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► **To cite this version:**

Frederic Chevallier, Francois-Marie Breon. Comment. Journal of the American Statistical Association, 2018, 113 (521), pp.173-175. 10.1080/01621459.2017.1419138 . hal-02976524

HAL Id: hal-02976524

<https://hal.science/hal-02976524>

Submitted on 1 Jul 2021

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To cite this article: Frédéric Chevallier & François-Marie Bréon (2018) Comment, Journal of the American Statistical Association, 113:521, 173-175, DOI: [10.1080/01621459.2017.1419138](https://doi.org/10.1080/01621459.2017.1419138)

To link to this article: <https://doi.org/10.1080/01621459.2017.1419138>



Published online: 16 May 2018.



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Funding

The authors gratefully acknowledge the financial support of NASA grants 15-HMA15-0030 and 15-cryo2015-0032.

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JOURNAL OF THE AMERICAN STATISTICAL ASSOCIATION
2018, VOL. 113, NO. 521, Theory and Methods
<https://doi.org/10.1080/01621459.2017.1419138>



Comment

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ABSTRACT

Based on the measurements of the OCO-2 satellite, Noel Cressie addresses a particularly hard challenge for Earth observation, arguably an extreme case in remote sensing. He is one of the very few who has expertise in most of the processing chain and his article brilliantly discusses the diverse underlying statistical challenges. In this comment, we provide a complementary view of the topic to qualify its prospects as drawn by N. Cressie at the end of his article. We first summarize the motivation of OCO-2-type programs; we then expose the corresponding challenges before discussing the prospects.

KEYWORDS

Atmospheric inversion;
Climate change; Orbiting
carbon observatory-2

1. A New Large International Climate Mitigation Effort

As rightly explained by the author, remote sensing of CO₂ from space is attempting to meet an increasing demand for information on the main drivers of climate change. Its stated ambition is to contribute both to the understanding of biogeochemical cycles (understanding the mechanisms underlying carbon sources and sinks to anticipate climate change), and to the monitoring of regulatory policies for the fluxes of these gases (quantifying the sinks to preserve and strengthen them, quantifying sources to regulate them and to monitor the reductions promised by the states, like the Nationally Determined Contributions of the Paris climate agreement). CO₂ measurement from space is therefore mainly motivated by the Level 4 product described by the author, not by the concentrations themselves (the Level 2 product described in the author's Section 2). This lack of interest for the Level 2 product in itself is specific to this field. It implies that the objectives of the satellite missions are often formulated in terms of Level 4 data (see, e.g., Crisp, Miller,

and DeCola (2008)) and that fulfilling them relies on a long and partly uncertain processing chain.

With these objectives, CO₂ remote sensing represents a new large international monitoring effort that will feed even larger information systems like the Integrated Global Greenhouse Gas System of the World Meteorological Organization (DeCola and WMO Secretariat 2017). Current results show an increasingly active and creative scientific field. The processing chains are developed within a strong international cooperation and a growing scientific community. They bring together "a large village of scientists and engineers" in the author's words. All the challenges encountered so far have stimulated and renewed the scientific problems related to the remote sensing of the atmosphere from space. The challenges remain high since Level 4 products generated by different groups still diverge strongly according to the transport model used and according to the assimilated satellite products (e.g., Houweling et al. 2015). In certain configurations, the results in some regions of the globe may seem plausible, but the whole still lacks coherence and, in some cases, realism (e.g.,

Reuter et al. 2017). Actually, a series of systematic errors have been identified, but not quantified, in the satellite processing chain, as explained in the next section.

2. Little Tolerance for Systematic Errors

Within a year, the variations of XCO_2 in space and time are usually smaller than the XCO_2 background value by two orders of magnitude or less. XCO_2 therefore requires exceptionally fine detection capabilities and processing quality. The large data volume offered by satellites rapidly renders random errors harmless for the estimation of surface fluxes from the concentrations, but systematic errors in the column measurements are hardly tolerated (Chevallier, Bréon, and Rayner 2007). In the case of intense emissions (e.g., large fossil fuel power plants), CO_2 plumes can be relatively dense, but anthropogenic emissions are better known than natural fluxes and bringing new knowledge leads to higher requirements. The interpretation of the measured spectra is penalized by errors in spectroscopic models and other variables that affect the spectrum Y (the non- CO_2 values in the state vector X , like concentrations of other gaseous or aerosol species, or surface properties). Unfortunately, many of them are systematic, at least for a given region of the globe and time of the year. The empirical calibration procedure of the Level-2 product (described at the end of the author's Section 2) already reveals significant systematic errors in the direct XCO_2 retrievals (i.e., the outcome of the process described in the author's Equation (4)). Some of them depend on variables that are themselves correlated with surface fluxes (Wunch et al. 2011), penalizing signal analysis. This is the case for surface albedo, which can be related to a change in the type of source or sink (e.g., low albedo on forests, CO_2 sinks, and strong on urbanized areas, CO_2 emitters). The dependence of systematic errors on the characteristics of the scene also disturbs the monitoring of the emission plumes during their dispersion.

