Towards Supporting Satellite Design through the Top-down Approach: A General Model for Assessing the Ability of Future Satellite Missions to Quantify Point Source Emissions

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Introduction

Monitoring and accurate quantification of emissions from significant point sources is essential for the implementation of emission reduction policies. It also helps to reduce uncertainty in emissions inventories and supports the global stocktake aimed at assessing the progress towards carbon-neutral targets.

Satellite observations can monitor global levels of CO_2 and CH_4 over an extended period by measuring solar backscatter spectra in the shortwave infrared (SWIR) bands. In term of improving the understanding of global anthropogenic emissions at different spatial scales, recently launched and scheduled satellites raise the question of promptly evaluating and establishing the primary technical characteristics to improve their detection capabilities.

Previous studies have identified the key factors that impact the detection and quantitative abilities of satellites, including spatial resolution and measurement precision. However, a comprehensive multi-parameter model for assessing satellite performance has not yet been developed.

Objectives

It is of paramount importance to achieve both high spatial resolution and measurement precision in order to ensure accurate monitoring of XCO_2 and XCH_4 emissions. The challenge of achieving an optimal balance between the two factors for the optimal performance of satellites in quantifying emissions remains a significant issue. This study presents a general methodology and corresponding database to support the design of the next-generation Chinese carbon monitoring satellite (TanSat-2). The methodology and database can be used to evaluate the satellite's ability to detect and quantify point source emissions, depending on several specific characteristics such as spatial resolution, measurement precision, emission intensity and wind speed. By using this approach and the accompanying database, the quantification capabilities of satellites can be promptly assessed, and optimal technical parameters for future satellites can be determined.

Methods

- **Gaussian dispersion model**

The vertically-integrated Gaussian dispersion model (2D model) is used to simulate the concentration enhancement in the atmosphere, which is expressed as

$$V(x,y) = \frac{Q}{\sqrt{2\pi}\,\sigma_y(x)u} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y(x)}\right)^2}$$

$$\sigma_y(x) = a\left(\frac{x}{x_0}\right)^{0.894}$$

To simplify subsequent analysis, we convert the unit of the simulated vertical column enhancement V to match that used by satellite products. The unit should be converted as

$$X_{gas} = V \cdot \frac{M_{air}}{M_{gas}} \cdot \frac{g}{P_{surf} - w \cdot g} \cdot 1000$$

- **Integrated mass enhancement (IME) method**

The total emission mass is calculated as the detectable total plume mass downwind with the formula

$$IME = \sum_{j=1}^{N} \Delta\Omega_j A_j$$

The emission intensity of the point source is calculated by

$$Q = \frac{IME}{\tau} = \frac{u}{L} IME$$

- **Parameterised assessment model**

The model uses two Gaussian distribution parameters (mean μ and standard deviation σ of the estimation relative bias) to evaluate the quantification capability of the satellites

$$\mu = f_1(Q, x, p, u) \qquad \sigma = f_2(Q, x, p, u)$$

Results

- **Assessment of satellite detection capability**

Figure 1 illustrates the spatial resolution and measurement precision required for the satellite to identify CO_2 and CH_4 emission plumes of varying intensities at a wind speed of 3 m/s. The requirement for spatial resolution and measurement precision in detecting plumes decreases with increasing emission intensity of point sources. For instance, to detect the plume from a CO_2 point source emitting more than 0.01 Mt/yr at a wind speed of 3 m/s, a satellite with a spatial resolution of 25×25 m² would require a measurement precision of 1 ppm. However, to detect the plume of a point source emitting more than 0.1 Mt/yr with the same spatial resolution, a measurement precision of only 10 ppm is required. Conversely, if the satellite has a measurement precision of 1 ppm, it only needs a spatial resolution of 0.25×0.25 km² to capture the plumes from the point source with the same emission intensity at a wind speed of 3 m/s. According to the study that power plants with an emission intensity greater than 1 Mt/yr contribute to 88% of the total emissions from power plants. This implies that it is crucial to monitor and accurately quantify point sources emitting more than 1 Mt/yr. To meet this requirement, the satellite measurement should have a spatial resolution of 2×2 km² and a measurement precision of 1.4 ppm. In some cases, a lower measurement precision may be accepted with a higher spatial resolution configuration. In our evaluation, we found that the OCO-2(3), TanSat, Microcarb, CO2M, and GeoCarb satellites are capable of measuring CO_2 plumes with detection capabilities of approximately 1.28 Mt/yr, 5.11 Mt/yr, 0.64 Mt/yr, 0.89 Mt/yr, and 14.75 Mt/yr for CO_2 point sources at a wind speed of 3 m/s, respectively.

