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REVIEW ARTICLE

A Spatial Survey of Environmental Indicators for Kazakhstan: An Examination of Current Conditions and Future Needs

Andrew Russell[1,2] · Mohamed Ghalaieny[2] · Bella Gazdiyeva[3] · Sara Zhumabayeva[3] · Aygul Kurmanbayeva[3] · Kanat Kambarovich Akhmetov[4] · Yelzhas Mukanov[4] · Meg McCann[2] · Maged Ali[5] · Allan Tucker[6] · Claudia Vitolo[7] · Abraham Althonayan[8]

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Abstract

The Republic of Kazakhstan, located in Central Asia, has experienced many years of environmental degradation, largely as a result of the poor management of its significant natural resources. In this survey, data relating to different environmental factors are critically analysed in order to understand the state of the environment. It was found that: warming trends are seen in sensitive areas (e.g. the steppe and near glaciers); drying trends are seen where there is already water stress (e.g. the Aral Sea); air quality has been declining recently (following improvements on the decadal timescale) in major urban centres, particularly Almaty; water quality appears to be improving in some areas (e.g. important lakes in the Aktobe and Zhambyl regions); and levels of exposure to radioactivity are below internationally recommended levels (where data have been found). More generally, there is an issue with data availability and quality, which requires attention if Kazakhstan is going to make the best use of its increasing investment in environmental actions. Current policies are reviewed and recommendations are made for future interventions.

Keywords Central Asia · Climate change · Air pollution · Water quality · Environmental policy · DPSIR

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✉ Andrew Russell
andrew.russell1@theccc.gsi.gov.uk

1 Committee on Climate Change, 7 Holbein Place, London SW1W 8NR, UK

2 Institute of Environment, Health and Societies, Brunel University London, Uxbridge, UK

3 Faculty of Natural Sciences, Sh. Ualikhanov Kokshetau State University, Kokshetau, Kazakhstan

4 Faculty of Chemical Technology and Natural Science, S. Toraighyrov Pavlodar State University, Pavlodar, Kazakhstan

5 Essex Business School, University of Essex, Colchester, UK

6 Department of Computer Science, Brunel University London, Uxbridge, UK

7 European Centre for Medium-Range Weather Forecasts, Reading, UK

8 Brunel Business School, Brunel University London, Uxbridge, UK

Introduction

The Government of Kazakhstan has stated that the aims of the United Nation's Sustainable Development Goals (SDGs) "coincide with the priorities of Kazakhstan" (Abdrakhmanov 2016). Implicit in this statement is that the nation is committed to delivering good health for its citizens (SDG3), clean water (SDG6), to take action on climate change (SDG13) and to sustainably manage life and resources below water (SDG14) and on the land (SDG 15). The first step in achieving these goals is to understand the current state of the environment and to identify where the most action is required. That is the high-level aim of this paper: to perform a spatial assessment of environmental indicators available from Kazakhstan and to interpret these data in terms of future needs for the country to make further progress towards its goals.

Environmental Issues in Kazakhstan

Kazakhstan is a developing nation whose population and gross domestic product (GDP) have been growing steadily since 2000 (Fig. 1; see Thomas (2015) for a more detailed discussion of Kazakhstan's development). It is the ninth largest country in the world and is estimated to hold vast reserves of many natural resources, including uranium, chromium, lead, zinc, manganese, copper, coal, iron and gold. However, health indicators such as life expectancy are lagging behind nations with similar economies (WHO 2005, 2014). It is likely that this "health lag" is, to a large extent, caused or aggravated by the poor state of Kazakhstan's natural environment. This degradation has been largely caused by lax environmental regulations, poor enforcement of regulations and exploitation of its natural resources. The key issues are:

1. Air quality—the energy, metallurgy, oil and chemical refining industries emit around three million tonnes of hazardous substances a year into the atmosphere (WHO 1999; Kenessariyev et al. 2013).
2. Water quality—there is widespread pollution from agricultural and industrial run-off (Jensen et al. 1997; WHO 2005), but monitoring is not widespread.

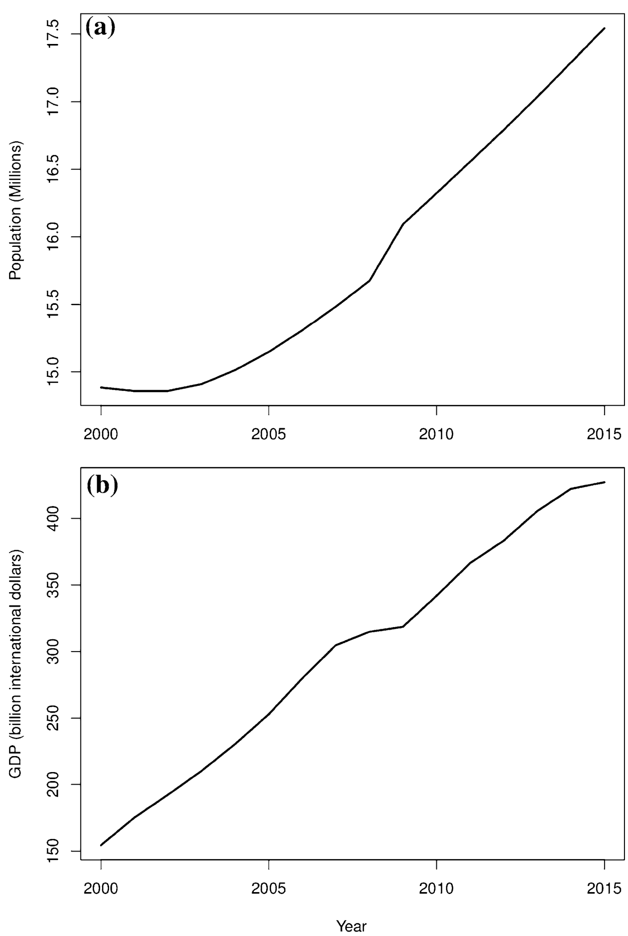

Fig. 1 **a** Population of Kazakhstan; and **b** gross domestic product (GDP) of Kazakhstan. GDP is presented using purchasing power parity rates (2011) and converted to international dollars

3. Radioactive contamination—there were Soviet era nuclear testing facilities in Eastern Kazakhstan—this area has been described as an "environmental disaster zone" (Government of Kazakhstan 1997)—and there is significant uranium mining in the country (Dahl and Kuralbayeva 2001).
4. The Aral Sea—the surface area of the sea has reduced by about 88% since 1960 due to irrigation projects, which have left behind plains covered in salt and toxic chemicals that produce harmful dust (Micklin 2010).
5. Climate change—Kazakhstan has undergone large temperature increases in recent years and it is expected to continue warming, potentially leading to water stress, soil degradation and desertification (IPCC 2013); and
6. Soil contamination—heavy metals, oil products and coal dust contaminate the land around industrial centres (Dahl and Kuralbayeva 2001).

These issues need to be understood in more detail and addressed as a matter of urgency if Kazakhstan is to continue its rapid development without significantly damaging the health of the population. In particular, with such a range of problems, and a finite budget to implement environmental remediation, mitigation and adaptation policies, it is important to understand the impacts of different issues so that this budget can be allocated efficiently and effectively.

