An update on low-cost sensors for the measurement of atmospheric composition

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Executive Summary

This report provides a comprehensive update on the use and operation of low-cost sensing devices for assessing atmosphere chemical composition. The original report, published by WMO in 2018, was fully revised to update new scholarly understanding of low-cost sensors (LCS) that was published in the peer-reviewed literature.

While some of the original conclusions and research are included in this version, the team analysed and synthesized best practices of LCS use and applications through the published peer-reviewed literature in August 2020. In some cases, scientific literature that had been accepted, but not yet published in a final form, was included in this review. Some national and international government documents were also included in this synthesis.

The report includes eight distinct sections, including an Introduction to the Report, Main Principles and Components, Evaluation Activities, Sensor Performance, Communicating LCS to Society, and Expert Consensus and Advice. Communicating LCS to Society is a new section to the original 2018 report and includes a consensus viewpoint on strategies for communicating LCS data and technologies more broadly to the lay public. This report also includes a set of specific expert consensus recommendations for LCS users across different user groups.

Summary of Findings

The development and use of low-cost sensors to monitor reactive air pollutants, particulate matter, and greenhouse gases has continued to accelerate and is a tool used throughout academic research, regulatory surveillance, and serves the public interest by individual, government, and business users. This report considers sensors that are designed for the measurement of atmospheric composition at ambient concentrations focusing on reactive gaseous air pollutants (CO, NOx, O3, SO2), particulate matter (PM) and greenhouse gases such as CO2 and CH4. These devices continue to be appealing to end-users because, as a class of instrumentation, they are relatively inexpensive to procure, are often available in small size and weight, use lower amounts of power, and can report a wide range of environmental information to the end user. Low-cost sensors can include simple electrochemical or metal oxide detectors or can be more complex miniaturized versions of more robust reference methodologies. It should be stressed that this report focuses on the active sensors and does not discuss passive sampling techniques, which are also inexpensive.

The report includes a summary and methodological description of many of the most common measurement techniques utilized by LCS devices currently available. They exist across a wide range of techniques and configurations, and can be used as a standalone instrument, or as part of a larger network of LCS. As a result of this diversity in uses and technologies, LCS can provide data that is equally diverse in quality, with some techniques performing better than others. In general, the smaller and/or lower cost devices tend to be less sensitive, less precise and less chemically specific to the compound or variable of interest. However, depending on application and measurement of interest to a user, this limitation may be balanced by the advantages allowed by increasing spatial measurement density in a network of low-cost sensors.

Proactive and reactive calibration and validation activities still remain an essential component of LCS operations. Ideally, users should strive to co-locate LCS applications in close proximity to equivalent reference monitoring instruments, and these reference monitors provide the best comparison when they are operated in environmental conditions similar to those found where LCS are intended to ultimately operate. This report updates existing evaluation programmes in operation globally that evaluate LCS, which typically include reference monitoring comparisons. While many LCS arrive from manufacturers with a ‘factory calibration’ applied to it, it is a best practice to assess calibration robustness within local conditions. These were viewed as crucial
steps to LCS assessment in order to retain the highest possible accuracy, precision, and reproducibility, which decreases measurement uncertainty. This is likely to improve data quality and generate additional insight into pollution behaviour.

It is critical to match a project or study with an appropriate sensor strategy, and there are a number of technical and logistical factors that must be considered by a user to meet the needs of the application. In general, users should also expect that there will be operational costs beyond those required to initially purchase a device that supports periodic calibration, data management, sensor repair, or other ancillary equipment or device that might be necessary to operate the sensor where it is required. This report assists prospective LCS users by illustrating many cases where LCS have been used successfully across the globe and encourages users to identify and select specific technologies that have been previously demonstrated to perform well in studies that share similar environmental characteristics.

The report highlights that low-cost sensors are still not a direct substitute for reference instruments, especially for purposes of mandatory monitoring, but they are being used successfully complementary to reference monitoring as a qualitative source of atmospheric composition data.

This report also provides a summary of strategies to consider when communicating of LCS, its data, and its impact on society. It is important to recognize the diversity of different audiences who have a stake in these data, as well as the rapidly growing interest in air quality and greenhouse gas information by the general public. At the same time, most LCS applications have inherent uncertainty with a measurement; this is true of all measurements. But LCS almost always have a higher degree of uncertainty in their data compared to reference monitors, and it is especially difficult to convey the importance of increased uncertainty meaningfully to the lay public. This can make the task of understanding data quality very challenging for all users of this data.

Previous studies in both the laboratory and field have shown that data quality from LCS are highly variable and there is no simple answer to basic questions like “are low-cost sensors reliable”? Even when the same basic sensor components are used, real-world performance can vary due to different data correction and calibration approaches.

**Key Findings**

(i) LCS continue a trajectory of rapid growth and are likely to continue to do so.

(ii) These devices are not yet suitable for replacing reference monitoring networks.

(iii) LCS should be operated under a protocol of rigorous quality assurance and quality control that meets or exceeds the objectives of the research application.

(iv) Almost all LCS have known and still-unknown issues that affect their precision and accuracy. These include sensors cross-sensitivity to the compounds that are not intended for measurements, effects induced by temperature and humidity, varied response times, and drifting baselines.

(v) Community engagement and outreach, and the use of LCS in educational contexts, are a particular strength of these devices.

(vi) LCS represent a logical tool to assess air quality in regions of the world that lack high quality atmospheric composition observations, and which are also understudied. But it is important to support these methods with appropriate calibration and validation platforms to ensure high quality data.
Expert Consensus

Manufacturers and system providers are an essential sector for LCS growth. There is agreement that manufacturers of LCS should be encouraged to provide as much information as possible on sensor characterization, design, performance, and expected lifetime. Data correction algorithms, which are sometimes used to correct or post-process data, should be as transparent as possible for users in a manner that can both protect intellectual property, but also allows data consumers to understand how data may have been manipulated, or deconstruct data adjustment methodology. Access to instrument metadata is very important.

It is important that users of LCS first define the specific questions they are seeking to address with a particular device. Once an appropriate selection has been made, users are strongly recommended to attempt efforts to calibrate or validate their sensor measurements against reference grade instrumentation. This is an important step of quality assurance and provides a user with confidence that observed results more closely reflect reference concentration information. This will allow users to test and even identify new questions that are relevant to LCS use.

Regulators and environmental decision makers are cautioned that LCS are not yet adequately robust, and lack innate quality assurance tools, to replace existing regulatory monitoring frameworks. However, in locations with at least some reference monitoring capacity, LCS represent an exciting possibility to extend monitoring capabilities beyond more spatially limited reference tools, but only if a robust LCS calibration and validation scheme is implemented to reduce uncertainty in these measurements.

For those who are considering LCS applications or LCS data use more broadly, the rise of LCS in society represents exciting new possibilities to assess the environment in new ways, by greatly expanding the reach of measurement tools into previously unmeasured locations, or sampling air pollutants in ways not previously possible. We should continue to support (with data, advice, resources) activities that improve validation and/or verification for LCSs and consider expanding to a wider range of environmental and pollution conditions. Such evaluation programmes or centres should be distributed worldwide to capture the variations in measurement environments and underpin as a resource the geographically diverse user communities that may want to adopt LCS approaches in the future.

Following the Recommendation 18 (EC-70) – Future WMO research and supporting activities (Executive Council - Abridged Final Report of the Seventieth Session (WMO-No. 1218)) (World Meteorological Organization 2018) that requests the Commission for Atmospheric Sciences, in collaboration with the Commission for Instruments and Methods of Observation to continue developing guidance on good practices for characterization and utilization of emerging measurement technologies, including low-cost sensors and reference instruments, this report presents the update of the original statement, Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications: valid as of May 2018 (WMO-No. 1215)). The report was developed in collaboration with WHO, UNEP, EMEP and IGAC and supported by those organizations.
Resumé analytique

Le présent rapport fait le point de façon exhaustive sur l'utilisation et le fonctionnement des dispositifs de détection à faible coût servant à évaluer la composition chimique de l'atmosphère. Il représente une mise à jour complète du rapport initial, publié par l'OMM en 2018, et s’appuie sur les travaux de recherche publiés dans la littérature évaluée par les pairs.

Si certaines des conclusions et recherches initiales sont reprises dans cette version, l’équipe de rédaction a analysé la littérature évaluée par les pairs qui a été publiée jusqu’en août 2020 pour synthétiser les meilleures pratiques concernant l'utilisation et les applications de ces capteurs. Elle a parfois tenu compte de publications scientifiques ayant été acceptées, mais non encore parues sous une forme définitive. Elle a aussi pris en considération des documents gouvernementaux nationaux et internationaux.

Le présent rapport comprend huit sections distinctes, qui, outre une introduction, portent notamment sur les principes et composants principaux, les activités d'évaluation, les performances des capteurs à faible coût, la sensibilisation du public aux capteurs et l’avis général des spécialistes. La section consacrée à la promotion de ces capteurs auprès du public est nouvelle. Y sont exposées des stratégies faisant l’unanimité pour diffuser plus largement les données de ces capteurs et les techniques correspondantes auprès du grand public. Le rapport contient aussi une série de recommandations spécifiques, faisant consensus parmi les spécialistes, à l’intention de différents groupes d’utilisateurs.

Résumé des conclusions

La mise au point de capteurs à faible coût et leur utilisation pour surveiller les polluants atmosphériques réactifs, les matières particulières et les gaz à effet de serre ont continué de s’accélérer. Ces capteurs sont des outils largement utilisés dans le cadre de recherches universitaires et d'activités de surveillance réglementaire. Ils servent l'intérêt public en fournissant des données à des utilisateurs individuels, gouvernementaux et commerciaux. Le présent rapport s’intéresse aux capteurs qui servent à mesurer la composition de l’air ambiant et en particulier les polluants gazeux réactifs (monoxyde de carbone, oxyde d’azote, ozone, dioxyde de soufre), les matières particulières et les gaz à effet de serre comme le dioxyde de carbone et le méthane. Dans leur catégorie, ces dispositifs continuent de séduire les utilisateurs finaux, car ils sont relativement peu coûteux à l'achat, se présentent souvent dans un format compact et léger, consomment peu d'énergie et peuvent transmettre une large gamme d'informations environnementales. Les capteurs à faible coût vont des simples détecteurs électrochimiques ou à oxyde métallique jusqu'à des systèmes plus complexes représentant des versions miniaturisées d'instruments de référence plus fiables. Il convient de souligner que le présent rapport porte sur les capteurs actifs et ne traite pas des techniques d'échantillonnage passif, qui sont également peu coûteuses.

Le présent rapport comprend un résumé et une description méthodologique de nombre des techniques de mesure les plus couramment utilisées à l’heure actuelle pour les capteurs à faible coût. Ces capteurs reposent sur des techniques et des configurations très variées. Ils peuvent être utilisés seuls, en tant qu'instruments autonomes, ou combinés dans de grands réseaux. En raison de cette diversité d'emplois et de techniques, ils peuvent fournir des données dont la qualité est tout aussi diverse, certaines techniques étant plus fiables que d'autres. D'une manière générale, les dispositifs plus compacts et/ou moins onéreux sont souvent moins sensibles, moins précis et moins adaptés aux caractéristiques chimiques de la variable ou du composé considéré. Toutefois, en fonction de l'application et des mesures qui intéressent les utilisateurs, cet inconvénient peut être compensé par les avantages qu’offre l’augmentation de la densité spatiale du réseau de mesure.
Les activités préventives et réactives d’étalonnage et de validation demeurent une composante essentielle de l’exploitation de ces capteurs. Dans l'idéal, les utilisateurs devraient s'efforcer de placer ces capteurs à proximité d'instruments de référence équivalents. En effet, c'est lorsqu'ils sont exploités dans des conditions environnementales similaires à celles dans lesquelles les capteurs sont censés fonctionner in fine que de tels instruments de référence fournissent la comparaison la plus utile. Le présent rapport dresse donc le bilan des programmes suivis actuellement dans le monde pour évaluer ces capteurs. De tels programmes incluent généralement des comparaisons avec des instruments de surveillance de référence. Bien que les fabricants livrent souvent les capteurs à faible coût avec un «étalonnage d’usine», il est préférable d’évaluer la fiabilité de l’étalonnage dans le contexte local. Ces étapes d’évaluation sont considérées comme cruciales pour conserver une exactitude, une précision et une reproductibilité aussi élevées que possible, et diminuer ainsi l'incertitude de mesure. Elles tendent à améliorer la qualité des données et à apporter un éclairage complémentaire sur le comportement des polluants.

Il est fondamental de choisir, pour un projet ou une étude, une stratégie appropriée de surveillance par capteurs. Les utilisateurs doivent tenir compte d'un certain nombre de facteurs techniques et logistiques pour répondre aux besoins des applications. En général, ils devraient également s'attendre à supporter des coûts d’exploitation en sus des coûts d'achat initiaux, notamment pour l’étalonnage périodique, la gestion des données ainsi que la réparation des capteurs ou de tout autre équipement ou dispositif auxiliaire qui pourrait être nécessaire au fonctionnement des capteurs. Ce rapport présente de nombreux cas d'utilisation fructueuse des capteurs à faible coût dans le monde entier afin d’aider les utilisateurs potentiels à recenser et sélectionner des techniques spécifiques dont les bons résultats ont été confirmés par des études menées dans des conditions environnementales similaires.

Il est souligné dans le rapport que les capteurs à faible coût ne constituent toujours pas une solution de remplacement par rapport aux instruments de référence, surtout dans le cadre d'activités de surveillance obligatoire. Ils n'en constituent pas moins une source qualitative de données sur la composition de l'atmosphère en complément de ces instruments.

Le présent rapport fournit également un résumé des stratégies à envisager pour faire connaître les capteurs à faible coût et leurs répercussions sur la société, et diffuser leurs données. Il est important de prendre conscience de la diversité des secteurs qui sont concernés par ces données, ainsi que de l'intérêt croissant du grand public pour les informations sur la qualité de l'air et les gaz à effet de serre. Par ailleurs, la plupart des mesures des capteurs sont entachées d'incertitude, laquelle est inhérente à toute mesure. Toutefois, cette incertitude est presque toujours supérieure à celle des instruments de référence et il est particulièrement ardu d’en faire comprendre l'importance au grand public. Il peut donc être très difficile pour les utilisateurs de ces données d'en appréhender la qualité.

De précédentes études menées en laboratoire ou sur le terrain ont révélé que la qualité des données des capteurs à faible coût était très fluctuante et qu'il n’était pas facile de répondre à des questions aussi élémentaires que celle de savoir si ce type de capteur était fiable. Même lorsque ce sont les mêmes composantes de base qui sont employées, les résultats obtenus sur le terrain peuvent varier lorsque les méthodes d'étalonnage et de correction des données différent.

**Principales conclusions**

(i) Les capteurs à faible coût sont en plein essor et cette expansion devrait se poursuivre;

(ii) Ils ne remplissent pas encore les conditions voulues pour remplacer les réseaux de surveillance de référence;

(iii) Ils devraient être exploités selon un protocole rigoureux d'assurance et de contrôle de la qualité, qui atteigne, ou dépasse, les objectifs des applications de recherche;
Presque tous les capteurs à faible coût présentent des problèmes, connus ou encore inconnus, qui ont des répercussions sur leur précision et leur exactitude. Il s'agit notamment de la sensibilité croisée des capteurs aux composés qui ne sont pas destinés à être mesurés, des effets de la température et de l'humidité, des temps de réponse variables et de la dérive des lignes de base.

La mobilisation et la sensibilisation de la population, ainsi que l'utilisation des capteurs dans des contextes pédagogiques, constituent une force particulière de ces dispositifs;

Les capteurs à faible coût représentent un outil logique pour évaluer la qualité de l'air dans les régions du monde qui manquent d'observations de qualité sur la composition de l'atmosphère et qui sont également peu étudiées. Néanmoins, pour obtenir des données de qualité, il est important de soutenir ces techniques par des programmes d'étalonnage et de validation adéquats.

Consensus des experts

Les fabricants et les fournisseurs de systèmes jouent un rôle essentiel dans l'expansion des capteurs à faible coût. On s'accorde à dire qu'il faudrait encourager ces fabricants à fournir autant d'informations que possible sur les caractéristiques, la conception, les performances et la durée de vie prévue des capteurs. Les algorithmes de correction des données, qui sont parfois utilisés pour corriger les données ou procéder à leur post-traitemet, devraient être aussi clairs que possible pour les utilisateurs, de manière à protéger la propriété intellectuelle tout en permettant aux consommateurs de comprendre comment les données ont pu être manipulées ou de déconstruire la méthode d'ajustement des données. L'accès aux métadonnées des instruments est aussi très important.

Il est nécessaire que les utilisateurs de capteurs à faible coût définissent d'abord les questions spécifiques auxquelles ils cherchent à répondre avec un dispositif en particulier. Une fois qu'ils ont sélectionné les capteurs adéquats, il leur est fortement recommandé de s'efforcer d'étalonner ou de valider les mesures obtenues avec des instruments de référence. Il s'agit d'une étape importante de l'assurance de la qualité, qui donne aux utilisateurs la certitude que les résultats observés correspondent davantage à des informations de référence sur les concentrations. Les utilisateurs peuvent ainsi effectuer des essais et même découvrir de nouveaux points à vérifier en lien avec l'utilisation des capteurs.

Il convient d'avertir les autorités de surveillance et les décideurs environnementaux que les capteurs à faible coût ne peuvent encore remplacer les cadres existants de surveillance réglementaire, parce qu'ils ne sont pas encore assez fiables et qu'ils n'intègrent pas de mécanismes d'assurance de la qualité. Cependant, dans les lieux où une surveillance de référence, même minimale, existe déjà, les capteurs représentent une possibilité intéressante de dépasser les capacités d'outils de référence plus limités dans l'espace, mais seulement si l'on met en place un programme rigoureux pour les étalonner et les valider.

Si l'on envisage les applications des capteurs à faible coût ou l'utilisation de leurs données de façon plus générale, l'essor de ces capteurs au sein de la collectivité ouvre de nouvelles possibilités passionnantes d'évaluer l'environnement de façon inédite, en étendant considérablement la portée des outils de mesure à des endroits où aucune mesure n'avait été effectuée auparavant, ou en échantillonnant les polluants atmosphériques de manière innovante. Nous devons continuer de soutenir les activités qui permettent d'améliorer la validation et/ou la vérification des capteurs à faible coût (par des données, des conseils et des ressources) et envisager de les élargir à un plus large éventail de conditions environnementales et de pollution. Les programmes et centres d'évaluation devraient être répartis dans le monde entier afin de prendre en compte les différents environnements de mesure et de fournir des ressources à l'appui de communautés d'utilisateurs variées sur le plan géographique et qui pourraient vouloir adopter les capteurs à faible coût à l'avenir.
Resumen

En el presente informe se ofrece información actualizada y exhaustiva sobre el uso y el funcionamiento de los dispositivos de detección de bajo costo utilizados para evaluar la composición química de la atmósfera. El informe original, publicado por la Organización Meteorológica Mundial (OMM) en 2018, se revisó completamente para incorporar los nuevos conocimientos académicos en materia de sensores de bajo costo que se han publicado en trabajos examinados por homólogos.

Si bien esta versión incorpora parte de las conclusiones e investigaciones originales, las mejores prácticas relativas al uso de sensores de bajo costo y sus aplicaciones se analizaron y sintetizaron a partir de los trabajos revisados por pares publicados hasta agosto de 2020. Esta revisión incluye también publicaciones científicas que habían sido aceptadas, pero cuya versión final aún no se había publicado. Además, se han tenido en cuenta para esta síntesis algunos documentos gubernamentales de carácter nacional e internacional.

El informe consta de ocho secciones que abordan cuestiones distintas, entre otras: Introduction to the Report (introducción al informe), Main Principles and Components (principios y componentes principales), Evaluation Activities (actividades de evaluación), Sensor Performance (rendimiento de los sensores), Communicating LCS to Society (suministro de información sobre los sensores de bajo costo a la sociedad) y Expert Consensus and Advice (consenso de los expertos y asesoramiento técnico). La sección destinada a informar a la sociedad sobre los sensores de bajo costo es nueva respecto al informe original de 2018. En dicha sección se recoge un punto de vista consensuado acerca de las estrategias para difundir de manera más amplia los datos obtenidos mediante sensores de bajo costo y las tecnologías conexas entre un público no especializado. Este informe también incluye un conjunto de recomendaciones específicas consensuadas entre expertos y dirigidas a distintos grupos de usuarios de sensores de bajo costo.

Resumen de las conclusiones

El desarrollo y el uso de los sensores de bajo costo para el seguimiento de los contaminantes atmosféricos reactivos, las partículas en suspensión y los gases de efecto invernadero evolucionan a un ritmo incesante. Actualmente, estos sensores son una herramienta que se utiliza en la investigación académica y la vigilancia reglamentaria y que sirve al interés público, a saber, los usuarios particulares, gobiernos y empresas. En este informe se examinan los sensores diseñados para medir las concentraciones ambientales de los componentes de la atmósfera, en particular los contaminantes gaseosos reactivos (CO, NOx, O3, SO2), las partículas en suspensión y los gases de efecto invernadero, como el CO2 y el CH4. Estos dispositivos siguen despertando el interés de los usuarios finales porque son un tipo de instrumento cuya adquisición es relativamente asequible, suelen ser compactos y ligeros, consumen poca energía y pueden proporcionar una amplia gama de información medioambiental al usuario final. Los sensores de bajo costo pueden consistir en sencillos detectores electroquímicos o de óxidos metálicos, o ser complejas versiones miniaturizadas de metodologías de referencia más robustas. Conviene destacar que esta publicación se centra en los sensores activos y no analiza las técnicas de muestreo pasivo, que también resultan económicas.

El informe incluye un resumen y una descripción metodológica de un buen número de las técnicas de medición más habituales que utilizan los sensores de bajo costo disponibles en la actualidad. Dichos dispositivos cuentan con una amplia gama de técnicas y configuraciones, y pueden utilizarse como instrumentos independientes o como parte de una red de sensores más amplia. A consecuencia de esta diversidad de usos y tecnologías, los sensores de bajo costo pueden proporcionar datos de una calidad no menos diversa, puesto que algunas técnicas resultan más eficaces que otras. Por lo general, los dispositivos más pequeños o de menor costo
tienden a ser menos sensibles, menos precisos y menos específicos respecto a la naturaleza química del compuesto o la variable de interés. Sin embargo, dependiendo de la aplicación y la medición de interés para el usuario, esta limitación puede contrarrestarse aumentando la densidad espacial de las mediciones en una red de sensores de bajo costo.

Las actividades de calibración y validación, tanto proactivas como reactivas, siguen siendo un componente esencial de la operación de los sensores de bajo costo. Lo ideal sería que los usuarios procuraran situar las aplicaciones de sensores de bajo costo cerca de instrumentos de vigilancia de referencia equivalentes, ya que la comparación con estos instrumentos de referencia es óptima cuando funcionan en condiciones medioambientales similares a las del lugar en el que se pretende utilizar los sensores de bajo costo. En este informe se proporciona información actualizada sobre los programas de evaluación de sensores de bajo costo en curso en todo el mundo, que suelen incluir comparaciones a los fines de controles de referencia. Aunque muchos sensores de bajo costo han sido "calibrados en fábrica" por sus propios fabricantes, es una mejor práctica evaluar la calidad de la calibración en las condiciones locales. Los pasos anteriores se consideraron fundamentales en la evaluación de los sensores de bajo costo con el fin de mantener la mayor exactitud, precisión y reproducibilidad posibles, lo que disminuye la incertidumbre de las mediciones. De este modo, es probable que se mejore la calidad de los datos y se generen conocimientos adicionales sobre el comportamiento de la contaminación.

