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NKS-177
ISBN 978-87-7893-243-3

NKS NordRisk. Atlas of long-range atmospheric dispersion and deposition of radionuclides from selected risk sites in the Northern Hemisphere

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July 2008

Abstract

Within the NKS NordRisk project, “Nuclear risk from atmospheric dispersion in Northern Europe”, the NKS NordRisk Atlas has been developed. The atlas describes risks from hypothetical long-range atmospheric dispersion and deposition of radionuclides from selected nuclear risk sites in the Northern Hemisphere. A number of case studies of long-term long-range atmospheric transport and deposition of radionuclides has been developed, based on two years of meteorological data. Radionuclide concentrations in air and radionuclide depositions have been evaluated and examples of long-term averages of the dispersion and deposition and of the variability around these mean values are provided.

Key words

Risk assessment; long-range transport; radionuclide; pollutants; deposition

NKS-177
ISBN 978-87-7893-243-3

Electronic report, July 2008

The report can be obtained from
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NKS-776
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DK - 4000 Roskilde, Denmark

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NKS NordRisk

Atlas of long-range atmospheric dispersion and deposition of radionuclides from selected risk sites in the Northern Hemisphere

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Introduction

Within the NKS NordRisk project, “Nuclear risk from atmospheric dispersion in Northern Europe”, the present atlas has been developed. The atlas describes risks from hypothetical long-range atmospheric dispersion and deposition of radionuclides from selected nuclear risk sites in the Northern Hemisphere. A number of case studies of long-term long-range atmospheric transport and deposition of radionuclides has been developed for the atlas, based on two years of meteorological data for the Northern Hemisphere. Radionuclide concentrations in air and radionuclide depositions have been evaluated and examples of long-term averages of the dispersion and deposition and of the variability around these mean values are provided in the atlas. For the present atlas, the risk indicators are time-integrated activity concentration in air and total wet and dry deposition fields. Other risk indicators, not included in this atlas, have been considered within the NORFA project Arctic Risk (http://glwww.dmi.dk/f+u/luft/eng/arctic-risk/main.html).

The atlas is intended as a practical tool for probabilistic risk assessment. Combined with release risk assessments for a nuclear installation, i.e. the source term, the atlas can be used in emergency preparedness planning as well as for educational purposes. In emergency management, following a hypothetical or an imminent release of radionuclides, the atlas may provide a first assessment of the possible range of the atmospheric transport of radioactive material. For continuous emissions of radionuclides or other contaminants from a risk site, the atlas directly provides the expected geographical scale of contamination. Although the main emphasis has been on the atmospheric transport of radioactive materials the analysis and atlas readily applies also to non-radioactive releases.

Risk Sites and Source Terms

Seven different release sites in the Northern Hemisphere have been selected for the atlas. All sites are associated with major nuclear installations: Chernobyl in Ukraine, Kola, Leningrad and Novaya Zemlya in Russia, Sellafield in the United Kingdom, Sinpo in North Korea and Savannah River in the USA. The sites are selected to be representative of different climates and to represent both coastal and continental regions. In Table 1, the location of the release sites are shown.

Site	Abbr.	Longitude	Latitude
Chernobyl	CHE	30.25°E	51.30°N
Kola	KOL	32.75°E	67.75°N
Leningrad	LEN	29.00°E	59.90°N
Novaya Zemlya	NOV	54.50°E	72.50°N
Sellafield	SEL	3.50°W	54.42°N
Sinpo	SIN	128.22°E	40.00°N
Savannah River	SAV	81.70°W	33.30°N

Table 1. Geographic coordinates in decimal degrees of the nuclear risk sites selected for the atlas.

Releases of three main radionuclides are considered separately for each release site: Cs-137 (aerosol), I-131 (aerosol) and I-131 (elementary gas). In Table 2, the assumed dispersion parameters specific to the three releases are listed. In all cases, non-buoyant ground-level releases are assumed and the radionuclides are released at a constant emission rate.

	Cs-137	**I-131 (aerosol)**	**I-131 (elementary)**
Half life (s)	9.50×10^{8}	6.97×10^{5}	6.97×10^{5}
Dry deposition speed (m/s)	0.0015	0.0015	0.015
Particle radius (μm)	0.30	0.33	0

Table 2. Dispersion and deposition parameters of released radionuclides.

Meteorological Data

The meteorological base is formed by analysed meteorological data from the global NWP model, operated and developed by the European Centre for Medium-range Weather Forecasts (ECMWF) (http://www.ecmwf.int). Data for the years 1983 and 1985 from the ECMWF re-analysis (ERA-40) archive have been used as input to the atmospheric dispersion model calculations. The data cover the Northern Hemisphere at a horizontal resolution of 1.125° in the Earth polar coordinate system and with three-hour time resolution. In the vertical, 28 hybrid levels are employed. In the lower atmosphere these levels follow the terrain; aloft they are constant-pressure levels.

The selected years 1983 and 1985 represent a large positive value and a neutral value of the North Atlantic Oscillation (NAO) index, respectively. The NAO is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America over Europe into Northern Asia. The NAO is a large-scale see-saw in atmospheric mass between the subtropical high and the Icelandic low.

A positive NAO index phase implies a stronger than usual subtropical high pressure centre and a deeper than normal Icelandic low, cf. Figure 1. The increased pressure difference results in more and stronger winter storms crossing the Atlantic Ocean on a northerly track. This results in warm and wet winters in Europe and in cold and dry winters in northern Canada and Greenland. The eastern USA experiences mild and wet winter conditions. A negative NAO index phase corresponds to a weak subtropical high and a weak Icelandic low. The reduced pressure gradient results in fewer and weaker winter storms crossing on a west-east pathway. They bring moist air into the Mediterranean and cold air to northern Europe. The North American east coast experiences outbreaks of cold air and hence snowy weather conditions. Greenland, however, will have higher winter temperatures. The NAO index varies from year to year, but exhibits a tendency to remain in one phase for intervals lasting several years (Figure 2).

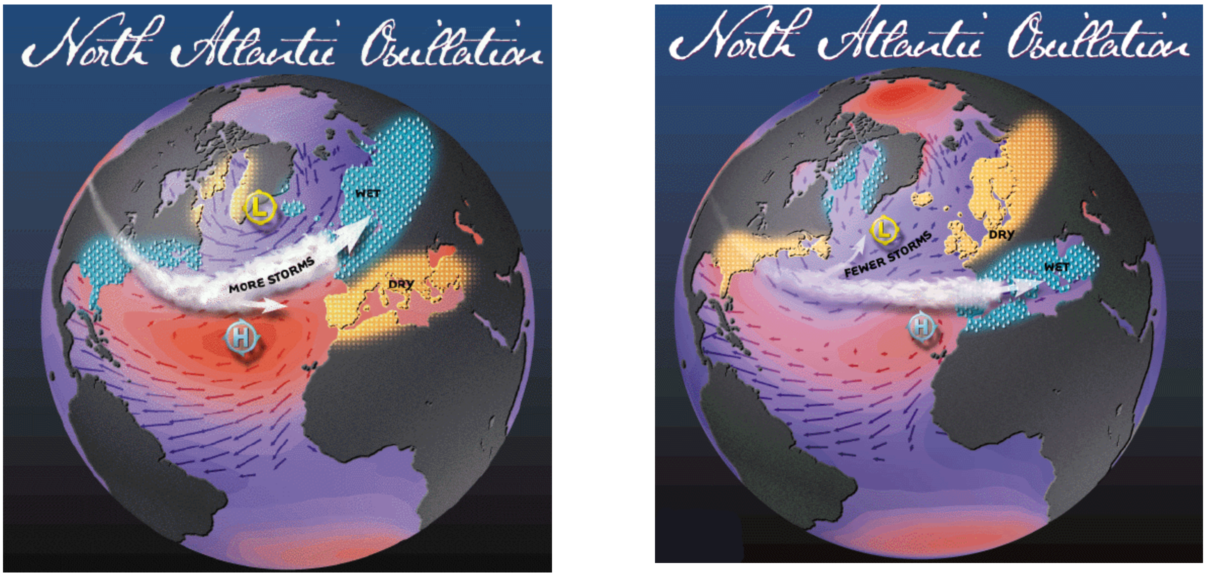

Figure 1. Weather patterns corresponding to a positive (left) and a negative (right) NAO index. Figure reproduced with permission from Hurrell *et al.* (2003).

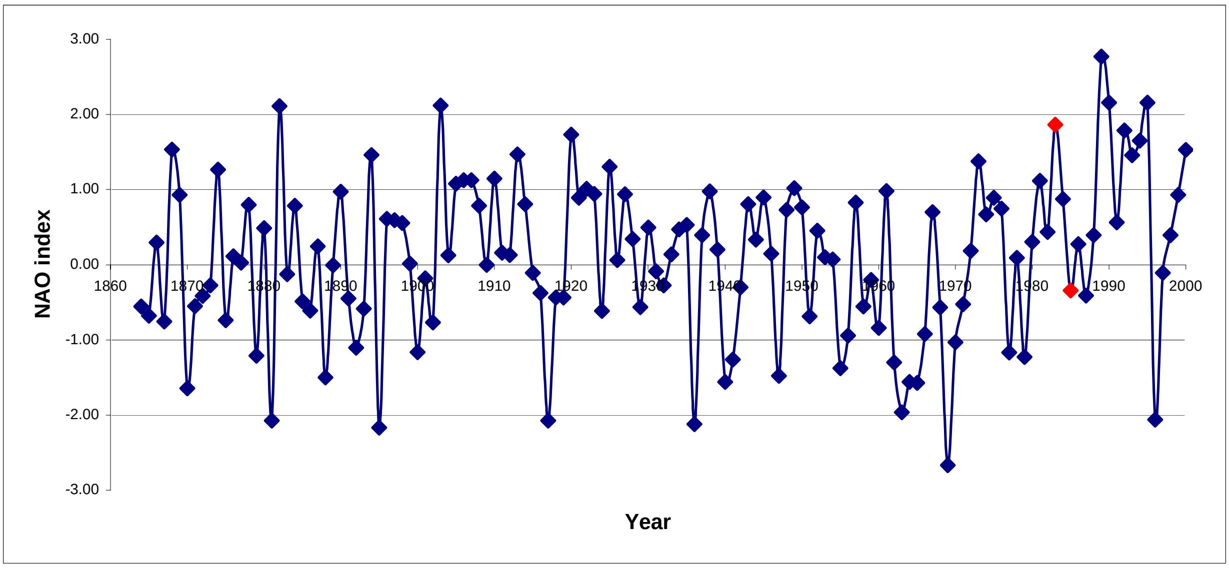

Figure 2. NAO index for the period 1864–2000 AD. The selected years 1983 and 1985 are marked in red colour.