Environmental Health

Whilst environmental conservation is an important goal in itself, the general motivation here is principally one of human health implications. Globally, the link between poor environmental conditions and non-communicable diseases, such as cardiovascular disease, is growing (Norman et al. 2013). Indeed, the main causes of mortality in Kazakhstan are non-communicable diseases, such as cardiovascular diseases (54%), cancer (15%) and respiratory diseases (4%) (WHO 2014). These are all likely to have environmental aggravations/causes, but the available data relating to such problems have not been analysed in much depth. Nonetheless, certain studies show concerning trends (e.g. Kenessariyev et al. 2013; Kurmanbayeva et al. 2016). Against this background, further investigations of the specific environmental stressors that exist in Kazakhstan is urgently required and addressed with this study.

Policy Interventions

Following the dissolution of the USSR, there have been two major environmental laws introduced in Kazakhstan. In 1997, the law on Environmental Protection came into force. One aspect of this dealt with the pressing water problems in Kazakhstan and included fines for polluters and excessive use of freshwater. Water efficiency measures were also introduced. However, legislation relating to air pollution was, at that point, still taken from Soviet era laws (Dahl and Kuralbayeva 2001).

In 2007, the Environmental Code of the Republic of Kazakhstan sought to consolidate most of the existing environmental legislation. It also introduced more general factors such as the principles of sustainable development, mandatory Environmental Impact Assessment (EIA) processes, and emissions reduction targets and procedures. A systems of permits and licences for air pollution, water pollution and greenhouse gas emissions were also developed and implemented.

Specifically on international climate change agreements, Kazakhstan was one of the last signatories to ratify the Kyoto Protocol (2009), but signed and ratified the Paris Agreement in 2016.

Overall, progress has been made on environmental protection and the budget for environmental protection measures has quadrupled since 2005 (Fig. 2), but further work is required to efficiently remediate damage that has been done in the past.

Aims of the Study

The survey presented here focuses on the compilation, critical analysis and contextualisation of reliable environmental datasets from and/or concerning Kazakhstan and to review environmental policies within the frame of the findings from the spatial survey. This overview is of significant value on its own, but we also present and discuss these data with a view to informing more detailed environmental health analyses in future work. Specifically, we aim to:

- Present observations and processed data products relating to the state of the environment, focusing on recent changes.
- Investigate potential future environmental changes, with a focus on climate projections.
- Discuss the relevance of these datasets to the environmental health of the nation.
- Analyse the gaps in the available datasets with a view to developing recommendations for future environmental monitoring efforts; and
- Review current policies and present recommendations for future interventions.

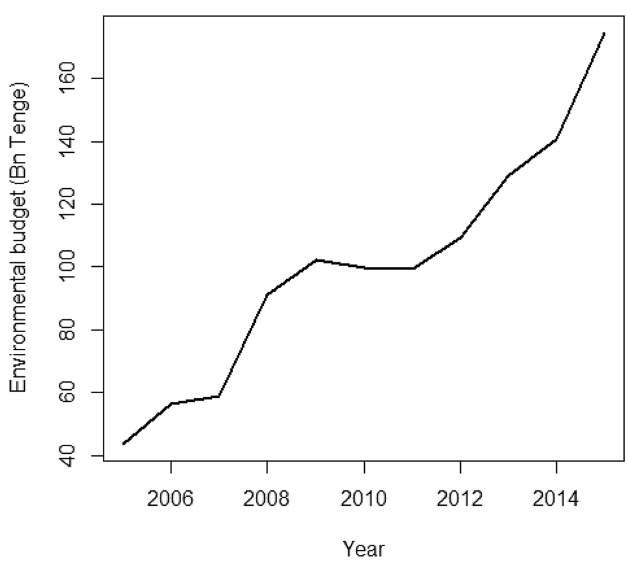

Fig. 2 Kazakhstan's environmental protection budget in billions Tenge from 2005 to 2015. One billion Tenge is approximately three million US Dollars (exchange rate from November 2017)

Data and Methods

Climate Data

To investigate the current and recent past climate, observations from weather stations in Kazakhstan were analysed. Specifically, data from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information's (NCEI) Global Historical Climatology Network (GHCN) version 2 were used. Analyses of daily mean temperature, daily minimum temperature, daily maximum temperature and daily precipitation are presented. These data have been quality assured by NCEI and only stations that include at least 50 years of data and that were operational up to 2016 were analysed here. However, in the case of precipitation, stations that were operational up to at least 2004 were also included to increase the sample size.

For projections of future climate changes, data from the 5th Phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) were used from all available ensemble runs from all the available models. This resulted in between 38 and 42 individual model runs from various models with different size ensembles for the different variables investigated, i.e. daily mean temperature, daily minimum temperature, daily maximum temperature and daily precipitation. Data were used from three different CMIP5 experiments, two of which aim to assess the impact of different levels of greenhouse gas emissions over the twenty-first century: the Representative Concentration Pathways (RCPs; van Vuuren et al. 2011): the RCP45 and RCP85 pathways were used for the period 2005–2100. These RCPs represent mid-range (RCP45) and high-end (RCP85) impacts on radiative forcing changes in the future. The third experiment used was called "historical", which provides a benchmark period that allows the model data to be compared with observations. This was used for the temporal window of 1850–2005 and data were averaged from the model grid cells that cover Kazakhstan (approximately 42°–55°N and 47°–87°E, but this varied slightly depending on the resolution of the different models).

Air Quality Data

Air quality data from Astana (51.16°N, 71.47°E) and Almaty (43.22°N, 76.85°E) were compiled from Kazhydromet (part of Kazakhstan's Ministry of Energy) and are presented alongside national emissions data from the Republic of Kazakhstan Committee on Statistics. Air quality data from other locations are available but not shown here as Almaty and Astana represent a good geographical range and cover a significant proportion of Kazakhstan's population (around 15%).

NOAA's Air Resources Laboratory's (ARL) HYSPLIT model (Stein et al. 2015) was used to run back trajectories for Astana and Almaty in order to identify potential sources of poor quality air. The trajectories were run using the Global Data Assimilation System (GDAS) 1° × 1° resolution, global data from the National Center for Environmental Prediction's (NCEP) Global Forecast System (GFS) model. The trajectories were initiated every 6 h for 3 years (2010–2012) from the relevant coordinates at 500 m above the surface. Trajectory coordinates were output every 6 h of the trajectory run.

Water Quality Data

Quarterly reports of water quality were collected from Kazhydromet and assessed for data quality and continuity. The reports present quarterly averages of measurements taken from consistent locations on some of Kazakhstan's key water bodies. We present data where there are minimal missing measurements from the following locations: Krasnojarka River (East-Kazakhstan region); Sherubaynura River (Karaganda region); Ilek River (Aktobe region); and Biylikol Lake (Zhambyl region). Data from other locations are available, but not shown here as the data continuity was not good.

Radioactivity

The Department of Consumer Protection of Akmola region of the Ministry of National Economy of the Republic of Kazakhstan collected data on exposure dose rate between 2013 and 2015. Akmola is a densely populated region close to significant uranium resources and mining facilities, as a result, significant radioactive waste has accumulated in the region, which is a source of radiation pollution (Kazymbet et al. 2006). Therefore, we present data from Akmola here in order to understand the impact of that industry. Despite the high profile of the Soviet era Semipalatinsk nuclear testing site, we have no available data to analyse from that area.