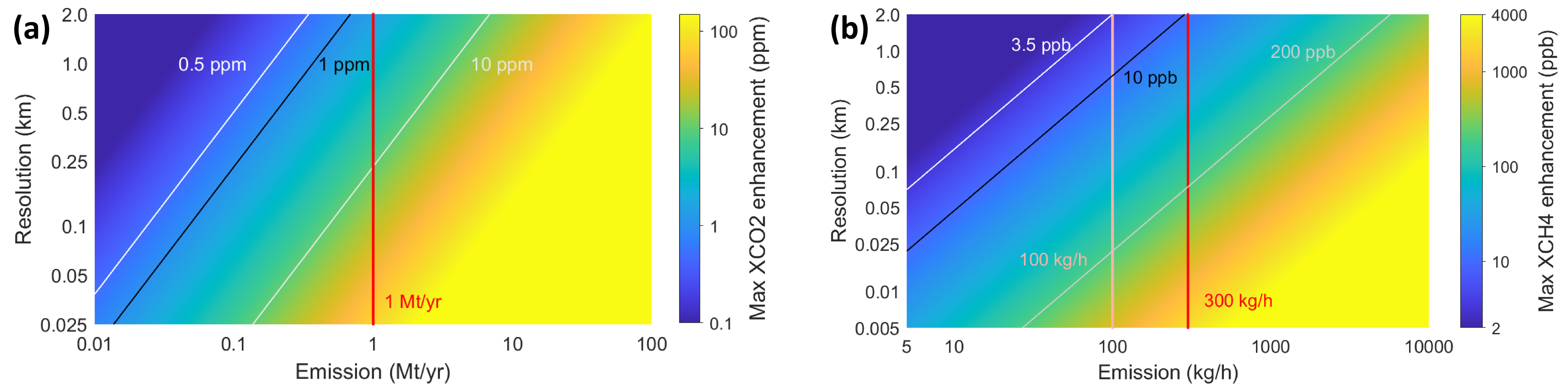

Fig1. Requirements for spatial resolution and measurement precision in detecting CO_2 (a) and CH_4 (b) emissions. The assessment is conducted under a wind speed of 3 m/s, without considering instrument noise. The red lines represent intensities of 1 Mt/yr for CO_2 emission and 300 kg/h for CH_4 emission, while the pink line represents CH_4 emission intensities of 100 kg/h. The white, black, and grey lines indicate maximum XCO_2 or XCH_4 enhancement of different values.

- **Assessment of satellite quantification capability**

Figure 2 show the mean and standard deviation of the relative biases for satellite-estimated CO_2 and CH_4 emissions, respectively. The unoccupied space in the upper right corner of each subfigure indicates the case where the satellite could not detect emission plumes to conduct emission estimates. For lower emitting CO_2 and CH_4 point sources, estimates may have relative biases above 100% due to limitations in satellite spatial resolution and measurement precision. The figures also display that the current satellite XCO_2 product, with a measurement precision of 1 ppm and a spatial resolution of 2×2 km², can accurately quantify CO_2 point source emissions with an intensity above 10 Mt/yr at a wind speed of 3 m/s. Satellites that can detect CH_4 with a spatial resolution of hundreds of square metres and a measurement precision of tens of ppb are capable of accurately quantifying CH_4 point source emissions with an intensity of more than 500 kg/h. It is also shown that as the emission intensity of point sources increases, the requirement for satellite spatial resolution and measurement precision to achieve unbiased emission estimation (μ=0) gradually decreases. Additionally, the standard deviation of the estimation bias decreases significantly with increasing point source emission intensity. This means that the estimation accuracy is more stable with higher point source emission intensity when the emission estimate is performed using satellites with the same spatial resolution and measurement precision.