Atmospheric Dispersion Modelling

Long-range atmospheric dispersion calculations are performed with the comprehensive atmospheric dispersion model DERMA (Sørensen, 1998; Sørensen *et al.*, 2007). DERMA is a three-dimensional Lagrangian stochastic puff-particle atmospheric dispersion model capable of simulating plume dispersion at ranges from about 20 km and up to the global scale (Sørensen *et al.*, 1998). DERMA is in use operationally in Denmark for emergency preparedness (Hoe *et al.*, 2002; Sørensen *et al.*, 2000, 2001; Mikkelsen *et al.*, 2003), and it is exercised and maintained within the EU ensemble modelling activities (Galmarini *et al.*, 2004a, b).

DERMA has also been used for probabilistic risk assessment, generating yearly average concentration and deposition fields (Lauritzen *et al.*, 2005, 2006, 2007; Baklanov *et al.*, 2003, 2007; Mahura *et al.*, 2003, 2005a, b). Methodological aspects of probabilistic long-term modelling using DERMA are described by Baklanov *et al.* (2006, 2007).

For the present calculations the integration domain is taken as the Northern Hemisphere. In the vertical the 28 vertical levels from ECMWF are used in DERMA long-range atmospheric dispersion simulations. Puffs are released every 15 minutes and the atmospheric dispersion and deposition of each puff is calculated for a period of three weeks following the release. The deposition comprises both wet and dry deposition. The results of the DERMA dispersion model are evaluated on the same grid as used for the meteorological data. Based on the 1983 and 1985 meteorological data daily and one-year averages of time-integrated air concentration and deposition density fields have been derived.

Results

Long-range atmospheric dispersion and deposition comprises a deterministic element as well as stochastic properties: The long term ensemble mean dispersion and deposition can be interpreted as the result of a deterministic flow of a one-particle density, while the air concentration and deposition fields resulting from a short-term release display stochastic fluctuations around the ensemble mean value (Lauritzen *et al.*, 2006; Baklanov *et al.*, 2007). From the present atmospheric dispersion model calculations both the ensemble mean value and the variability have been estimated.

A. Long-term averages

The annual averages of the radionuclide time-integrated air concentration and deposition for each of the two years considered are shown in the maps M1-M15. These long-term averages constitute an approximation to the ensemble mean values.

Deposition and air concentration maps have been generated for releases from the seven selected nuclear risk sites: Chernobyl in Ukraine, Kola, Leningrad and Novaya Zemlya in Russia, Sellafield in the UK, Sinpo in North Korea, and Savannah River in the USA. Total deposition (dry plus wet) and time-integrated concentration in ground level air have been calculated following a unit release of Cs-137 aerosols, I-131 aerosols, and I-131 gas, respectively. In Maps M1-M14 annual mean values are shown for the years 1983 and 1985, and in Map M15, dry and wet deposition fields are shown separately for the Leningrad release site for the three radionuclides.

B. Variability

The dispersion and deposition fields estimated from the one-year continuous releases appear to a first approximation to be isotropic in the horizontal. Hence, a simple parameterization of the deposition fields will be $c = \bar{c}(r) \cdot w$, where $\bar{c}(r)$ denotes the ensemble mean value, and the fluctuations are described by a stochastic variable w. Because of the near isotropic dispersion, $\bar{c}(r)$ depends only on the distance r from the release site.

Both $\bar{c}(r)$ and the probability density function (pdf) $p(w)$ describing the variability may be estimated from the observed air concentration or deposition data. The actual form of $p(w)$ depends both on the release site, the release duration, the averaging time, as well as prevailing meteorological conditions. Wet deposition, as opposed to dry deposition only, may result in large spatial fluctuations in the deposition field. The release duration has a large effect on the form and the variance of the pdf, with shorter release durations giving rise to increased variability. Short averaging times, e.g. considering monthly or seasonal rather than annual averages, is expected to imply larger variability.

Examples of the variability are shown in Figure M16, where releases from the Leningrad NPP are considered. In the top panel, the pdf $p(w)$ is estimated from the spatial variation of the annual mean deposition, and provides an estimate of the deviations from the ensemble mean deposition. In the lower panel, an example of the pdf for a short-term release is provided. Based on releases of 24 hours duration, the pdf $p(w)$ for deposition of ^{137}Cs at 2000 km from the release site is shown. In this case, the pdf describes the expected deviations from the long-term average deposition for a short-term (accidental) release.

Based either on historical data or on modelling data, the pdf constitutes a probabilistic risk assessment (PRA) for long-range dispersion and deposition of radioactivity, i.e. $p(c) = \bar{c}(r)^{-1} \cdot p(w)$. Care should be taken, however, that such a PRA only applies under similar release conditions and meteorological conditions as in the historical data or used in the model assumptions.

Acknowledgment

NKS conveys its gratitude to all organizations and persons who by means of financial support or contributions in kind have made the work presented in this report possible.

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Maps

In maps M1–M15, the unit of the time-integrated air concentration field is $\mathrm{h\,m^{-3}}$, and the unit of the deposition field is $\mathrm{m^{-2}}$. Hence, radionuclide activity deposition density ($\mathrm{Bq\,m^{-2}}$) and time-integrated air concentration ($\mathrm{Bq\,h\,m^{-3}}$) is obtained by scaling the concentration maps with the released activity (Bq).

List of Maps:

Figure M1. Chernobyl, time-integrated air concentration

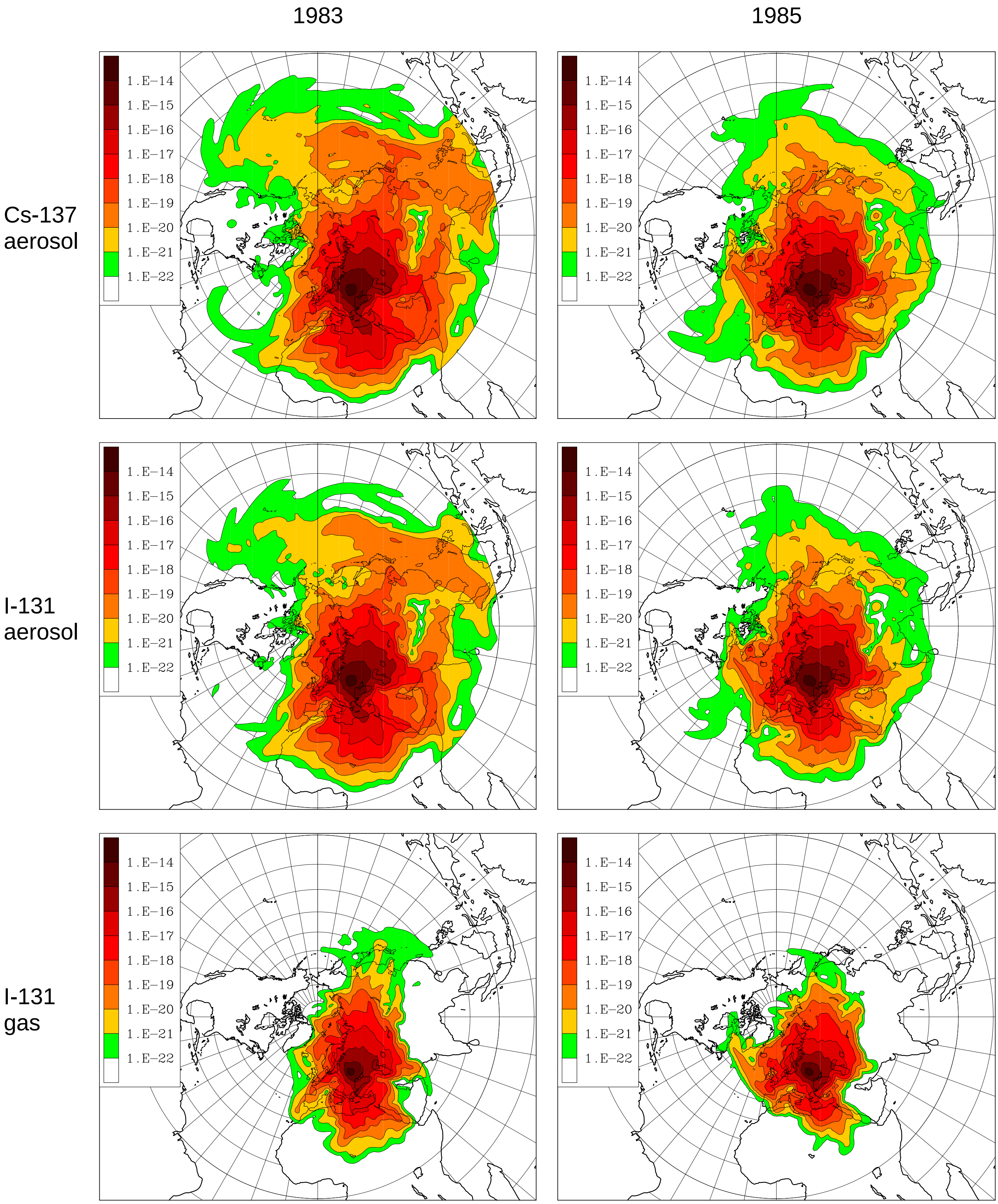


Figure M2. Chernobyl, total deposition

1983 | 1985

Cs-137 aerosol

I-131 aerosol

I-131 gas

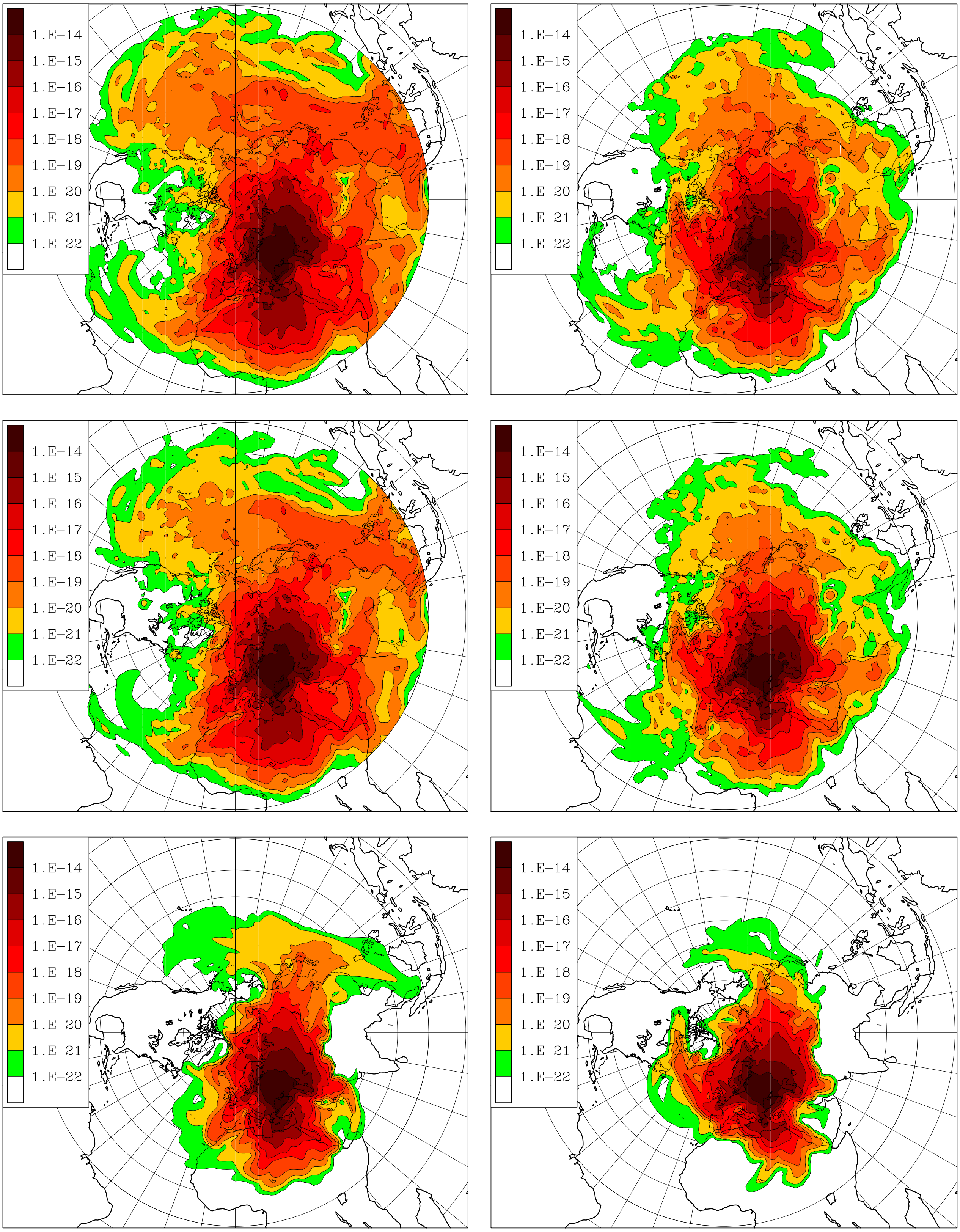


Figure M3. Kola, time-integrated air concentration

1983 | 1985

Cs-137 aerosol

I-131 aerosol

I-131 gas

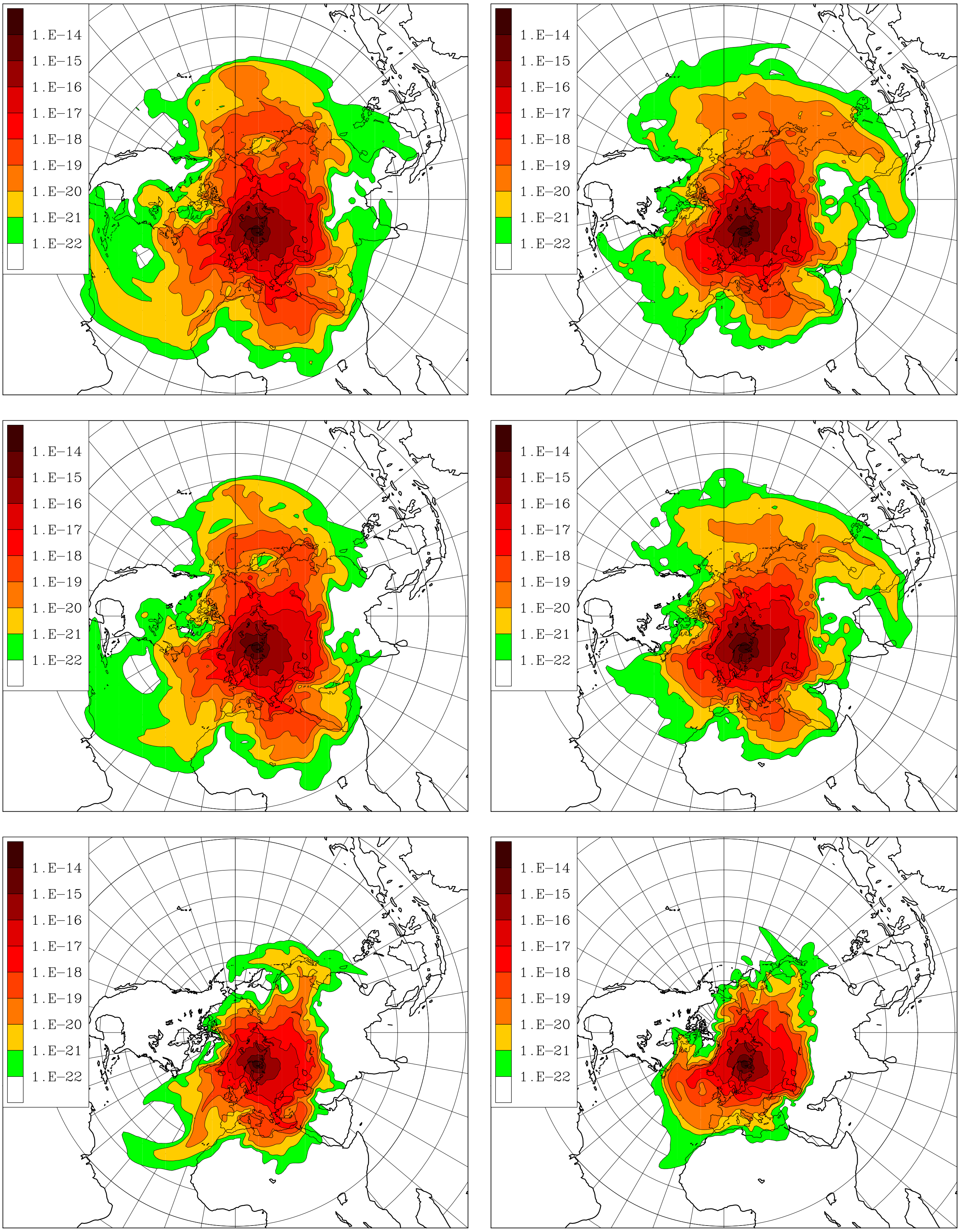