Es fundamental que el proyecto o estudio vaya acompañado de una estrategia adecuada en materia de sensores, puesto que hay una serie de factores técnicos y logísticos que el usuario debe tener en cuenta para satisfacer las necesidades de la aplicación. En general, los usuarios deben prever que, además de los costos iniciales de adquisición de un dispositivo, también deberán afrontar costos operativos asociados a la calibración periódica, la gestión de los datos, la reparación del sensor, y la adquisición de otros equipos o dispositivos auxiliares que puedan ser necesarios para el funcionamiento del sensor. Con el fin de ayudar a los futuros usuarios de sensores de bajo costo, en el presente informe se ilustran numerosos casos en los que este tipo de sensores se han utilizado de manera satisfactoria en todo el mundo, y se alienta a los usuarios a que busquen y seleccionen tecnologías específicas que hayan demostrado un buen rendimiento en estudios con características medioambientales similares.

En el informe se pone de relieve que los sensores de bajo costo todavía no son un sustituto directo de los instrumentos de referencia, especialmente para fines de vigilancia preceptiva, aunque se están utilizando eficazmente de forma complementaria a la vigilancia de referencia como una fuente cualitativa de datos sobre la composición atmosférica.

Asimismo, este informe incluye un resumen de las estrategias que deben tenerse en cuenta a la hora de comunicar acerca de los sensores de bajo costo, sus datos y su impacto en la sociedad. Es importante reconocer la diversidad de públicos interesados en estos datos, así como el creciente interés del público en general por la información sobre la calidad del aire y los gases de efecto invernadero. Por otra parte, la mayoría de las aplicaciones de sensores de bajo costo conllevan una incertidumbre inherente a la medición. Aunque esto sucede en todas las mediciones, en el caso de los sensores de bajo costo el nivel de incertidumbre de sus datos casi siempre es más elevado que el de los instrumentos de referencia. Es especialmente difícil transmitir de forma significativa la importancia del aumento de la incertidumbre al público no especializado, lo que puede entorpecer notablemente la comprensión de la calidad de los datos por parte de todos los usuarios.

Estudios previos tanto en laboratorio como sobre el terreno han demostrado que la calidad de los datos obtenidos mediante sensores de bajo costo varía de manera considerable, y que no hay respuestas sencillas a preguntas básicas como “¿son fiables los sensores de bajo costo?”. Incluso cuando se utilizan los mismos componentes básicos de un sensor, el rendimiento real puede variar a causa de diferentes criterios de calibración y corrección de los datos.
**Principales conclusiones**

(i) El uso de los sensores de bajo costo evoluciona rápidamente y es probable que esta tendencia se mantenga.

(ii) Estos dispositivos aún no son adecuados para sustituir a las redes de vigilancia de referencia.

(iii) Los sensores de bajo costo deberían utilizarse con arreglo a un protocolo estricto de aseguramiento y control de calidad que cumpla o supere los objetivos de las aplicaciones de investigación.

(iv) Casi todos los sensores de bajo costo presentan problemas, tanto conocidos como otros que aún se desconocen, que afectan a su precisión y exactitud, entre otros, la sensibilidad cruzada de los sensores a compuestos distintos de los que se pretende medir, los efectos provocados por la temperatura y la humedad, la variedad de los tiempos de respuesta y la desviación de los valores de referencia.

(v) La implicación de la comunidad en las acciones relativas a los radares de bajo costo, las actividades de divulgación de estos sistemas, y el uso de sensores en contextos educativos son algunos de los puntos fuertes de estos dispositivos.

(vi) Los sensores de bajo costo constituyen una herramienta lógica para evaluar la calidad del aire en aquellas regiones del mundo que carecen de observaciones de calidad de la composición atmosférica, y que además están poco estudiadas. No obstante, es importante respaldar estos métodos con plataformas de calibración y validación adecuadas para poder obtener datos de calidad.

**Consenso de los expertos**

Los fabricantes y proveedores de sistemas son un sector fundamental para el desarrollo de los sensores de bajo costo. En este sentido, hay acuerdo en que se debería alentar a los fabricantes de sensores de bajo costo a que proporcionen toda la información posible sobre la caracterización, el diseño, el rendimiento y la vida útil prevista de los sensores. Los algoritmos de corrección de datos, que en ocasiones se utilizan para corregir o posprocesar los datos, deberían ser lo más transparentes posible para los usuarios, de tal forma que pueda protegerse la propiedad intelectual, y que los usuarios de datos puedan entender cómo se han manipulado los datos o puedan deconstruir la metodología de ajuste de los datos. El acceso a los metadatos de los instrumentos reviste una gran importancia.

Es fundamental que los usuarios de sensores de bajo costo definan en primer lugar las cuestiones específicas que pretenden abordar mediante el uso de un dispositivo determinado. Una vez realizada la selección adecuada, se recomienda encarecidamente a los usuarios que intenten calibrar o validar las mediciones de sus sensores comparándolas con los instrumentos de referencia. Este es un paso importante para garantizar la calidad y permite al usuario confiar en que los resultados observados reflejan más fielmente la información de referencia sobre las concentraciones. De este modo, los usuarios podrán examinar e incluso definir nuevas cuestiones que sean pertinentes para el uso de sensores de bajo costo.

Se advierte a las instancias normativas y decisorias en materia de medioambiente que los sensores de bajo costo aún no son suficientemente sólidos, y carecen de sus propias herramientas de aseguramiento de la calidad para sustituir los actuales marcos reglamentarios de vigilancia. Sin embargo, en lugares con al menos cierta capacidad de vigilancia de referencia, los sensores de bajo costo ofrecen una posibilidad interesante de ampliar dicha capacidad superando las herramientas de referencia que presentan una mayor limitación espacial, pero para ello debe aplicarse un plan sólido de calibración y validación de los sensores con el fin de reducir la incertidumbre de estas mediciones.
Para aquellos que se estén planteando hacer un uso más amplio de las aplicaciones de sensores de bajo costo o de sus datos, el auge de estos sensores ofrece nuevas y diferentes posibilidades de evaluar el medioambiente, dado que amplían considerablemente el alcance de las herramientas de medición que pueden llegar a lugares donde antes no se realizaban mediciones y permiten el muestreo de contaminantes atmosféricos de formas que hasta ahora no eran posibles. Deberíamos seguir brindando apoyo (con datos, asesoramiento y recursos) en relación con las actividades que mejoran la validación y la verificación de los sensores de bajo costo, así como considerar la posibilidad de abarcar una gama más amplia de condiciones medioambientales y de contaminación. Dichos programas o centros de evaluación deberían estar distribuidos por todo el mundo para captar las variaciones en los entornos de medición y constituir un recurso de apoyo a las comunidades de usuarios de diversas regiones geográficas que deseen adoptar enfoques basados en los sensores de bajo costo en el futuro.

Atendiendo a la Recomendación 18 (EC-70) — Futuro de la investigación en la Organización Meteorológica Mundial y actividades de apoyo (Informe final abreviado de la septuagésima reunión del Consejo Ejecutivo (OMM-Nº 1218), Organización Meteorológica Mundial, 2018), en la que se pide a la Comisión de Ciencias Atmosféricas que, en colaboración con la Comisión de Instrumentos y Métodos de Observación, siga elaborando orientaciones sobre buenas prácticas para la caracterización y la utilización de nuevas tecnologías de medición, incluidos los sensores de bajo costo y los instrumentos de referencia, este informe presenta la actualización de la declaración original, Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications — valid as of May 2018 (WMO-No. 1215) (Sensores de bajo costo para la medición de la composición de la atmósfera: panorama general del tema y aplicaciones futuras, válido a partir de mayo de 2018). El informe fue elaborado en colaboración con la Organización Mundial de la Salud (OMS), el Programa de las Naciones Unidas para el Medio Ambiente (PNUMA), el Programa de Cooperación para la Vigilancia y la Evaluación del Transporte de los Contaminantes Atmosféricos a Larga Distancia en Europa (EMEP) y el Proyecto Internacional de la Química de la Atmósfera Global (IGAC) y recibió el apoyo de dichas organizaciones.
В настоящем докладе содержится исчерпывающая обновленная информация об использовании и эксплуатации недорогостоящих приборов зондирования для оценки химического состава атмосферы. Первоначальный доклад, опубликованный ВМО в 2018 году, был полностью пересмотрен с целью отражения в нем нового научного представления о недорогостоящих датчиках (НД), которое было опубликовано в рецензируемой литературе.

Хотя текущая версия доклада содержит некоторые из первоначальных выводов и результатов исследований, в нем изложен передовой опыт использования и применения НД, который проанализирован и обобщен группой специалистов, работавших в августе 2020 года с опубликованными рецензируемыми изданиями. В некоторых случаях в этот обзор была включена научная литература, которая была принята, но еще не опубликована в окончательном виде. Также был проведен обобщающий анализ некоторых национальных и международных официальных документов.

Доклад состоит из восьми самостоятельных разделов, в том числе таких: «Введение», «Основные принципы функционирования датчиков и их компоненты», «Деятельность по оценке работы датчиков», «Режимы работы датчиков», «Информирование общества о НД», а также «Общее мнение экспертов и рекомендации». В первоначальном докладе за 2018 год отсутствовал раздел «Информирование общества о НД», содержащий единую точку зрения насчет стратегий более широкого информирования общественности о данных и технологиях относительно НД. Настоящий доклад также включает набор конкретных, согласованных экспертами рекомендаций для различных групп пользователей НД.

Резюме выводов

Разработка и использование недорогостоящих датчиков для мониторинга химически активных загрязнителей воздуха, взвешенных частиц (РМ) и парниковых газов продолжают набирать обороты, являются инструментом научных исследований, нормативного регулирования и служат общественным интересам отдельных лиц, правительств и коммерческих пользователей. В настоящем докладе рассматриваются датчики, предназначенные для измерения состава атмосферы и уровня концентрации в окружающей среде прежде всего химически активных газообразных загрязнителей воздуха (CO, NOx, O3, SO2), взвешенных частиц и парниковых газов CO2 и CH4. Эти устройства по-прежнему пользуются спросом, поскольку они как класс приборов являются относительно недорогими, зачастую отличаясь компактностью, малым весом и низким энергопотреблением, кроме того, их функционал позволяет конечному пользователю получать широкий спектр информации об окружающей среде. Недорогостоящие датчики могут быть оборудованы простыми электрохимическими или металлоэлектродными детекторами или представлять собой характеристики повышенной технической сложностью уменьшенные копии более надежной эталонной аппаратуры. Следует подчеркнуть, что в настоящем докладе основное внимание уделяется активным датчикам, в нем не идет речь о методах пассивного отбора проб, которые также не являются затратными.

Доклад включает краткий обзор и методологическое описание многих наиболее распространенных методов измерений, которые проводятся с помощью существующих НД. Они отличаются широким спектром вариантов применения и возможностей для конфигурации: их можно использовать в качестве автономного прибора или элемента более крупной сети. Такое обилие вариантов использования и технологий создает условия для того, чтобы НД могли передавать данные, которые являются столь же разнообразными по качеству, учитывая, что одни методы работают лучше других. Для более компактных и/или менее дорогостоящих устройств, как правило, свойственна сниженная
чувствительность, точность и химическая специфичность применительно к наблюдаемому соединению или переменной. Однако, в зависимости от условий применения и измерения, представляющих интерес для пользователя, это ограничение можно компенсировать преимуществами, позволяющими увеличить пространственную плотность измерений в сети недорогостоящих датчиков.

Мероприятия по предварительной и последующей калибровке и проверке работы НД по-прежнему остаются важной составляющей их эксплуатации. В идеале пользователям следует стремиться к тому, чтобы применять НД в непосредственной близости от аналогичных эталонных приборов для мониторинга, при этом добиться наилучшего результата сравнения показателей можно в том случае, когда такие приборы работают в условиях окружающей среды, схожих с теми, в которых в итоге предполагается эксплуатировать НД. В настоящем докладе содержится обновленная информация о действующих по всему миру программах оценки работы НД, которые обычно включают сопоставление результатов измерений с показателями эталонного мониторинга. Многие НД поступают от производителей с заводской калибровкой, однако оценку ее качества лучше всего проводить на местах. Речь идет о важнейших шагах по оценке работы НД в целях дальнейшего обеспечения максимально возможной точности, прецизионности и воспроизводимости результатов измерений, что снижает их неопределенность. Такой подход, по всей видимости, позволит повысить качество данных и получить дополнительные знания о механиках загрязнения.

Крайне важно согласовать проект или исследование с соответствующей стратегией использования датчиков, поскольку существует ряд технических и логистических факторов, которые должны учитывать пользователи для удовлетворения потребностей в конкретных условиях применения датчиков. В целом пользователям следует также быть готовыми к тому, что эксплуатационные расходы будут превышать первоначальные издержки на покупку устройства, нуждающегося в периодической калибровке, управлении данными, ремонте датчика или другого вспомогательного оборудования или аппаратуры, которое может при случае потребоваться для работы датчика. Иллюстрируя многие случаи успешного использования таких датчиков по всему миру, настоящий доклад служит подспорьем для потенциальных пользователей НД в выборе и выявлении конкретных технологий, которые уже хорошо себя зарекомендовали в исследованиях, проведенных в схожих условиях окружающей среды.

В докладе подчеркивается, что недорогие датчики по-прежнему не являются очевидной заменой эталонных приборов, особенно для целей обязательного мониторинга, однако они успешно используются в дополнение к эталонному мониторингу в качестве источника качественных данных о составе атмосферы.

В настоящем докладе также приводится резюме стратегий, которые необходимо учитывать при распространении информации о НД, относящихся к ним данных и их воздействию на общество. Важно признать разнообразие групп лиц, которые заинтересованы в этих данных, а также быстро растущий интерес к информации о качестве воздуха и парниковых газах со стороны широкой общественности. В то же время большинству применений НД присуща неопределенность измерений; это верно для всех измерений. Однако НД почти всегда отличаются более высокой неопределенностью в плане поступающих с них данных по сравнению с эталонной аппаратурой для мониторинга, и особенно трудно донести важность возросшей неопределенности до сведения непрофессионалов. Это обстоятельство может крайне усложнить задачу по повышению осведомленности всех пользователей данных об их качестве.

Результаты предыдущих лабораторных и полевых исследований продемонстрировали крайне неоднородное качество данных с НД и отсутствие однозначного ответа на один из главных вопросов: являются ли недорогостоящие датчики надежным источником информации? Даже в случае использования одинаковых базовых компонентов датчика
фактические результаты могут быть разными ввиду отличий в подходах к корректировке данных и калибровке.

Основные выводы:

(i) НД по-прежнему быстро набирают популярность и, вероятно, эта тенденция сохранится;
(ii) эти устройства пока не подходят для замены сетей эталонного мониторинга;
(iii) НД должны работать в соответствии с протоколом строгого обеспечения и контроля качества, который отвечает целям проведения исследования или превосходит их;
(iv) почти у всех НД есть известные и до сих пор не известные недостатки, которые влияют на их прецизионность и точность. К ним относятся поперечная чувствительность датчиков к соединениям, не предназначенным для измерений, эффекты, вызываемые воздействием температуры и влаги, различное время реагирования и смешивающиеся точки отсчета;
(v) особым преимуществом этих устройств является интерес, проявляемый к ним со стороны общества, что позволяет использовать их в просветительских и образовательных целях;
(vi) НД представляют собой практичный инструмент для оценки качества воздуха в тех регионах мира, в которых не проводятся высококачественные наблюдения за составом атмосферы и которые также остаются недостаточно изученными. Но для обеспечения высокого качества данных важно подкреплять эти методы наличием соответствующих платформ для калибровки и проверки.

Общее мнение экспертов

Изготовители и поставщики систем имеют большое значение для роста рынка НД. Достигнуто согласие о том, что изготовителей НД следует стимулировать к тому, чтобы они предоставляли как можно больше информации об эксплуатационных характеристиках, конструкции, режимах работы и ожидаемом сроке службы датчиков. Алгоритмы коррекции данных, которые иногда используются для исправления или постобработки данных, должны быть как можно более прозрачными для пользователей — так, чтобы они могли не только обеспечивать охрану интеллектуальной собственности, но и давать возможность потребителям данных понять, каким образом можно было бы обращаться с данными, или разобраться в методологии уточнения данных. Доступ к метаданным приборов имеет очень большое значение.

Важно, чтобы пользователи НД сначала сформулировали конкретные вопросы, которые они хотят решить с помощью определенного устройства. После того как соответствующий выбор будет сделан, им настоятельно рекомендуется предпринять усилия по калибровке или проверке измерений датчиков на соответствие показателям эталонных приборов. Этот важный шаг позволяет обеспечить качество измерений и дает пользователю уверенность в том, что наблюдаемые результаты более точно отражают информацию об эталонной концентрации. Такой подход даст пользователям возможность провести испытания и даже определить другие параметры датчиков, которые могут потребовать проверки.

Надзорные органы и лица, принимающие решения в области охраны окружающей среды, осведомлены о том, что НД еще не являются достаточно надежными и что не существует средств обеспечения качества, чтобы можно было заменить существующую нормативно-правовую базу в области мониторинга. Однако в местах, где имеется хотя бы незначительный потенциал для эталонного мониторинга, НД отлично подходят для расширения его возможностей, обеспечивая выход за рамки более ограниченных в пространственном отношении эталонных инструментов, но только в том случае, если для
снижения неопределенности в этих измерениях будет реализована надежная схема калибровки и проверки таких датчиков.

Для тех, кто рассматривает вопрос о применении НД или данных с них в более широком смысле, рост интереса к ним в обществе открывает неизведанные горизонты для оценки окружающей среды новыми способами, значительно расширяя сферу применения измерительных приборов в местах, где ранее не проводились измерения, или создавая условия для отбора проб загрязняющих веществ воздуха способами, использовать которые прежде не представлялось возможным. Нам следует и дальше поддерживать (с помощью данных, консультаций, ресурсов) деятельность, направленную на совершенствование процесса проверки и/или аттестации НД, и рассмотреть возможность их применения в более широком диапазоне условий окружающей среды и загрязнения. Такие программы или центры оценки следует учредить по всему миру, с тем чтобы отразить различия в условиях проведения измерений и заложить основу для взаимодействия с различными с географической точки зрения сообществами пользователей, которые, возможно, захотят внедрить у себя подходы на основе НД в будущем.

В соответствии с рекомендацией 18 (ИС-70) «Будущие научные исследования ВМО и сопутствующие виды деятельности» (Исполнительный совет: Сокращенный окончательный отчет семидесятой сессии (ВМО-№ 1218)), в которой Комиссии по атмосферным наукам в сотрудничестве с Комиссией по приборам и методам наблюдений поручено продолжать разработку руководства по эффективной практике определения характеристик и использования новых технологий измерений, включая недорогостоящие датчики и эталонные приборы, в настоящем докладе представлен обновленный вариант первоначального заявления Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications: valid as of May 2018 (Недорогостоящие датчики для измерения состава атмосферы: обзор темы и будущих применений: действует по состоянию на май 2018 г.) (WMO-No. 1215). Доклад был разработан в сотрудничестве с ВОЗ, ЮНЕП, ЕМЕП и ИГАК и при поддержке этих организаций.
执行摘要

针对用于评估大气化学成分的低成本传感设备的使用和操作，本报告提供了最新的全方位信息。报告最初由WMO于2018年发表，现已全面修订，更新了学术界在同行评议文献中发表的对低成本传感器(LCS)的最新理解。

本版本包含了一些初始结论和研究，与此同时，撰写团队通过2020年8月发表的同行评议文献，分析并综述了LCS使用和应用的最佳做法。有些案例中，已被接受但尚未以最终形式发表的科学文献也纳入了综述。本综述还收录了一些国家和国际政府文件。

报告有八个互不相同的部分，包括报告的引言、主要原则及组成部分、评估活动、传感器性能、LCS的社会传播、以及专家共识和建议。LCS的社会传播是2018年初始报告后新增的章节，内含针对扩大向普通大众传播LCS数据和技术的战略的共识性观点。本报告还包括一套特别的、面向跨不同用户组LCS用户的专家一致建议。

研究结果摘要

用于监测活性空气污染物、颗粒物和温室气体的低成本传感器的开发和利用在持续加速，是贯穿学术研究、监管督察所用的工具，并服务于个人、政府和企业用户的公共利益。本报告所考虑的传感器，其设计目的是测量环境浓度下的大气成分，重点是活性气态空气污染物（CO、NOx、O3、SO2）、颗粒物（PM）和CO2和CH4等温室气体。这些设备能不断吸引终端用户，是因为作为一类仪器，其采购成本相对较低，通常尺寸和重量都较小，耗电量较低，且可向终端用户报告大范围的环境信息。低成本传感器可以包括简单的电化学或金属氧化物检测器，也可以是更复杂的小型版、更稳健的基准方法。需要强调的是，本报告的关注点是有源传感器，这里并不讨论同样低成本的无源采样技术。

本报告包括了对当前LCS设备所用的许多最常见测量技术的总结和方法学描述。它们广泛存在于各种技术和配置中，可作为独立仪器使用，也可作为更大的LCS网络的组成部分。正因为有如此多样的用途和技术，LCS才能提供同样多种品质的数据，其中有些技术的性能比其他的好。一般而言，较小和/或较低成本的装置往往对相关化合物或变量不太敏感、不够精确、化学特异性较低。不过，因用户感兴趣的用途和测量而异，通过在低成本传感器网络中增加空间测量密度，它带来的优势可抵消这个限制。

主动性和反应性校准与验证活动仍然是LCS运行的重要组成部分。理想状态下，用户应努力将LCS应用程序放置在同等基准监测仪器附近，当它们在类似于LCS最终运行条件下运行时，这些基准监测器就可提供最佳比对。本报告更新了现有的全球LCS评估计划，通常包括基准监测比对。尽管许多LCS来自应用了“工厂校准”的制造商，但最佳做法还是在当地条件下评估校准的稳健性。这些对LCS评估而言是关键步骤，这样可以尽可能保持最高的准确度、精度和再现性，降低测量不确定性。如此，就有可能提高数据质量，并对污染行为有进一步的深刻了解。

将一个项目或一项研究与适当的传感器策略相匹配，这一点非常重要。要满足应用的需求，有几个技术和后勤因素用户必须加以考虑。一般情况下，用户还要预计到，除了最初购买设备所需的成本外，还需要有支持定期校准、数据管理、传感器维修或其他在运行传感器时可能所需的辅助设备或装置的运行成本。通过成功使用LCS的众多全球实例，本报告将为潜在LCS用户提供帮助，并鼓励用户识别和选择在以往相似环境特征下的研究中表现良好的特定技术。

报告强调，低成本传感器仍不能直接替代基准仪器，特别是在强制性监测方面，但它们正被成功地用作大气成分数据的定性来源，是对基准监测的补充。

本报告还总结了在传播LCS、其数据及其社会影响时需考虑的策略。重要的是要认识到，与这些数据有利害关系的受众各不相同，以及公众对空气质量与温室气体信息的兴趣在迅速提升。同时，大多数LCS应用都存在测量所固有的不确定性；所有的测量都是如此。但与基准监测器相比，LCS的数据不确定性常常更高，且很难向
普通大众说清楚不确定性上升的严重性。对所有此类数据用户来说，这会给理解数据质量的挑战带来很大的挑战。

以往在实验室和现场的研究均表明，LCS的数据质量变化很大，对于“低成本传感器是否可靠？”这样的基本问题，并没有一个简单答案。即便使用了相同的基本传感器组件，由于数据校正和校准方法不同，实际性能也会有所不同。

主要发现

(i) LCS 继续保持快速发展的轨迹，并有可能继续增长。
(ii) 这些设备尚不适合取代基准监测网络。
(iii) LCS 应在严格的质量保证和质量控制协议下运行，以达到或超过研究申报的目标。
(iv) 几乎所有 LCS 都有一些已知和未知问题，影响其精度和准确度，这些问题包括传感器对未打算用于测量的场所的交叉敏感性、湿度和方向带来的影响、不同的响应时间和基线漂移。
(v) 社区参与和推广，以及在教学环境中使用 LCS，是这些设备的特殊优势。
(vi) 在世界上缺乏高质量大气成分观测且研究不足的地区，LCS 是评估空气质量的合理工具。但重要的是要用适当的校准和验证平台来支持这些方法，以确保高质量的数据。

专家共识

对 LCS 的成长而言，制造商和系统提供商是重要的部门。人们一致认为，应鼓励 LCS 制造商尽力提供关于传感器特性、设计、性能和预期寿命的信息。时而用于数据校正或后处理的数据校正算法，应尽可能对用户透明，要既能保护知识产权，又能让数据消费者了解数据可能被如何操纵，或解构数据调整方法。仪器元数据的获取权非常重要。

LCS 用户首先要明确他们希望通过特定设备解决的具体问题，这一点很重要，一旦做出了适当选择，强烈建议用户尝试根据基准级仪器，校准或验证其传感器的测量值。这是质量保证的重要步骤，用户也会因此更确定观测结果能如实地反映基准浓度信息。这将允许用户测试甚至识别 LCS 使用中的新问题。

监管者和环境决策者需要注意的是，LCS 还不够稳健，并缺乏固有的质量保证工具以取代现有的监管监测框架。不过，令人振奋的是，在起码有一定基准监测能力的场所，LCS 代表了一种可能性，即可将监测能力扩展到空间更有限的基准工具之外，但前提是设立一个稳健的 LCS 校准和验证计划，以减少这些测量的不确定性。

对于那些正在考虑扩大使用 LCS 应用或 LCS 数据的人而言，LCS 在社会中的兴起代表了一种新的令人振奋的可能性。即通过将测量工具的范围极度扩展到以往无法测量的场所，或以之前无法进行的方式对空气污染物采样，采用新方式进行环境评估。我们应继续（通过数据、咨询意见、资源）支持改善 LCS 验证和/或核查的活动，并考虑扩展到更大范围的环境和污染条件。此类评估计划或中心应分布于世界各地，以捕捉测量环境的变化并作为一种资源，支持地理条件各不相同、未来拟采用 LCS 方法的用户群体。

“建议 18(EC-70) – WMO 未来的研究和支持性活动”（《执行理事会第七十届会最终节略报告》（WMO-No.1218）(世界气象组织，2018 年)要求大气科学委员会与仪器和观测方法委员会协作，继续制定针对新兴测量技术（包括低成本传感器和基准仪器）特性和利用的优良做法的指导意见。在此基础上，本报告是对原声明《大气成分测量的低成本传感器：主题与未来应用概述：2018 年 5 月起生效》（WMO-No.1215）的更新。本报告与 WHO、UNEP、EMEP 和 IGAC 合作编制，并得到了这些组织的支持。
موجز تنفيذي

يدعم هذا التقرير تحديداً شاملاً عن استخدام أجهزة الاستشعار المنخفضة الكٹلية (LCS) وتشغيلها لتقديم التكوين الكيميائي والتحليلات للفلاف الجوي. وقد أنتج التقرير الأصلي الذي شاركت المنظمة (WMO) في عام 2018، تقيماً كاملاً لتحديث الفهم العلمي لجلد الأجهزة (LCS) الذي تُنشر في المؤلفات التي يستعملها النظام.