Socio-economic Data

Using data from the Republic of Kazakhstan Committee on Statistics a picture of the environmental background, including certain proxies for environmental policy, is presented. In particular, we use: population; GDP; emissions of pollutants; total waste generation; emissions of greenhouse gases; and money spent on environmental protection.

Summarising Results Using a Well-Established Communication Tool (DPSIR)

In order to present the results in as meaningful a way as possible for end-users, the Drivers–Pressures–State–Impact–Response, or DPSIR, model will be used. We will use the terms as outlined in Maxim et al. (2009): Drivers—this refers to the socio-economic drivers of the issue at hand; Pressures—the stress exerted on the environment; State—the resultant state of the environment; Impacts—the subsequent impacts on human health; and Response—the recommended societal response to the problem.

Results: State of the Environment

Climate

Figure 3 shows the trends in daily temperature (mean, maximum and minimum) and daily precipitation over Kazakhstan whilst Fig. 4 presents the time series for daily mean temperature and daily precipitation from the individual stations. These data show a clear warming trend over the entire country, particularly since 1970. There are also positive trends in maximum and minimum temperatures, although there are far fewer stations that recorded these data. The pattern of precipitation changes is less straightforward: there are negative trends in the west and around Astana; and there are positive trends in the south and north. However, Fig. 4 shows a relatively consistent increase over the last decade. Most of these results are consistent with the analysis of Salnikov et al. (2015), although the positive precipitation trend in recent years was less prominent in that study as their analysis only uses data up to 2011. Salnikov et al. (2015) also used data from a larger number of meteorological stations, which will account for other, less significant differences.

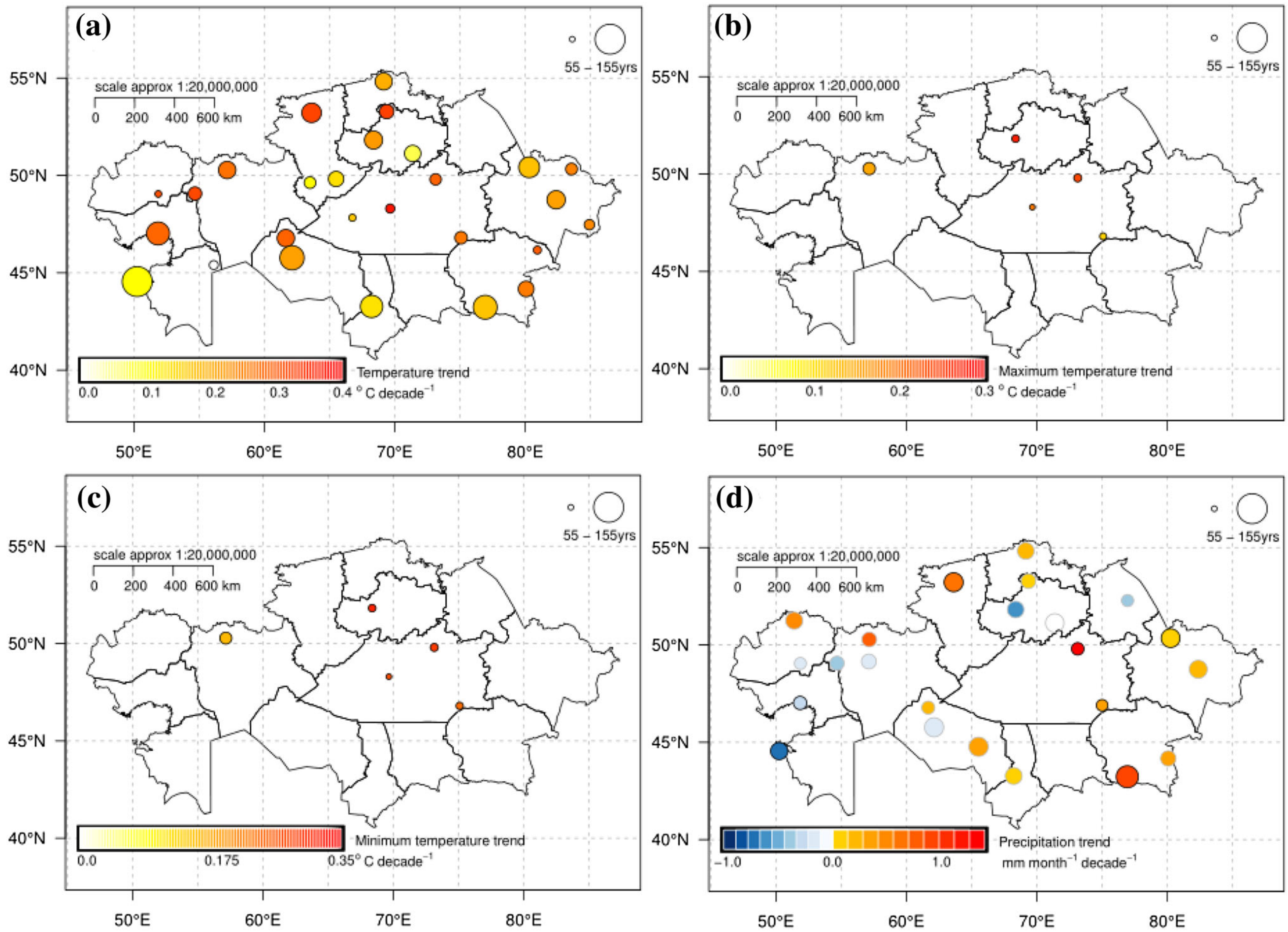

Fig. 3 Linear temperature trends from weather stations that have observations for over 50 years and observations up to 2016. The shading of the circle indicates the strength of the trend (see colour bar for scale—note that the scale is different in each plot) and the size of the circle indicates the length of the record (see circles in the top right hand corner for scale). The data presented are the decadal trends for: **a** mean daily temperature; **b** maximum daily temperature observations; **c** minimum daily temperature observations; and **d** daily precipitation. For **d**, the circles with a black outline show data from stations that were operational up to 2016 whilst circles with a grey outline show data from stations that were operational up to 2004

Looking to the climate projections, Fig. 5 also shows a consistent increase in mean, maximum and minimum daily temperature across Kazakhstan. This is true for both the medium (RCP45) and high (RCP85) emissions pathways and all the ensemble members from the different models. For precipitation, the picture is, again, less clear with different models showing positive and negative changes out to 2100. As the observations showed spatial variability across Kazakhstan (Fig. 3d), the large range in the precipitation projections may be caused by the averaging of the grid cells over Kazakhstan in this analysis. Indeed, the regions that have seen a reduction in precipitation in recent years (e.g. around the Aral Sea) show much less positive precipitation trends into the future in RCP45 and RCP85 than the overall average for Kazakhstan (not shown).