Figure M4. Kola, total deposition

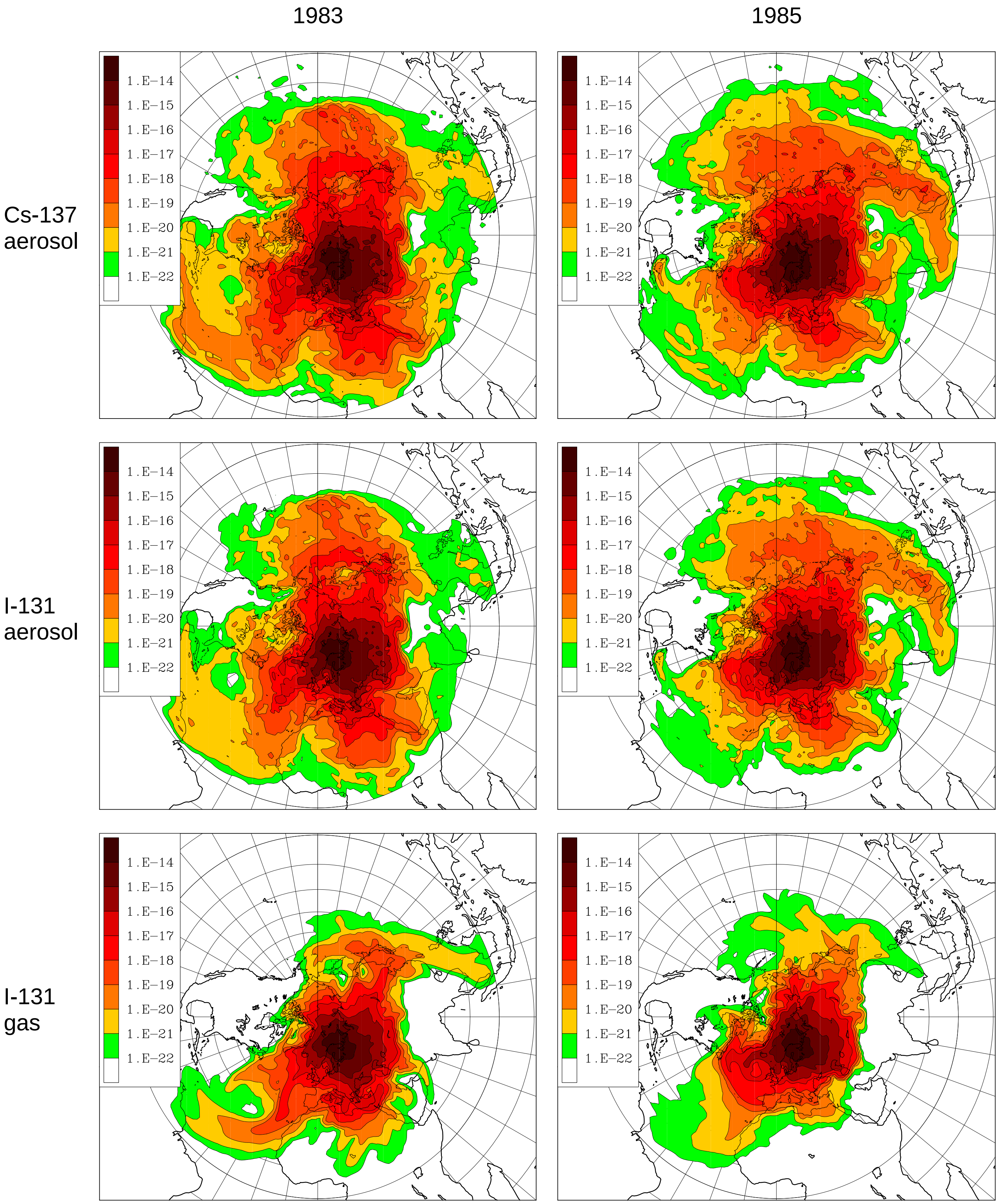


Figure M5. Leningrad, time-integrated air concentration

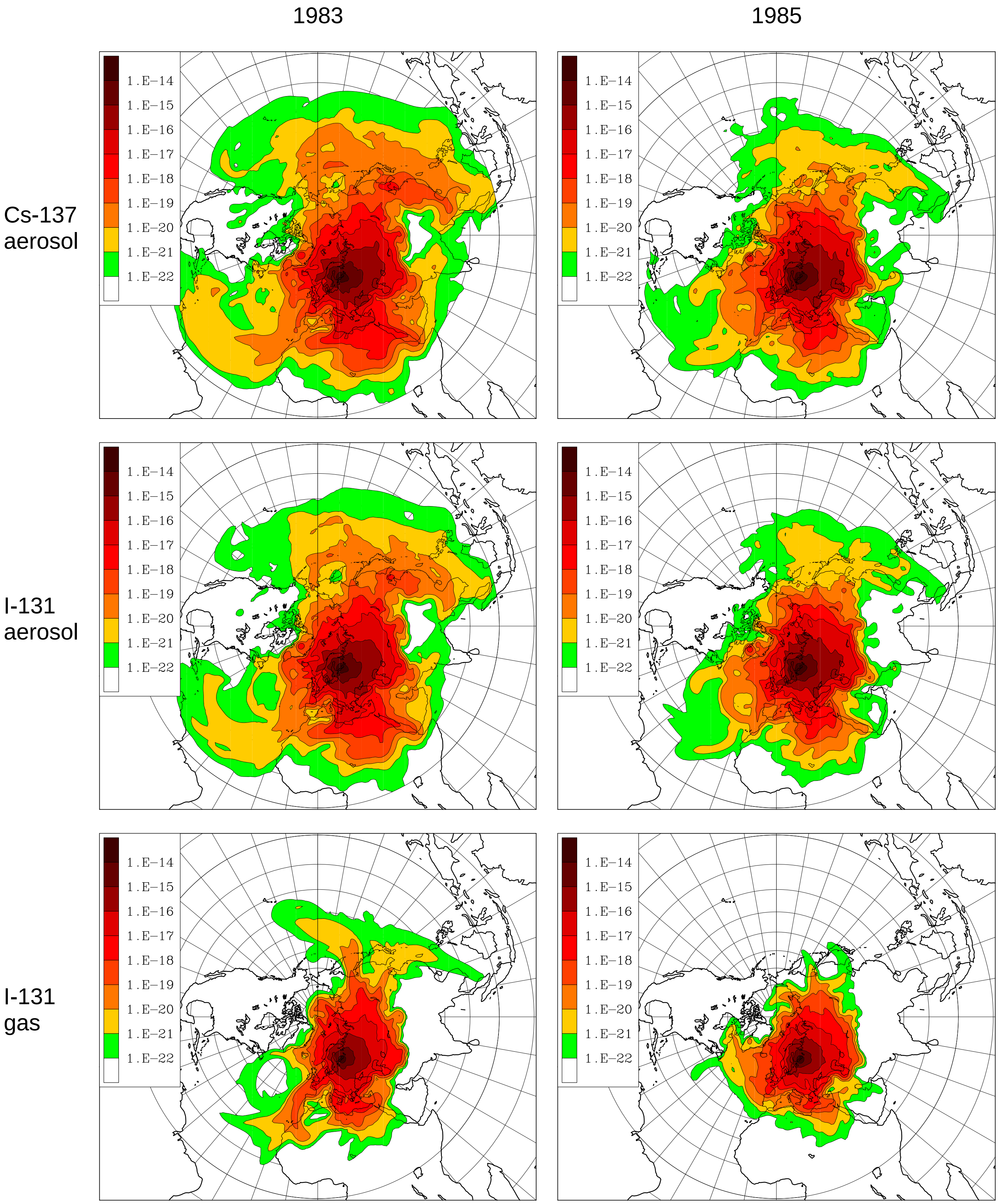


Figure M6. Leningrad, total deposition

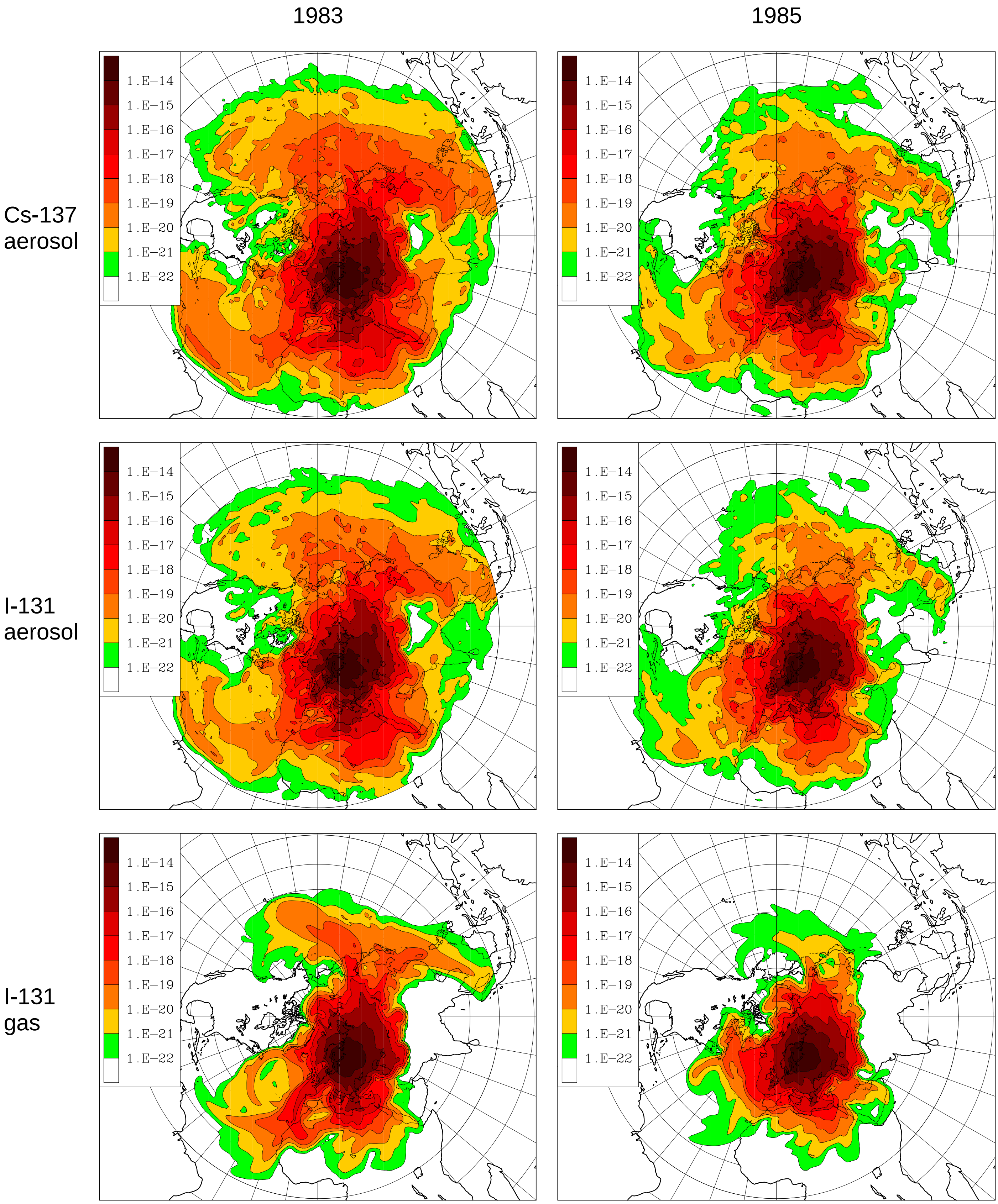


Figure M7. Novaya Zemlya, time-integrated air concentration

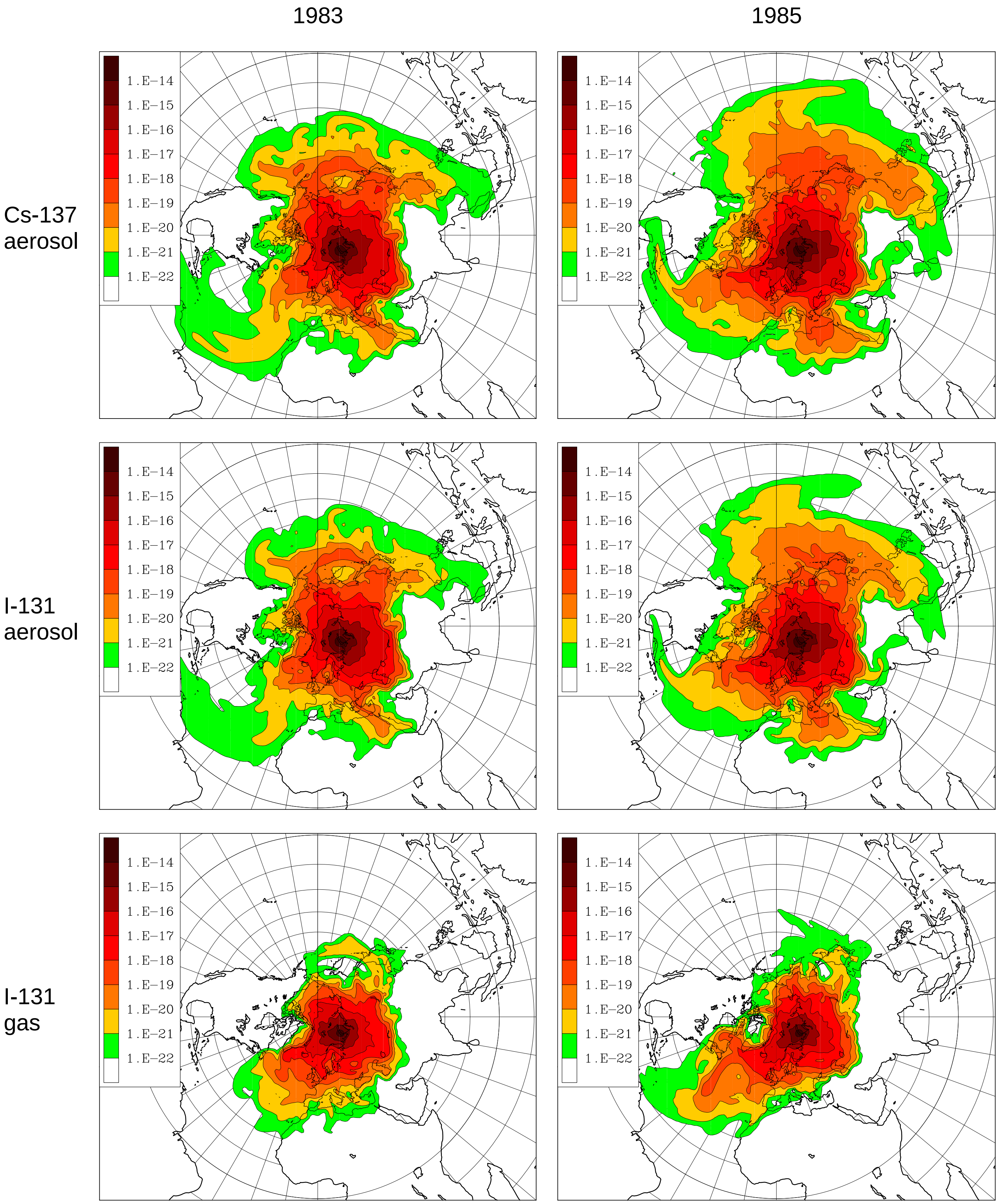


Figure M8. Novaya Zemlya, total deposition