وأثنى التقرير على بعض الاستنتاجات واليدوات الأصلية مدرجة في هذا النص حيث أن الفرقة قد حددت وضعت أفضل الممارسات لاستخدام الأجهزة (LCS) وتطويرها لتحسين انتاجية التكوين الكيميائي للفلاف الجوي. وقد نُقِّح التقرير الأصلي، الذي نُشرته المنظمة (WMO) في عام 2018، تقوياً كاملاً لتوحيد الفهم العلمي لجلد الأجهزة (LCS)، الذي نشر في المؤلفات التي تُستخدمها المستخدمين.

ويتضمن التقرير ثمانية إعداد بيانات المختلفة، تحليلًا لمعنى النتائج والمبادئ الرئيسية، وأنشطة التقييم، وآداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجيات توصيل بيانات أجهزة الاستشعار المصنفة لقياس تكوين الفلاف الجوي في ظل الترقيات المحتملة، مع التركيز على ملخصات الوضع، والتحديات، وتحميات الأجهزة، ونتائج الأبحاث، وتقديم المشورة، والاجتماع المبادئ والمكونات الرئوية، وأنشطة التقييم، وأداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجيات توصيل بيانات أجهزة الاستشعار المصنفة لقياس تكوين الفلاف الجوي في ظل الترقيات المحتملة، مع التركيز على ملخصات الوضع، والتحديات، وتحميات الأجهزة، ونتائج الأبحاث، وتقديم المشورة، والاجتماع المبادئ والمكونات الرئوية، وأنشطة التقييم، وأداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجيات توصيل بيانات أجهزة الاستشعار المصنفة لقياس تكوين الفلاف الجوي في ظل الترقيات المحتملة، مع التركيز على ملخصات الوضع، والتحديات، وتحميات الأجهزة، ونتائج الأبحاث، وتقديم المشورة، والاجتماع المبادئ والمكونات الرئوية، وأنشطة التقييم، وأداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجيات توصيل بيانات أجهزة الاستشعار المصنفة لقياس تكوين الفلاف الجوي في ظل الترقيات المحتملة، مع التركيز على ملخصات الوضع، والتحديات، وتحميات الأجهزة، ونتائج الأبحاث، وتقديم المشورة، والاجتماع المبادئ والمكونات الرئوية، وأنشطة التقييم، وأداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجيات توصيل بيانات أجهزة الاستشعار المصنفة لقياس تكوين الفلاف الجوي في ظل الترقيات المحتملة، مع التركيز على ملخصات الوضع، والتحديات، وتحميات الأجهزة، ونتائج الأبحاث، وتقديم المشورة، والاجتماع المبادئ والمكونات الرئوية، وأنشطة التقييم، وأداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجيات توصيل بيانات أجهزة الاستشعار المصنفة لقياس تكوين الفلاف الجوي في ظل الترقيات المحتملة، مع التركيز على ملخصات الوضع، والتحديات، وتحميات الأجهزة، ونتائج الأبحاث، وتقديم المشورة، والاجتماع المبادئ والمكونات الرئوية، وأنشطة التقييم، وأداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجيات توصيل بيانات أجهزة الاستشعار المصنفة لقياس تكوين الفلاف الجوي في ظل الترقيات المحتملة، مع التركيز على ملخصات الوضع، والتحديات، وتحميات الأجهزة، ونتائج الأبحاث، وتقديم المشورة، والاجتماع المبادئ والمكونات الرئوية، وأنشطة التقييم، وأداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجيات توصيل بيانات أجهزة الاستشعار المصنفة لقياس تكوين الفلاف الجوي في ظل الترقيات المحتملة، مع التركيز على ملخصات الوضع، والتحديات، وتحميات الأجهزة، ونتائج الأبحاث، وتقديم المشورة، والاجتماع المبادئ والمكونات الرئوية، وأنشطة التقييم، وأداء أجهزة الاستشعار، وتعريف المجتمع بالأجهزة (LCS)، وتوافق أراء الخبراء، وتقدير المجموعة. وعرضت النتائج الأولى، وهو يضمن وصلة نظر تأهيلية حول استراتيجية الاستشعار والفاعلية وتنشيط الاحتكار نصتاً أساسياً في عمليات الأجهزة (LCS)، ولحقاق تحقيق أكبر.

وتتطلب استراتيجية الاستشعار والفاعلية وتنشيط الاحتكار نصتاً أساسياً في عمليات الأجهزة (LCS)، ولحقاق تحقيق أكبر.

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أنت تكون قد خضعت لعملية "معايير المصنع"، فمن الممارسات الفضلى تقييم دقة المعايير في ظل الظروف المحلية. وقد رأت أن هذه الخطوات هامة لتحديد دقة المعايير (LCS) من أجل حفاظ على أعلى مستوى من دقة القياسات وتقديرها وقابلية استنفادها، مما يقلل من مستوى عدم اليقين في القياس. ومن المراجع أن يؤدي ذلك إلى تحسين نوعية البيانات، وتوفير نظرة متميزة إضافية في سلك الثروة.

ومن المهم للغاية أن يكون هناك موافقة بين المشروع أو الدراسة، والاستراتيجية الملاحقة لجهاز الاستشعار، فضلاً عن ضرورة أن يراعى المستخدم عددًا من العوامل الفنية واللوجستية لتنزيل احتياجات التطبيق. ويوجبة على المستخدمون أيضاً أن تكون هناك تكاليف تشغيلية تتجاوز تكاليف الأولية المطلوبة لشراء الجهاز، وفد إجراء عمليات معاداة دورية، وإدارة البيانات، وإصلاح أجهزة الاستشعار، وغير ذلك من معادلات أو أجهزة أخرى قد يلزم تفوقه تشغيل جهاز الاستشعار حتى يضم الحاجة إلى استخدامه. ويساعد هذا التقرير مستخدمي الأجهزة المحتملين من خلال توضيح العديد من الحالات التي تم فيها استخدام الأجهزة (LCS) بنجاح في جميع أنحاء العالم، ويشجع المستخدمين على تحديث واختبار تكنولوجيات بを与え أثبت الفعل دراسات أجريت في ظروف بيئية مماثلة حسن أدائها.

وببرز التقرير أن الأجهزة (LCS) لا تزال لا تشكل بديلًا مباشرًا للأدوات المرجعية، ولا سيما لأغراض المراقبة الإلزامية، ولكنها تستخدم بنجاح كمكمِّل للمراقبة المرجعية باعتبارها مصدراً نوعياً لبيانات تكوين الغلاف الجو.

وقد أظهرت الدراسات المخبرية والبدنية السابقة أن جودة البيانات الأجهزة متغير جدًا، وليس هناك إجابة بسيطة عن أسئلة بديهية من قبل "هل يمكن التعديل على الأجهزة (LCS)"؟. فحتى عند استخدام نفس المكونات الأساسية في أجهزة الاستشعار، بتبين الآدة على أرض الواقع نظراً إلى اختلاف نهج تصميم البيانات والمعرفة. وقد عارضت الدراسات المخبرية والميدانية السابقة أن جودة بيانات الأجهزة (LCS) متغيرة جداً، وليس هناك إجابة بسيطة من قبل "هل يمكن التعديل على الأجهزة (LCS)"؟. فحتى عند استخدام نفس المكونات الأساسية في أجهزة الاستشعار، بتبين الآدة على أرض الواقع نظراً إلى اختلاف نهج تصميم البيانات والمعرفة.

الاستنتاجات الرئيسية

1. تواصل الأجهزة (LCS) مسار التمويل السريع، ومن المرجع أن تستمر في ذلك.
2. هذه الأجهزة ليست مناسبة حتى الآن لتحل محل شبكات المراقبة المرجعية.
3. ينبغي تشغيل الأجهزة (LCS) بموجب بروتوكول صارم لضمان الجودة ومراقبة الجودة، بلبي أهداف تطبيق البحث، أو بتجاوزها.
4. جميع الأجهزة (LCS) تقريباً لديها مشاكل معروفة وغير معروفة حتى الآن، تؤثر على دقة قياساتها وعلى تقارب هذه القياسات. ويتمثل هذا فشل حساسية أجهزة الاستشعار للمركبات غير المعرفة لها بالقياس، والأثار الناجمة عن درجة الحرارة والرطوبة، وتباين قارئ الاستجابة، وإنزلاق خطوط الأساس.
5. من أسباب قوة هذه الأجهزة المشاركة المجتمعية وتوعية المجتمع، واستخدام الأجهزة (LCS) في السياقات التعليمية.
عند الإجراء المبكر، يوصى بشدة بأن ينشئ المستخدمون الجهد لاستخدام قياسات أجهزة الاستشعار، أو التشغيل من ناحية تطوير البيانات، التي تستند أيضاً إلى تصنيف البيانات أو معالجتها اللاحقة، تماشياً مع الإمكان بالنسبة للمستخدمين، بحيث يمكنها في أن تحقق الزوايا الفنية، وأيضًا تمكن مستشاري البيانات من ذلك ما قد يكون هناك من تعديل البيانات، أو تشكيل منهجية تعديل البيانات، والوصول إلى البيانات السليمة للدورة أمر مهم جداً.

من المهم أن يحدد مستخدم النظام (LCS) أولى الاستخدامات المحددة التي يسعى إلى معالجتها باستخدام جهاز معين. وبعد إجراء الاختبار المناسب، يوصى بشدة بأن ينشئ المستخدمون الجهود لاستخدام قياسات أجهزة الاستشعار، أو التشغيل من صحة هذه البيانات، مقارنة بأجهزة القياس المرجعية. وهذه خطوة مهمة لضمان الجودة، فضلاً عن أنها توفر للخدمات النتائج المرجعية في أن تتجاوز الأدوات المرجعية المحدودة مكلاً، ولكن هذا لا يتأتي إلا بتطبيق نظام قوي للمعذرة والتحقق من قياسات (LCS) للأجهزة، بل واستخدام مسائل جديدة تتضمن استخدام الأجواء (LCS).

وتدرك الجهات التنظيمية وتصانع القرارات البيئية أن الأجهزة (LCS) ليست دقيقة بما فيه الكفاية حتى الآن، وألا تقتصر إلى الأدوات لضمان الجودة، لكي تحمل أطر البيئة التنظيمية الرسمية. ومع ذلك، فإن الأجهزة (LCS) تثير الاهتمام في الواقع التي تمنح على الأقل بعض الفهرسة على المراقبة الموضوعية، لأن هذه الأجهزة تتبع معاينة توسع نطاق قياسات المرجعية إلى ما تتجاوز الأدوات المرجعية المحددة مكلاً، ولكن هذا لا يتأتي إلا بتطبيق نظام قوي للمعذرة والتحقق من قياسات (LCS) لحد من عدم الابتعاد في هذه البيانات.

و بالنسبة إلى الذين يفكرون في استخدام تطبيقات أو بيانات الأجهزة (LCS) على نطاق أوسع، فإن زيادة استخدام الأجهزة (LCS) في المجتمع يفتح فرصة جديدة لإنتاج البيئة بطرق جديدة، من خلال زيادة مدى ونطاق أدوات القياس زيادة كبيرة بحيث تشمل إلى مواقع لم تكن سابقًا، أو بأخذ عينات من مولثات الهواء بطرق لم تكن ممكنة من قبل. ويشمل نماذج دعم (بالمثال المشروعة والمواد) الأنشطة التي تتمحون اعتماد أو التحقق من صحة بيانات الأجهزة، والنظر في توسيع نطاق استخدامها ليشمل مجموعة أكبر من الظروف البيئية وظروف التلوث. وينبغي توزيع برامج أو مراكز التقييم هذه في جميع أنحاء العالم لإدراك التغيرات في بيانات القياس، ودعمها بمراقبة لجامعات LCS في المستقبل.

بناء على التوصية 18 (EC-70) - بحث المنظمة (WMO) في المستقبل والأنشطة الداعمة لها (المجلس التنفيذي - التقرير النهائي الموجز للدورة الستين (مطابع المنظمة رقم 1215)). (المنظمة WMO 2018 (WMO))، التي "تطلب من لجنة علوم التفتيش (CIMO) العلمي للغلاف الجوي (CAS) للقيام بالتعاون مع لجنة أدوات وطرق الرصد) بمثابة إعداد إرشادات بشأن (LCS) علم الغلاف الجوي (CAS) الخدمات الجديدة لتحديد صناعة الأجهزة تعديل تكنولوجيات الفضاء الاستشعار، بما في ذلك أجهزة الاستشعار المدمجة، والأجهزة الأخرى، واستخدامها"، يعرض هذا التقرير تحديات البيئة الأخرى، أجهزة الاستشعار متخصصة لقياس تكوين الغلاف الجوي (LCS) ومعظم النظام العالمي المتعدد للبيئة (UNEP) ومعضول الأمم المتحدة للبيئة (WHO) والشفاء الأرضي والتحذيرات البيئية لدراسة LCS وبحث التوافق بين منظمة الصحة العالمية (WHO) والمشروع الدولي لدراسة LCS (IGAC).

وقد أعط التقرير التوافق بين منظمة الصحة العالمية (WHO) والمشروع الدولي لدراسة LCS (IGAC) نظامًا للتشخيص، وتعزيز الاتصال البيني لمولاًت الهواء في اوروبا وأسيا، ودعم من تلك المنظمات.
Objectives of this document

The document is intended to be a resource for: (i) the atmospheric science community including research, operational and pollution management sectors; (ii) WMO Member States, other United Nations agencies with direct interests in air pollution and greenhouse gases (World Health Organization, United Nations Environment Programme, etc.); (iii) sensor and sensor system manufacturers/developers; and (iv) other organizations including governmental, intergovernmental and NGOs, as well as citizen science practitioners and community users with broader interests in the evolution and management of air pollution and greenhouse gases.

This document is an update of a prior version published in 2018. As sensor technology is a fast-developing area, the original document required reflections on the most recent developments. In the last years, the demand and supply of sensor systems has increased and their use in research projects, smart cities platforms and community monitoring is increasing. For that reason, it is important to compile the current knowledge and best practices.

This report was constructed by six lead author teams who each partnered with several contributing authors. Expertise was sought across the fields related to low-cost sensors, including experts in atmospheric chemistry, atmospheric physics, laboratory and field-testing methods, data analysis, and LCS commercial applications. Individual sections were constructed by each team, and then reviewed internally by a second set of lead author teams for accuracy and clarity.

Low-cost sensing technologies for atmospheric composition monitoring are an appealing solution that is of interest to varied stakeholders for use in diverse and complex applications. As a result, potential users must be afforded access to unbiased expert guidance that describes different LCS technologies and LCS applications that are of likely interest to stakeholders. The document is not a full systematic review of evidence in the domain, but instead represents the consensus expert opinion of an international group convened by WMO, drawing from the peer-reviewed literature published through August 2020. The rapidly changing nature of the field in terms of basic technologies means some of the sensor systems referred to in the document may have been superseded by newer versions.

The objectives of this report are to provide prospective LCS users with knowledge that describes:

1. The specific technical principles and components of different sensor technologies;
2. How these sensors have been used and evaluated in real-world monitoring efforts;
3. How an operator of LCS should maintain and monitor optimal sensor performance;
4. Provides strategies for communicating LCS data more broadly.
Introduction

Measurements of air pollutants and greenhouse gases underpin a huge variety of applications that span from academic research, environmental monitoring through to regulatory functions and services for individuals, governments, and businesses. Two such examples are observations of greenhouse gas concentrations used to support national and international climate commitments and obligations, as well as the measurement of air pollutant concentrations which are frequently compared against legally binding standards for air quality and for the protection of human health.

In contrast to some basic meteorological parameters, atmospheric composition measurements have traditionally been the preserve of specialist organizations and skilled users. The majority of current atmospheric composition measurements used by researchers and regulators are designed to deliver traceable and reproducible measurements that meet predefined standards in relation to precision, accuracy, limit of detection, just to mention few of them. For many species there have been global efforts to promote and establish equivalence of atmospheric composition measurements through WMO programmes such as the Global Atmosphere Watch (GAW) and wider technical endeavours of meteorology and metrology institutes working to report universal, traceable SI units. Air pollution measurements of relevance to human health typically follow highly prescribed analytical methods, set by national or international conventions and agreed technical guidelines.

While the vast majority of observations of both greenhouse gases and air pollutants continue to use established analytical reference methods, the use of sensor systems to monitor atmospheric composition is increasing, despite they might not always deliver traceable and reproducible measurements. Although there are reviews published in the scientific literature, there is still not a standard protocol for comparing and evaluating the agreement between sensor systems and reference observations. There are protocols developed by research institutes and national standardization institutes, like for instance South Coast Air Quality Management District (AQMD, http://www.aqmd.gov) and United States Environmental Protection Agency (US EPA). There is also a European joint effort to create standards (CEN/TC 264 Air Quality-Performance evaluation of air quality sensors-Part 1: gaseous pollutants in ambient air and Part 2: Performance evaluation of sensors for the determination of concentrations of particulate matter in ambient air). These protocols set different requirements, including sensor data treatment, levels and duration of tests, seasonality of tests, sensor averaging time, and type of reference measurements to which sensor data are compared to.

Sensor systems are cheaper, smaller, lower weight and have lower power consumption than reference equivalent instruments, what makes them very interesting for applications where the use of reference instrumentation is difficult or not possible, as for instance monitoring in remote areas with no power supply or estimation of personal exposure to air pollution.

Sensor systems are often described generically as “low-cost sensors” (sometimes abbreviated to LCS, see Annex: Definitions). Low-cost in this context is typically referring to the cost of the basic sensing analytical component (sensor) needed to make a measurement and does not reflect the total operational costs of using sensor systems. Sensor systems contain a number of common components in addition to the basic sensing/analytical element that is used for atmospheric composition detection. Additional components within a sensor system may include: sampling capability (e.g. pump), power system (e.g. batteries), sensor signal processing (e.g. signal amplification), local data storage, data transmission capability (e.g. WiFi, 4G), housing and weatherproofing (e.g. IP65). Many commercial sensor systems combine multiple atmospheric constituent sensors in one system and often include sensors for non-pollutant parameters such as humidity and temperature. In addition, some sensor systems also offer data post-processing and data visualization “in the cloud”. The price of sensor systems can vary
depending on the number of sensors included (i.e. geophysical variables measured), the quality of the electronics and housing, and also the extended services (e.g. web visualization, data treatment, user support). Despite all units on the market are sold for significantly lower prices than reference analysers, there are large price differences between them. Moreover, it is important to note that the life of the sensing component is about 1–5 years, and it is not always possible to replace the sensing component without replacing the full sensor system. Thus, when evaluating the cost of sensor systems, it is important to consider both the expense of the initial purchase of the sensor system and then the (usually) considerable ongoing costs of operation, including power, servicing, data processing, calibration and data quality assurance. While comparing the cost of the sensor system with a reference one, the sensor lifetime and the total cost of the continuous update of the system during the typical lifetime of the reference system (with a one-time investment) should be taken into consideration.

The possible applications of sensor systems are explored in later sections, but the emergence of this type of devices can, in principle, enhance current monitoring systems, create new atmospheric applications, offer innovative services and potentially support the inclusion of a new cohort of users in atmospheric monitoring. Sensor systems have been successfully applied by citizen science projects and grass roots movements, providing a greater sense of ownership of issues related to local air quality or climate change. For research and government users, they may offer an additional route to test knowledge of atmospheric processes, dispersion and emissions and contribute to validation of atmospheric models and forecasts at high temporal and spatial resolution. For regulators, sensor systems may allow finer scale assessment of air pollution concentrations, for example to identify hotspots and inform more targeted policy action. For the air quality and health community using portable sensors with high time resolution means that more representative data on personal exposure can be obtained.

The exciting technological potential brings with it new challenges and at present there are measurement limitations that need to be assessed and characterized. Low-cost devices tend to be less sensitive, less precise and less chemically specific to the compound or variable of interest than reference methods. The application of advanced calibration and intelligent corrections has shown to improve significantly the sensor data quality. Nevertheless, sensor systems are not currently a direct substitute for reference instruments, especially for regulatory purposes, as they do not reach the same high data quality, reliability and longevity as reference instruments. Sensor systems are, however, an important complementary source of information on atmospheric composition, provided that the appropriate sensor system is used, and calibration and quality control routines are in place.

Determining the optimal calibration model to transform the raw data from the sensor to a usable format, or to improve the quality of sensor data, is an active field of research. The most employed options are variations of a parametric regression using multiple parameters (e.g. multilinear regression) and non-parametric/nonlinear/machine learning approaches. However, both calibration approaches are limited by the data employed to derive the calibration model. For instance, if the sensor is calibrated during summer, the model might not perform well during winter.

Improving the quality of the data from low-cost sensors using field calibration is a very common approach. In some occasions the calibration algorithms are very complex and might include predictor variables not measured by the sensor system itself. Table 1 shows a proposed unified terminology of processing levels for low-cost atmospheric composition sensor systems, to add clarity regarding the level of sensor data processing and thus providing a correct use and interpretation of LCS data.