The lack of tolerance for systematic errors also applies to the transport models B_p that simulate these columns to estimate the fluxes afterwards. It is difficult to quantify their uncertainty, but numerical intercomparison exercises suggest significant sensitivity of the recovered fluxes to the characteristics of the underlying transport models (e.g., Houweling et al. 2010). Some approaches combine XCO_2 retrievals with observations about the carbon cycle of different types, like column-averages of carbon monoxide concentrations or indices of vegetation activity (e.g., Rayner, Utembe, and Crowell 2014; MacBean et al. 2016). They require coupling the transport model B_p with (uncertain) flux-process models, that themselves significantly increase the error budget and its systematic part (Kuppel, Chevallier, and Peylin 2013; Ammoura et al. 2016). In this case, complexity may be moved around (e.g., from estimating unknown CO_2 emission fluxes to estimating unknown emission ratios of CO over CO_2) but not necessarily reduced. The situation is different when XCO_2 retrievals are combined with direct observations of atmospheric transport (typically pressure or wind measurements) if they do not require the addition of a new physical model. Indeed, such measurements reduce the error budget of atmospheric inversion without counter effects (e.g., Lauvaux et al. 2016).

3. Discussion

In this context, it may be too early to guess the actual performance of Level 4 products when they reach maturity and whether they can really form the basis of a CO_2 Monitoring and Verification System for climate policy like in the author's argument. N. Cressie quotes NASA's "if you can't measure it, you can't manage it", but this line does not imply by itself that carbon fluxes will be best monitored from space (given possible technological improvement of the surface measurements, as illustrated by Wu et al. (2016)). In order not to lose time in this strategic domain, space agencies in the US, Japan, China, France, and the UK are proactive and prepare for the best. Indeed, the current satellites described in the author's Section 5 should be followed within the next five years by about five missions. Most of these missions include technological improvements or novel measurement concepts. More improvements are under study for application in the following decade, for instance based on spectro-imagery (e.g., European Commission 2015).

Ultimately, statistics provide the scientific basis for assessing the utility of the satellite products with respect to possible applications, to guide users and to help measurement agencies to design future systems. However, given current difficulties explained in Section 3, a specific and essential contribution from statistics to these missions is identifying and quantifying systematic errors in existing products at all levels to remove them and ideally to attribute them to an origin. These biases may depend on one or several geophysical variables among many, like the non- CO_2 values in X . They may be found in the misfits between these products and other measurements or between these products and appropriate model simulations that have distinct patterns of systematic errors. N. Cressie touches this question throughout his text, in particular in a paragraph about calibration in Section 2.4, but it is hoped that future reviews of the use of statistics in this domain can give it the central viewpoint based on significant future progress.

Some of the systematic errors come from inappropriate balance between the weights of each information piece in the end result (i.e., within Level 4). This is challenging because the corresponding information flow, which is spread over the globe and over the years along spectral channels, soundings and a series of (uncertain) physical models, is massive and heterogeneous. The statistical hypotheses are usually not even consistent throughout the various product levels (Chevallier 2015). Ranking the information content gets more complex when the Level 4 product includes data other than the measurements from a given satellite, like surface air sample measurements or data from other satellites, because it involves more expertise and more aspects of the transport models. Uncertainty in the corresponding parametric statistical models hampers progress, which suggests moving toward what the author calls Case 2, where the parameters θ of the statistical model are explicitly unknown and random. Additionally, the statistical models themselves, usually normal distributions, are not fit for all input data. Case 2 should also try to improve them, for instance to introduce positivity constraints for some of the fluxes like the emissions from fossil fuel burning, while leaving natural fluxes free to reach reasonable negative values. Even within fossil fuel fluxes, the statistical characterization may differ, like between

road traffic and point sources from industry. The statistical tools used for quality assurance in the inversion systems also need to consistently evolve.

The question of the statistical models encloses that of the effective dimension of the inference problem. If we follow the argument brought by N. Cressie in Sections 3 and 4, it may well be that the number of independent pieces of relevant information conveyed by the measurements is relatively small ($r \ll n$ in the author's Section 3.2), which would put a focus on appropriate dimension reduction methods and on the processing techniques that benefit from them. In contrast, we may also imagine that the effective dimension of the real inverse problem is large. This is actually our analysis after considering the amount of prior information that is fed to the processing chain. A large dimension would then put a focus on new data processing paradigms that would address complexity directly to find the optimal estimate efficiently. As a practical example of the current research needs, Case 2 would ideally allow ranking, in terms of statistical optimality, N. Cressie's approach for Level 3 products, which yields smooth XCO₂ fields (see the author's Figure 5), and our own approach, which yields discontinuous XCO₂ fields (see Figures 3 and 4 in Chevallier et al. 2017).

Assigning error statistics becomes particularly problematic if we extend the processing chain to policy decisions about CO₂ management (Level 5, as defined in the author's last section). Policy decisions are not only informed by facts (e.g., Level 4), but also by ethics, values and beliefs. Weighing these is more a matter of choice than of statistics. For the last level of the processing chain, the statistician has to make way for the citizen, who will ultimately judge whether all "Missions CO₂ntrol" were worth the investment.

Funding

Copernicus Atmosphere Monitoring Service, implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission.

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