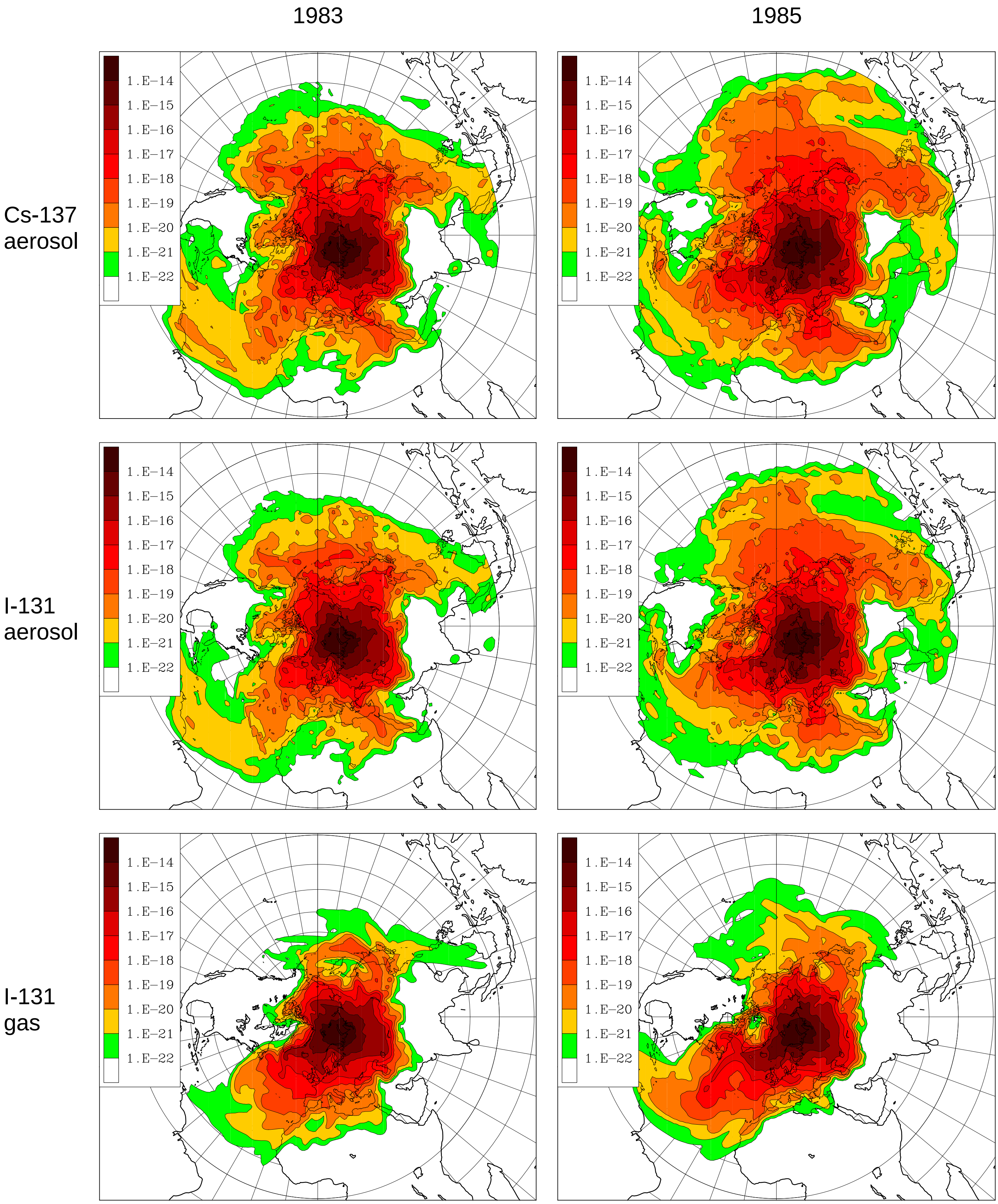


Figure M9. Sellafield, time-integrated air concentration

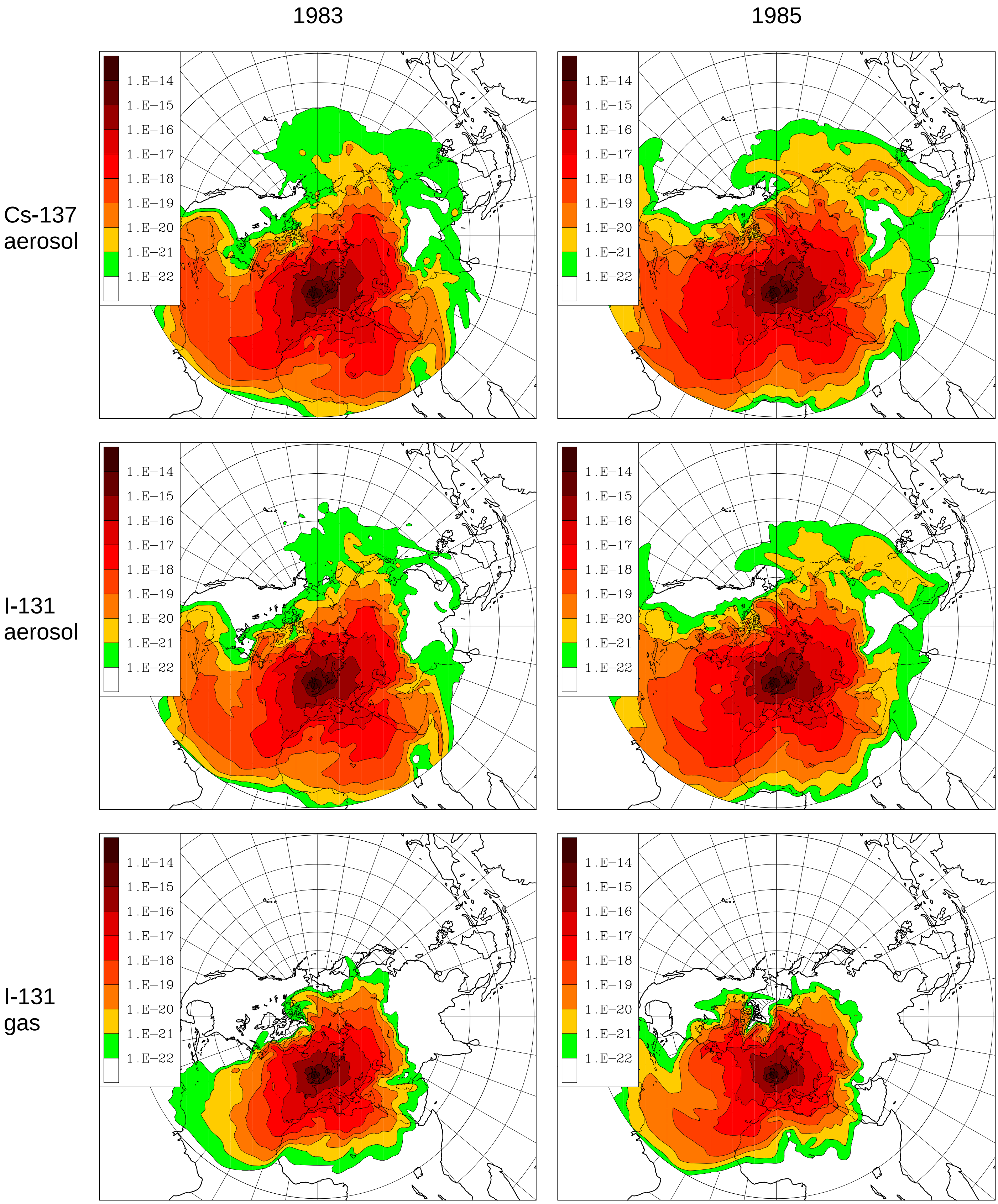


Figure M10. Sellafield, total deposition

1983 | 1985

Cs-137 aerosol

I-131 aerosol

I-131 gas

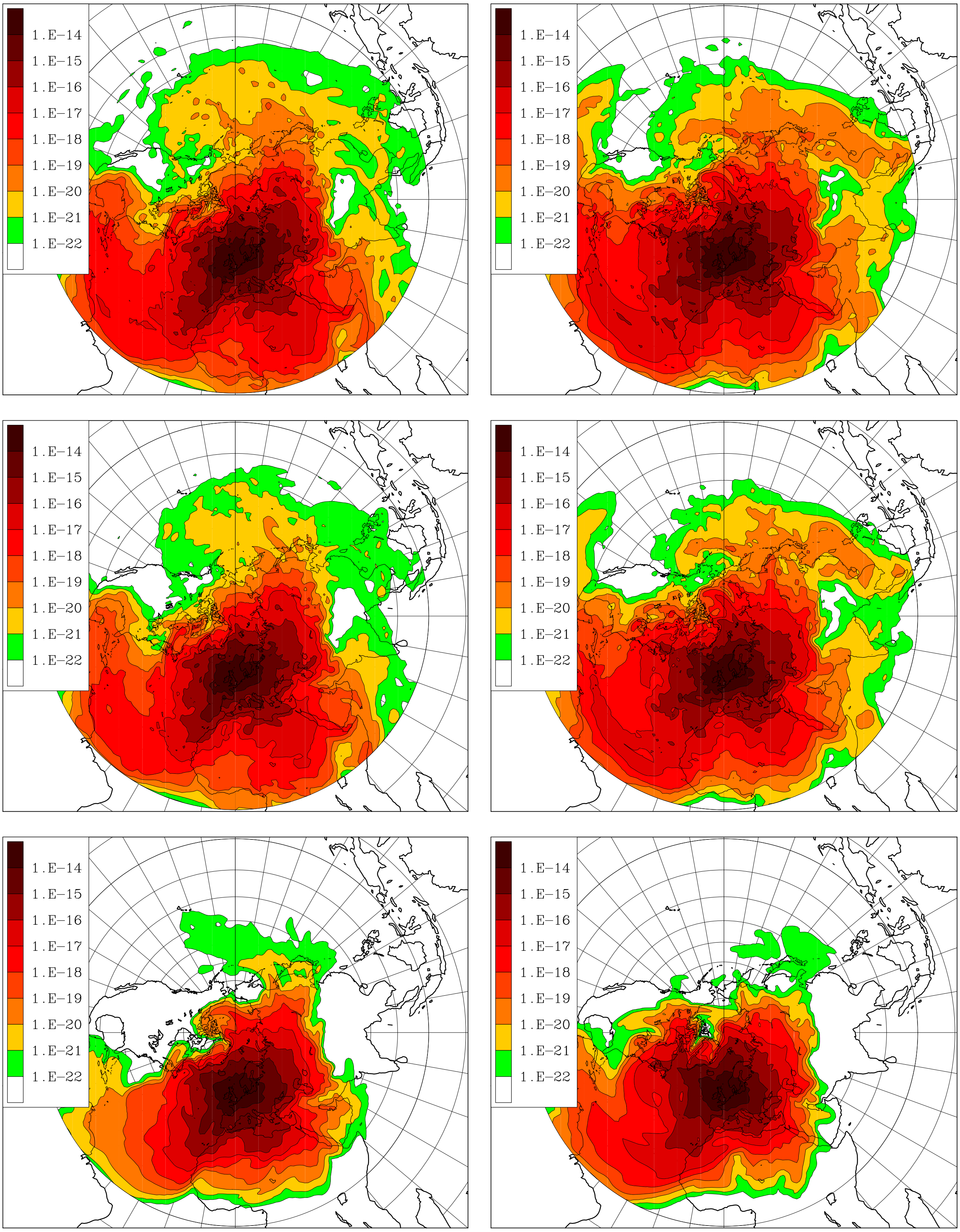


Figure M11. Sinpo, time-integrated air concentration

1983 1985

Cs-137 aerosol

I-131 aerosol

I-131 gas