Aside of the quality assessment, another important aspect is the quality control of the sensor system itself. Quality control is designed to assess the long-term performance of the sensor system during deployment (i.e. not co-located with a reference station) to ensure it remains in calibration. Quality control should advice the user when the sensor system needs re-calibration and also when the life of the sensor has ended. There are several parameters that need to be
monitored over time, as for instance baseline drift and changes in sensitivity. Several approaches on how to improve quality control procedures have been proposed, but we are not in position to recommend one or the other. Automated quality control approaches become essential to increase consistency of data, save time and effort, and support quality checks on large number of sensors, especially as sensor networks move from tens to thousands of sensor systems.

Table 1: Summary of the proposed processing levels of data of low-cost sensor systems

Source: (P. Schneider et al. 2019a)

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>NAME</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEVEL-0</td>
<td>Raw measurements</td>
<td>Original measurand produced by sensor system.</td>
</tr>
<tr>
<td>LEVEL-1</td>
<td>Intermediate geophysical quantities</td>
<td>Estimate derived from corresponding Level-0 data, using basic physical principles or simple calibration equations, and no compensation schemes.</td>
</tr>
<tr>
<td>LEVEL-2A</td>
<td>Standard geophysical quantities</td>
<td>Estimate using sensor plus other on-board sensors demonstrated as appropriate for artefact correction and directly related to measurement principle.</td>
</tr>
<tr>
<td>LEVEL-2B</td>
<td>Standard geophysical quantities-extended</td>
<td>As Level-2A but using external data demonstrated as appropriate for artefact correction and directly related to measurement principle.</td>
</tr>
</tbody>
</table>

**MEASUREMENT/PREDICTION BOUNDARY**

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>NAME</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEVEL-3</td>
<td>Advanced geophysical quantities</td>
<td>Estimate using sensor plus internal/external inputs, not constrained to data proven as causes of measurement bias or related to measurement principle.</td>
</tr>
<tr>
<td>LEVEL-4</td>
<td>Spatially continuous geophysical quantities</td>
<td>Spatially continuous maps derived from network of sensor systems.</td>
</tr>
</tbody>
</table>

As any other analytical instrument, including reference instruments, sensor systems will require regular calibration and will show changes in drift and long-term changes in sensitivity. Data from sensor devices have higher uncertainty than data from reference instruments. Moreover, the quality of the data collected by sensor systems changes with time, due for instance to interferences with weather conditions (humidity and temperature) or to the deterioration of the sensing element. The characterization of the uncertainty from a sensor system is not straightforward and that does not necessarily fit easily within the existing technical frameworks for data quality. To date, the vast majority of information on atmospheric composition that is in the public domain is derived from trained practitioners following accepted and traceable methods of measurement. Nowadays we

The exciting technological potential brings with it new challenges and at present there are measurement limitations that need to be assessed and characterized.
see the emergence of new data providers, with information on atmospheric composition coming from a far more diverse range of sources and with a wider range of data quality. Sensor systems, despite their current limitations, do however represent a useful tool to expand research and operational capacity beyond traditional practitioners and approaches, though one must be cognizant of the inherent limitations of these devices.

Data quality is a key issue determining the usability of any measurement system, and the necessary level of data quality will be dictated by the user and application. For example, users interested in the technological aspect of hobby (do-it-yourself) will have lower expectations than organizations interested in operational air pollution management. Nevertheless, independently of the different requirements for accuracy, there is a critical need to establish a cohesive approach for the evaluation and performance assessment of sensor systems prior to their large-scale adoption in atmospheric science.

Currently, many sensor systems operate as black boxes, and the calibration, validation and quality control methods offered by manufacturers are proprietary and non-transparent (i.e. commercially confidential). However, it is essential that the type and amount of processing performed on sensor systems is communicated transparently so that the users can make informed decisions. This is particularly important for scientific, operational, and policy applications where methods have to be thoroughly documented and their fitness for purpose demonstrated.

**Current and future applications**

Within this document we consider a range of different applications and science domains that rely on information about atmospheric composition. The document considers specifically sensors that are designed for the measurements of atmospheric composition at ambient concentrations of the following constituents:

1. Air pollution gases including NO, NO₂, O₃, CO, SO₂, and an operational metric defined as ‘total VOC’.
2. Long-lived greenhouse gases: CO₂ and CH₄.
3. Airborne particulate matter (PM) in various size classes (e.g. PM₁, PM₂.₅ and PM₁₀).

There is a range of peer-reviewed literature that is available for consideration, although the depth and volume of that literature is variable depending on the pollutant of interest in the study. A very important point to note is that the technical field is rapidly evolving, and individual sensor systems are in many cases frequently updated by manufacturers. The general trajectory for sensor systems is clearly one of ever-improving capability, and newer ones tend to outperform older versions. The rate of technological change does mean that for some currently commercially available sensors and sensor systems, there may not yet be peer-reviewed or open-source traceable methods of evaluation that can be referred to when collating this report.
When new sensor systems are introduced to market, manufacturers are strongly recommended to engage in validation activities that place independent traceable evidence of performance in the public domain. A notable strength of sensor systems is that they are typically modular in nature and new sensor components can be introduced much more easily by manufacturers than is the case for many existing reference methods. Given the typical small footprints, portability, and low consumption, it is relatively easy to collocate sensor systems with reference instruments for evaluating their performance and obtaining improved calibration models.

At present, there are six broad areas where atmospheric composition measurements are required, and which are currently serviced by established reference instruments. Each is described briefly in Table 2 alongside the key data requirements from measurements that service that application area, and how that application is supported in terms of data quality and traceability.

Table 2 is intended to provide an illustrative view of current applications and the supporting frameworks that ensure measurement methods/instruments report data to a quality that is appropriate for that application. It is notable that sensor systems are particularly attractive for the emerging applications of air quality management, public information and estimation of exposure to air pollution. These areas often, but not always, have less stringent requirements for data quality. While some supporting frameworks or guidelines are now available to ensure data is fit for purpose, gaps still remain in consensus on what would constitute appropriate data quality standards for many sensor applications. This can be contrasted with some of the other application areas where the requirements for traceable and accurate data have resulted in extensive national and international supporting frameworks and best practice being built up around individual methods of measurement. These may well emerge for sensor systems over the next few years and the ongoing work of a range of international environmental measurement entities is acknowledged in this regard.

The general trajectory for low-cost sensors is clearly one of ever-improving capability and newer sensors tend to outperform older versions.
Table 2: Applications of the atmospheric composition measurements, related measurement requirements and evaluation

All acronyms defined in the footnote.

<table>
<thead>
<tr>
<th>Application</th>
<th>Type of measurement, purpose, and user</th>
<th>Measurement requirements</th>
<th>Critical evaluation¹</th>
</tr>
</thead>
</table>
| Research in atmospheric sciences | Type | Short and long-term observations of atmospheric composition | - Compound-specific, generally needing quantitative measurements and statistical treatment of data  
- Where available, traceable to identifiable reference materials/methods  
- Reported as concentrations with uncertainty  
- External check on data quality and measurement methods through extensive peer-review | Peer-review for new methods and applications. NMIs or other accepted methods for calibration, i.e. those recommended by GAW, of established parameters  
Research labs for calibration of emerging properties |
| Purpose | Basic and applied research | | Sensor systems are beginning to play a role in areas such as model or emissions validation and spatial variability in pollution. |
| User | Primarily research organizations/ institutes and universities | | |
| Long-term global change | Type | Trends and behaviour of key atmospheric composition parameters | - Quantitative, reproducible measurements  
- Methods follow prescriptive methods / best practice guidelines  
- High data quality and accuracy  
- Compatibility of concentration data between operators/locations/nations  
- Participation in international calibration protocols  
- Adoption of methods only after extensive technical and peer evaluation of analytical performance | Peer-review for new methods and applications  
NMIs, EURAMET, NOAA, etc. for calibration  
WMO / GCOS for best practice |
<p>| Purpose | Track global change, support international activities such as UNFCCC, GCOS, WMO/GAW and environmental conventions | | |
| User | Primarily research organizations / institutes, government bodies, meteorological agencies | | Sensor systems are beginning to play a role as complementary information to well established reference monitoring systems. |</p>
<table>
<thead>
<tr>
<th>Application</th>
<th>Type of measurement, purpose, and user</th>
<th>Measurement requirements</th>
<th>Critical evaluation</th>
</tr>
</thead>
</table>
| **Air Quality management**          | **Type**<br>Observations of air pollution concentrations                     | o Quantified degree of compatibility with air quality compliance measurements  
|                                     | **Purpose**<br>Operational transport authorities, local government offices and environmental agencies | o Substantial degree of confidence in data since it forms part of decision-making  
|                                     | **User**<br>decision makers at local or regional levels, for example, in transport planning or emissions control | o Quantitative or qualitative measurements to capture baselines, trends, and other changes in pollutant concentrations  
|                                     |                                                                             | o Some degree of data quality standard and reliability  
|                                     |                                                                             |  
|                                     |                                                                             | *This is already an early application area for sensor systems.*  
|                                     |                                                                             | Variable  
|                                     |                                                                             | No specific requirements for methods, calibration or best practice.  
| **Air Quality compliance/ regulation** | **Type**<br>Observations of air pollution concentrations                     | o Quantitative measurements  
|                                     | **Purpose**<br>Demonstration that a location has met national or trans-national (e.g. EU) standards for air quality | o High data quality with traceability to identifiable reference materials/methods for legal reporting  
|                                     | **User**<br>Primarily operational bodies, commercial contractors, environmental agencies | o Reported as concentrations  
|                                     |                                                                             | o Follow fully prescribed methods and best practice  
|                                     |                                                                             | o Instruments certified for use based on demonstration of measurement equivalence  
|                                     |                                                                             | o Follow national protocols for calibration and methodologies that meet existing legally defined data quality objectives  
|                                     |                                                                             | It is unlikely for sensor systems to be adopted for these applications unless standardized protocols are developed for calibration, operation, and data usage.  
|                                     |                                                                             | NMIs for calibration  
|                                     |                                                                             | ISO, CEN, USEPA, etc. for methods  

1: Critical evaluation refers to the maturity and reliability of application areas for sensor systems.
<table>
<thead>
<tr>
<th>Application</th>
<th>Type of measurement, purpose, and user</th>
<th>Measurement requirements</th>
<th>Critical evaluation¹</th>
</tr>
</thead>
</table>
| **Public Information / community monitoring** | Observations of air pollution parameters                                                                 | o Quantitative or qualitative measurements  
   o Flexibility in reported units  
   o Indicative  
   o Methods not legally prescribed, but should avoid conflict with air quality data generated from compliance/regulatory applications | Already identified as a class of applications for sensor systems.  
   Not yet defined, although cannot diverge significantly from air quality compliance |
| **Purpose** | Support public engagement and awareness, citizen science activities, education, provide data for advocacy and local empowerment |                                                                                  |                                                                                  |
| **User** | Operational bodies, NGOs, academic researchers, businesses or private individuals                      |                                                                                  |                                                                                  |
| **Proxy for exposure** | Alternative exposure measurements that can be compared to official data, or in lack of official data, can provide some order of magnitude of the exposure of a population in specific areas or buildings | o Quantitative measurements  
   o Measurement equivalence to regulatory observations generally preferred, but not required or always possible  
   o To support health/medical decision-making, data quality requirements would be more rigorous | Limited currently to research and occupational health.  
   Peer-review for methods acceptance  
   National/Trans-national occupational health-approved regulatory devices |
| **Type** | Observations of personal exposure to air pollution                                                   |                                                                                  |                                                                                  |
| **Purpose** | Observations of personal exposure to air pollution                                                   |                                                                                  |                                                                                  |
| **User** | Academic researchers, operational agencies, public health officials etc. assessing the human health impacts of air pollution |                                                                                  |                                                                                  |

Sensor systems and their application in the atmospheric sciences therefore need to be evaluated not only in terms of the technical performance of individual devices but also in terms of the hardware, software, and data analysis frameworks that are required to support their use for specific kinds of applications. New services enabled by sensors continue to emerge conceptually and in trial experiments and so it is inevitable that the measurement supporting tools (e.g. data quality approaches, data correction algorithms, calibration methodologies, maintenance and so on) will also evolve as consensus is reached on best practices.

For academic use of sensor systems, it would be expected that the overarching data quality framework associated with peer-review will persist well into the future. For those interested in using such devices for novel purposes or applications, the responsibility will be placed largely on those making the measurements to demonstrate that data meets an appropriate quality threshold, ensuring that each device used was fit for purpose, in their publications. Over time the need to demonstrate this may diminish as methods and sensors become accepted and others repeat and confirm sensor and sensor system performance.

For operational use, measurements are expected to meet some predetermined standard of data quality that are defined by the existing frameworks prescribing reference instrument performance. Depending on the context, this may be a framework that is legally defined or one that is operationally defined through participation in some broader international activity. Many existing atmospheric applications (for example regulatory compliance, long-term global change) have well established requirements in terms of data quality for particular parameters, and it is unlikely that performance requirements will be relaxed as they are driven by the specific need. It is essential for these types of high precision applications that low-cost sensors are considered in terms of what complementary information or outcomes they might add to the understanding of any given monitoring application, rather than whether they are a like for like replacement for reference instruments.

An interesting space for new thinking is for future users of sensor systems who may be trying to achieve new insight with atmospheric composition data, e.g. for applications such as city air pollution management or public information, where sensor system data requirements have yet to be firmly established and methods of exploiting sensor data are becoming more successful. In parallel, the users of sensor systems already include citizen science projects, NGOs and individuals. These users may not necessarily be experienced in measurement science, air quality monitoring, or data interpretation. These new non-expert user-led applications may particularly benefit from the development over time of targeted guidance and support frameworks, as currently exist for research and operational users and through the various type testing schemes. Examples of
such guidance and support frameworks currently available for all users – experts and non-experts alike – include the Air Sensor Toolbox from the US EPA and European efforts to develop sensor performance standards and these guidance and frameworks must be actively promoted in a non-expert community who may be not aware of them. A challenge in developing sensor system guidance and other frameworks targeted to non-expert users will be that such users may not wish or need to publish their data, methods or results through open or peer-reviewed systems and therefore it may become increasingly difficult to anticipate the diversity of applications pursued by non-experts or to incorporate their feedback for ongoing improvement. The scientific community is encouraged to engage these groups who share their results across general communication channels (such as blogs or social media), and, in turn, encourage these groups to publish measurement metadata as completely as possible in order to have a more complete understanding of sensor performance.
Main Components and Principles

Low-cost sensor systems are composed of core components and supporting hardware (see example in Figure 1). Core components are the sensing/analytical elements used for detection and components that acquire, process, and output data. Depending on the sensor system, these are augmented with other power, security, usability, and data display features. Key hardware and software/firmware components in a sensor system include:

**Sensing Elements or Detectors:** A sensor system may combine multiple atmospheric composition constituent sensors as well as other sensors for non-chemical parameters such as humidity or temperature which may or may not be required for instrument operation, signal correction or data processing.

**Sampling Capability:** Sensor elements need to be exposed to the atmosphere in a way as to be representative of the target environment. This can be achieved with passive (via inlets or apertures) or active (pump or fan) systems.

**Operational Hardware:** On-board computational capability (e.g. microcontrollers or single board computers) is needed for sensor control, signal management, analogue to digital conversion, on-board processing, local data management and telemetry.

**Power Systems:** Power resource access (e.g. batteries, mains, supercapacitors or solar) and power management (e.g. smoothing, stabilization, saving and backup).

**Data Management:** This includes storage (e.g. long-term, temporary, local and remote) and transmission capability (telemetry) (e.g. WiFi, cellular mobile data networks spanning from GSM¹ to 5G, or other low-power wide-area network (LPWAN)). A wide range of telemetry options are available for a range of applications (e.g. LPWAN for dense spatial monitoring). Early examples of the General Packet Radio Service (GPRS) linked to 2G and 3G networks are now surpassed by the emerging 5G infrastructure.

A number of different approaches and deployment locations are needed to evaluate the capabilities of low-cost sensors

**Physical enclosure or housing:** (e.g. weatherproofing, electro-magnetic shielding, mounting) depending on application.

**Accurate spatio temporal reference:** Knowledge of location and provision of accurate time are needed, particularly in the case of relatively dense sensing networks. This may be a reference point (i.e. a single known location and time) from which further times or positions are determined or a more active system with regular or periodic updates (e.g. GPS uplink).

**Software requirements:** These include on-device and/or cloud-based software for data acquisition, processing, management, transfer and remote device management.

**Data analytics:** These include techniques and processes to convert raw data into valuable information and visualize the processed data (e.g. via the cloud). Sensor systems connected to cloud servers may use cloud algorithms to process the data before final logging and display.

¹ Global System for Mobile communications
Figure 1: An example of a low-cost sensing system that is comprised of many different components. Photo Courtesy of R Jones, Cambridge University, UK

For those considering using individual LCS or LCS deployed in a network, it is often the initial purchase price of the device that are most relevant or appealing to users (see Annex 1: Definitions). It is important to note that there are meaningful costs that go beyond initial purchase prices. For example, many devices require periodic or routine maintenance to assess and ensure instrument functionality or to replace non-functional parts/devices. One may need site-specific support systems (e.g. weatherproof enclosures, reliable power availability, or adequate cellular signal strength), which may incur additional costs. In many cases, deployment of LCS in a network requires more advanced planning, and additional maintenance and operations costs. Users may need to establish data management systems. If devices are owned by a user, but maintained or operated by a third-party institution, there may be meaningful post-processing costs required for a vendor to convert raw data to finalized data prior to delivery to the owner. To respond to this breadth of costs, there are a number of business models which seek to provide these services as costs to a user. For example, there are different models in which an individual can purchase a sensor and integrate its data into your own data management system, another where you can purchase a sensor that is delivered with its own data management system, as well a third where everything is provided in a 'sensors-as-a-service' framework. Each model has advantages and disadvantages, and while this document does not specifically advocate any of the available models, it is critical to recognize that there are meaningful costs associated with LCS use that go beyond the initial purchase price.

It is worthwhile to highlight that although individual sensors have inherent deficiencies and uncertainties in comparison to high quality air quality monitors, the strength of LCS systems lies in their potential for deployment in relatively large numbers as networks or as part of networks, and often in locations where reference instrumentation use is impractical. Application of advanced data fusion algorithms over sensor networks can be used to
minimize (Okafor et al. 2020) known limitations of individual sensors and enable the collection of valuable and appropriate air quality information. Thus, it is often advantageous to an end user to deploy a network of monitors across a measurement domain, however, this introduces additional logistical complexity in LCS approaches.

High spatiotemporal granularity is likely both an advantage and burden to an LCS user. While the advantages of additional datapoints are fairly clear (increased average precision, better spatial understanding of pollutants, etc.), sensor networks sometimes require improved data handling infrastructure. Figure 2 shows an example framework for managing data, and a user may need to consider issues related to data security and ethics, following established measurement protocol, and deliver data to a management system. While Figure 2 illustrates specific platforms and frameworks used in a specific example, the intent of this is to illustrate the complexity of dataflow through different layers of processing. There are many methods for managing sensing network, which include a growing number of commercial operators. But it is important to reiterate that this type of infrastructure, and its inevitable costs, should be considered if one is to establish a LCS network in their community.

![Figure 2: A Dispersed Heterogeneous Environmental Sensing Network architecture](adapted from "An Example of a Generalized Network Architecture for Environmental Sensing" Mead et al in preparation).

An important challenge in assessing LCS component performance through traditional academic or government research studies is the time-lag between collection of results and their final publication and conclusions. This process occurs on a longer timescale than the pace of new sensor technology development. This warrants some pause as the performance reported in these examples may not necessarily indicate what might be achieved if the same experiments were conducted now with the most recent technologies. In addition, any
given study is unlikely to experience the full range of real-world meteorological or environmental conditions and so they may only capture a subset of possible component-driven effects. Therefore, a number of different approaches and locations are needed to evaluate the applications and capacities where LCS can be successfully implemented.

Because each LCS device has particular strengths and weaknesses that depend, in part, on the technology and components chosen or the environment in which it operates, it is informative to examine some recent users’ experiences and to identify some of the generic issues that have been seen in the comparison of sensor-based approaches against reference methods. A more detailed summary of influencing factors for various sensor types is given in Annex 2: Sensor Issues.

An Example of Low-Cost Sensor Costs

This report does not explicitly define what ‘low’ means, though understanding cost is an area of keen interest for prospective users. Often, the initial procurement costs for hardware are one of the more attractive features for LCS, however, they usually require substantial additional support costs that need to be considered for a successful monitoring operation. This is particularly true for large networks of sensors where a robust support system is usually required.

In purchasing a LCS network, one must consider the varied costs that are required to support the network. Hardware costs might include the cost of purchasing LCS (including instrument housing, data streaming equipment, and miscellaneous supplies). Software costs can include PC- or cloud-based data management systems that collect, store, and process LCS data, and provide data outputs (graphs, tables, reports) to users. One must also account for quality assurance and quality control costs which include active calibration assessments. And lastly, there are routine maintenance and operation costs, such as payment of utilities or data transfer fees, rental of space, and replacement of failed equipment.

The costs indeed vary considerably, based on geographic location, atmospheric components to be monitored, the available local resources, etc, and it is not possible to capture the breadth of varied global costs with much precision. But as a thought exercise in this report, it is useful to investigate and report hypothetical costs for NO2 and PM2.5 LCS in different network sizes. Here, we have made a number of assumptions based on our own experience in best operational practices, and included total cost estimates based on the range of monitoring location site counts for continuous operation over five years (Figure 3). Briefly, this exercise assumes purchasing LCS device(s) that cost $1,000 and are replaced annually, there are increasing operational costs with increasing network sizes (though scale discounts reduce the marginal costs of these operational expenses) in order to support the network, and data are collected and analysed using a best practices approach and includes appropriate data management and quality assurance/quality control applications. A table of assumptions and calculations are included in Annex 3: Example Cost Comparisons.

As expected, there are escalating total costs with increasing numbers of monitoring locations over five years. But in this hypothetical example, per unit operational costs appear to reach a maximum marginal cost in networks on the order of 10 units and decrease in marginal costs in larger networks. Total costs continue to rise, of course, but at a more modest rate of increase. As a network exceeds roughly 100 nodes, marginal cost improvement begins to converge though total costs continue to escalate because networks of larger sizes require additional operational support, such as personnel, logistics, and more robust data management systems.
Figure 3: An example of total costs and per unit operational costs over five years for a low-cost sensing network of various sizes.

Though this is a hypothetical example, and is meant only to reflect an estimate of cost expectations for potential LCS users, there are a few generalizations that can be learned from this exercise:

(i) If considering an LCS network, users may find it most cost effective for medium sized networks (50–250 nodes) rather than small networks (<25 node).

(ii) While very small networks can sometimes be managed by inexpensive data management systems (e.g. collecting and analysing data on office productivity spreadsheets), all networks require personnel to oversee their operation, and in small networks, the personnel effort becomes a substantial fraction of network costs.

(iii) Very large networks (i.e. those greater than 250 nodes) likely require additional management and oversite, which increase costs. But these costs are thought to be directly proportional to network size.

(iv) Prospective LCS users are encouraged to perform a similar cost exercise to better predict costs for their specific application.

It is important to reiterate that this is simply a thought exercise in estimating costs and is based on a number of cost assumptions which will vary globally. But it is useful to point out that LCS networks of any size are likely substantially less expensive that reference networks; recent work by Brauer and colleagues (Brauer et al. 2019) modelled costs for establishing reference monitoring networks of various sizes (785–8600 nodes) in India and conclude that five-year operational costs alone are on the order of $ 175,000 (USD) per node.
Calibration and Quality Assurance/Quality Control of LCSs

LCS are in many ways different from reference instruments and therefore require adoption of new and different approaches for QA/QC to those currently used for the measurement of air pollution and greenhouse gases using reference instruments. It is however important that the data processing performed during QA/QC of LCS is transparent and properly documented.

