SnT2017 T2.4-P19

Use of IMS Data and Its Potential for Research Through Global Noble Gas Concentration Maps

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CTBTO PREPARATORY COMMISSION

Abstract

CTBTO is establishing a global monitoring system for atmospheric xenon radioactivity as part of the International Monitoring System (IMS). Daily activity concentrations have been collected worldwide for over 15 years, of which the past 5 years with reviewed results in IDC Operations, providing unique data sets with long term time series that can be used for the identification of regional sinks and sources and to analyse atmospheric circulation dynamics on the time-scale of the radioxenon isotope half-life (between 9 hours and 11 days). In this study, we use the worldwide noble gas observations at IMS stations for reconstructing global ^{133}Xe concentration maps. This reconstruction is compared with ATM simulations based on known sources. By creating a residual plot, we can optimize the rendering process of the reconstruction map and improve the understanding of the source estimation on a regional basis. The motivation of this work results from the need to get a better understanding of the global distribution of the activity releases from radioxenon background sources to enhance the Treaty monitoring capabilities. Moreover, this study highlights the unique value for civil and scientific applications that is accrued in more than 15 years of worldwide IMS data on atmospheric radioactivity concentrations.

Introduction

- The CTBTO has established an International Monitoring System (IMS) to detect nuclear explosions. Noble gas monitoring is one method to detect nuclear explosions and the IMS is designed to contain 40 noble gas systems of which 25 are already operational.
- Xenon-133 is the most likely noble gas isotope to be detected in the atmosphere at IMS stations following an underground nuclear explosion. (1)
- Xenon-133 is also released from nuclear power plants and medical isotope production facilities, which can create various background levels at IMS stations around the world. A global emission inventory of xenon-133 has been maintained and extended during the development of the IMS and improved understanding of the background levels. (2, 3)