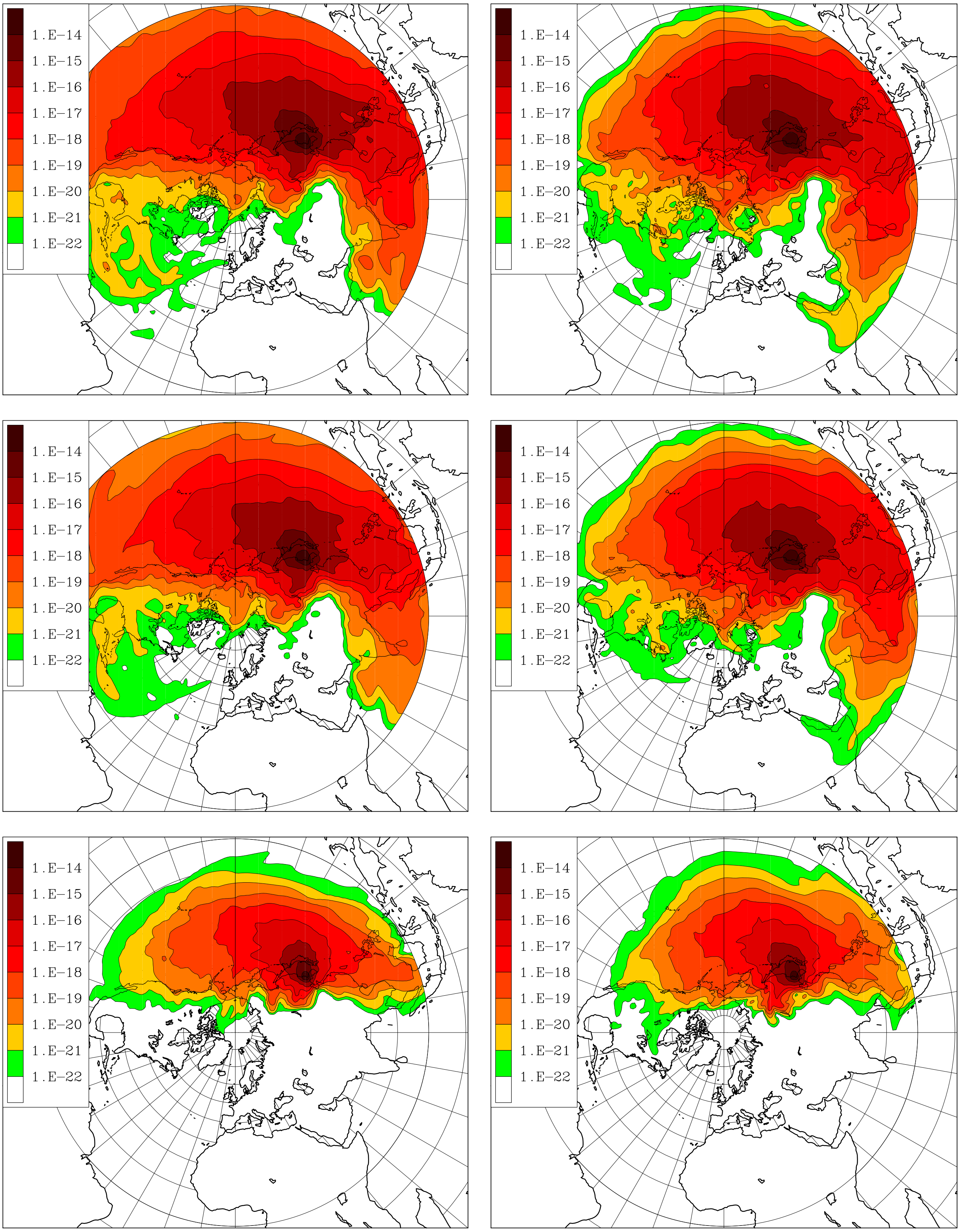


Figure M12. Sinpo, total deposition

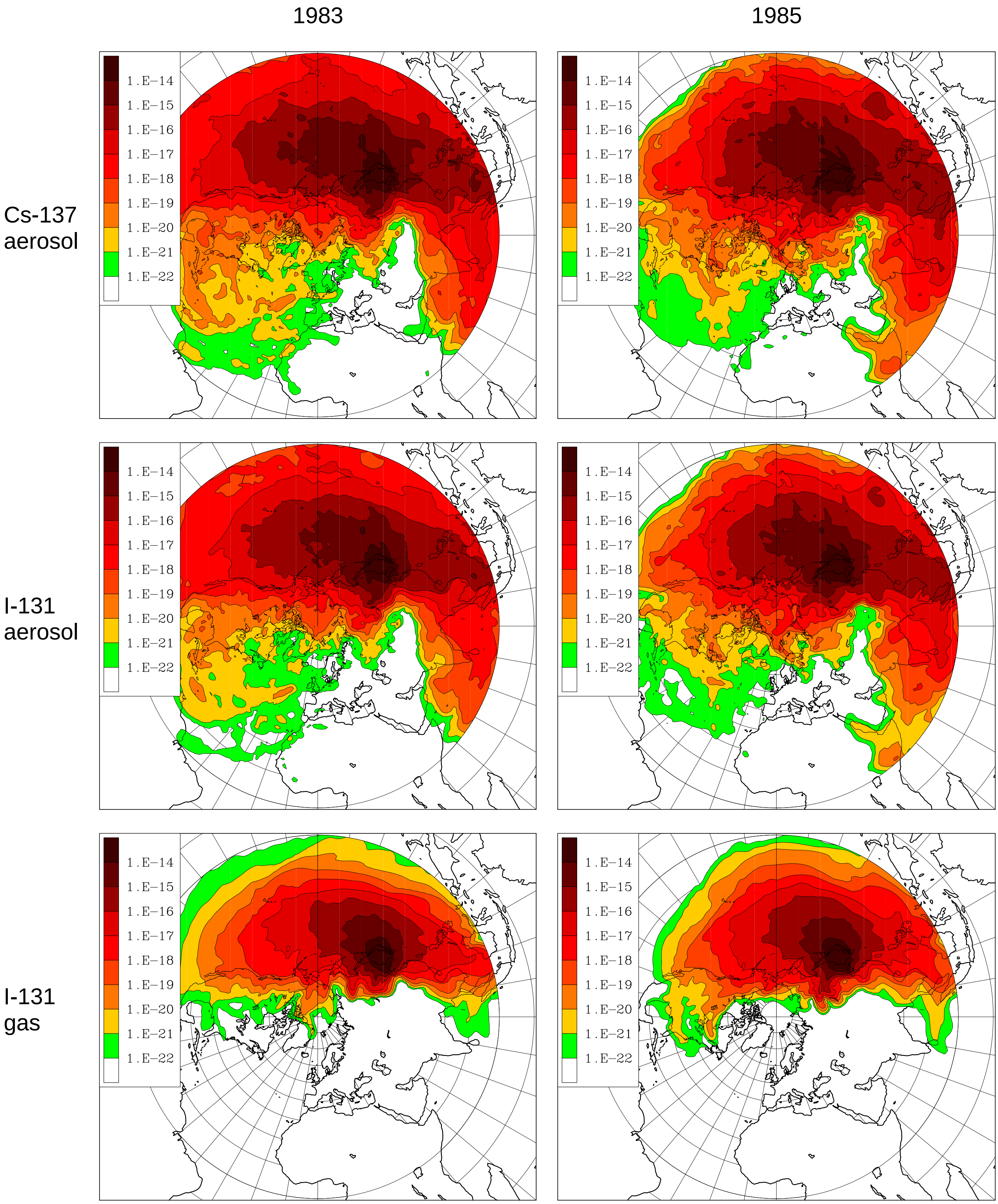


Figure M13. Savannah River, time-integrated air concentration

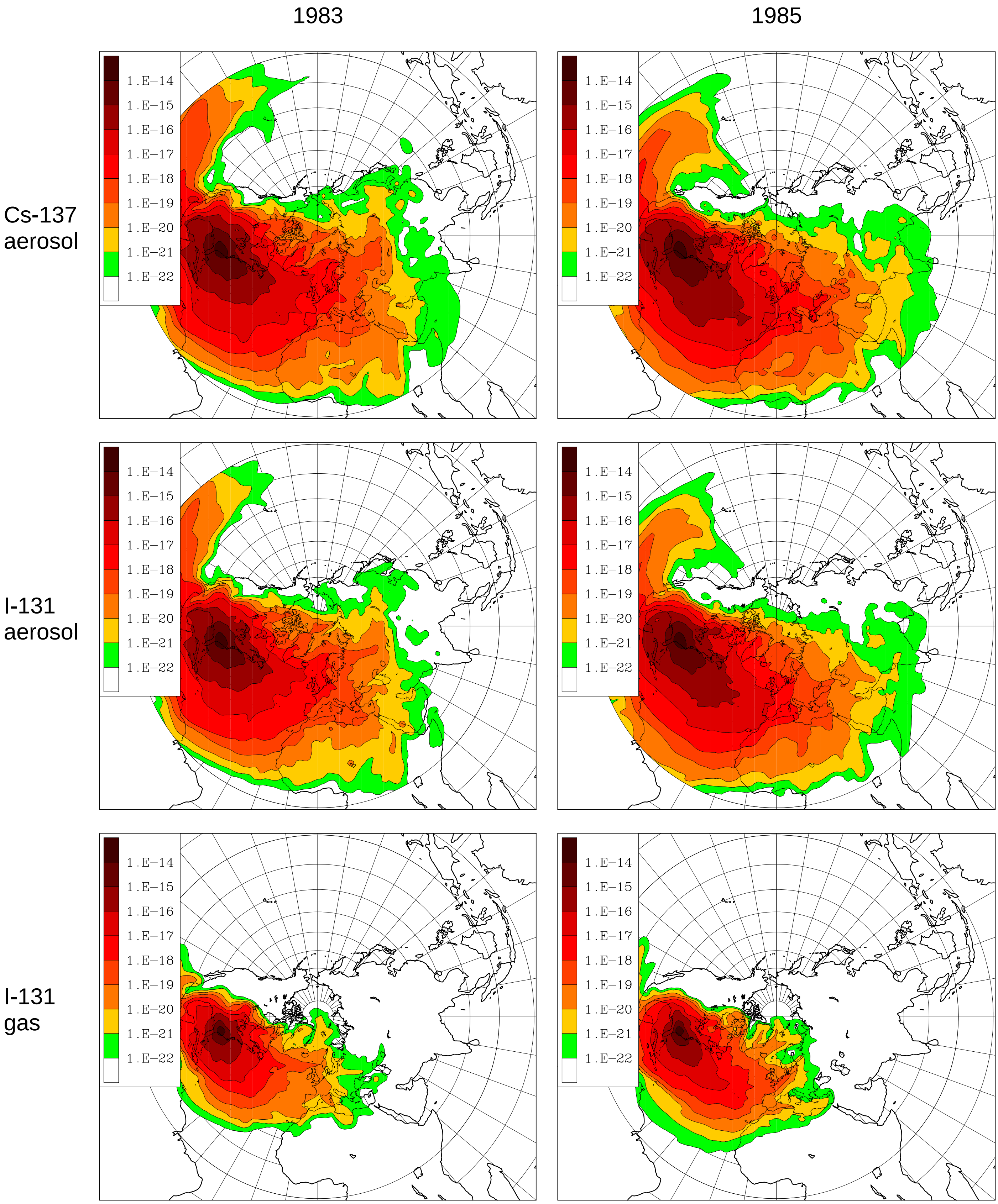


Figure M14. Savannah River, total deposition

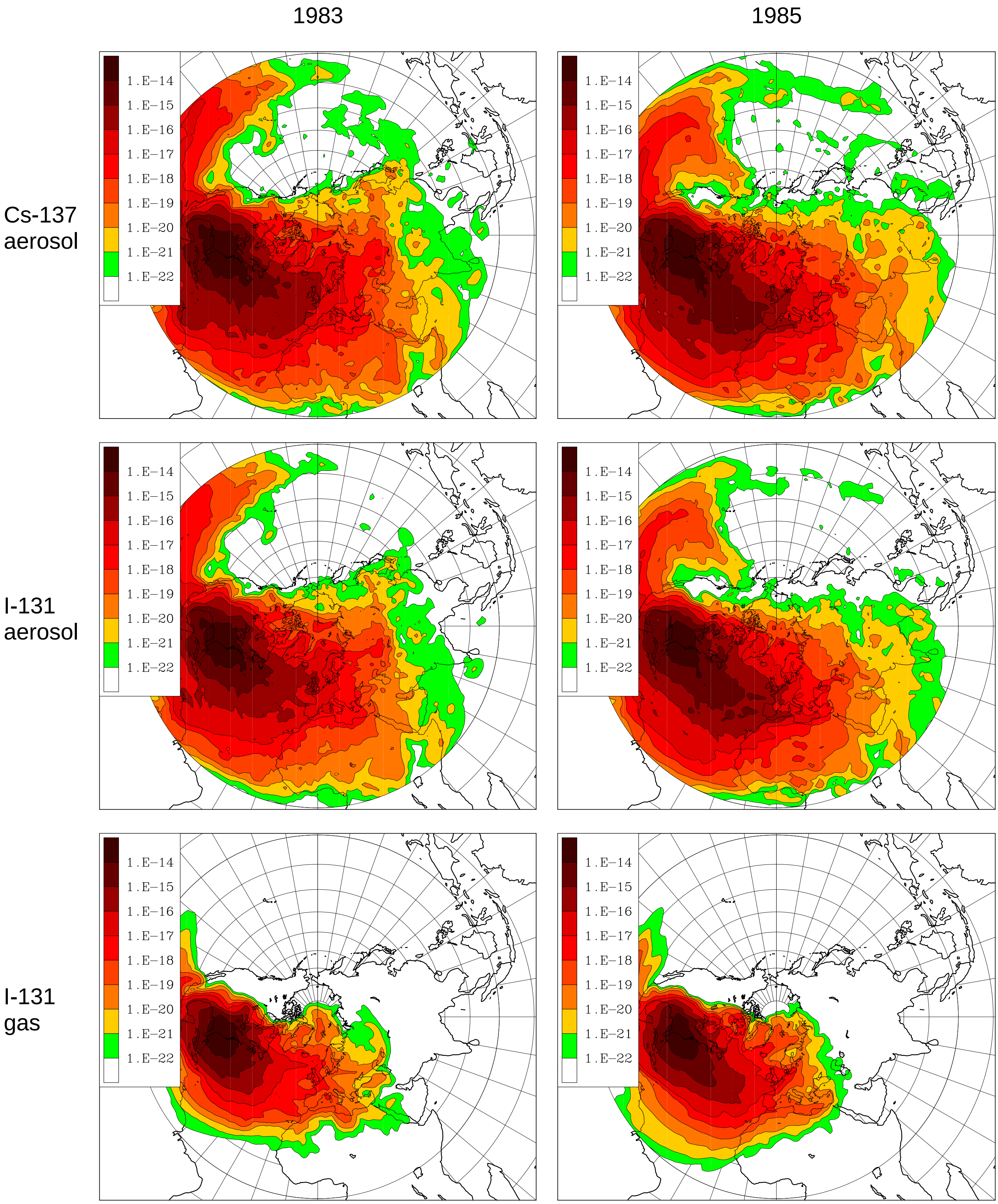


Figure M15. Leningrad NPP, dry and wet deposition

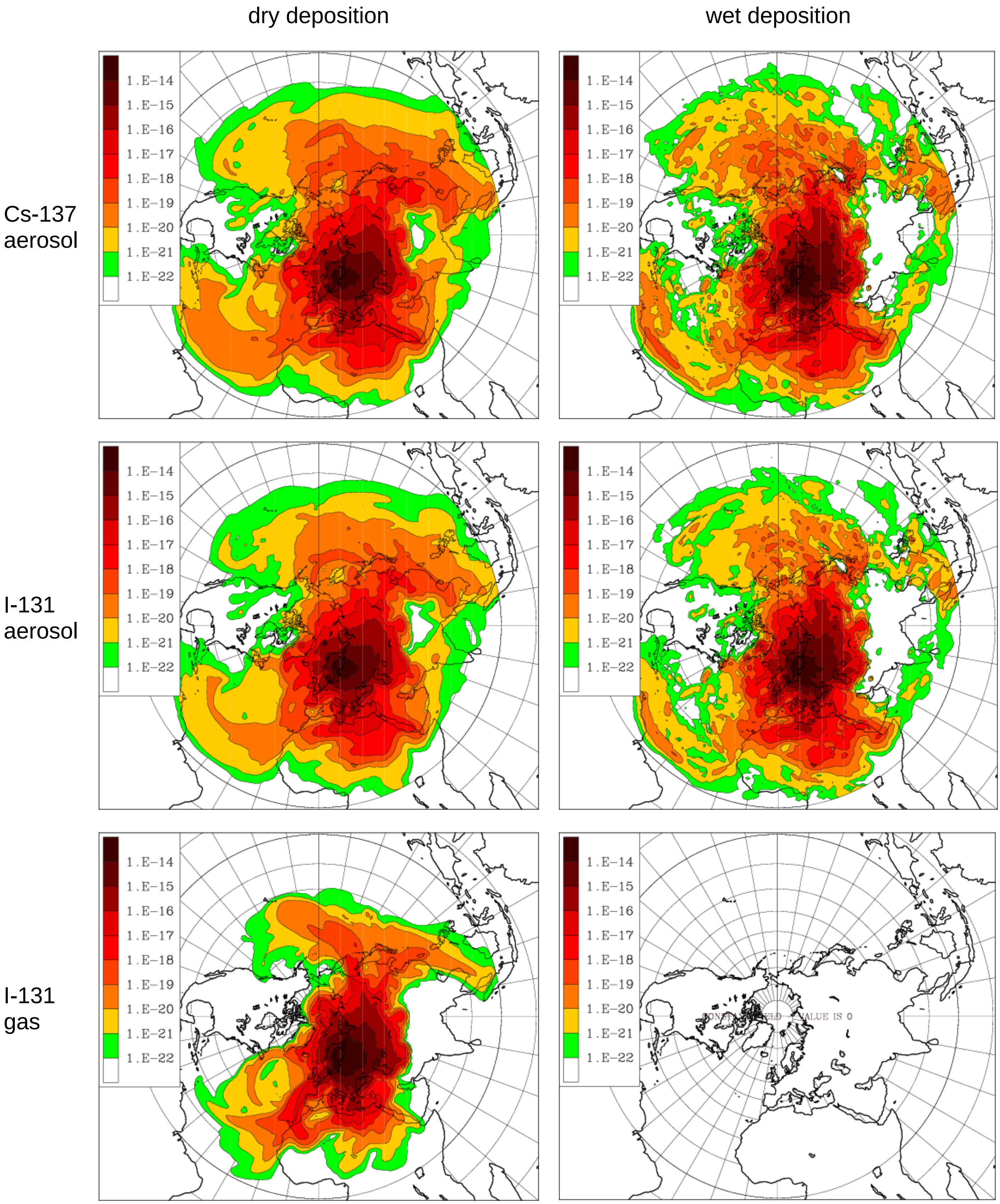