While various stakeholders will have different requirements for accuracy and traceability, it is imperative that there is a transparent characterization of how a given sensor behaves – after all, “data of poor or unknown quality is less useful than no data since it can lead to wrong decisions” (Snyder et al. 2013). To address this issue, there is a critical need to establish a cohesive approach for the evaluation and performance assessment of LCSs prior to their large-scale adoption in atmospheric science (Karagulian et al. 2019; Lewis and Edwards 2016). Activities such as CEN TC 264 Working Group 42 is one example of an international coordinated effort to address these issues for reactive air pollutants and particulate matter.

That being said, atmospheric composition sensors should be treated as any other analytical instrument; they will require regular calibration and will show drift and changes in sensitivity on different timescales. For the purpose of this document, we define a calibration of an LCS as the establishment of a relationship between the output of a LCS and a measurement standard, where a measurement standard in this context can be either a calibrated reference instrument or a gas/particle reference material. It should be appreciated that this definition on calibration falls within the definition of the term as recognized by WMO, but such an approach is not necessarily viewed as being calibration by some National Meteorology Institutes.

Quality Assurance and Calibration

Quality assurance is the process of ensuring that the data arising from a sensor is consistent with the same data arising from a known standard measurement. This is almost always performed using calibration techniques where a sensor reports a result of the same environmental sample as a reference instrument or certified standard. Quality assurance, through a process of understanding and applying an appropriate calibration to any device, ensures that data that a sensor produces are robust and accurate. It allows a user to answer the question ‘does my sensor produce accurate and/or precise concentration data’.

Calibration of LCSs involves determining a model that can be used to convert the measured parameter (e.g. light absorption, voltage, or conductivity) into desired output variable (e.g. pollutant/species concentration). For some sensors, the factory calibration settings are published in data sheets, other sensors resemble a black box and the applied data conversion model remains unknown to users. At present it is likely many users continue to rely on these factory calibration settings as the main method of calibration. However, factory calibrations for many sensors are not yet sufficient for robust, long-term accuracy across the range of possible environments in which the sensor may be used. As a result, a
validation (quality assurance) of the data should be performed in an environment similar to the one in which the LCS will be used, which will result in increased confidence in accuracy and precision of LCS data.

![Calibration](image1.png)  
**Calibration** Sensors compared to known standard (values) under laboratory or field conditions that the LCS operates. Performed using traceable instruments/systems at regular intervals (e.g., every 6 months) and as needed based on periodic performance checks.
- ✔️ “Sensor is calibrated for the range of conditions tested.”

![Co-Location](image2.png)  
**Co-Location** Sensors compared to a reference instrument closely located (e.g., with 10 meters). Best performed at the beginning of study, during study (every two months), and at study completion.
- ✔️ “Sensor is validated under the test conditions.”

![Comparison](image3.png)  
**Comparison** Sensor data compared to nearby data to determine if sensors measure reasonable values and changes. Best performed by continuously comparing to reference measurements, modelling data, satellite data, etc.
- ✔️ “Sensor is quality checked.”

**Figure 4: A schematic of typical levels of validation of sensors**

Currently, there are two main approaches to calibrating LCSs: laboratory calibration against reference materials and field co-location with reference monitors which have themselves been calibrated against reference materials; both methods have benefits and drawbacks. In order to increase data quality and confidence in a measurement, it is important to follow the hierarchy of validation (Figure 4) as high as possible, with an ideal measurement reaching ‘calibration’. However, it is recognized that attaining this is often not possible. As detailed below, calibration of LCS is a complex task that requires expert knowledge and resources.

Laboratory calibration typically involves the same approaches used to calibrate reference and research-grade analytical chemistry instruments: subjecting the sensor to a series of known concentrations of pollutant/species using known measurement standards in a controlled environment. This approach has been explored extensively in the literature (Castell et al. 2017; Mead et al. 2013; Muller et al. 2020; Piedrahita et al. 2014); unfortunately, the conditions under which sensors are calibrated in the laboratory do not often overlap with the full range of conditions encountered in an ambient environment. These differences include the presence of cross-sensitive gaseous species (Lewis et al. 2016), changes in relative humidity and temperature, and ever-evolving aerosol physical and optical properties, all of which are known sources of error for LCS measurements.
Laboratory experiments are also limited to those with the resources and/or opportunity to access the necessary equipment, which may not be all future user groups of LCSs. However, laboratory experiments can be very useful for determining how LCSs behave under very specific, controlled conditions which contribute to our fundamental understanding of how they work. If using a laboratory test as a primary calibration approach, it is important to mimic the deployment environment of the sensors as closely as possible (e.g. using an environmental chamber to scan the typical range of temperature, humidity, pressure, etc.).

To overcome some of the limitations encountered in the laboratory, many have found ambient co-location against reference monitors to be an effective method of validation whereby calibration parameters can be applied to a LCS. Here, the sensor (or sensors) is placed in the field near a reference instrument for a period of time to provide a direct comparison of the LCSs output to that of a calibrated reference instrument. It can be difficult however to experience the entire dynamic range of target species, cross-sensitive species/pollutants and environmental parameters in a short period of time and this can make comprehensive calibrations rather time intensive (Hagler et al. 2018). On the other hand, co-located measurements over a longer time period, such as months to years, can be unfavourable given the short lifetime of some LCSs. Access to locations and calibrated reference equipment can also be an issue, and a LCS user must ensure that an accurate clock record (e.g. local time or universal time) is maintained. The seasonal change of the field environmental conditions should be considered (in addition to the LCS drift) to determine the frequency of the field co-location calibration.

When planning and performing a calibration of a LCS, important factors to consider are temperature, relative humidity, and cross-sensitive gas species (details can be found often in LCS data sheets) for gas-phase sensors, and relative humidity, composition, size distribution and optical properties for particle sensors. For large deployments, calibration of every single LCS can be logistically- or cost-prohibitive. It is generally understood that there may be significant measurement differences between identical models of LCS measuring the same environment (Collier-Oxandale et al. 2020a) As a result, where feasible, it is best to calibrate all LCS as an ensemble. If not, the batch calibrations may be effective to characterize and quantify these differences within a single LCS model.

For both approaches mentioned above, an active area of research is determining the optimal algorithm used to convert raw sensor data (often current or voltage for gas sensors, histogram or raw counts for particle sensors) into a usable format (concentration, mixing ratio, aerosol loading). Many have used variations of a parametric regression with some success (Jiao et al. 2016; Lewis et al. 2016; Masson et al. 2015; Mueller et al. 2017; Popoola et al. 2016; Sadighi et al. 2018; Smith et al. 2017) though many non-parametric/non-linear/machine learning approaches have appeared recently in the literature (Bigi et al. 2018; Cross et al. 2017; Hagan et al. 2018b; Spinelle et al. 2015a; Zimmerman et al. 2018) as they can account for less obvious environmental effects and interference with cross-sensitive species.
Some form of comparison between LCS against existing reference instruments is essentially the only way in which their potential utility as complementary devices can be assessed. The calibration of LCS against reference instruments can improve the accuracy of a sensor network. Recent advances in data analytics using statistical methods and machine learning can contribute to the development of in-field corrections for LCS networks (Karagulian et al. 2019; Wang et al. 2020a). Calibration models (such as multiple linear regression or random forest regression) are trained on a few sensors either in-field or in the laboratory that is then expanded to a larger sensor network (Simmhan et al. 2019; Wang et al. 2020a) with the aim to develop sensor prediction models.

However, these strategies for sensor data processing raise important questions as stated by Hagler et al. (2018): (a) How confident are we that calibrated sensors provide a sufficient data quality when deployed at other locations? (b) What are the appropriate parameters to include in sensor data adjustment algorithms? (c) At what point do adjusted sensor data depart from an independent measurement? Hagler et al. (2018) present a scheme for the type of parameters that can be used for sensor data treatment (defendable parameters) and those that should not be used (questionable parameters).

It is important to have a clear framework to compare data treatment algorithms (calibration/data correction/data adjustment) and different sensors so that a user can easily understand how each algorithm improves or degrade the quality of data compared to a reference measurement. Many studies currently use a combination of the correlation coefficient (R²), root mean squared error (RMSE), and mean absolute error (MAE) to describe their model performance (Karagulian et al. 2019). While these are valuable, it is equally important to record, report, and understand the conditions under which a calibration was performed, for example the duration and seasonality of the test measurements, the sensor averaging time and the types of reference measurements used (Bigi et al. 2018).

An active area of research is focused on determining drift over time, with reported drift timescales varying from days (Smith et al. 2017) to several months (Bigi et al. 2018; Hagan et al. 2018b; Mead et al. 2013; Popoola et al. 2018) for gas-phase LCS.

Another important issue is ensuring the robustness of calibrated sensors to re-location. As described in Karagulian et al. (2019), the data quality of sensors used for co-location calibration may be different from those in a new location. This can lead to confounding or other sources of error that can affect a measurement. It is also important to recognize that is it not possible to measure and calibrate for every possible interfering parameter using a reference sensor, and that some potentially interfering parameters may be correlated with other unmeasured ones in some locations, but not others. For example, perhaps an LCS device is fundamentally sensitive to interference from SO₂. It is possible that in one location, SO₂ and NOₓ are well-correlated with one another, and you can use a reference measurement of NOₓ to calibrate the sensor. But in a second location, where SO₂ and NOₓ are not correlated, you may erroneously adjust your LCS to your reference NOₓ measurement in a manner independent of the interfering compound, which will lead to error.

Many manufacturers routinely provide factory setting sensor calibration data, which is often developed under proprietary laboratory conditions. Sensor responses may well be altered when used under different measurement conditions (i.e. calibration coefficients under
ambient measurements are often different from the ones under laboratory conditions), and therefore, reliance on manufacturer calibrations alone, without reference comparison, is insufficient for quantitative data applications.

Quality Control of Sensors and Sensor Networks

![Quality Control Diagram]

**Figure 5: Span of current capabilities and applications across different types of atmospheric composition measurement networks**

Quality control is the act of monitoring the long-term performance of a LCS during deployment in a sensor network to ensure it remains in calibration, and can help notify the appropriate party when a LCS needs to be corrected or removed and undergo re-calibration, likely when the bias exceeds the measurement uncertainty. It is an assessment of whether or not a sensor is performing in a manner consistent with its requisite design for data quality and is an assessment of sensor performance. Quality control allows a user to answer the question ‘how well does my sensor produce data of high quality’.

Like their reference instrument counterparts, LCSs have a limited service lifetime, but this has yet to be determined for many LCSs, and can depend greatly on the environment in which a LCS is deployed (e.g. high pollution environments can cause PM sensors to foul, low humidity environments can cause sensitivity decay in electrochemical gas sensors). Quality control is also the method for determining end-of-life for a sensor. A user should apply quality control statistics to define the end-of-life for LCSs if using them over a sufficiently long period of time.

Several approaches to quality control have been proposed in the literature. One approach is to periodically compare the values obtained with a LCS to a nearby (but not co-located) reference monitor (Mueller et al. 2020; Mueller et al. 2017). There are important differences between this type of assessment, which is focused on quality control, and a true calibration (quality assurance) because the different sensors may be subjected to different...
environmental conditions (e.g. temperature, relative humidity, presence/absence of interfering compounds), they may be sampling different air masses, or there could be different inlet differences between the two sensing devices. In some locations, especially those throughout Europe and the United States, reference data are made available by regulatory agencies and can be accessed either through their websites or via public groups such as OpenAQ (https://openaq.org/#/). However, it is important to be aware of possible limitations with this approach, since the concentrations of gases and particles may vary significantly near sources and sinks, even over modest spatial lengths of a few meters, and thus these efforts should be viewed as quality control activities designed to evaluate a sensor’s performance to produce quality data, and not specifically a measurement of concentration differences.

A second approach that has recently appeared in the literature, is to use knowledge of regional atmospheric chemistry in combination with a small number of anchor points (reference stations) to perform remote calibrations (Kim et al. 2018). Similarly, statistics-driven quality control checks based on transport phenomena could provide information on relative differences amongst sensors within a localized network. However, the use of regional chemistry models can also lack the necessary spatiotemporal granularity to sufficiently eliminate uncertainty.

A third approach may include the establishment of ‘mission-specific’ platforms designed for routine and periodic calibration activities. These can be employed either in a centralized location where LCS are returned for regular performance assessment, or they can be employed in a mobile setting, where reference instrumentation could be brought on site. Neither of these strategies are yet in widespread use, but it would be a useful option to consider in developing quality assurance and quality control infrastructure for LCS use.

While these approaches are still under active development, they do appear to be promising methods that could increase consistency of data, save time, resources, and effort and support quality checks on large numbers of sensors, especially as sensor networks move from tens of sensors to thousands of sensors. However, it is currently unlikely that any LCS network can competently deliver the same capabilities as more traditional monitoring approaches, such as those based on satellite observations, those from regulatory networks, or those delivered by large-scale research networks (Figure 5). In this work we can refer only to studies where approaches are described in the open literature. There are some proprietary methods for large-scale LCS data QA/QC for networks being offered by manufacturers, but the technical basis for these is often not clear and cited as commercially confidential. The open publication of principles behind large-scale QA/QC approaches is strongly encouraged.

The data processing steps performed for calibration and during QA/QC of sensors in networks should clearly be communicated. Without transparency about the amount and type of performed data processing, users do not know when sensor data depart from an independent measurement and are rather a type of model output. LCS manufacturers may prefer to retain their proprietary information on data processing methods, but in doing so, can make it difficult for an end user to understand how their measurement was determined. (Schneider et al. 2019). Whenever and wherever possible, it is important to produce data in a transparent manner.

Moving forward, as public interest in the utility of sensor networks continues to grow, it will be important to develop and refine new scalable calibration and quality control approaches that allow users to better understand the quantitative capabilities of their sensors and are resource-efficient such that they keep the overall cost of LCS network operation low.
Refining both the techniques used as well as the ways in which researchers, industry, and stakeholders validate the performance of networks is important. Developing, optimizing, and refining advanced techniques for sensor calibration and validation is an important area of ongoing research and is absolutely central to obtaining reliable and meaningful data from low-cost atmospheric composition sensors. We summarize the current position regarding best practices for operation and calibration for different network types in Table 3.

Table 3: Best practices for operating networks to produce high quality datasets

<table>
<thead>
<tr>
<th>Network attributes</th>
<th>Research networks</th>
<th>Regulatory networks</th>
<th>Sensor networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Established primary standard</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Traceability to the primary standard via direct comparison</td>
<td>✓</td>
<td>✓</td>
<td>✪</td>
</tr>
<tr>
<td>Best practices for measurement guidelines and SOPs</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Use of data quality objectives (e.g. precision, accuracy, stability, drift) for an application</td>
<td>✓</td>
<td>✓</td>
<td>✪</td>
</tr>
<tr>
<td>Onsite maintenance</td>
<td>✓</td>
<td>✓</td>
<td>✪</td>
</tr>
<tr>
<td>Implementation of the QA (e.g. calibration, validation) procedures</td>
<td>✓</td>
<td>✓</td>
<td>✪</td>
</tr>
<tr>
<td>Comparison among instruments/sensors in the network</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Independent site and instrument audits</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>Open/transparent data processing algorithms</td>
<td>✪</td>
<td>✪</td>
<td>✪</td>
</tr>
<tr>
<td>Open data sharing</td>
<td>✓</td>
<td>✓</td>
<td>✪</td>
</tr>
<tr>
<td>Site and instrument operation log</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
<tr>
<td>In-depth training available</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
</tbody>
</table>

✓ Required and consistently performed
✪ Common practice but not consistently occurring
❓ Encouraged, but new techniques needed
Evaluation activities

Over the past decade, there have been worldwide efforts to evaluate the performance and applications of LCS technology. Performance evaluation projects have focused on determining the quality of the data produced by sensor systems by comparing their response to reference instruments in the laboratory and in the field. These programs can allow access to quality assured atmospheric composition instrumentation to provide at least basic quality control assessments for the variety of LCS on the market. Data from these activities should be viewed as a measurement of a sensor’s ability to produce high quality data, and not assurance that a sensor is fundamentally accurate and/or precise. These tools allow a user to answer the question ‘what degree of quality does my LCS produce data in comparison to a well-characterized reference measurement’.

Complementary to this, a number of projects have demonstrated the use of sensor systems for a variety of applications including educational outreach, hotspot identification, supplemental monitoring, source characterization, personal exposure monitoring, mobile monitoring, and emergency response. There are many interested users engaged in sensor evaluation and use including governmental organizations, research groups, public health agencies, towns and cities, community groups, and individuals. The following two sections describe notable evaluation efforts, lessons learned from those efforts, and performance metrics that are important to evaluate for the common use cases.

Performance evaluation programmes

Performance evaluation programmes have been undertaken by many different organizations, all seeking to evaluate in quantitative terms how LCSs compare to reference measurements in laboratory and ambient field sampling conditions. These programmes establish and operate LCS testing locations that can be engaged by sensor manufacturers, and typically include one or more appropriate reference monitors for comparisons. There are both controlled laboratory programmes, as well as ambient outdoor testing programmes.

Laboratory evaluations allow researchers to control conditions and examine the response of sensors to a wide range of temperatures, relative humidity, gas or particle concentrations, and other potential interferents. It also allows sensors to be tested under conditions that occur more rarely in the environment; yet important for potential applications (e.g. wildfire response). Evaluation in outdoor conditions provides a more “real-world” test of the sensor systems but may be limited to the range of atmospheric conditions experienced at a particular location and some interfering variables may not be visible or measured during the test phase.

Several independent and foundational evaluation efforts are occurring in Europe and the US. These efforts are characterizing the performance of specific air sensors often resulting in evaluation reports that attempt to describe the precision and accuracy for potential consumers (Borrego et al. 2016; Borrego et al. 2018; Collier-Oxandale et al. 2020a; Crilley et al. 2018; Crilley et al. 2020; DeWitt et al. 2020; Duvall et al. 2016; Jiao et al. 2016;
Karagulian et al. 2019; Kosmopoulos et al. 2020; Tryner et al. 2020; Wang et al. 2020b). This work has demonstrated that the way a sensor component is integrated into a sensor package matters, as does how the data is processed. Thus, results from sensor evaluations are manufacturer, model, and firmware specific, and one should not assume all sensor models for a particular compound, even those that use the exact same sensor components, will perform similarly (Borrego et al. 2016; Borrego et al. 2018). Typically, evaluations compare a small number of sensor systems which tend to show varying degrees of precision or comparability (AQ-SPEC, EPA evaluations). Commercially available sensors are often tested in triplicates (i.e. three units of the same make/model) both in the field (about one-month of collocated measurements) and in the lab (chamber testing time may vary depending on sensor tested/pollutant measured/other variables). There is a growing awareness of the need to test the variability between batches of identical sensors as well. Evaluation efforts have demonstrated both common and unique data quality issues among a variety of air sensors, but few manufacturers detail the issues users may encounter or offer data flagging or suggest quality control procedures. Such observations highlight the need for simple common data quality indicators.

The Joint Research Centre (JRC) has been evaluating air sensors since the late 2000s. They have a laboratory for evaluating gas sensors and have conducted many laboratory and field evaluations of sensor systems (Spinelle et al. 2015b; Spinelle et al. 2016). Initial efforts focused on evaluating O₃ and NO₂ sensors (Aleixandre and Gerboles 2012; Penza et al. 2014). JRC has also been active in the development of a protocol for evaluating sensors (Schneider et al. 2019; Spinelle et al. 2014; Spinelle et al. 2015a; Spinelle et al. 2017b) and the development of open-source AirSensEUR sensor platform (Kotsev et al. 2016).

EuNetAir Air Quality Joint Intercomparison Exercise, organized in Portugal in 2014, focused on the evaluation and assessment of gas, PM, and meteorological microsensors, versus standard air quality reference methods through an experimental urban air quality monitoring campaign. A mobile laboratory was placed at an urban traffic location in the city centre of Aveiro to conduct continuous measurements with standard reference analysers for CO, NOₓ, O₃, SO₂, PM₁₀, PM₂.₅, temperature, humidity, wind speed and direction, solar radiation and precipitation. Approximately 200 sensors were co-located at this platform. Combined with machine learning approaches, the correlations between sensors and reference instruments were improved for CO, NO₂, O₃, PM₁₀, PM₂.₅, and SO₂. The performed analysis also suggested the possibility of compliance with the data quality objectives defined by the European Air Quality Directive (2008/50/EC) for indicative measurements (Borrego et al., 2018).

US Environmental Protection Agency (USEPA) began evaluating air sensors in 2013. Initially these efforts involved laboratory tests of O₃ and NO₂ sensors (Williams et al. 2014) and were later expanded to test VOC sensors as well. Field evaluations were subsequently added involving PM, O₃, NOₓ, CO, and SO₂ sensors at the Air Innovation Research Site (AIRS) on the USEPA campus in Research Triangle Park, NC and in various other locations throughout the United States under ambient conditions (Clements 2018; Frederick 2020; Jiao et al. 2016; Williams et al. 2019). Further, USEPA has tested some sensors under specific conditions including under wildland fire smoke (Holder et al. 2020b) near sources, in the presence of leaks within facilities for leak detection (Thoma et al. 2017), and indoors (https://www.epa.gov/air-research/wildfire-study-advance-science-partnerships-indoor-reductions-smoke-exposures). USEPA continues to conduct and sponsor a wide range of sensor development, evaluation, and application projects with results published on their Air Sensor Toolbox website (https://www.epa.gov/air-sensor-toolbox). USEPA has also been working on two reports outlining recommended testing protocols, performance metrics, and target values for PM₂.₅ and ozone air sensor technologies used in ambient, outdoor, fixed
site environments for non-regulatory supplemental and informational monitoring (NSIM) applications, which are available at https://www.epa.gov/air-sensor-toolbox/air-sensor-performance-targets-and-testing-protocols. The main goal of this work is to provide consistent and standard protocols for evaluating and describing the performance of air sensors to help streamline the presentation of sensor evaluation results, help consumers make informed decisions on choosing appropriate sensors for their desired application.

The South Coast Air Quality Management District (Los Angeles, USA) started the Air Quality sensor performance evaluation centre (AQ-SPEC) in 2014. The centre’s goal is to provide rigorous testing results and unbiased information on the performance of commercially available LCS for air quality measurements in different environmental conditions, and guidance on the application of sensors, promote use of sensor technology and minimize confusion with users purchasing and using new LCSs. During the past six years the AQ-SPEC programme has tested more than 100 commercially available LCS for measuring a wide range of particle and gaseous species including key EPA criteria pollutants and some air toxics. The AQ-SPEC programme has developed field and laboratory testing methods to evaluate the performance of different sensor devices. Example of (data from this programme is shown in Figure 6. It reflects measurement performance by a single LCS system that reports very different levels of data agreement depending on measured parameter. A number of reports from field tests of different sensor types appear on the AQ-SPEC website (http://www.aqmd.gov/aq-spec).

AIRLAB (Paris, France), Airparif’s air quality solutions accelerator started the Microsensors Challenge in 2018 – a periodic evaluation campaign seeking to meet the growing demand from potential users for an independent and objective evaluation of the performance of commercially available low-cost sensor systems. The Microsensors Challenge is governed by an international consortium that includes representatives from regulatory monitoring organizations, developmental agencies, research, and industry. Designed as a holistic approach to sensor system evaluation, the Challenge considers ergonomics, portability, pertinence to the targeted application, and cost, as well as metrological performance. Candidate solutions are submitted voluntarily by manufacturers or vendors for different use case categories grouped into three large classes based on the application.
domain (e.g. outdoor air, indoor air, and personal monitoring). They are subsequently tested in parallel in real-world conditions, with the evaluation protocol and the results publicly available online (http://www.airlab.solutions/en/projects/microsensor-challenge). The Microsensors Challenge has already gone through two iterations, with 34 sensor solutions evaluated in its latest edition.