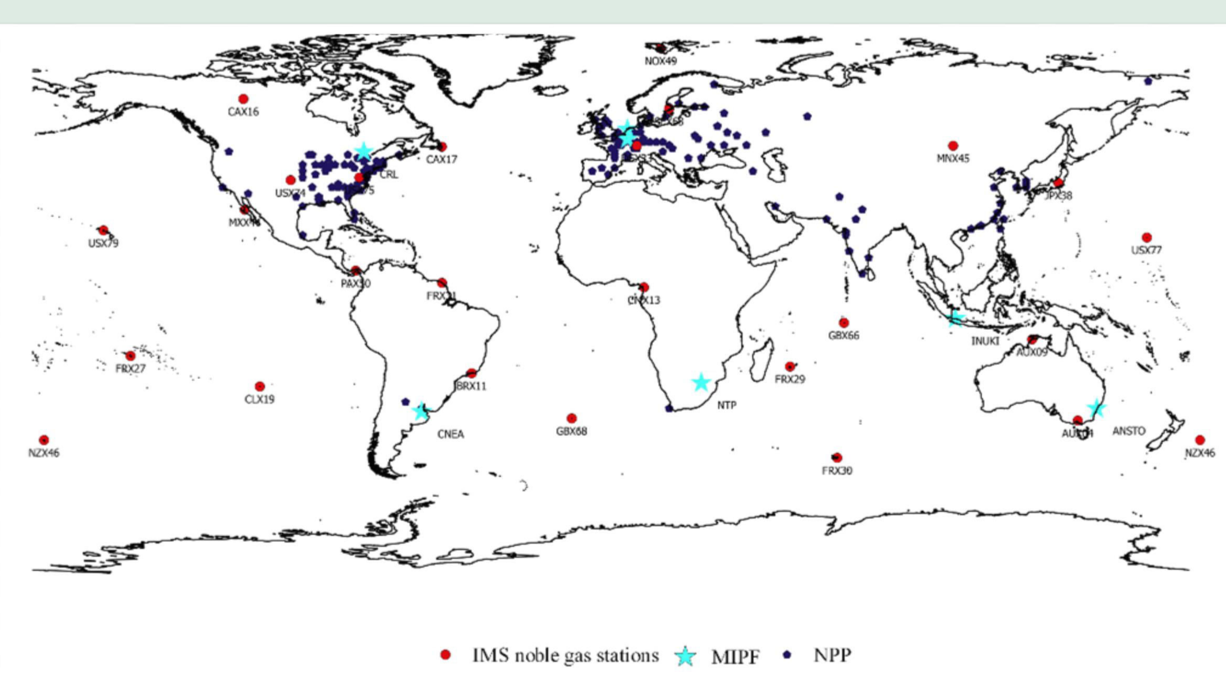

Figure 1. Map showing all operational IMS noble gas systems as of early 2017 and civilian sources[1] of ^{133}Xe : medical isotope production facilities (MIPF) and nuclear power plants (NPP).

- The objectives of this study are
  1. The creation of Xe-133 concentration maps based on IMS measurements of 2014,
  2. The creation of Xe-133 concentration maps based on atmospheric transport modelling and a global xenon-133 emission inventory,
  3. Calculating the residual as the difference between simulated and observed data to drive a direct feedback into the emission inventory.

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Observed data

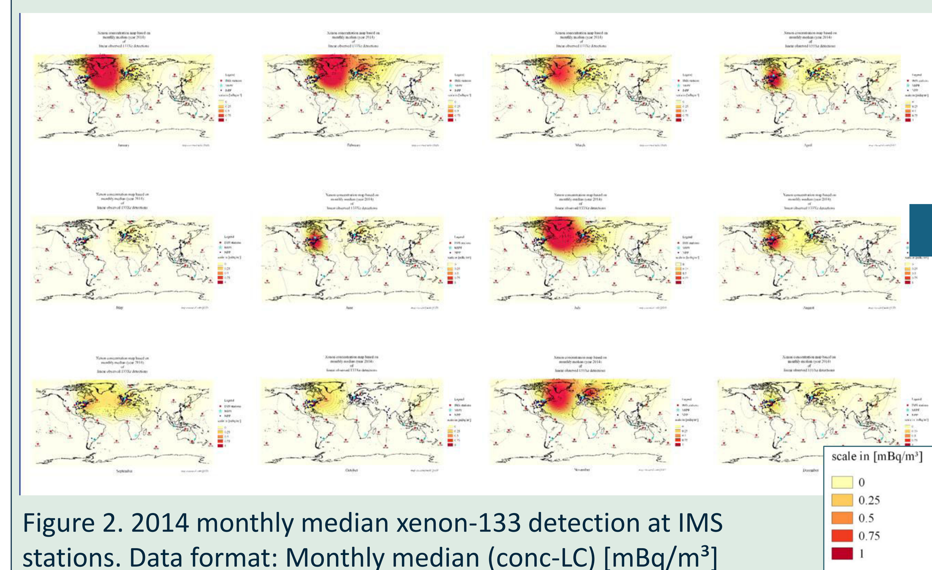

Figure 2. 2014 monthly median xenon-133 detection at IMS stations. Data format: Monthly median (conc-LC) [mBq/m³] interpolated with b-spline method.

- Figure 2 shows the interpolated median of detected xenon-133 concentration at IMS stations.
- Observed data are based on xenon-133 detections from 11504 quality-controlled samples from 25 noble gas systems for the year 2014.

Station Code	System	Data platform	N. of samples
AUX04	Sauna	Testbed (100%)	567
AUX09	Sauna	Ops	455
BRX11	Sauna	Ops	714
CAX16	Spalax	Ops	356
CAX17	Spalax	Testbed (55%)	315
CLX19	Sauna	Testbed (100%)	637
CMX13	Spalax	Ops	199
DEX33	Spalax	Ops	324
FRX27	Spalax	Ops	355
FRX29	Spalax	Ops	232
FRX30	Spalax	Ops	310
FRX31	Spalax	Ops	44
GBX66	Sauna	Ops	652
GBX68	Spalax	Ops	467
JPX38	Sauna	Testbed (35%)	677
MNX45	Spalax	Ops	358
MXX44	Sauna	Ops	704
NOX49	Sauna	Ops	396
NZX46	Sauna	Ops	386
PAX50	Spalax	Ops	298
SEX63	Sauna	Ops	433
USX74	Sauna	Ops	518
USX75	Sauna	Ops	684
USX77	Sauna	Ops	714
USX79	Sauna	Ops	709
		Total n. of samples:	**11504**

