyko outlined his hope for the establishment of a regulated global ecological system, thus, helping to prolong the existence of the biosphere (Ref 54, p. 460).

Budyko's understanding of the relative instability of the earth's climatic and ecological systems, his acceptance of humankind's growing influence in this regard, as well as the moral imperative evident in Vernadsky's noosphere concept, found expression in his work related to the potentially damaging impact of thermonuclear war. While he saw the rapid developments within science and technology as key to the creation of a regulated global ecological system, which in turn underpinned the shift to the noosphere, technology was also understood as a threat to the very existence of the biosphere (e.g., Ref 54, pp. 452–453). Debate over the catastrophic potential of nuclear war emerged strongly during the Cold War environmental debates of the 1980s. Jacob Hamblin (Ref 55, pp. 237) suggests in his recent book, *Arming Mother Nature*, that '[I]n the United States, the sharpest dispute about climate change in the 1980s was not about carbon dioxide but rather about the possibility of "Nuclear Winter".' He draws attention to the initiative taken by American scientists such as Carl Sagan with respect to this issue and subsequent support from the Soviet side, a development which did not sit easily with some quarters in the United States who perceived the Soviet's use of such claims as part of a broader political agenda to undermine the US nuclear threat (Ref 55, pp. 238–239). Hamblin also alludes to the lack of computing power within the Soviet Union at this time, helping to undermine efforts to carry out effective modeling work. Budyko emerges, at least for Hamblin, as a steadying influence amongst the politically and ideologically charged rhetoric surrounding the concept of a nuclear winter. In the preface to a 1986 edited volume with G.S. Golitsyn and Yu. A Izrael entitled *Global Climatic Catastrophes* (published in English in 1988), Budyko and his coauthors highlighted the danger of large-scale nuclear warfare placing such work within a broader conceptual framework concerning the 'initiation of global catastrophes' which they argued had emerged during the late 1960s with the development of physical climatology (Ref 56, p. v). Furthermore, they made the point that Soviet work on 'aerosol climatic catastrophes,' which forms a key element of understanding related to the concept of nuclear winter, could be traced back to the 1970s, implying that Soviet responses to US work in this general area were not entirely reactionary (Ref 56, p. vi).

BUDYKO AND THE WEST

This review has been chiefly interested in the development of Budyko's main ideas concerning climate systems as reflected in his published work. It is clear from the above analysis that Budyko's work was disseminated relatively widely in the West via the translation of key works from the 1950s onwards and this also included English translations of his published articles in Soviet journals such as *Meteorology and Hydrology* (*Meteorologiya i gidrologiya*). While beyond the central focus of this paper, it is worth reflecting a little more on the extent to which Budyko engaged with Western climate scientists and international initiatives around climate change toward the end of the Soviet period.

One of Budyko's most high profile international roles was linked to the activities of the aforementioned joint US–USSR Commission on the Protection of the Environment which emerged in 1972 and included a Working Group VIII concerned with 'The influence of environmental changes on climate.' Budyko would act as Co-chair of this particular Working Group. A Special Report was published in 1990, right at the end of the Soviet period, which pooled the findings of the various activities associated with the Working Group that had taken place during the late 1970s and 1980s. The introduction to the Special Report made some bold statements including: 'Since the 1970s, Soviet and US scientists have recognized that global warming would be inevitable as a consequence of the ongoing perturbations to atmospheric composition.' (Ref 57, p. xi). It went on to highlight two important areas of collaboration, the first linked to a deeper empirical analysis of climate via the accumulation of both contemporary and historical data, and the second to the development of sophisticated models 'that explicitly represent the dynamics, thermodynamics, and hydrology of the atmosphere based on the fundamental laws of physics.' (Ref 57, p. xii).

Budyko and his work would also feature significantly in the pioneering activities of the IPCC. He contributed to section five of the first Scientific Assessment concerned with 'equilibrium climate change and its implications for the future' and was a named peer reviewer for this report together with three other Soviet scientists, namely G.S. Golitsyn, I.L. Karol, and V. Meleshko.[58] His jointly authored work with Yuri Izrael, entitled *Anthropogenic Climate Change*,[59] was also heavily cited in the

accompanying volume dealing with Impacts Assessment.[60] Writing in the foreword to the English-language translation of this book, Alan D. Hecht of the US Environmental Protection Agency noted that their analyses suggested that anthropogenic climate change may have some benefit for significant parts of the northern hemisphere, thus, encouraging Budyko 'to argue that international measures to reduce the emissions of greenhouse gases are not justified' (Ref 59, p. ix). The policy consequences of Budyko's work concerning climate change are beyond the scope of this paper and yet worthy of further investigation.

CONCLUSION

Budyko was an influential scientist both at home and abroad, having a significant impact on the development of physical climatology and cognate areas of science. His relative success in navigating the ideological and political barriers of the Cold War period facilitated his engagement with relevant Western science and *vice versa*. In order to assist in an assessment of his main intellectual contributions, three main stages in the development of his work have been identified in the paper. His early work focused on understanding and quantifying the relationship between the lower atmosphere and the earth's surface culminating in his well-received 1956 publication *Heat balance at the earth's surface*. From this base, his interests broadened during the course of the 1960s to encompass processes of natural and anthropogenic climate change and associated efforts to explore the nature of the contemporary global climate system. A further shift in the character of his work was evident during the 1970s and early 1980s when a series of publications reflected on the growing influence of humankind on climate and the biosphere more generally.

Budyko's research agenda was shaped by long-standing traditions within Russian climate science as well as other areas of the physical sciences. This paper has placed particular emphasis on the intellectual legacies of V.I. Vernadsky, A.I. Voeikov, and V.V. Dokuchaev. The early work of Voeikov concerning climate systems provided an impetus for Budyko's subsequent focus on the heat and water balances at the earth's surface. Furthermore, the emphasis of Dokuchaev and Vernadsky on the intimate links between living matter and the physical environment ensured an influential framework for Budyko's later efforts to conceptualize the relationship between a relatively unstable global ecological system and the activities of humankind. Budyko was fully aware of the negative consequences of human actions, epitomized by the possibility of thermonuclear war and threatened undermining of the biosphere. However, his engagement with the noosphere concept, with its emphasis on the fundamental evolution of the biosphere to a new state or 'sphere of reason,' reflected his belief in the potential of humankind to utilize science in order to ensure a regulated global ecological system.

NOTES

[a] In 1924, it was renamed the Main Geophysical Observatory. And, it would be named after A. I. Voeikov in 1949 to coincide with its one hundred year anniversary.

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