Emissions and Air Quality

Table 1 shows the annual emissions from industrial and societal activities in Kazakhstan and Fig. 6 shows how emissions of certain species of air pollutants have changed over time. All these pollutants have decreased over this period and most were declining up to 2015, with the exceptions of cadmium, NO_x and NMVOC, which were increasing in concentration between 2005 and 2015. Several of the species have peaks around 2000–2005, which coincides with a period of industrial growth in Kazakhstan—this can be seen in Fig. 7, which shows a large peak in total waste produced in Kazakhstan as a result of the expanding mining and heavy industry sector. CO_2 emissions (Fig. 8) have declined since 1990, but have been increasing from the minima in 2001. The introduction of

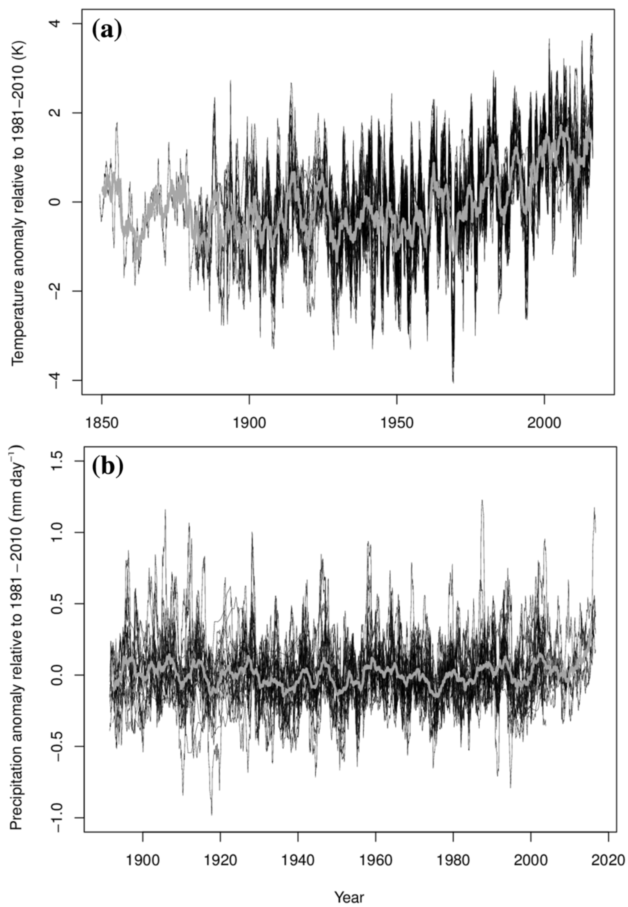

Fig. 4 Spaghetti plots of the 13-month running mean (thin black lines) of monthly data relating to: **a** mean temperature (27 stations); and **b** precipitation (23 stations). The thick grey line shows the 37-month running mean of the different stations

the Environmental Code in 2007 is also likely to have had an impact here in terms of emissions reductions.

Figure 9 shows the air quality in Kazakhstan's two largest cities: Almaty (1.5 M population in 2013); and Astana (0.8 M population in 2013, likely over 1.0 M in 2017). Concentrations of pollutants in Astana are approximately twice as high as those in Almaty. Both cities are characterised by increasing levels of NO_2 since 2014 and Almaty also saw SO_2 rise up to 2016. Almaty experienced a significant peak in CO in late 2014/early 2015 whilst Astana experienced a major SO_2 peak in late 2013/early 2014. Both cities have data problems with significant gaps present in these short records.

Figure 10 shows the typical origin of air masses at Almaty and Astana. For Almaty, the air masses mostly come from the southwest, passing over the Almaty, Zhamby and South Kazakhstan provinces and Kyrgyzstan, Tajikistan and Uzbekistan as well as China to the east. These regions are not characterised by much heavy industry and, therefore, most likely explains the lower concentration of atmospheric pollutants in Almaty when compared to Astana. Southeasterlies at Almaty are very rare because of the location of the Tian Shan mountains. In contrast, trajectories for air masses arriving at Astana travel over the much more industrialised provinces of Karaganda and Pavlodar. Indeed, emissions from these two provinces are typically 6–10 times greater than the other provinces (Thomas 2015).

Fig. 5 Spaghetti plots of the 13-month running mean (thin black lines) of monthly data relating to: **a** RCP45 mean temperature (42 model runs); **b** RCP85 mean temperature (39 model runs); **c** RCP45 maximum temperature (41 model runs); **d** RCP85 maximum temperature (38 model runs); **e** RCP45 minimum temperature (40 model runs); **f** RCP85 minimum temperature (38 model runs); **g** RCP45 mean precipitation (42 model runs); and **h** RCP85 mean precipitation (39 model runs). The thick grey line shows the 37-month running mean of the different variables ▶

Looking to the poor air quality events in Almaty in late 2014/early 2015 and Astana in late 2013/early 2014, Fig. 10 shows the air mass sources specifically for these times. The pollution event in Almaty (Fig. 11a) is associated with trajectories that come from much further west than seen in Fig. 10a. These trajectories are likely to come over the petrochemical operations in Uzbekistan to the south of the Aral Sea. For Astana (Fig. 11b), the trajectories are almost all tracking over Karaganda, with more coming from the Aral Sea area than the more climatological picture presented in Fig. 10: these are both very polluted areas.

Water Quality

Figure 12a shows average concentrations of copper from various locations around Kazakhstan but, due to the missing data in the middle of the records, it is not possible to confidently assess whether there is a consistent trend towards a reduction in this chemical in the water bodies. However, Fig. 12b–d presents relatively convincing evidence that BOD (biological oxygen demand), boron and zinc have decreased in concentration in the locations where reliable data have been collected. The decrease in BOD at Biylikol Lake is particularly important as the lake was exhibiting very high values before the decrease around 2014, which is indicative of high levels of organic pollutants.

Radioactivity

Figure 13 shows the measurements of exposure dose rates from various towns and cities in the Akmola region. With only 3 years of data it is not possible to identify any long-term trends. However, in 9 of the 19 records, the value for