Data usage: In the case of [conc > LC] we used the difference: [conc-LC]. Otherwise, if [conc < LC] then no detection over the month, clean background and we used [conc-LC=0]. For SAUNA systems, if the net count is below LC then no detection is present with 95% confidence. For SPALAX systems as LC is not available for post-processing, LC has been approximated by MDC/2. System down times were not considered.

Table 1. IMS noble gas systems details. Selection of samples was based on: Stable xenon volume > 0.2 ml, Sampling time > half-standard cycle and Acquisition time > half-standard cycle.

Observations

- Figure 2 shows clear concentration patterns and high variability in monthly changes. Possibly causes are meteorological seasonal trends and the production cycle of civilian sources, or a combination of both.
- The northern hemisphere has most and strongest sources, mostly located in North America and Europe. The observed seasonal cycle is a convolution of seasonal wind variation and possibly production trend.
- Low concentrations are found in the Southern Hemisphere due to fewer sources.
- Interpolation does not take into account the meteorological dispersion patterns, therefore, stations close to a source with high background levels can play a strong role in the interpolation process.
- Seasonal changes of boundary layer thickness could be influencing the concentration trends.

Simulated data

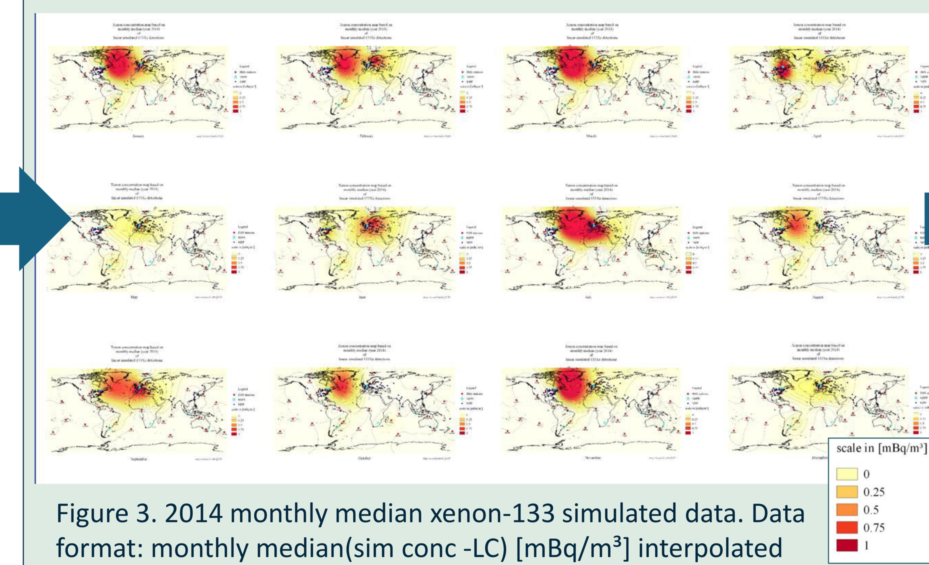

Figure 3. 2014 monthly median xenon-133 simulated data. Data format: monthly median(sim conc -LC) [mBq/m³] interpolated with b-spline method.