Generalizations Across Specific Atmospheric Components

Like all instruments that measure atmospheric composition, there is a variable degree of uncertainty in when sampling from an unknown environment, and LCS are no exception. In fact, it is likely that even within a single class of atmospheric components to be measured, there exists a great deal of inter- and intra-manufacturer variability in how quantitative a sensor may be. Here, we provide broad guidance in a manner organized by atmospheric component in order to allow a user to make more informed choices in selecting an appropriate LCS application. With any choice, a user must be aware of the limitations of their selection. This summative analysis is complementary to similar conclusions found elsewhere in this document.

Particulate Matter

There are a large number of particulate matter (PM) sensors on the market. Most sensors report in data in units of ug/m³ but some still report particle counts. The conversion between particle number and mass concentration is not straightforward. PM sensors have progressed over the past 10 years with newer sensors showing better linearity compared with reference measurements. Very small particles (<0.5 µm) are often not detected because the sensors use optical principles for particle detection. Most PM₂.₅ sensors have response times on the order of a minute or less, but require comprehensive calibrations to make reported concentrations more comparable to reference concentrations (Feenstra et al. 2019; Jayaratne et al. 2020). Air sensors may over or underestimate concentrations and be impacted by saturation effects, where sensors are unable to quantify about certain high concentration; this varies by sensor model and technology. Most PM₁₀ sensors underestimate concentrations often as a result of low flow rates and poor aspiration which makes it difficult for air sensors to sample coarse particles (Qin et al. 2020; Tagle et al. 2020). In locales where the coarse fraction of particulate is low and PM₂.₅ dominates, PM₁₀ sensors can perform well.

Ozone

Field evaluations have generally indicated performance of O₃ sensors as being encouraging. Metal oxide O₃ sensors tend to exhibit slow response times, non-linear relationships with reference data, limits of detection of several ppbs, limited interferences with other gases, but some sensitivity to temperature and humidity (Spinelle et al. 2015a; Williams et al. 2014). Borrego et al. (2018) found R² values ranging between 0.12–0.77 for O₃ sensors, though it is unclear whether these were all metal oxide sensors. Metal oxide sensors show more long-term drift than electrochemical sensors. Electrochemical O₃ and NO₂ sensors show very fast response times with minimal rise and lag times which suggests potential use for continuous or near-continuous environmental monitoring, linear response (Spinelle et al. 2015a; Williams et al. 2014) and appropriate detection limits for ambient applications. O₃ sensors have shown good repeatability in laboratory evaluations (Spinelle et al. 2015a). Borrego et al. (2016; 2018) found R² values ranging between 0.02–0.89 for NO₂ sensors. Several studies demonstrate O₃ sensors interference from NO₂ and NO₂ sensors interference from O₃ (Spinelle et al. 2016; Williams et al. 2014).
Carbon Monoxide

More limited evaluations of CO sensors have occurred but most show good linearity with reference measurements with $R^2$ of 0.53 – 0.87 (Borrego et al. 2018) and few interferences. When coupled with machine learning or modelling corrections, low-cost CO detection techniques can result in a high degree of correlation ($R^2 = 0.95–0.99$) with uncertainty in the 10–15% range at ambient concentrations (Zimmerman et al. 2018) However, CO sensors may be linear over a limited range of concentrations so the choice of CO sensor should be tailored to the concentration range for which it will be used (Duvall et al. 2020).

Sulfur Dioxide

Evaluations show that under most ambient conditions, SO₂ sensors initially showed poor agreement with reference monitors ($R^2$: 0.09 – 0.20 (Borrego et al. 2016)) which might be the result of the low concentrations of SO₂ in the ambient air. More recent SO₂ sensor results have proven useful in some near-source applications (Borrego et al. 2018; Hagan et al. 2018a) where concentrations are much higher and data quality appear to be good. Thus, LCS may not yet be widely suitable for typical ambient SO₂ detection but could be a good choice for specific source detection where concentrations are higher. But much work likely remains in understanding how LCS can be leveraged to address this atmospheric component.

Hydrogen Sulphide and VOC sensors

Evaluations of H₂S & VOC sensors show that they do not agree well with reference data which is likely a result of low concentrations and significant interference from meteorology (AQ-SPEC). Most currently available low-cost VOC sensors cannot distinguish between individual VOC species and instead report a measurement of total VOC (tVOC). This measurement does not correlate to the direct sum of various VOC concentrations which typically requires much higher cost instrumentation, and is therefore, these data are very difficult to interpret in any quantitative way. Development continues on speciated VOC measurements. Limited testing of benzene sensors indicated that the technology is not currently able to accurately and selectively measure benzene at the sub-ppb ambient levels needed for ambient applications (Spinelle et al. 2017a). Some successful applications include near-source monitoring and qualitative leak detection where concentrations are higher, and plumes can more easily be detected from variations due to fluctuations in temperature and relative humidity.

Greenhouse Gases: Carbon Dioxide and Methane

Comparatively few studies using sensors for atmospheric measurements of GHGs are available in the literature. Most of them have utilized sensors for CO₂ and only very limited number of publications were found examining sensors for CH₄ (Collier-Oxandale et al. 2018; Eugster and Kling 2012). The CH₄ sensor in (Collier-Oxandale et al., 2018; Eugster and Kling, 2012; Suto and Inoue, 2010) was based on a metal oxide semiconductor as the gas sensing material.
For CO₂, LCSs are usually based on non-dispersive infrared absorption (NDIR). Shusterman et al. (2016) presented the use of a NDIR absorption sensor in each node in a network (BEACO₂N). Some low-cost greenhouse gas sensors have been shown to possess adequate sensitivity to resolve diurnal as well as seasonal phenomena relevant to urban environments (Rigby et al., 2008) and in hardware terms, have costs that are one to two orders of magnitude lower than commercial cavity ring-down instruments commonly used in global carbon tracking networks.

Most of the published studies using LCSs for CO₂ have focused on the characterization of the sensor performance from comparison against reference instruments under field conditions. Recent efforts (Muller et al. 2020) using a large network of CO₂ sensors suggests improvements in accuracy and precision over a relatively long operational time (19–25 months of continuous operation), and with careful data processing, it is possible to detect changes larger than about 30ppm. However, they caution that this approach still should not be used to detect small regional gradients, or long-term trends. Like prior work, (Spinelle et al.2017b) data need to be assessed and corrected for interfering factors such as ambient temperature and relative humidity.

Low-cost sensor Applications

Low-cost sensing applications are diverse, and a number of demonstration projects have resulted in improved understanding of potential opportunities for LCS use. This section provides an update and summary of demonstration project applications for LCS. While the aim of many LCS are intended for use in an ambient monitoring network or as part of basic research in an atmospheric science laboratory, there are a wide range of broader application impacts in which LCS can be leveraged. Users are encouraged to also review the section on Performance in this report, which discusses some of the analytical concerns with many of these listed applications.

Supplemental Ambient Use Applications

The use of low-cost sensor systems for supplemental monitoring targets the complementary integration of such devices into regulatory networks for monitoring of compliance to national or trans-national standards of air quality, for a given outdoor location. This implies relatively high requirements for the quality of data produced and their traceability to reference instruments. However, no unifying international standard exists for the data quality requirements for this type of application. The European Air Quality Directive 2008/50/EC (UNION 2008) specification for indicative methods could represent a good candidate for the requirements of systems targeting supplemental monitoring, but is not currently universally accepted. The directive specifies the data quality objective of 25% uncertainty for NO₂, NOx, and CO, 30% for O₃, and 50% for particulate matter. Examples of projects that have targeted this type of application include the Zürich O₃ & NO₂ network (Mueller et al. 2017) and the low-cost sensor network in support of the “Voies sur berge” study in Paris (Airparif 2017).
To be pertinent for supplemental monitoring applications, sensor systems should target the main regulated pollutants (e.g. NO₂, O₃, PM₂.₅, and PM₁₀) and additional problematic components specific to the application site (e.g. H₂S, NH₃, CH₄). The relevance of the targeted pollutants and the metrological quality of the measurements are the most important criteria for evaluating sensor systems for supplemental monitoring, while additional criteria of performance are seen as secondary (e.g. ergonomics, portability, and, to a certain extent, cost).

Many existing traditional air monitoring networks were designed to analyse trends in ambient air quality over time. As a supplement to existing regulatory networks, some users may wish to use LCS to monitor air quality trends at local and community scales too. Currently, most LCS have finite lifetimes and either fail to function, lose sensitivity, or drift significantly over time making long-term trend analysis difficult, if not impossible. At present, PM sensors are most suited for this application because lifetimes can be several years. However, recent work has shown the low-cost nephelometric PM sensors can abruptly, and unexpectedly, drift over a time period of 100 days, and suggests caution must be warranted for any trend monitoring activities that utilized LCS technologies (Clements et al. 2019). Further development of LCS is needed to make this application more feasible.

Many existing regulatory monitoring networks were designed to measure generalized ambient pollutant concentrations. Thus, source characterization and near-source community impact monitoring are desired applications for LCS. Common concerns include particle sources (e.g. quarrries, construction sites, and dirt roads), industrial facilities, and oil and gas operations. Both pollution emitters and communities have a vested interest in the data collected. As such, accuracy, precision, and selectivity are key performance metrics to evaluate. Pollutant concentrations can decrease rapidly as one moves away from a facility into the community and concentrations near sources can be near ambient or elevated depending on the facility’s operating condition. This will require performance testing over a wide range of concentrations thus likely requiring both field and laboratory evaluations. Sources can have unique signatures which may impact sensor performance. For instance, PM sensor response can vary based on the characteristics of the aerosol (e.g. size distribution and composition). As mentioned previously, tVOC sensors are responsive to a wide range of VOCs and respond to each to various degrees (i.e. response to benzene is different than response to toluene). Thus, the sensor response changes based on the relative concentration of these compounds as well as to variations in concentration making the results difficult to interpret (USEPA 2018b). One successful example project was the assessment of the impacts on a rural community near a quarry in Israel with a network of five nodes for particle number concentrations (Yuval et al. 2019).

Other Applications

Citizen science initiatives have been a particularly significant fraction of demonstration projects; some projects have been in partnership with traditional research institutions, while others have been managed by public organizations like governmental agencies or NGOs or by private sector groups (industry) or individuals interested in atmospheric composition measurement. LCS represent a clear opportunity to support citizen science initiatives and make new measurements in low and middle-income countries which are often understudied by the public health and atmospheric science research communities. They can also be leveraged in educational outreach for non-traditional audiences (such as school children).

One example of the educational outreach projects is the Location Aware Sensing System (LASS) project began in 2016 in Taipei and has expanded to have more than 4000 nodes in elementary schools, residential communities and locations around industrial parks.
(https://airbox.edimaxcloud.com/). Students have used these data to conduct exploratory research. The near real-time data is displayed with several options of visualization and the data portal is maintained by Academia Sinica in Taipei (https://pm25.lass-net.org/). This network integrates data from several different PM$_{2.5}$ LCS devices (Chen et al. 2017). Research teams also use these technologies in parallel with their educational components to develop new calibration nodes and methods to calibrate this network (Wang et al. 2020b).

LCS devices have been used in community-scale studies for **hot spot identification**. This can be carried out by fixed-location monitoring or mobile monitoring (discussed later in this section). For fixed-location monitoring, pollutant levels can be monitored with high spatial and temporal resolutions by deployment of multiple devices installed in light poles at street levels. Identification of PM$_{2.5}$ emission sources within communities and quantification of source contribution to the community was carried out in the CitySpace project in the US (Feinberg et al. 2019) and in the AS-LUNG project in Taiwan, China (Lung et al. 2020). Despite increased uncertainty attributed to LCS devices, they may also be a useful tool for community screening to identify unknown or illicit pollution sources; in this case, qualitative data may be all that is needed to make a determination, but this needs to be verified with more quantitative data.

An educational use for LCS is to explore the relative difference in pollutant microenvironments. In some ways, this is similar to ‘hot spot’ detection as described above but here, they can be used in a framework designed for education. One or more sensors can be used to make measurements in two or more locations to determine which is higher or lower. Many educational and community applications use relative difference measurements to help users learn where concentrations in their community or home are the highest (e.g. USEPA Lesson Plans). If this application uses just one sensor, minimal drift over time and minimal response to meteorology are the most important metrics to evaluate. If multiple sensors are used, there must be good agreement between different sensors in order to appropriately interpret the data.

For individual users, carrying an LCS device would contribute to raise **personal awareness** on air pollution and warn them about nearby sources. In such cases, acceptable data quality requirements may be lower than for other more quantitative applications. These sensors aim only at coherence to reference devices and not at equivalence. Data visualization of short-term trends or concentration spike indicators can help citizens avoid hot spots and provide a useful personal warning device. For devices that target awareness raising, data access and interpretation should be clear and straightforward. The USEPA has developed a number of lesson plans to assist in educational activities and to raise personal awareness of air quality and how personal actions can change exposure to air pollution (USEPA Lesson Plans, https://www.epa.gov/air-sensor-toolbox/educational-resources-related-air-sensor-technology).

Closely related to personal awareness raising is the application of LCS to questions of **personal monitoring**. Often, these applications involve a sensor system that is attached to an individual throughout their regular daily activities. Personal exposure assessment targets the evaluation of the impact on human health of air pollution. The measurements used for this type of application must be quantitative and preferably have an equivalent to regulatory measures. The main pollutants with a demonstrated impact on health in both outdoor (e.g. NO$_2$, O$_3$, PM$_{2.5}$) and indoor environments (e.g. CO, CO$_2$, CH$_2$O, VOCs) should be monitored by devices targeting these applications.
LCS devices have been used to assess personal PM$_{2.5}$ exposure levels and exposure sources with quantification of the specific source contributions. The advantages of small size, lightweight, and free-of-noise-and-vibration allow LCS devices to more closely assess exposure levels without interfering with the daily routines of the subjects. For example, Alphasense OPC-N2 sensors were used in Hong Kong, China for 73 subjects (Yang et al. 2019), and another portable aerosol nephelometer in Beijing for 31 subjects (Liang et al. 2019). And in a panel study of 36 subjects in Taiwan, China and 32 subjects in Indonesia (Lung et al. 2020; Sinaga et al. 2020).

Adequate sensors for personal monitoring applications need to be able to operate in motion while being worn over several hours by a human being. As such, the portability of these devices is an essential performance metric, which should cover the mass, volume and energy autonomy of the device. Since these devices should be easy to use by non-technical users, device and system services should take into account ergonomics and user-friendliness aspects. In terms of the evaluation protocol, care should be taken to cover all the typical microenvironments that can be expected for the targeted application (e.g. office spaces, public transportation, personal vehicle, residential, as well as outdoors).

In addition, by combining air sensors with wearable sensors for health indicators, exposure-health relationships of immediate effects of these pollutants can be evaluated for high-exposure subpopulations and for ordinary citizens. One example was the evaluation of the relationships of PM$_{2.5}$ and heart rate variability for a panel study of 36 subjects in Taiwan, China (Lung et al. 2020). The application of LCS devices for air pollutants along with smart wearable devices for biological signals to detect subclinical events, which can be clinically important, has potential not only in environmental research but also on clinical practices to identify adverse environmental effects on human health (Molho et al. 2019). Moreover, LCS devices also offer expanded opportunities to evaluate the metrics (mass, number, surface areas, etc.) of PM that are most relevant to health outcomes (Lowther et al. 2019).

The application of LCS devices in indoor air quality is also rapidly expanding. Indoor-outdoor pollutant ratios and relative variability among rooms with different functions could be evaluated with multiple deployment of LCS devices to assess the origin of the pollution. The identification and quantification of indoor sources is of great interest in the research community and citizen sciences; the growth of LCS in indoor environments may shift the paradigm of indoor air quality research and point out new research directions. Nevertheless, real-time measurements within residences raise important ethical concerns since these environmental measurements can be used to infer whether the residents are at home (Lowther et al. 2019).

Mobile monitoring applications encompass all situations in which a subset or all devices in a deployment are not static. The idea of using mobile sensing in the context of air quality monitoring has been gaining momentum over the last decade, with sensing systems using mobility vectors including private citizens (Mead et al. 2013; Zappi et al. 2012), bicycles (Elen et al. 2013), public transportation vehicles (Aberer et al. 2010; Castell et al. 2015; X. Qin et al. 2020), and unmanned aerial vehicles (UAVs) (Pochwala et al. 2020; Wei et al. 2020). Typically, these are applications that make use of vehicle mobility (e.g. personal cars, taxis, delivery vehicles, public buses, bicycles, etc.) to increase the spatial coverage of the sensor network. Data from these applications can be used for awareness raising, supplemental monitoring, and/or personal monitoring depending on its quality.
The use of mobility implies a number of challenges for both system implementation and evaluation. While not as significant as for the personal monitoring applications, the portability, energy source, and form factor of the device (i.e. volume and mass) should be considered for devices targeting mobile applications.

The sensor response time is an important metrological metric in this context, as a slow-reacting sensor (typical for electrochemical and metal oxide sensors) can induce significant distortion of the measured underlying signal. This effect can be viewed as analogous with motion-blurring in photography, which happens when the exposure time of a camera system is long relative to its movement speed. The severity of the distortion will vary depending on the speed of the mobile platform (Arfire et al. 2015). The response time of a sensor can usually be evaluated in laboratory conditions with controlled chamber concentrations.

If supplemental monitoring is the end goal of the mobile application, all the aforementioned meteorological performance metrics (e.g. drift, sensitivity, precision, etc) will play a primary role in the evaluation, while other criteria, such as ergonomics and cost, will be secondary. In terms of the evaluation protocol, the reference material to which the sensor systems will be compared should ideally be mounted on the same test vehicle. Rendezvous comparisons with static stations could be interesting for a cross-analysis but would generally be impractical to obtain reliable statistics. This aspect presents a challenge in itself as not all reference material can tolerate mobility. Examples of projects targeting mobile monitoring are the Swiss Opensense project (Aberer et al. 2010), the European Citi-Sense-MOB project (Castell et al. 2015; Yang et al. 2016) and the new French project in the Ile-de-France region, “Mesures et perceptions de la qualité de l’air”2, which targets the deployment of a regional network of 600 static and mobile sensor nodes.

LCS are particularly attractive for emergency response applications where sensors need to be deployed quickly and in areas with limited infrastructure and communication. In these applications, sensors must respond quickly, provide real-time data, be highly accurate over a wide range of concentrations (or at least at concentrations near and above action levels), be minimally sensitive to environmental conditions, have few outliers, and require minimal data processing. Ideally sensors used for this application would be precise out of the box so they can be deployed quickly and show limited drift over time so that they can be used as long as needed or even left in place to proactively be available should emergencies arise. Evaluation efforts should test each of these parameters. Evaluations will likely require both field and laboratory components. Field tests can test sensor performance with common pollutants and interferences that are likely to be present in the environment where they will be used. Emergency situations can result in pollutant concentrations that are much higher than those that are routinely measured. Because they are rare, field tests are not likely to encounter and measure the high concentration. Thus, laboratory tests at high concentrations are vital but should include potential interferences as well. A timely emergency response often does not provide time for traditional collocation activities but with tight precision among sensors, a network of LCS measurements can be validated with a mobile reference instrument that can be deployed within the sensor network. Some of the most common emergency response applications include measurement of wildland fire smoke impacts on communities and first responders (Holder et al. 2020a).

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2 [http://www.airlab.solutions/fr/actualites/mesures-et-perceptions-de-la-qualité-de-l’air](http://www.airlab.solutions/fr/actualites/mesures-et-perceptions-de-la-qualité-de-l’air)
In summary, larger multi-node sensor networks based on LCSs have already been deployed as test projects in a number of locations around the world, and the above examples are only illustrative examples, many more exist. The most important area of uncertainty from the current round of demonstration studies is how to most effectively utilize these new measurements given that there are known issues regarding data quality and the stability of responses over time. In the past two years, more studies apply LCS devices in various applications as described above; in particular, there were campaigns running over the course of a year or longer. The evaluation of the stability of LCS devices over time can be expected in the literature soon. Care should be taken to understand the exact intentions of each demonstration study, for example whether the projects were designed to test the ability of a network to quantify air quality or greenhouse gases, or whether the network was used to test the technical feasibility of deployment, citizen engagement or wider issues associated with deploying a sensor network.
Sensor Characterization

In this section we describe in broad terms the work that has been carried out to characterize commonly used low-cost sensors, and outline major results related to potential measurement interferences, calibration approaches, and long-term stability. This discussion is divided first by technology (gas sensors, PM sensors), and then by application (stationary monitoring, mobile monitoring, and source characterization). The field of low-cost sensors is rapidly evolving: new generations of sensors are released regularly by manufacturers, and approaches for sensor characterization and data analysis are continually being improved upon. Thus, sensor performance may be substantially better than what has been found in previous work; nonetheless, the key points discussed (the need for calibration, correcting for interferences, and monitoring long-term drift) are likely to remain important considerations for the foreseeable future.

Characterization of Gas-phase Sensors

The gaseous atmospheric components that are most typically measured using low-cost sensors are nitrogen monoxide (NO), nitrogen dioxide (NO2), ozone (O3), sulfur dioxide (SO2), carbon monoxide (CO), carbon dioxide (CO2), and to a more limited extent, total volatile organic compounds (VOCs). These are important because of their direct and/or indirect adverse effects on human health, ecosystem health, or the climate. NO2, O3 and CO are known to be directly harmful to health, as are some individual VOCs (e.g. benzene, formaldehyde, 1.3-butadiene). These species have regulatory limits or target values for their concentrations in ambient air in many countries. Measurements of the gaseous pollutants are typically reported either as a mixing ratio (e.g. ppm or ppb), or in mass concentration units (e.g. µg m⁻³).

In general air pollutants/reactive gases are detected using either electrochemical (EC) sensors, metal oxide semiconductor (MOS) sensors, miniature photoionization detectors (PIDs) or NDIR. For literature reviews of the subject area, see, for example, Baron and Saffell (2017), Morawska et al (2018), and Khan et al (2019). Khan et al. (2019) summarized the advantages and limitations of each technology. This is also shown in the Annex 2 on Known Sensor Issues. The performance of various technologies for low-cost gas sensing is discussed below.

Electrochemical (EC) sensors

In electrochemical (EC) sensors a gaseous pollutant undergoes a chemical reaction that results in a signal – typically manifested as a current – that is related to the concentration of the target gas in the air. EC sensors are available for a variety of gases which vary in their accuracy and reliability depending on the species being measured. Common air pollutants measured with EC sensors include O3, NO, NO2, CO, and SO2. Sensitivity of EC sensors can be quite high (in the ppb range), but accuracy (i.e. how well sensor output agrees with that of co-located regulatory-grade monitors) appears to be a strong function of the specific sensor and electronics, the calibration used (i.e. factory calibration vs. one determined by the user), and the environment being studied. This last one is particularly important, as, EC response can be a strong function of temperature and relative humidity, requiring corrections in order to obtain reliable results e.g. (Aleixandre and Gerboles 2012; Castell et al. 2017; Cross et al. 2017). Interferences by other gases and the ageing of the electrolyte are also known problems. In the last several years there has been substantial work aimed at developing calibration approaches that account for such interferences. Such
approaches, mostly developed by co-locating sensors with higher-grade monitors, include corrections for baseline drift (Mead et al. 2013) as well as various multivariate (e.g. machine learning-based) approaches for decoupling interferences by temperature, relative humidity, and other pollutants (Cross et al. 2017; Hagan et al. 2018b; Malings et al. 2020; Zimmerman et al. 2018). This work is ongoing but shows real promise for obtaining accurate measurements from EC sensors.