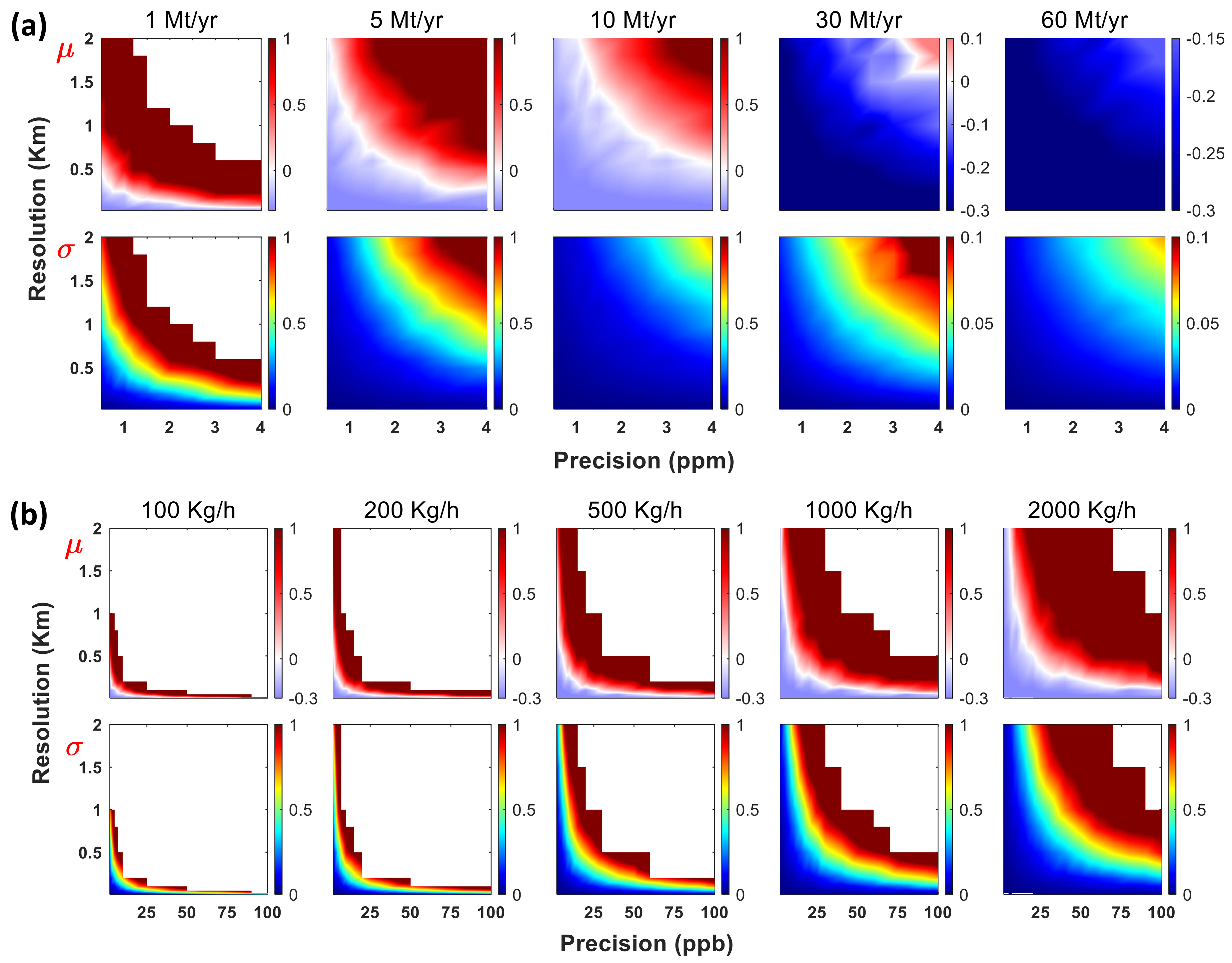

Fig2. The ability of satellite measurements to quantify CO_2 (a) and CH_4 (b) emissions from point sources at a wind speed of 3 m/s. The estimation accuracy is represented by the mean (μ) and standard deviation (σ) of the relative bias of the satellite-estimated CO_2 and CH_4 emissions, displayed in the top and bottom panels. The CO_2 and CH_4 point sources shown here have different emission intensities.