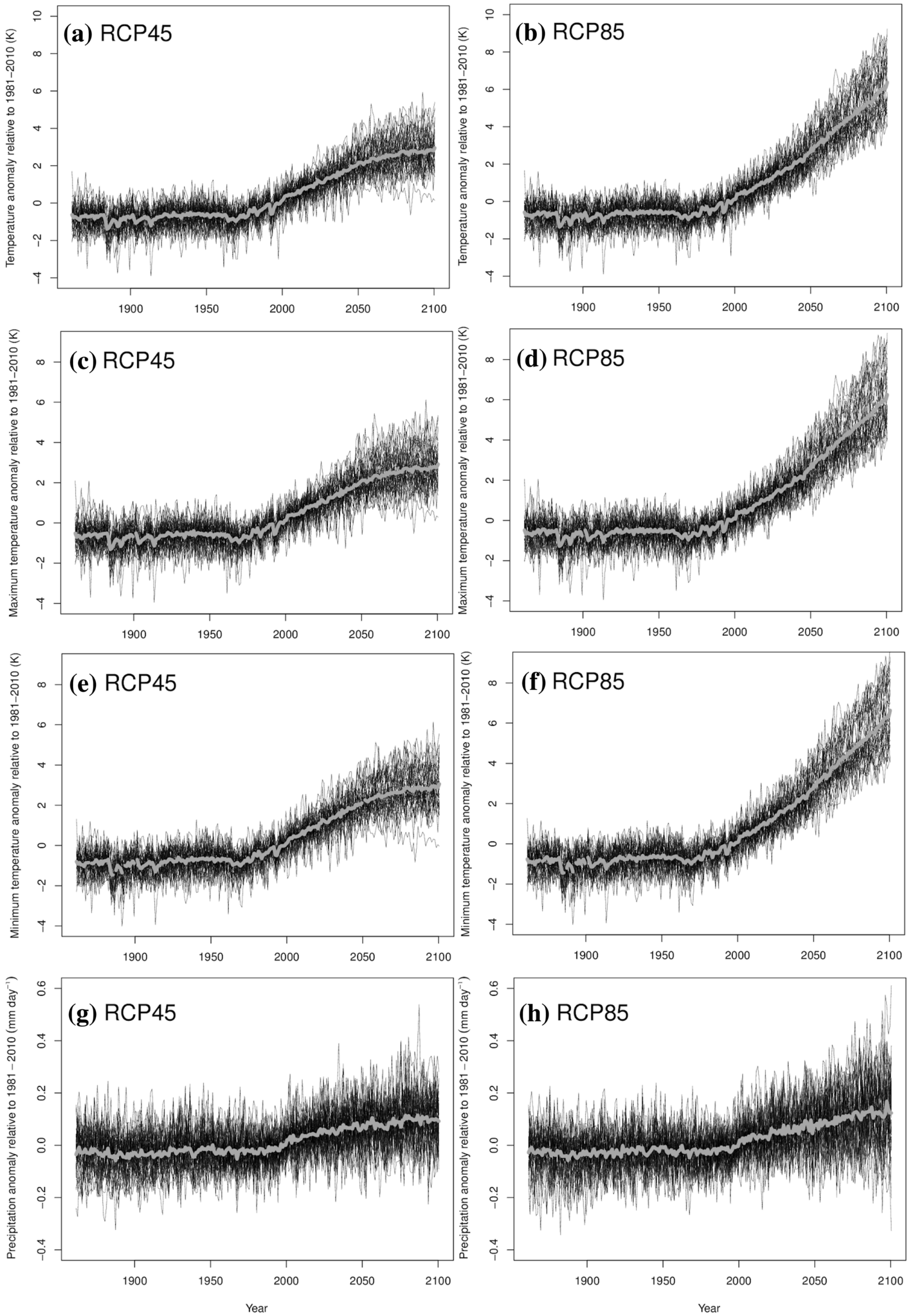
(a) RCP45
(b) RCP85
(c) RCP45
(d) RCP85
(e) RCP45
(f) RCP85
(g) RCP45
(h) RCP85
Temperature anomaly relative to 1981–2010 (K)
Maximum temperature anomaly relative to 1981–2010 (K)
Minimum temperature anomaly relative to 1981–2010 (K)
Precipitation anomaly relative to 1981 – 2010 (mm day⁻¹)
Year
1900
1950
2000
2050
2100

Table 1 Total emissions of selected pollutants within Kazakhstan for 1990 (or 2000 where [a]appears by the value) and 2015 measure in ×1000 tons/years (or tons/year where [b]appears by the value)

Species	1990 emissions	2015 emissions
Sulphur dioxide	1483.5	710.6
Nitrogen oxides	330.1	243.4
Non-methane volatile organic compounds	168.1	105.1
Ammonia	3.7	2.3
Carbon monoxide	841.3	451.2
Hydrocarbons	139.9	66.1
Total suspended particles	1683.3	466.0
Lead	4621.4[a,b]	636.3[b]
Cadmium	3.1[a,b]	1.2[b]
Mercury	0.3[a,b]	0.2[b]
Copper	1941.7[a,b]	254.5[b]
Arsenic	1606.6[a,b]	40.5[b]

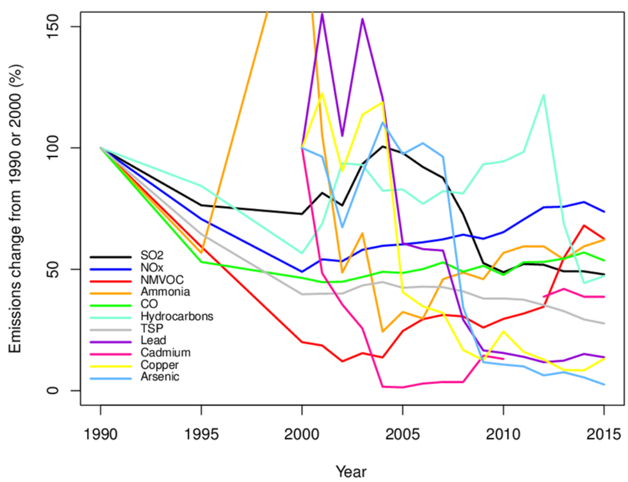

Fig. 6 Plot of percentage change in emissions from Kazakhstan relative to the first data point, which is 1990 for most species but 2000 for lead, cadmium, copper and arsenic. The data point for ammonia for 2000 is 208%—this was not included on the axis to improve the presentation of the other lines. The absolute values at 1990 or 2000 can be seen in Table 1

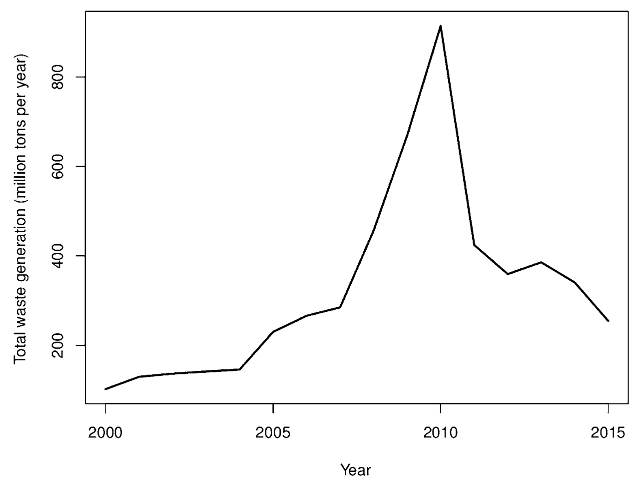

Fig. 7 Total waste generation from Kazakhstan

the first year (2013) is higher than the other 2 years. There is only one location (Essilskiy) where there is a consistent positive trend over the 3 years.

Discussion

Climate Change Impacts

"Climate" presents data that imply climate change is likely to have a significant impact on Kazakhstan in the coming decades. For example, warming and decreasing precipitation in the arid western regions of Kazakhstan are likely to increase current stresses on human health as well as food and water availability (Lioubimtseva and Henebry 2009). Furthermore, glaciers play an important role in Central Asia's hydrological cycle (Kaser et al. 2010; Sorg et al. 2014) and increasing temperatures due to climate change can, of course, cause glaciers to retreat or disappear and there is evidence of this retreat in Kazakhstan (Bolch 2007). The impact of this on water resources in this region could be dramatic, indeed, similar pressures have existed in the recent past (e.g. Howard and Howard 2016). If there is an extended period of net mass loss, glacier runoff will increase at first until the glacier reaches a peak discharge rate and, once reached, the runoff will then decrease as glacier volume decreases (Jansson et al. 2003; Huss 2011).

In Kazakhstan, the Aral Sea is dependent on the runoff from two glacier fed rivers, the Syr darya, and the Amu darya, starting in the Pamir and Tian Shan mountains (Lioubimtseva 2015). The Pamir mountains are located south of Kazakhstan, mainly in Tajikistan, while the Tian Shan mountains lie along the border with Kyrgyzstan and Northern China. Kaser et al. (2010) found that shrinking glaciers feeding the Aral Sea basin, resulting in lower seasonally dependent glacier melt, will result in even lower water levels in the Sea.