**Metal oxide semiconductor (MOS) sensors**

Metal oxide sensors (MOS) have an exposed surface film that changes its electrical properties (typically resistance) when exposed to the target gas. Small changes in conductivity/resistance are measured and are proportional to the concentration of the adsorbed gas. This relationship is usually non-linear in nature, and these sensors are sensitive to changing environmental conditions and interferences from other gases that may be present (e.g. (Fine et al. 2010; Peterson et al. 2017; Rai et al. 2017; Wetchakun et al. 2011). The service life for semiconductor sensors is 1–2 years. Compared with electrochemical sensors, the cost is lower, but the sensitivity and performance is lower as well.

**Photoionization detector (PID) sensors**

Photoionization detectors (PID) are commonly used in LCS applications for total volatile organic compounds (VOC) measurement. They use ultraviolet light to ionize organic molecules and generate a small current as sensor output signal. The PID lamps have specific photon energy levels and the compounds that have similar or lower ionization energies can be ionized and then resulting current can be detected. A major limitation of PIDs is that they do not ionize VOCs with equal efficiency across compounds: some compounds are efficiently ionized (and detected) while other compounds are less efficiently ionized (and less efficiently detected). As a result, “total VOC” measurements by LCS are not quantitative measurements of total concentration, but rather are a strong function of the composition of the VOC mixture; nonetheless, they likely reflect the overall VOC levels in a qualitative sense.

**Non-dispersive infrared (NDIR) sensors**

Non-dispersive infrared (NDIR) sensors use infrared absorption to measure CO2, which is a greenhouse gas, a tracer of combustion sources and an indicator of building ventilation. An advantage of such techniques is that performance can be evaluated from first principles knowledge of sensor design features such as path length and absorption properties of the specific gas of interest. Some low-cost greenhouse gas sensors have shown adequate sensitivity to resolve diurnal as well as seasonal phenomena relevant to urban environments (Rigby et al. 2008), and have costs that are one to two orders of magnitude lower than commercial cavity ring-down instruments commonly used in global carbon tracking networks. As with the other gas-phase sensors described above, the performance of low-cost NDIR sensors has been assessed via comparisons against co-located reference measurements (e.g. (Spinelle et al. 2015a; Zimmerman et al. 2018); these studies found reasonable agreement between the two (to within 5%) using both parametric and non-parametric (e.g. machine learning) methods for calibration. Keeping a high data quality during field deployment over several months requires procedures for data filtering and the correction of drift and jumps in the sensor signal (Muller et al. 2020).
Characterization of PM Sensors

Particle measurements using low-cost sensors are in many ways more complex than gas measurements. The performance of PM sensors depends on a variety of factors such as measurement principles and particle characteristics (chemical composition, density, hygroscopicity, refractive index, shape and size distribution). Particles can also be highly reactive and reported mass concentrations are subject to sampling biases if, during the process of being sampled, the particles are transferred across strong temperature/humidity gradients.

Low-cost PM mass concentration measurement techniques most commonly rely on light-scattering-based optical methods, which typically use a low-power light source – either an LED or laser – and the light scattered by intercepting particles is measured by a photon detection component. There are two broad measurement techniques employed by LCS applications including nephelometers, which measures particle light scattering of an ensemble of aerosols, and optical particle counters (OPCs), which count particle number as a function of size bins. Neither technique directly measures particle mass, but output (total scattered light for nephelometers, size-binned particle counts for OPCs) can be related to particle mass loading; this is typically done by performing a linear regression between sensor output and mass loading as measured by a reference measurement for a given aerosol population. It should be noted that there are some reference monitoring techniques that use similar optical principles as LCS devices, though these methods typically employ improved environmental condition of samples, well-controlled, active sampling flow, and improved (and often more expensive) optical sources and detectors. The measurement of PM mass by optical low-cost sensing has a number of performance limitations:

- Limit of mass concentration detection in the range of 1–10 μg m⁻³ have been reported for low-cost optical particle counters e.g. (Holstius et al. 2014; Jovašević-Stojanović et al. 2015; Kumar et al. 2015), though this is usually estimated under more optimal laboratory conditions. Such sensors have been shown to have non-linear calibration with two or more response functions. They also have upper detection limits, typically in the range of 500–1000 μg m⁻³, making them unsuitable for extremely polluted locations.

- Limit of particle size detection of low-cost light scattering devices is mostly ~300 nm – 10,000 nm size range, and are generally insensitive to particles outside of this range (Wang et al. 2015). The lack of detection of the smaller-sized particles can lead to underestimates in PM mass loading, since a large fraction of PM mass can be present in these low size bins (e.g. near roadways). This inherent error may be ameliorated by application of a correction factor that includes the expected contribution from the small particles (cite); however, this assumes a constant particle size distribution, which may not be the case, when used in locations with different aerosol sources.

- Related to this, there are currently no LCS devices capable of measuring the size distribution of ultrafine particles diameter <100 nm), and these types of particles can only be assessed at present with reference instrumentation and techniques.

- Another major source of difference in mass concentration measurements made by low-cost optical PM sensors and reference grade instruments relates to the relative humidity (RH) due to water uptake by hygroscopic particles, leading to increased size. Such differences are especially pronounced at high relative humidity (80–85%) (Crilley et al. 2018). This RH effect has been the subject of considerable study in recent years, and different methods for correcting for it have been proposed (Jayaratne et al. 2018).
However, since this effect is a strong function of particle hygroscopicity, fully correcting for water uptake requires taking into account particle composition in real-time, which represents a major challenge for low-cost PM sensing.

- In addition, differences in aerosol optical properties can also lead to measurement errors in optical PM sensors. Differences in the refractive index of the material being measured leads to differences in the amount of light scattered per unit mass, and low-cost PM sensors generally lack the ability to measure and correct for changes in refractive index. While the optical properties of the aerosol may not change drastically under normal conditions, they can change measurably when a new source (e.g. from combustion or dust) is introduced (Crilley et al. 2020).

While it can be difficult to correct for each of the above factors individually, they are often treated together within a single calibration. Typically, RH is treated as the dominant interfering variable and thus RH impacts sensor performance and is used to correct for changes in the hygroscopic growth of particles (Crilley et al. 2018; Crilley et al. 2020; Malings et al. 2020). In addition, efforts have been made to correct for composition and/or size (Malings et al. 2020). Some correction approaches that have been used rely on time-averaging over long periods (hours to days) and/or post-processed data (offline analysis) and may not work for real-time, highly time-resolved sensor measurements. Improved real-time characterization of size distributions and particle composition would enable sensor data to rapidly be corrected for these factors, improving the accuracy of LCS mass measurements. Development of new, low-cost techniques for PM measurement based on non-optical methods will be especially helpful in addressing many of the above limitations associated with light-scattering-based approaches.

Despite the above limitations, literature supports that: (1) low-cost approaches can be useful for qualitative assessment of particle concentrations in a moderately polluted environment, and that; (2) deployment of many sensors on a community or neighbourhood-scale can provide sufficient data granularity to provide insight into spatial and/or temporal patterns and source apportionment. This may be useful for refinement of modelling approaches, assessing human exposures, or producing datasets for long-term trend analysis, particularly once known LCS limitations are resolved.

Sensor Characterization in Stationary Long-Term Deployment

Many sensors are subject to zero-drift and ageing effects, which will affect calibrations and can lead to systematic errors that can worsen over time. Long-term calibration of sensors is challenging for several reasons:

1. Some of the measured pollutants (including O₃, VOCs, PM, and NO₂) have seasonal characteristics in nature, exhibiting clear profiles that vary with season. As a result, sensor performance is improved if calibration exercises are performed across different seasons.

2. For long-term monitoring, weatherproof is a necessary consideration to avoid interference of weather conditions for such applications. The needed frequency of evaluation to ensure data quality in different real-world conditions is an area of active research. The possibility of in-situ calibration by machine learning techniques or other data analysis methods are currently explored by the research community (Delaine et al. 2019; Maag et al. 2018; Smith et al. 2019).
3. Environmental factors vary greatly with the season, which presents challenges to the calibration algorithm. Seasonal variability in factors, such as temperature or relative humidity, can play a critical role in sensor performance, with different environmental variables impacting sensor performance across the range of encountered conditions. A number of efforts have been made in literature to develop methods for correcting the environmental conditions and improving the long-term performance of LCS. For example, Peng et al (2020) designed a look up table (LUT) as a function of temperature interval to improve the sensor data quality in the long-term measurement covering different seasons. The method is a principle-based algorithm built on the known impact of temperature on sensor sensitivity and baseline. The comparison with multiple linear regression method and machine learning methods shows it produces significantly improved performance for sensors in long-term deployment.

4. The lifetime of low-cost gas sensors is relatively short, generally on the order of one or two years, which makes them unable to perform over the long-term. Thus, replacement sensors are needed in any long-term monitoring, and these require repeated calibration (Malings et al. 2020). Best practices for reference monitoring replacements usually require substantial collocation and overlap between new and old instrumentation. This is not likely feasible for LCS due to their relatively short lifetime, but it is still important to provide as much overlap as possible to ensure like for like replacement of new sensors. The amount of time requires likely varies substantially across measured constitution, technology used, and the heterogeneity of the environment to be sampled.

5. The generation of particulate matter is more difficult than that of standard gas, and the evaluation of particulate matter sensors is usually realized by running in parallel with standard instruments in the field environment. Recent studies have also focused on long-term assessments of particulate matter sensors performance with seasonal impact and PM episodic events, such as winter cold air pools, fireworks, and wildfires (Bathory et al. 2019; Liu et al. 2019), finding that particle size selectivity may play an essential role in the sources of errors (Kuula et al. 2020) and the long-term field performance is driven by size distribution and chemical composition of the factory calibration aerosol and the ambient aerosol (Malings et al. 2020).

Sensor Characterization in Mobile Applications

As is the case with other sensing applications, one of the main advantages of mobile sensors lies in the potential of extending spatial coverage for a given number of sensor units. However, the implementation of sensors on mobile platforms can lead to a significant degradation of the sensor’s performance, depending on the underlying sensor technology, but also on its integration within a sensing system. Electrochemical and metal oxide sensors have response times that range from tens of seconds to multiple minutes. While for static deployments, this issue can be largely neglected, for mobile sensing systems it can induce significant distortion of the measured signal with respect to the underlying concentration levels. The severity of the distortion will vary depending on the speed of the mobile platform (Arfire et al. 2016) and will need to be evaluated. The sensitivity of electrochemical sensors to variations in relative humidity can also be a challenge for mobile measurements that include various different types of environments (e.g. both indoor and outdoor). Finally, for all low-cost sensor systems used for mobile applications (i.e. including PM sensors), special care needs to be given to the design of the air sampling system to reduce performance degradation due to poorly controlled flow conditions.
Mobile sensors require higher temporal resolution to represent more accurate spatial locations, which means that the data set of mobile sensors is larger and more complex. The implementation of sensors on mobile platforms can, however, lead to a significant degradation of the sensor’s performance, depending on the underlying sensor technology, but also on its integration within a sensing system. Therefore, careful data analysis methods are very important in the application of mobile sensors.

Sensor Characterization in Exposure Applications

The small size and low-power requirements of most LCS make them ideally suited for personal exposure monitoring. Portable air sensors can revolutionize health studies by providing highly resolved reliable exposure metrics at a large-scale to investigate the underlying mechanisms of the effects of air pollution on health. The performance of multipollutant portable sensors has been assessed in a number of recent studies (Chatzidiakou et al. 2019; Jerrett et al. 2017; Piedrahita et al. 2014).

However, many of the limitations described above, especially those for mobile applications, apply to personal monitoring using portable LCS as well. Accurate estimates of personal exposure to pollutants requires taking into account possible interferences (temperature, relative humidity, other pollutants), necessitating the use of the calibration approaches described above. The abrupt changes in relative humidity that can occur between indoor and outdoor environments, for instance, can lead to aberrant measurements. Additionally, fast time resolution is often needed, both to capture short spikes in local pollution (e.g. by interception of an exhaust plume), and to take into account sudden changes in environmental parameters (e.g. going from indoors to the outdoor environment).

Sensor Characterization in Source Applications

Low-cost sensors can provide information on pollutant sources, assuming they are suited for purpose. Low-cost sensors can help identify nearby sources, facilitate real-time monitoring and quantitative analysis of pollution sources, and raise public awareness of more fine-scale temporal and spatial variations in environmental air pollutants. To carry out such studies, crucial considerations to LCS performance are sensor siting, to ensure local sources can be identified, and careful analysis of sensor measurements in order to separate contributions from various local and non-local sources (Thorson et al. 2019). Recent applications of LCS to identify or quantify sources include studies of airport air quality, in which airport emissions could be unequivocally distinguished from more regional pollution, and emission source factors could be inferred the various airport activities (Popoola et al. 2018); and studies of air quality in urban regions, in which measurements by multiple sensors enabled the identification of local pollution “hotspots” and likely sources (Caubel et al. 2019; Collier-Oxandale et al. 2020b). Given the diverse performance – both in strengths and weaknesses – of LCS sensors, as well as the diversity of source applications, one must be judicious and informed in selecting the best available sensing technologies that will ensure high quality measurements specific to the components of interest.
Communicating LCS to Society

Until recently, almost all public air quality information originated from governmental organizations tasked with air pollutant measurements for regulatory purposes. These regulatory monitoring networks use extensive guidelines for siting conditions and which air pollutants are to be measured where and how often (EC 2015; USEPA 2020a). These guidelines also extend to the instrumentation to meet certain standards for certification as well as calibration, maintenance, and quality checking protocols (USEPA 2018a). Such requirements ensure high quality data that are generally comparable across site type globally. Air quality data can be made available as individual pollutant concentrations or as one air quality index number (AQI) that combines data from multiple air pollutants.

![Comparing AQI Break Points for PM2.5](image.png)

**Figure 7: AQI scores and relative severity for PM$_{2.5}$ in six different nations**

Image courtesy of Urban Emissions, S Guttikunda

Air quality index values are calculated and presented differently in different regions of the world depending on the general level of pollution and the regulatory limit values set by countries. Figure 7 depicts the widely different ranges of AQIs, and their relative health-based severity indicator, for six nations for 24-hour average PM$_{2.5}$. The number of pollutants included in the AQI calculation can also vary, even within one country. For example, the US AQI is calculated based on the number of pollutants available within a certain area – so if PM$_{2.5}$, O$_3$, and NO$_2$ are included in the AQI calculation, but only PM is available, the AQI for that area would be based only on PM. If information on three pollutants is available, then the highest (worst) value for any given pollutant is used as the overall AQI value (USEPA 2018a).
Beyond emission sources, meteorology also influences air pollutant concentrations. Rainy or windy conditions may reduce air pollutant concentrations, for example, while stagnant, sunny conditions can favour ozone production. But windy conditions can also exacerbate long-range transport from distant emission sources or scour arid soils to generate crustal particulates. So, while communicating air quality information has a certain level of complexity, regulatory monitoring data can ensure a level of trust in the data owing to the data quality requirements.

With the technological developments that have made LCS possible, the availability of air quality data has dramatically increased in the past 5–10 years as more and more of these devices become available to consumers. There are now myriad examples of networks of LCSs that are linked to open access web platforms where anyone who is interested can view the air quality data reported by these LCSs in real-time. Similar to the regulatory networks, these data can be reported as air pollutant concentrations or as AQI values. The main difference being that anyone can purchase or self-assemble a sensor and install and operate it anywhere. However, with this ease of use and increasing number of networks reporting LCS data, comes an added level of complexity in effectively communicating air quality information.

There are a number of complicating factors for understanding and interpreting LCS (and LCS network) data. These factors include for example, variable performance/lack of certification, interferences that affect sensor performance from weather conditions and/or other chemical compounds, no standardization of instrument siting, high-resolution data (e.g. data point every second) associated with a higher degree of uncertainty, and differing limitations depending on the sensor system. While LCS networks and combinations of LCS and reference- or regulatory-grade sensors are often designed or intended to offset some of the measurement error by providing an aggregation of more data points, there are also many factors that affect the efficacy of the configuration in doing so. Many of these limitations are discussed in detail within this report.

At present, there are no standardized certification procedures for LCSs or networks of LCSs, although there are efforts going in this direction to improve the performance of air sensors (USEPA 2020b). This is an important development in the broader distribution and use of LCS. It is known that many LCSs have issues with interferences under certain relative humidity and temperature conditions, or other chemical compounds, which can compromise the integrity of the measurement. It has been shown that measurements made with most PM LCS are less accurate above a relative humidity of 85% (see section on Sensor Characterization). In those instances, data should be flagged as uncertain. Future implementation of standardized certification procedures should be able to capture these types of deficiencies.

All of these factors together mean that communicating and interpreting air quality data from LCS can have a lot of pitfalls and added complexity. This is compounded by the fact that some LCS applications or configurations of LCS use proprietary algorithms, which cannot readily be evaluated, to manage data and perform quality control. Nevertheless, the ease of use and wide available of LCS is enabling more applications from individual awareness of air quality to identifying hot spots and the ability to qualitatively evaluate air pollution improvement interventions. LCSs have already shown to be useful for increasing engagement and understanding of air quality and air pollution.

Effective communication of air quality information obtained from LCSs, ideally requires a certainty in the quality of the data, information on the context under which air quality data was collected, what information can and cannot be gained from the use of LCSs, as well as
an available explanation of the details about the data collection, processing, quality control, etc. Communicating these conditions would allow for an effective use of LCSs and their data that would build trust and understanding of the information communicated.

In this chapter we aim to provide information for those who currently use or would like to use LCSs, specifically aimed at addressing the factors that can make communication of air quality data from these sensors more challenging. We hope that the framework we lay out here can foster responsible use, and effective communication of robust air quality information for the benefit of all.

Potential for using LCS to increase awareness and understanding of air pollution

Increasing public understanding of air pollution is regarded as a necessary condition for promoting measures to reduce emissions. The emergence of a new generation of inexpensive, portable air quality sensors offers the technical basis for community-based environmental monitoring. Several recent studies have shown that participants’ experiences in the monitoring of air quality increase levels of involvement (Bales et al. 2012; Boso et al. 2020; Kim and Paulos 2010; Oltra et al. 2017), empowerment (Wong-Parodi et al. 2018) and generate discussion about problems related to air pollution (Ngo et al. 2017). However, fostering pro-environmental behaviour from the sensor data is not always a simple task.

LCSs can make the invisible visible, quickly attracting people's attention. However, careful message design is needed to embrace the views of different societal groups. Lay people are perfectly able to reason with complex technical matters like air pollution. Even more, they usually include a more comprehensive range of considerations in their reasoning processes than those who are only concerned in measuring (Horlick-Jones and Prades 2015). Therefore, it is better to present the information in units and at scales that people can link to their everyday lives. Information on concentrations of pollutants in bicycle lanes or at particular intersections, for example, is more likely to make the potential health impacts of pollution personally salient than general ambient concentrations for a city. Designing forms of feedback that encourage users to reflect on how social conventions, habits and routines affect air pollution are more effective than simply providing numbers. The information provided by the LCSs to the lay public can also become more effective if stated in compelling terms. More important, researchers, practitioners, and decision makers interested in promoting citizen science or participatory sensing projects must make a concerted effort to understand and recognize citizen contextual knowledge from the first stages.

Individual users can employ LCSs but working with local groups could be the best form to promote behavioural change using these devices. In community-based programs, people commit to act to help their neighbours and the information provided by sensors can be used to build collective efficacy more effectively. However, community engagement is not always easy. Distrust, preconceived notions or prejudices from different collectives involved in promoting LCSs can hamper their installation and practical use. The free flow of opinions,
goals, and values between experts and lay citizens can be crucial to successfully engaging communities with LCSs.

By visualizing and taking control of air pollution data, LCSs users tend to feel more aware of the problem and more prone to initiate mitigation actions (Kim and Paulos 2010; Wong-Parodi et al. 2018). However, perceived lack of self-efficacy or anxiety and anger can also be triggered by the monitoring experience (Boso et al. 2020). In short, LCSs information can make a difference in promoting pro-environmental behaviour, but it will work only when the main external barriers to action will be removed. In this sense, in addition to helping communities to collect or display data, it is also crucial to support them in translating information into positive actions and significant social change.

Considerations for communicating LCS data to different audiences

With any new technology, there are early adopters and proponents, and there are entrenched skeptics. These differing viewpoints are healthy for advancing LCS. Many perceptions of LCS exist, and with good reason, the market is rapidly evolving, manufacturing quality varies, applications are not yet proven, etc. Even as the technology is improving, there continues to be some long-held perceptions from people/organizations with different perspectives that are important to consider when communicating LCS data.

The traditional regulatory and scientific community has been monitoring and studying air quality and creating air quality policy for decades. These organizations need accurate, reliable, and reproducible data to accomplish their missions. Some perceptions and truths about LCS in this community include:

- Data are qualitative and cannot be used for quantitative analysis or scientific inquiry
- Calibration and adjustment using traditional methods is not possible
- Commonly used “black box” (e.g. machine learning or proprietary algorithms) methods are not transparent and cannot be evaluated
- Devices often have a short service life and cannot be used to determine long-term trends

Other users of LCS include people and organizations new to air quality and some less familiar with some of the nuances of air pollution monitoring. Potential users include schools, municipalities/governmental organizations, the public, citizen groups, media, and other non-air quality experts. These users often perceive LCS as:

- Accurate enough for an application and potentially could replace reference instruments
- Able to provide local and high time resolution data that is relevant to their personal exposure; even if the data is less accurate, it is worth the trade-off of more accurate reference stations located farther away
- Useful for identifying sources of air pollution at hotspot areas

These differing perceptions are a natural part of an evolving technology. However, it is essential when communicating LCS data to consider the different perspectives and beliefs about this technology and address them. It is also critical to understand the purpose and motivation of a prospective LCS user. For example, for some, it may be quantitative
monitoring, others as an educational medium, and still others it may simply be a hobby. The framework below should help in communicating data and information and ultimately building trust in this new technology.

Framework for best practice use in communicating data from LCS

Communicating data and information derived from LCS data can be a challenge due to some of the uncertainties and limitations of LCS data. To address some of the challenges and perceptions of LCSs, it’s crucial to communicate details about the data, including data collection, processing, and quality assurance. This enables those using and interpreting data to understand its strengths and limitations. Publishing the “good” and “bad” aspects of LCS data is a responsibility for anyone or any organization using LCS. And as with all scientific inquiry, describing limitations or uncertainty in a measurement is a strength, not a weakness.

Communication of LCS data by users can occur across different media methods. This might include LCS operators who report their data automatically to data archives or websites. Or LCS data might be delivered from those websites directly to consumers who only wish to know the data but played no role in data collection. Or individuals who have LCS data available to them may wish to share this data with peers. There exists a complex web of communication of LCS information that flows in many directions, and it is important to recognize that each constituent in this web may include (or exclude) varied information with these results. Some may include basic details about the data or study, whereas others are solely publishing raw data to a data archive for others to use. Still others are using LCS data in analyses and publishing the results in traditional peer-reviewed literature, and even communicating data in real-time on a mobile app to showing rapidly changing conditions (e.g. smoke from wildfires). We must recognize that the producers and consumers of this data all have a unique objective and interest in the data, which can be highly variable.

Communicating about LCS, LCS data, and information derived from LCS data in a fully open and transparent way helps the community build trust in the new and rapidly evolving technology. While there are many ways and methods to publish and communicate data, the following framework offers some essential elements that need to be considered.

1. **Identify the purpose or objective for collecting the data.** Because LCS may be appropriate for one application and not another, it is crucial to identify and describe how LCS were used to meet the objectives. For example, LCS data could identify a local hotspot of PM$_{2.5}$ from biomass burning that might warrant further investigation; however, because LCS have a higher degree of uncertainty than a reference monitor, they may not be appropriate as a standalone tool to be used for alerting or warning local community members or members of the public when action needs to be taken. As discussed in Table 4, there are many applications, some of which are appropriate for LCS, while others are not. Understanding these limitations can better inform the application of LCS.

2. **Describe data collection and processing.** One major challenge of LCS, as described in this document, is that there are no standards for determining performance, data collection and processing, and reporting results. Being open and transparent about how the data were collected and processed builds trust. We recommend when discussing LCSs, whether it is in a journal article, smartphone application, or elsewhere, that information on the following topics be addressed or made easily accessible:
(a) **Calibration/adjustments.** LCS data always require some level of calibration or adjustment. A description of efforts made to adjust data should be included.