- Figure 3 shows interpolated median of simulated data. Xenon-133 emission inventory is based on annual estimates.
- Simulated data are based on xenon-133 emission inventory from civilian sources, which are identified and analysed in the literature. (2, 3, 4)

Source	^{131m}Xe	^{133m}Xe	^{133}Xe	^{135}Xe
IRE	$3.2\ 10^{12}$	$5.0\ 10^{13}$	$2.0\ 10^{15}$	$1.9\ 10^{12}$
NORDION	$3.0\ 10^{13}$	$3.5\ 10^{14}$	$1.5\ 10^{16}$	$1.1\ 10^{13}$
NTP	$1.9\ 10^{13}$	$1.0\ 10^{15}$	$2.3\ 10^{16}$	$2.2\ 10^{15}$
MALLINCKRODT	$7.3\ 10^{8}$	$1.4\ 10^{10}$	$7.3\ 10^{11}$	$8.8\ 10^{6}$
ANSTO	$1.4\ 10^{12}$	$1.6\ 10^{13}$	$6.8\ 10^{14}$	$6.8\ 10^{11}$
INUKI	$4.0\ 10^{11}$	$4.8\ 10^{12}$	$2.0\ 10^{14}$	$4.6\ 10^{14}$
CNEA	$1.7\ 10^{10}$	$1.5\ 10^{11}$	$7.4\ 10^{12}$	$7.4\ 10^{8}$
NPPs Africa	$2.3\ 10^{11}$	$7.4\ 10^{10}$	$3.4\ 10^{12}$	$1.9\ 10^{12}$
NPPs Asia	$9.3\ 10^{12}$	$3.0\ 10^{12}$	$1.4\ 10^{14}$	$7.7\ 10^{13}$
NPPs Europe	$1.4\ 10^{13}$	$4.2\ 10^{12}$	$2.6\ 10^{14}$	$3.4\ 10^{14}$
NPPs North America	$1.5\ 10^{13}$	$7.4\ 10^{12}$	$2.6\ 10^{14}$	$5.3\ 10^{13}$
NPPs South America	$5.7\ 10^{11}$	$1.9\ 10^{11}$	$8.5\ 10^{12}$	$4.7\ 10^{12}$
Total	$9.3\ 10^{13}$	$1.4\ 10^{15}$	$4.2\ 10^{16}$	$2.7\ 10^{15}$

Table 2. Global radioxenon inventory [Bq/year] based on annual estimates of emissions from 174 nuclear power plants and 7 medical isotope production facilities.

- Activity concentrations were estimated through source-receptor-sensitivity (SRS) fields produced from Atmospheric Transport Modelling performed by the PTS with the Lagrangian Particle Dispersion Model FLEXPART and ECMWF historical weather data (1 degree spatial resolution and 3h temporal resolution). (1, 5, 6, 7)

Observations

- Similar to measurements, simulations show seasonal trends and high variability from month to month.
- High concentrations in the Northern Hemisphere and low concentrations in the Southern Hemisphere are observed.
- Because simulations assume constant emissions over the year, the observed patterns are due to seasonal meteorological patterns.

Dataset Access (vDEC)

Dataset used in this paper can also be accessed by the scientific community via the virtual Data Exploitation Centre (vDEC). vDEC provides scientists and researchers with access to CTBTO IMS data to conduct research and to publish new findings. Further details on data request procedure can be found at www.ctbto.org.