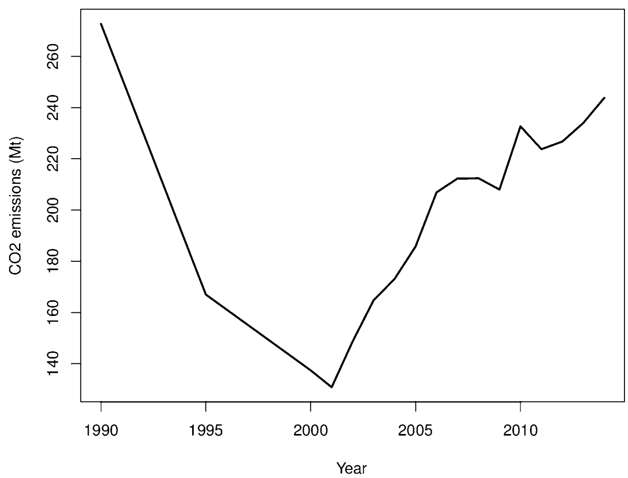

Fig. 8 Carbon dioxide (CO_2) emissions from Kazakhstan for 1990–2015

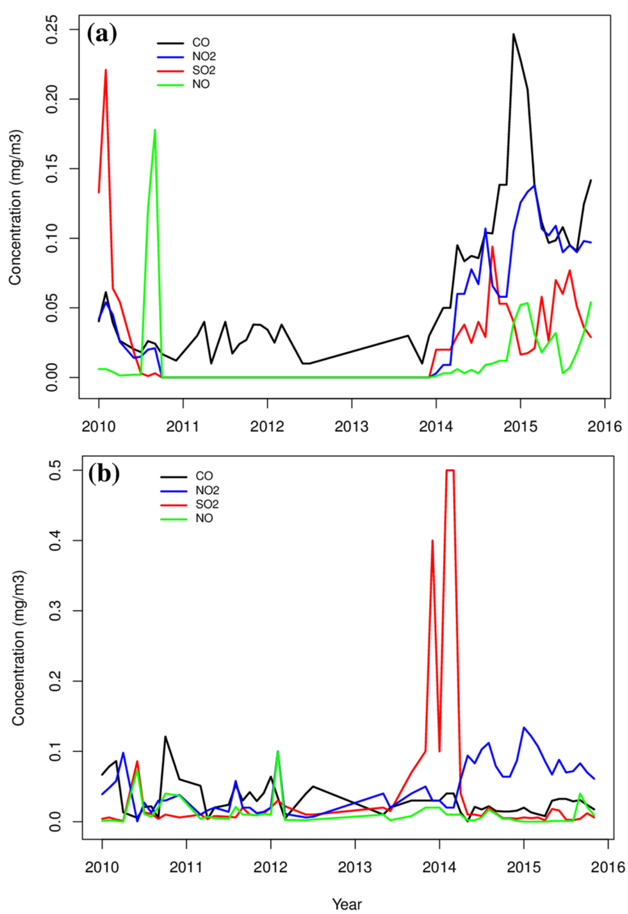

Fig. 9 Atmospheric concentration of carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and nitric oxide (NO) in **a** Almaty and **b** Astana. The CO concentrations have been divided by 10 so that the data can be plotted in the same range as the other species

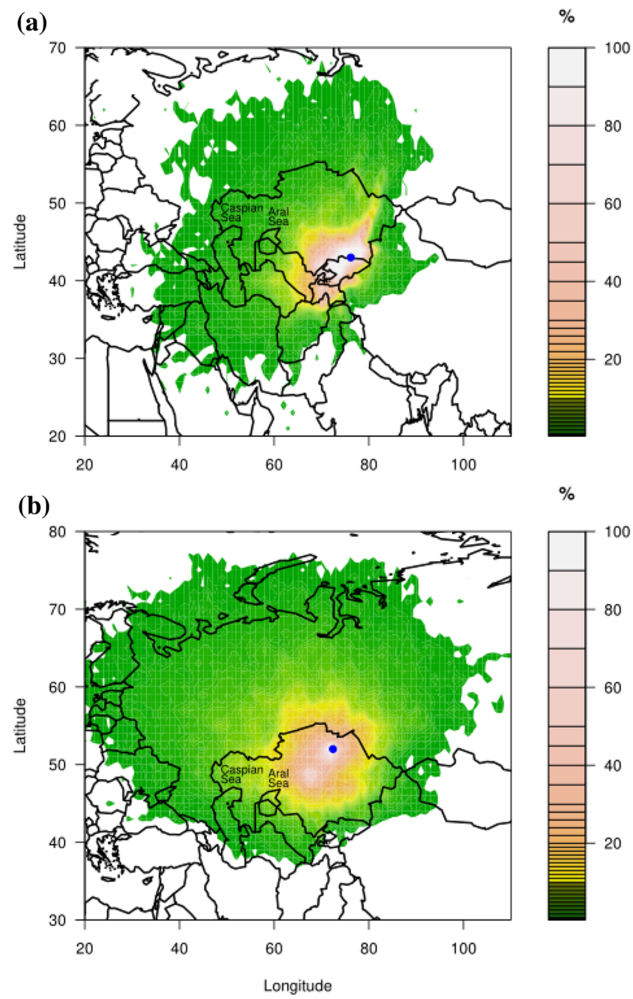

Fig. 10 Percentage of coordinates (output every 6-h) of 4-day back trajectories that pass through any 1×1 degree box at any point during their run. The trajectories were initiated every 6 h for 2010–2012 for: **a** Almaty; and **b** Astana. Note that the colour scale is nonlinear and that the latitude range on the two plots is different

Climate driven, or influenced, changes in environments unique to Kazakhstan (e.g. the steppe, the Caspian Sea) may also have impacts on ecological niches and further endanger native species, e.g. Saiga Antelope (Kamp et al. 2016), Caspian Seal (Harkonen et al. 2012).

However, there may also be positive outcomes: longer growing seasons could lead to increased cereal yields in Kazakhstan (IPCC 2014) and any increase in temperature may reduce cold weather-related mortality rates. Either way, Kazakhstan requires a National Adaptation Plan to prepare for the changes that are to come, with a particular focus on health and food and water resources. Indeed, whilst many nations have well developed plans, Kazakhstan has only recently started these preparations with the support of the UN (UNDP 2017).