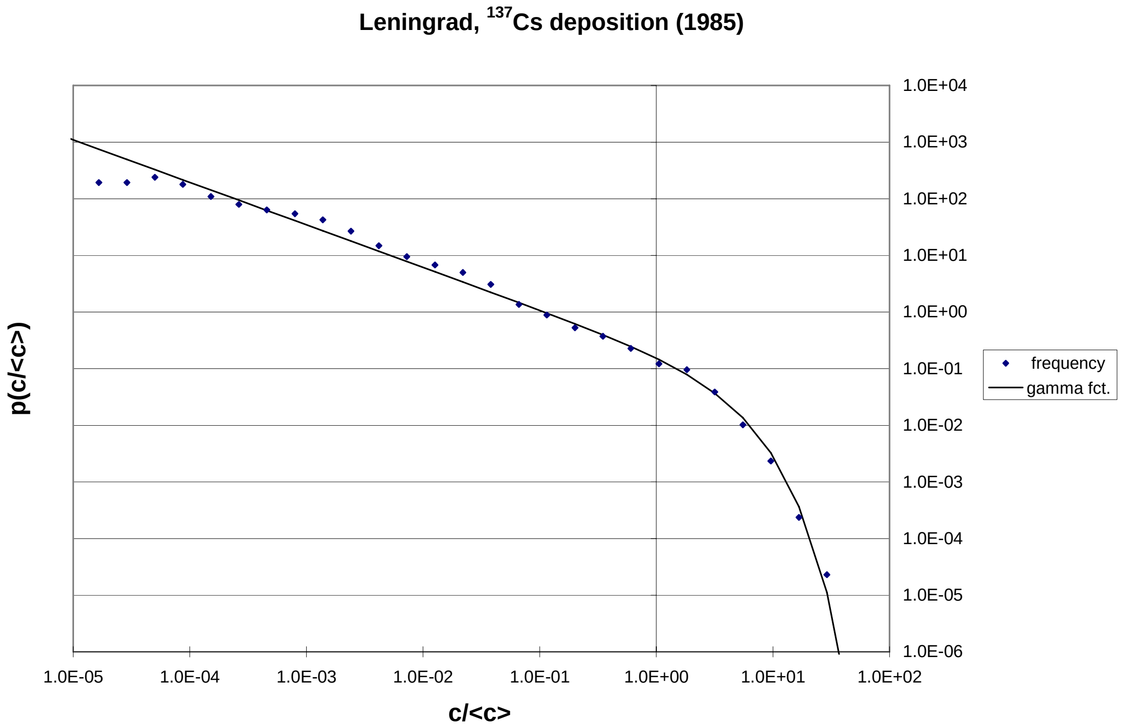
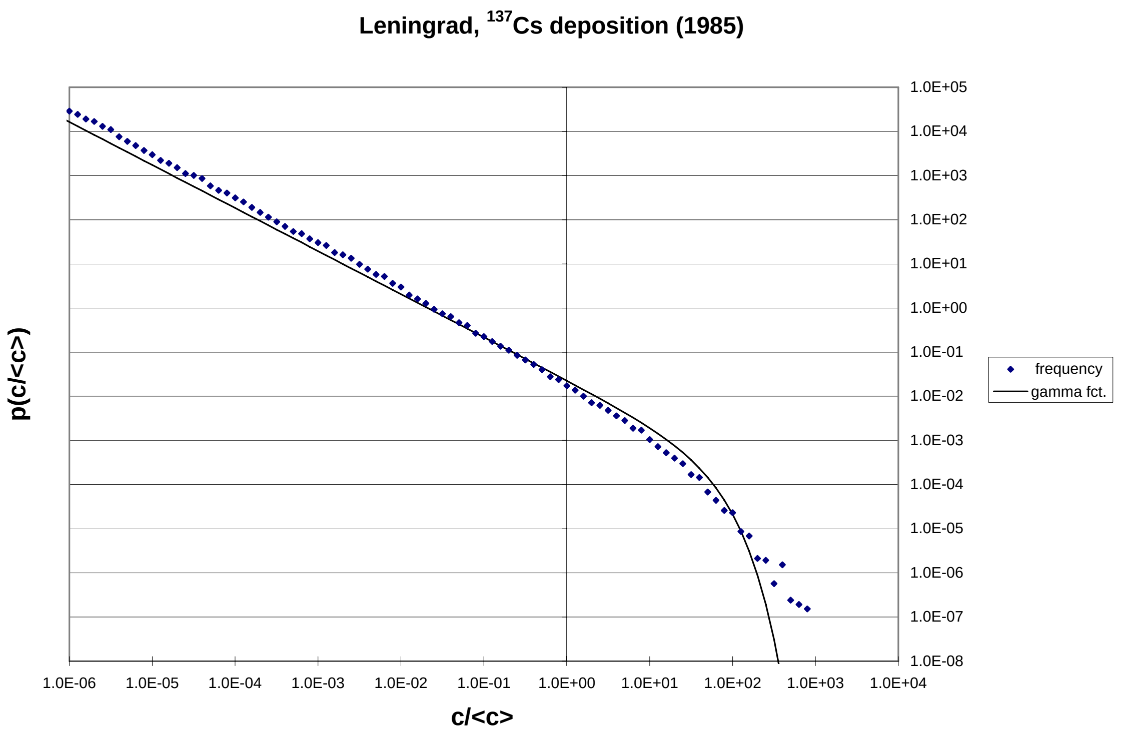


Figure M16. Leningrad NPP, variability



a.. Pdf for the relative deposition density $c/\langle c\rangle$ *where* $\langle c\rangle$ *is the isotropic mean field. The solid line is a gamma model distribution (of unit mean) with shape parameter* $1/\phi = 0.25$.



b. Pdf for the relative deposition density at 2000 km from the release site based on 24-hours releases. The solid line is a gamma model distribution with shape parameter $1/\phi = 0.025$.

Bibliographic Data Sheet NKS-177

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ISBN	978-87-7893-243-3
Date	July 2008
Project	NKS-B / NordRisk
No. of pages	24
No. of tables	2
No. of illustrations	18
No. of references	21
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