(b) **Maintenance and operations.** Describe how the LCSs were deployed, maintained, and operated.

(c) **Quality control.** LCS will need an enhanced level of scrutiny and evaluation to ensure high quality data. Describe the steps taken.

(d) **Uncertainty.** As we show in this report, LCS data can have more uncertainty than traditional reference instruments. It is useful to disclose this uncertainty whenever possible.

(e) **Limitations of the data and air sensors.** Clearly describe all of the known limitations with the LCS (e.g. interference issues) and the data produced.

3. **Document the metadata.** Clearly describe aspects of the LCS that allows others to gain confidence in the data and results. Include information about the placement and siting of the sensors, along with quality control indicators, time standards, and units. It is useful to retain these records for a period of time beyond the service life of the LCS as it may be important to retroactively adjust data as we learn more about their functionality.

4. **Interpretation of the data.** Interpreting LCS data can be more challenging due to its high time resolution, greater uncertainty, and increased complexity of obtaining machine-readable data for analysis for the average non-expert user. While there are many ways to communicate LCS data, here are a couple of suggestions. First, find methods to share the uncertainty along with the data. Second, when using an air index (e.g. Air Quality Index), it is necessary to understand the index, how it is formulated, and its associated thresholds. One common mistake is using high time resolution data (e.g. 5-second concentrations) and converting that to an air quality index number. Most air indexes are based on longer averaging period (e.g. 24-hours) and health effects and precautionary language corresponding to data with a longer averaging period.

Providing LCS data and supporting information clearly and transparently lets others fully understand your data and builds trust in this new technology, the data it produces, and your results.
### Table 4: Air quality applications and data/information needs for each application

<table>
<thead>
<tr>
<th>Applications</th>
<th>Usage</th>
<th>Application needs</th>
<th>Data Needs</th>
<th>Complexity / Level of Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current</td>
<td>LCS Appropriate</td>
<td>Single LCS or Network of LCS</td>
</tr>
<tr>
<td>-----------------------------------</td>
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<td>---------</td>
<td>-----------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Education</td>
<td></td>
<td>Widely</td>
<td>Yes</td>
<td>Single LCS</td>
</tr>
<tr>
<td>Public education</td>
<td></td>
<td>Widely</td>
<td>Yes</td>
<td>Single LCS</td>
</tr>
<tr>
<td>Outreach</td>
<td></td>
<td>Emerging</td>
<td>Yes</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Air quality forecasting</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Air quality index reporting</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Single LCS</td>
</tr>
<tr>
<td>Exposure reduction (personal)</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Single LCS</td>
</tr>
<tr>
<td>Decision Making</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Epidemiological studies</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Single LCS</td>
</tr>
<tr>
<td>Exposure reduction (personal)</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Single LCS</td>
</tr>
<tr>
<td>Occupational Safety &amp; Health</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Single or Network of LCS</td>
</tr>
<tr>
<td>Hot-spot detection</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Near-source monitoring</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Supplemental monitoring</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Emergency response</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Model Input</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Model verification</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS</td>
</tr>
<tr>
<td>Atmospheric research</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS, Hybrid</td>
</tr>
<tr>
<td>Regulatory and Policy</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS, Hybrid</td>
</tr>
<tr>
<td>Source verification</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS, Hybrid</td>
</tr>
<tr>
<td>Enforcement of large air quality emission events</td>
<td></td>
<td>Emerging</td>
<td>Yes, if used properly</td>
<td>Network of LCS, Hybrid</td>
</tr>
<tr>
<td>Source apportionment</td>
<td></td>
<td>Not yet</td>
<td>Not yet</td>
<td>Reference Instruments</td>
</tr>
<tr>
<td>Regulatory and policy support</td>
<td></td>
<td>Not yet</td>
<td>Not yet</td>
<td>Reference Instruments</td>
</tr>
</tbody>
</table>
Expert Consensus and Advice

LCS and LCS networks will likely continue to grow across all use sectors. These technologies are generally on a trajectory of ever-improving capability with advances in features such as improved detection limits and chemical specificity, more robust precision, more complete system components, and, often, decreasing procurement costs. However, LCS still should not be viewed as fully operational replacements for more sophisticated measurements techniques, and caution is warranted. Here, we present a summary of the advice from this document, specific to end user needs.

For manufacturers and systems providers

Manufacturers should provide information on the characterization of sensors and sensor system performance, in a manner that is as comprehensive and transparent as possible, including results from in-field testing. Controlled laboratory comparison results alone are viewed as incomplete evidence of performance if the intent of the sensor is for ambient use. Data reporting should, where possible, parallel the approaches used for reference instrument specifications, including information on the calibration conditions. While not all users will actively use this information, it will support the general improvement of LCS across a variety of applications. Openness in assessment of sensor performance across varying conditions would be valuable in guiding new user applications and continue to foster sensor innovation.

More information on sensor lifetimes and degradation over extended periods of time is needed. Most research evaluations of sensor performance are limited to weeks or months and there is a lack of information on changes over the annual timescale and longer.

Where algorithms and data manipulations are used to improve data quality, the basic principles of this should be made clear to the user. Accepting that some parts of this process may be proprietary intellectual property (IP), the principles of the techniques used must be clear to users and particularly any dependencies on reference instruments or model data. It is a best practice to provide as much methodological transparency as possible in order to assess data quality from a sensor, or from a sensor-as-a-service approach. This mirrors the open publication of data retrieval approaches of the Earth Observation community which are seen as a model of good practice (see proposed levels, Table 1). It should, however, be possible to balance external scientific scrutiny of methods while retaining IP for commercial exploitation. Clear versioning management of data correction methods is needed so that historical data can be updated as scientific understanding grows.

For users and operators of LCSs

Users of LCSs should have a clearly defined application scope and set of questions they wish to address prior to selection of a sensor approach. This will guide the selection of the most appropriate technology to support a project. Some questions that may guide a user towards selection include:

- Is the data for education or outreach purposes, if so, how might the public use the data?
- Will the data be used to inform personal decision-making?
- Who be the owner of the data and can we use it for any purpose?
• Will the data be integrated into urban pollution decision or control systems, and what are the range of dependencies and consequences?

• Will the data from one sensor be used in isolation, or is the intention to use data from a network of many sensors?

• Does infrastructure/capacity exist to appropriately evaluate/calibrate the sensor systems?

The user community should continuously evaluate LCS performance through verification and/or comparisons performed under real-world conditions ideally by field deployments against reference instruments and report those results openly. LCSs may be delivered with factory calibrations, but this represents only a baseline level of accuracy and performance. This performance needs to be verified under the environmental conditions in which the LCS is expected to operate. Users are encouraged to engage with the many global performance evaluation programmes to better understand their sensing data or consider establishing new evaluation programmes were data are currently lacking, but there are interesting atmospheric composition questions to address. Characterization of LCSs against reference instrumentation is needed to discern changes in LCS response arising from interferences, changing environmental conditions, etc. Reference sites can be found via local, national, and intergovernmental pollution monitoring agencies. Several independent data aggregators are also available online and can provide this information, often at no cost.

Further efforts should be made to evaluate the following LCS device characteristics to inform extended use, data quality, and calibrations: time for sensor decay or degradation in real-world conditions; baseline drift for different types of application; time-dependence and environmental-dependence of calibration validity (this may take months to years for thorough evaluation); interferences from other co-existing pollutants, including for reactive gas LCS devices and the composition/humidity dependence of LCS particle sensors.

To ensure a suitable level of data quality measures should be developed to monitor multiple performance metrics over time, including baseline drift (change in intercept) and sensitivity decay (change in slope). Furthermore, new calibration approaches should be developed and refined that allow users to better understand the quantitative capabilities of sensors.

There is a need to develop harmonized standards and guidelines for sensor performance evaluation. There is no single metric of data quality that can be applied to sensor systems, however, to facilitate comparison across studies, we advise the use of the following three metrics at a minimum (R², RMSE, MAE). Further metrics may well be needed as is continuous discussion of the best practices for assessing performance.

Demonstration and research projects should, where possible, strive to include locations or nodes within LCS networks where several identical sensor systems are co-located together. This would increase the evidence base to evaluate inter-sensor performance, manufacturing reproducibility and if alongside reference instruments, guide long-term calibration.

Taking these issues into account, deployment of LCSs and pilot projects that explore new, untested applications of LCSs, especially in highly polluted areas, are particularly encouraged. These efforts should be supported by community building to exchange best practices and documentation (e.g. SOPs) of such implementations. Collection and reporting of LCS metadata (hardware, sensor version, data processing algorithms, mounting location, expected types of pollutant sources, etc.) is especially important. Knowledge from fixed LCS measurements can inform on the applicability, opportunities and limitations of LCS deployment on mobile platforms including vehicles and carried by individuals.
Best practices for data management and documentation of associated data regarding implementation conditions should be adopted and utilized. This can be based on existing and de novo approaches for data management and documentation.

For regulators and environmental decision makers

LCS units can provide meaningful data, but not yet at a level of robustness in which reference monitoring will not be required. In part, this is because many LCS projects lack sufficient quality assurance and quality control to trace LCS-derived data to reference monitoring data. We are not yet aware of any LCS device that is capable of producing data at a level of quality equivalent to reference monitoring data without having a reference monitor available for routine calibration services.

In communities in which at least one appropriate reference monitor is available, LCS represent an opportunity to expand knowledge on local air quality. However, there remain a number of scientific complexities that must be considered such as a well-designed quality assurance and calibration procedure that must be continually applied. For example, a single co-location of a LCS with a reference monitor for a short duration is likely inadequate to guarantee that an LCS will consistently perform under varying ambient conditions and over long periods of time in a manner that is useful for regulatory agencies. As a result, LCS need to operate in a well-designed standard operating procedure that provides routine calibration and quality control.

We encourage the consideration of creating regional reference monitoring platforms that could be shared openly across nations to provide inexpensive comparisons between LCS and reference monitors. While it is an ideal to operate high quality reference monitoring networks more universally, these networks are expensive and can be difficult or prohibitive to operate and maintain for many nations. There is value in emulating some of the existing reference-based evaluative platforms for LCS in under monitored regions of the world to expand the utility of LCS. This could provide the technical ability to perform calibrations at low/no cost and could standardize the framework for further LCS use in nations that currently lack air quality data, as well as build new national expertise.

For the broader community who are considering LCS or LCS data use

Renewed efforts are needed to enhance engagement and sharing of knowledge and skills between the data science community, the atmospheric science community, the environmental regulatory community, and others to improve LCS data processing and analysis methods. Improved information sharing between manufacturers and user communities should be supported through regular dialogue on emerging issues related to sensor performance, best practice, and applications.

Adoption of open access and open data policies, including metadata, to further facilitate the development, applications, and use of LCS data is essential. Such practices would facilitate exchange of information among the wide range of interested communities including national/local government, research, policy, industry, and public, and encourage accountability for data quality and any resulting advice derived from LCS data.

We should continue to support (with data, advice, resources) activities that improve validation and/or verification for LCSs and consider expanding to a wider range of environmental and pollution conditions. Such evaluation programmes or centres should be distributed worldwide to capture the variations in measurement environments and underpin as a resource the geographically diverse user communities that may want to adopt LCS approaches in the future.
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Definitions

This report refers frequently to three key technical descriptors, “reference instruments”, “sensors”, and “sensor systems” alongside a general classification of devices as being “low-cost”. In fact, it is becoming clearer that initial purchase cost of a device, which may be perceived as ‘low-cost’, is sometimes only a small fraction of the total cost required to support and sustain that instrument. For example, a device may also require periodic repair and adjustment, costs associated with data access, necessary additional sensor system components, application and management of a quality assurance programme, etc, which add considerable to the total cost of ownership. Furthermore, as sensors are used more widely across the globe, economical affordability disparities continue to persist both in relative cost terms, as well as the global availability of facilities, instrumentation, and equipment that may be needed to keep lower cost sensing instrumentation operable. As a result, there is no single international consensus definition of these terms, but for clarity we operationally define these here as:

**Reference instrument**: in an air pollution context, a reference instrument is most commonly understood to be one with a certification that comes from an official regulating body and can be associated with a reference method notified in legal drivers. For example, instruments to measure air pollutants for regulatory compliance purposes must be approved by the Environmental Protection Agency (EPA) for use in the USA or nominated for type testing according to European Committee for Standardization (CEN) for use in the European Union. Reference instruments measure specific air pollutants to predefined criteria, such as precision, accuracy, drift over time and so on, to provide data that meets regulatory requirements. In extremis reference data on air quality can have validity in courts of law. In the context of this report we also consider as reference instruments any instrument with well-established prior art, for example where the analytical methodologies have been rigorously tested and reported through peer-reviewed literature and where suitable reference materials are available to calibrate such instruments. Any instrument that has been demonstrated to meet the data quality and traceability requirements of international programmes such as WMO/GAW, for example, would be considered a reference instruments in this context.

**Sensor**: the basic subcomponent technology that actually makes the analytical measurement of a greenhouse gas or an air pollutant. The presence of a relevant gas or particle is typically converted into an electrical signal where the relative magnitude of that signal is related to the atmospheric concentration. Examples include sensors for temperature and pressure, capacitive sensors, electrochemical sensors, metal oxide sensors, optical sensors including ultraviolet (UV), non-dispersive infrared sensor (NDIR) absorption cells and optical light scattering sensors.

**Sensor system**: an integrated device that comprises one or more sensor sub-components and other supporting components needed to create a fully functional and autonomous detection system. A sensor system can include components that reside remotely from the physical sensor and include remote data transfer and data processing steps. Sensor systems are also called in the literature IOT air quality sensors, environmental sensors, low-cost sensors, air sensors, etc.

**Low-cost sensor (LCS)**: in the document, the term low-cost sensor is used indistinctly of the term sensor system. The term “low-cost” refers to the initial purchase cost of a single functional sensor system when compared against the purchase cost of reference instrument(s) measuring the same or similar atmospheric parameter(s). The definition of low-cost is intentionally not defined in a prescriptive way in this report but could be inferred to mean an initial capital cost reduction of at least one order of magnitude, and commonly be greater than this, over reference instruments.
Low-cost in this report does not refer to the costs of installation and operation since these will vary considerably depending on desired data quality and data coverage. Within this document we consider a single sensor system as “low-cost” if the price of such a system is one or more orders of magnitude lower than a comparable reference instrument(s). It should be noted that some agencies have different low-cost definitions, and it should be recognized that “low-cost” might have a different meaning to different communities.
Known Sensor Issues

Low-cost air sensors have a range of known issues. Sensor systems can be designed to overcome these issues such as cross-sensitivity, interference, correction, etc. This is an incomplete list but is provided to offer a prospective LCS user with an understanding of the types of limitations of many of these sensor types.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Pollutant</th>
<th>Known issue (effect) with sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrochemical</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ozone (O₃)</td>
<td>Relative humidity&lt;br&gt;Temperature&lt;br&gt;Cross-sensitivity of oxidizing gases (e.g. NO₂, H₂S, Cl₂)&lt;br&gt;Long-term stability (ageing or drift)</td>
</tr>
<tr>
<td></td>
<td>Nitrogen Dioxide (NO₂)</td>
<td>Relative humidity&lt;br&gt;Temperature&lt;br&gt;Cross-sensitivity of oxidizing gases (e.g. O₃, H₂S, Cl₂)&lt;br&gt;Long-term stability (ageing or drift)&lt;br&gt;Relatively long start-up time to sensor stabilization</td>
</tr>
<tr>
<td></td>
<td>Sulfur Dioxide (SO₂)</td>
<td>Relative humidity&lt;br&gt;Temperature&lt;br&gt;Cross-sensitivity of reducing gases (e.g. NO₂, H₂S)&lt;br&gt;Long-term stability (ageing or drift)</td>
</tr>
<tr>
<td></td>
<td>Carbon monoxide (CO)</td>
<td>Relative humidity&lt;br&gt;Temperature&lt;br&gt;Cross-sensitivity of reducing gases (e.g. H₂S, SO₂, CH₄, Alcohols, NH₃, etc.)&lt;br&gt;Long-term stability (ageing or drift)</td>
</tr>
<tr>
<td>Metal oxide</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ozone (O₃)</td>
<td>Response time &gt; 5 min&lt;br&gt;Sensor response is not linear&lt;br&gt;Relative humidity&lt;br&gt;Temperature&lt;br&gt;Long-term stability (drift)&lt;br&gt;Varying baseline after re-start</td>
</tr>
<tr>
<td></td>
<td>Nitrogen Dioxide (NO₂)</td>
<td>Response time &gt; 5 min&lt;br&gt;Sensor response is generally not linear&lt;br&gt;Relative humidity</td>
</tr>
<tr>
<td>Sensor type</td>
<td>Pollutant</td>
<td>Known issue (effect) with sensors</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>Relative humidity</td>
<td>Cross-sensitivity of reducing gases (e.g. H₂S)</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>Relative humidity</td>
<td>Cross-sensitivity of reducing gases (e.g. CH₄, Alcohols, NH₃, etc.)</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>Relative humidity</td>
<td>Cross-sensitivity of reducing gases (e.g. CO)</td>
</tr>
<tr>
<td>Photoionization detectors</td>
<td>Total Volatile Organic Compounds (VOCs)</td>
<td>Relative humidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All VOCs with Ionization Potential lower than the lamp output are detected (e.g. benzene, toluene, ethylbenzene, xylene, esters, alcohols, ketones, etc.)</td>
</tr>
<tr>
<td>Optical detectors (light scattering, NDIR)</td>
<td>Particulate Matter (PM₁₀, PM₂·₅, PM₁₀)</td>
<td>Relative humidity (creates overestimate of PM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harsh environments (high humidity and high temperature) decrease the accuracy of the sensors.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stability of the flow of the sensor that alters the quantity of particles being sampled and modifies the distribution of PM. For example, low flow (or velocity) may prevent the heavy particles from entering into the sensor.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Density, colour, shape and refractive index of PM</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide (CO₂)</td>
<td>Relative humidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(it is not a gaseous interferent in IR, while humidity may alter the optical beam)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressure</td>
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</table>
Example Costs

These data provide an estimated accounting of typical costs one might expect in the operation of a low-cost sensing network of various sizes. Because of the comparatively small capital costs of sensor procurement (here, we assume procurement of an LCS for $1,000) of total cost of ownership, we include all cost estimates as operational costs (OpEx) for various sized sensor networks. This again makes assumptions on best practice for operation of a professional air quality monitoring system and will vary across different network designs.

Table 7: Estimates of annual operational costs to operate various sized networks for LCS networks.

<table>
<thead>
<tr>
<th>Low-Cost Air Sensors</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>25</th>
<th>50</th>
<th>100</th>
<th>250</th>
<th>500</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2.5 &amp; NO2</td>
<td>$1,000</td>
<td>$1,000</td>
<td>$10,000</td>
<td>$15,000</td>
<td>$10,000</td>
<td>$100,000</td>
<td>$150,000</td>
<td>$100,000</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>Shelter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibrator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supplies</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supporting H/W</td>
<td>$10</td>
<td>$150</td>
<td>$150</td>
<td>$1,500</td>
<td>$1,750</td>
<td>$1,500</td>
<td>$15,000</td>
<td>$17,500</td>
<td>$15,000</td>
</tr>
<tr>
<td>Annual Maintenance</td>
<td>$158</td>
<td>$173</td>
<td>$163</td>
<td>$1,725</td>
<td>$1,313</td>
<td>$1,625</td>
<td>$17,250</td>
<td>$13,125</td>
<td>$16,250</td>
</tr>
<tr>
<td>Discount (%)</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>25%</td>
</tr>
<tr>
<td>Discount (amt.)</td>
<td>$1</td>
<td>$1</td>
<td>$1</td>
<td>$1</td>
<td>-$1,306</td>
<td>-$13,225</td>
<td>-$13,063</td>
<td>-$16,125</td>
<td>-$130,625</td>
</tr>
<tr>
<td>Subtotal</td>
<td>$1,323</td>
<td>$1,613</td>
<td>$13,225</td>
<td>$13,063</td>
<td>$12,819</td>
<td>$119,025</td>
<td>$197,563</td>
<td>$195,125</td>
<td>$191,875</td>
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<tr>
<td>Software</td>
<td>100</td>
<td>$100</td>
<td>$100</td>
<td>$1,000</td>
<td>$1,500</td>
<td>$1,000</td>
<td>$10,000</td>
<td>$15,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Discount (%)</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>10%</td>
<td>15%</td>
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<tr>
<td>Discount (amt.)</td>
<td>$1</td>
<td>$1</td>
<td>$1</td>
<td>$1</td>
<td>-$100</td>
<td>-$1,500</td>
<td>-$1,750</td>
<td>-$1,500</td>
<td>-$15,000</td>
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<tr>
<td></td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>25</td>
<td>50</td>
<td>100</td>
<td>250</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>----------------------</td>
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<td>--------</td>
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<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>$100</td>
<td>$100</td>
<td>$1.000</td>
<td>$1.500</td>
<td>$1.500</td>
<td>$11.250</td>
<td>$12.500</td>
<td>$15.000</td>
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</tr>
<tr>
<td><strong>OpEx</strong></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>QA/QC &amp; Data Assessment</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of personal (FTE)</td>
<td>0.01</td>
<td>0.04</td>
<td>0.23</td>
<td>0.23</td>
<td>0.5</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
<td>2</td>
</tr>
<tr>
<td>Personnel (costs)</td>
<td>$150.00</td>
<td>$122</td>
<td>$1.769</td>
<td>$14.615</td>
<td>$14.615</td>
<td>$15.000</td>
<td>$112.500</td>
<td>$112.500</td>
<td>$112.500</td>
</tr>
<tr>
<td>Independent Audits</td>
<td>$100</td>
<td>$100</td>
<td>$100</td>
<td>$1.000</td>
<td>$1.500</td>
<td>$1.000</td>
<td>$10.000</td>
<td>$15.000</td>
<td>$10.000</td>
</tr>
<tr>
<td>Subtotal</td>
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<td>$1.269</td>
<td>$15.615</td>
<td>$17.115</td>
<td>$10.000</td>
<td>$122.500</td>
<td>$137.500</td>
<td>$162.500</td>
<td>$100.000</td>
</tr>
<tr>
<td><strong>Maintenanc e &amp; Ops</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of personal (FTE)</td>
<td>0.02</td>
<td>0.13</td>
<td>0.23</td>
<td>0.50</td>
<td>0.5</td>
<td>0.75</td>
<td>0.75</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Personnel (costs)</td>
<td>$150.00</td>
<td>$1.466</td>
<td>$19.726</td>
<td>$14.615</td>
<td>$15.000</td>
<td>$15.000</td>
<td>$112.500</td>
<td>$112.500</td>
<td>$112.500</td>
</tr>
<tr>
<td>Misc. parts</td>
<td>$10</td>
<td>$10</td>
<td>$150</td>
<td>$100</td>
<td>$1.250</td>
<td>$1.500</td>
<td>$1.000</td>
<td>$12.500</td>
<td>$15.000</td>
</tr>
<tr>
<td>Subtotal</td>
<td>$1.516</td>
<td>$19.976</td>
<td>$15.115</td>
<td>$16.250</td>
<td>$17.500</td>
<td>$117.500</td>
<td>$125.000</td>
<td>$175.000</td>
<td>$150.000</td>
</tr>
<tr>
<td><strong>Grand Total (5-year)</strong></td>
<td>$14.301</td>
<td>$166.789</td>
<td>$124.779</td>
<td>$144.639</td>
<td>$1.124,094</td>
<td>$1.837,625</td>
<td>$1.906,563</td>
<td>$1.875,625</td>
<td>$1.084,375</td>
</tr>
</tbody>
</table>

These cost estimates are provided courtesy of Tim Dye of TD Environmental, LL