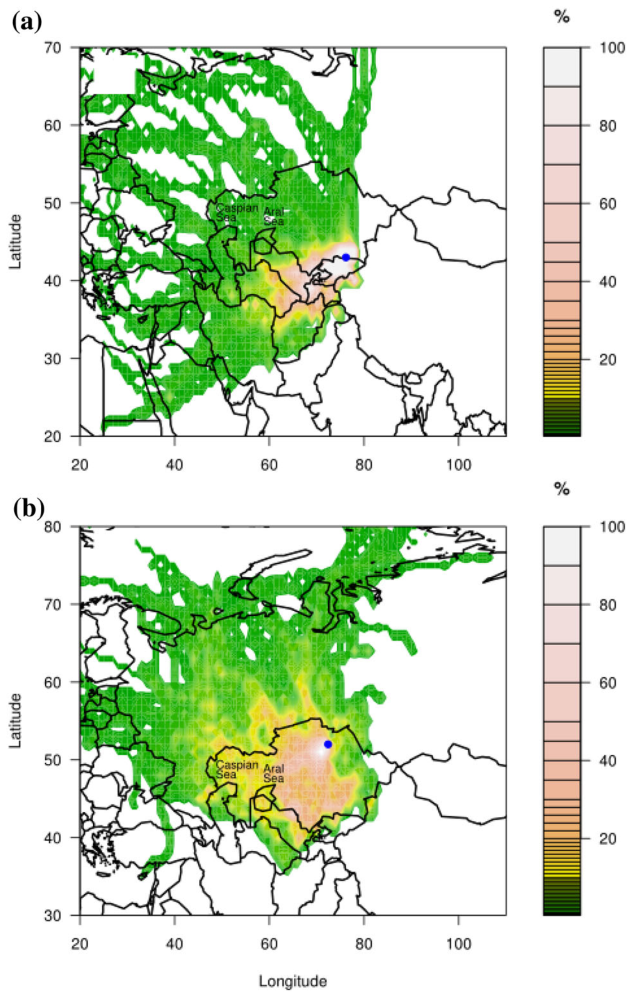

Fig. 11 Percentage of coordinates (output every 6 h) of 4-day back trajectories that pass through any 1 × 1 degree box at any point during their run. The trajectories were initiated every 6 h for: **a** December 2014 and January 2015 for Almaty; and **b** December 2013 and January 2014 for Astana. Note that the colour scale is nonlinear and that the latitude range on the two plots is different

Air Quality

Despite a long-term trend of improving air quality in Kazakhstan from the levels reached in the 1980s (Thomas 2015), the data available to us provide evidence that concentrations of key pollutants are increasing again in the major cities. Indeed, where Kazakhstan has targets that can be compared to these data (e.g. annual NO_2 mean should not exceed 40 μg/m^3) these have not been met in the last 2 years of data at Almaty: 2014—87 μg/m^3; 2015—68 μg/m^3. This requires particularly urgent attention because the effects of climate change are likely to exacerbate the air quality impact on mortality in this region (Silva et al. 2017). Under these circumstances, the availability of air pollutant data is important so that efforts to achieve improvements in air quality are well informed by good quality data. Improvements in low-cost air pollutant sensor technology show great potential in that regard (Mead et al. 2013; Kumar et al. 2015).

Whilst Kazakhstan has engaged in the international debate on emissions reduction (e.g. the Montreal Protocol, the Kyoto Protocol) and developed environmental policies to tackle pollution (i.e. the Environmental Code) a large proportion of the air pollution reductions are linked to the decline in industrial activity associated with regional and global economic problems (e.g. dissolution of the Soviet Union, the 2008 financial crash). For a more environmentally sustainable future, it is likely that a proactive move towards renewable energy sources would drive a longer term improvement in air quality. This would, naturally, have to occur alongside a reduction in the exploitation of Kazakhstan's abundant natural resources, which is a major challenge (Karatayev et al. 2016).

Water Quality

Decreasing levels of copper in the water bodies examined is positive as it can be toxic to microorganisms. High levels of organic pollutants (indicated by high BOD) in certain water bodies are concerning as some of these compounds are carcinogens. Boron is an irritant and can have fertility consequences over long time periods, again, the decrease is welcomed. Similarly, zinc, which can cause stomach problems in humans, is decreasing in concentration. Given the stresses that climate changes are likely to bring to the region, it is recommended that a more comprehensive water quality monitoring framework is adopted so that remediation efforts can be targeted in the most efficient ways. This would represent the optimum response to a problem with multiple causes.

Radioactivity

The data presented here show that the exposure for the Akmola region are low when compared to the World Nuclear Association's "Average total global dose from natural background radiation", which is 2.4 mSv/year. The highest value recorded here (0.22 μSv/h) is less than 2.4 mSv/year. Nonetheless, continued monitoring is recommended given the size of the local uranium mining industry.

The significance of the effect of the Semipalatinsk nuclear tests requires some further attention. It has previously been shown that exposure to fallout from nuclear tests in the 1940s and 1950s approximately doubled germline mutation rates (Dubrova et al. 2002). However, the more general effect of the contamination from the longer term testing between the 1940s and 1980s remains to be identified and recent medical analyses imply that

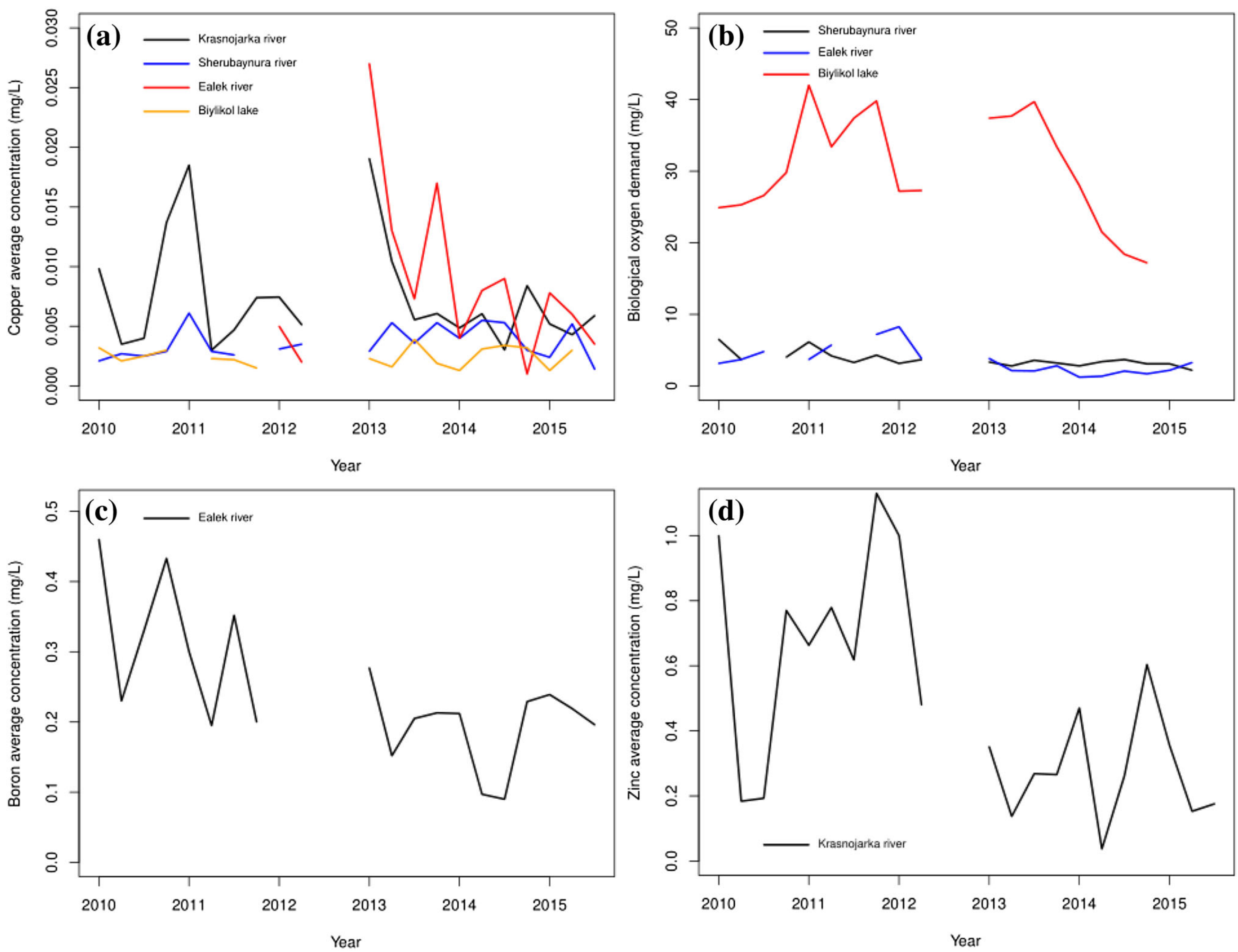

Fig. 12 Average concentration (mg/L) of **a** copper, **b** BOD, **c** boron and **d** zinc for four different rivers and lakes from Kazakhstan