Residual data

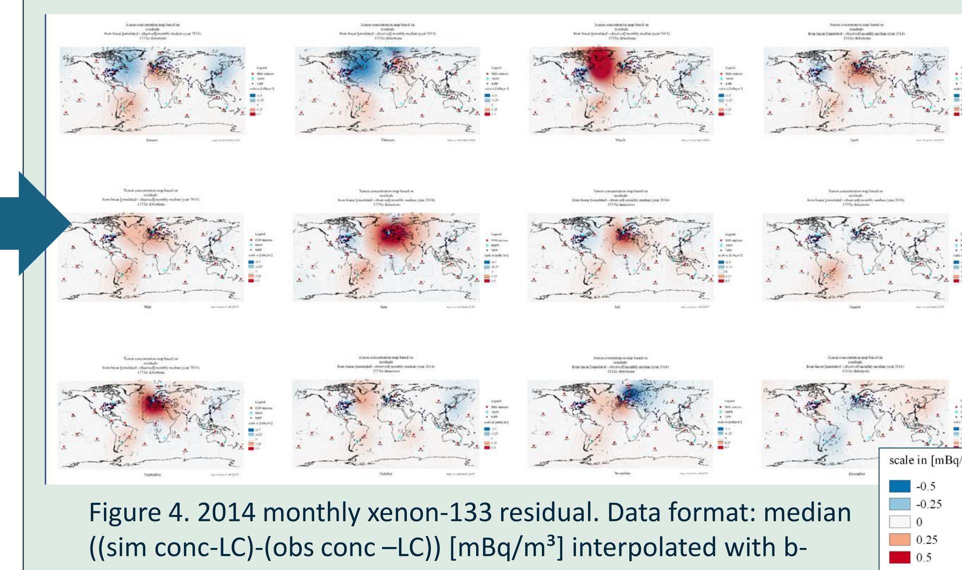

Figure 4. 2014 monthly median xenon-133 residual. Data format: median ((sim conc-LC)-(obs conc –LC)) [mBq/m³] interpolated with b-spline method.

- Figure 4 shows interpolated residuals, i.e. differences between simulated and detected xenon-133 concentrations.

Observations

- Larger discrepancies (positive and negative) are found in the Atlantic region due to higher total source strength.
- Residual discrepancies are most likely caused by seasonal production trends of medical isotope production facilities.
- The southern hemisphere shows a good consistency throughout the year.
- South East Asia presents a general under estimation over the year, except for December, possibly due to unidentified sources in the region.
- Residual data gives opportunity to identify discrepancies of the emission inventory and learn about seasonal emission patterns.

Emission inventory feedback

The average residuals per hemisphere can be used to recognize discrepancies in the emission inventory. The first step is to check the annual emission inventory.

	Annual inventory discrepancy
Northern Hemisphere	+1%
Southern Hemisphere	+1%

- Annual emission inventories of both hemispheres seem in good agreement with actual emissions and are only slightly overestimated by about 1%.
- Larger discrepancies are found on monthly time scales. The discrepancies for the monthly emission inventories can be calculated:

	Emission inventory discrepancy	
	Northern Hemisphere	Southern Hemisphere
January	**-4%**	+1%
February	**-7%**	0%
March	**+4%**	+1%
April	-1%	0%
May	+2%	+1%
June	**+6%**	+1%
July	+0%	0%
August	0%	+1%
September	+3%	0%
October	-1%	0%
November	**-4%**	0%
December	-2%	0%

- Both annual and monthly factors can be fed into the emission inventories of the hemispheres to adjust simulated background levels.
- The resulting adjusted residuals will on average be closer to zero, where zero represent the perfect match between simulated and observed data.

Conclusions

- Xenon-133 activity concentration maps based on IMS observed data and based on simulated data have been created to study global and regional background levels.
- Possible reasons for residual discrepancies:
  - Unidentified sources (→ underestimation).
  - General over- or underestimation of source term (→ long-term over- or underestimation at station).
  - Strong time dependence of releases (→ alternating over- and underestimation).
- Annual and monthly residuals could be used to improve the emission inventory with regard to total emission strength and seasonal trends.
- Xenon-133 detections at IMS stations provide an interesting dataset for the scientific community to study atmospheric processes. In particular for phenomena in the ITCZ region which is highly impacted by wash out effect to which radioxenon is immune.

Outlook

- Extending time range to more years, increasing time resolution to weekly data, further regional partitioning to address regional source strength variations.

References

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(5) Atmospheric transport modelling in support of CTBT verification—overview and basic concepts – G. Wotawa et al. (Atmospheric Env, 2003)
(6) SIMPAX: A Prototype Software Application Simulating the Impact of Radioxenon Emissions from Civil Sources on IMS Stations – Gheddou et al., SNT2017, T2.4-P12.
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Acknowledgements

The data presented in the study were obtained thanks to IMS Station Operators, IMS support staff and IDC analysts.