there was no increased risk of thyroid cancer for those exposed (Grosche et al. 2017). The apparent contradiction here requires clarification.

Data Availability

Investigations such as this, and extensions that investigate links with mortality and morbidity data, require high-quality, long time-scale, high spatio-temporal resolution datasets. Unfortunately, this is often not the case. Whilst climate data are available for a long time period at multiple locations in Kazakhstan, air quality, water quality and radioactive contamination data were not available for periods greater than 5 years. These datasets also had missing data. Table 2 summarises the datasets used in this investigation in terms of length, continuity and identified trends.

In order to maximise the value of work in this area, it would be ideal if reliable past data were identified, quality controlled and made available in a consistent, digital form. Further, current and future measurement networks should be maintained, and potentially expanded, again with quality control, consistency and cost-effectiveness (e.g. low-cost sensors) in mind. It could prove beneficial to explore and assess the in-country expertise with regard to data handling in order to ensure that data and their important metadata are adequately preserved and subjected to an appropriate level of quality assurance and control in order for the data to be useful both to analysts and policymakers.

It is not clear what measurement technology is being used in the Kazakhstan air quality monitoring stations, but depending on the type of instruments being used, the use of low-cost, high-density air quality measurement sensor networks could provide an enhancement and expansion to

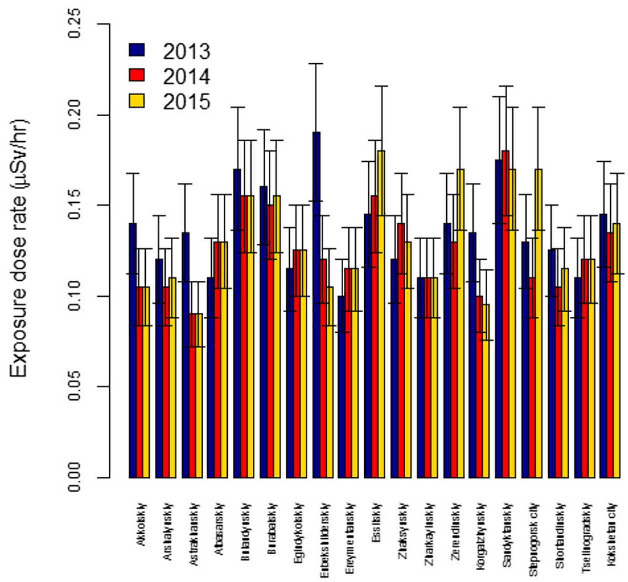

Fig. 13 Exposure dose rate (μSv/h) from 19 towns and cities in the Akmola region of Kazakhstan. The error bars show the range of values recorded

Table 2 Summary of the datasets analysed in this study

Dataset	Length	Data continuity	Spatial coverage
Mean temperature	Good	Good	Good
Max temperature	Poor-to-adequate	Good	Adequate
Min temperature	Poor-to-adequate	Good	Adequate
Precipitation	Good-to-adequate	Good	Good-to-adequate
Air quality	Poor-to-adequate	Poor	Adequate
Water quality	Poor	Poor	Poor
Radioactivity	Poor	Poor	Poor

Assessments are subjective

the present monitoring network enabling better spatial analysis of air quality within urban areas in addition to allowing better approximations of personal exposure to air pollutants.

DPSIR Summary

Table 3 presents the results of the DPSIR analysis. These results are summarised from the preceding analysis and discussion so are not examined any further here.

Conclusions

The environment of Kazakhstan has been assessed using data covering climate, air quality, water quality, radioactivity and socio-economic factors. A key conclusion is that data are spatially sparse, temporally inconsistent and of variable quality. This causes problems in terms of environmental assessments and for understanding what the environmental impacts may be on human health and ecosystems more generally.

Where data are appropriate to use, the indications are concerning. For example: warming trends are seen in sensitive areas; drying trends are seen where there is already water stress; and air quality is declining in major urban centres. More positively, though: water quality appears to be improving in some areas; levels of exposure to radioactivity are below international recommended levels; and investment in environmental actions in Kazakhstan is increasing. The examination of these data together is considered a significant result in itself, but has extra value as this dataset can be used in the development of new, multivariate, environmental health analyses. Relevant methods have recently been tested using data from the UK (Vitolo et al. 2017) and can now be applied to Kazakhstan to see how they perform with shorter and more inconsistent input data.

With an increasing awareness of environmental issues in Kazakhstan (e.g. the “Future Energy” EXPO 2017 in Astana), there is an opportunity to make progress in this area. The recommendations from this work are to: collect and recover as much, high-quality environmental data as possible; to develop methods for understanding the combined impact of environmental stressors; and to focus Kazakhstan’s environmental budget on efficient and enforced environmental policies and remediation activities. Alongside this, continued engagement with international environmental initiatives is encouraged (e.g. the Paris Agreement, the Water Convention) and strategies to

Table 3 Summary of the survey results presented within the DPSIR framework

	Climate change	Air quality	Water quality	Radioactivity
Drivers	Global industrialisation	Regional industrialisation	Local industrialisation Local environmental management lagging behind development	Local industrialisation Use of Kazakhstan as a nuclear test site
Pressures	Global emissions of greenhouse gases	Local/regional emissions of pollutants to the air Atmospheric circulation Climate change	Local discharge of pollutants to water Local water use regulations lagging behind development	Local uranium mining Historic nuclear tests
State	Warming trend over most of Kazakhstan Changes in hydrological cycles (increases and decreases) (High confidence)	Recently degrading air quality after long period of improvement (Medium–high confidence)	Improving water quality (Medium–low confidence)	Improving background radiation (Low confidence)
Impact	Water shortages Reduced food production Decrease (increase) in cold (hot) weather-related mortality Exacerbates air quality impacts	Respiratory problems, cardiovascular disease, lung cancer and other health problems	Increase in exposure to toxic and carcinogenic compounds	Increased risk of cancers
Response	Influence international climate change mitigation efforts Work on domestic emissions reductions Develop national climate change adaptation plan	Develop and/or enforce emissions limits Develop air quality warning system Improve monitoring of air quality	Develop and/or enforce discharge limits Improve monitoring of water quality Investigate remediation options	Improve monitoring of radioactivity Investigate remediation options

respond to future challenges should be developed and implemented (e.g. a national climate change adaptation plan).

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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