CLIMATE DOES MATTER- UNCERTAINTY IN AIR QUALITY NETWORKS

Air quality monitoring stations (termed Automatic Urban and Rural Networks- AURNs in the UK) us either certified reference or equivalent instrumentation. They are trusted for their accuracy and uncertainty to measure air pollutants, monitoring compliance with the legislated Limit Values for gases and particles. Unfortunately, we cannot afford to deploy the number of AURNs needed to properly map our urban air pollution. To remedy this situation, we now have low cost air quality (AQ) networks, comprising from ten to hundreds of sensor systems throughout an urban area, providing near-real time pollution maps. Their cost is about 5% the cost of an AURN, but ensuring their calibration is a serious problem and is the focus of much current research, with Machine Learning (ML)[1,2], baseline correction[3] and reference co-location[4] being three popular calibration methods.

One problem without a solution is the simple fact that most low cost AQ networks are built and calibrated in either Europe or North America, in temperate climates. They are then deployed globally, especially in the most polluted cities in countries including India, Pakistan, China and Mexico; the climates are very different from where they were calibrated. Does that matter? Yes, climate matters. Temperature, humidity and pressure change continually, with different environmental profiles in different climates. This is important because low cost sensors also respond to temperature, humidity and pressure, leading to potentially significant errors in the reported pollutant concentrations.

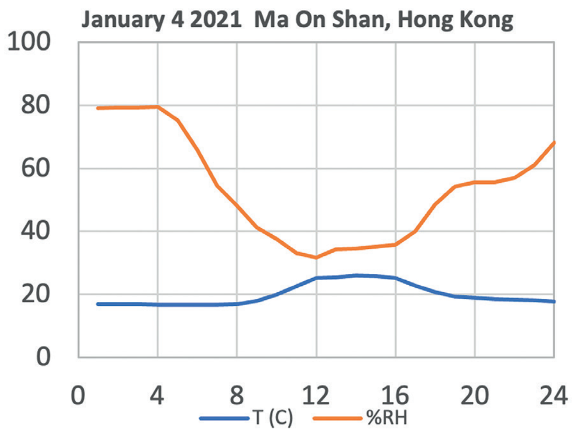
Environmental Effects on Low Cost Sensors

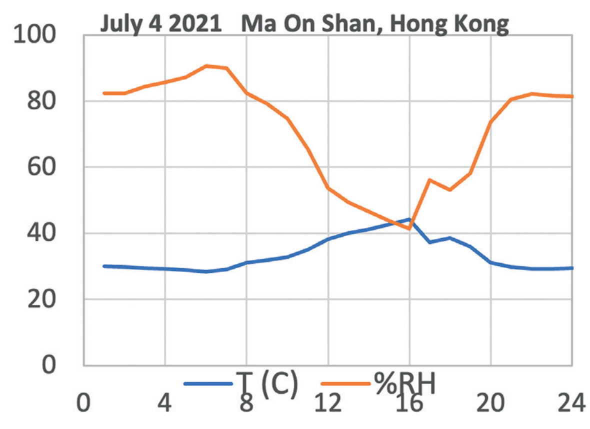
Four technologies dominate sensors for low cost AQ sensor systems: electrochemical gas sensors and metal oxide chemresistors for gases, laser scattering for particulate matter (PM) and non-dispersive infrared (NDIR) for CO_2 and other gases. How do they each respond to environmental conditions?

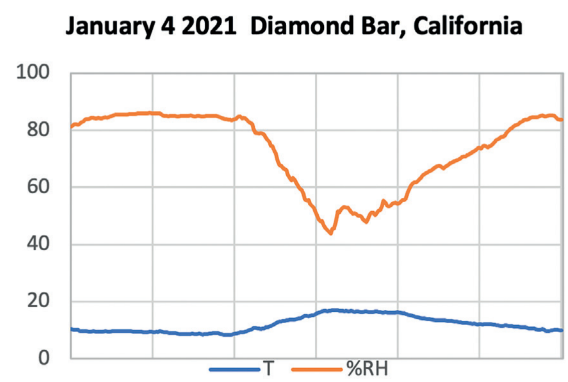
Electrochemical cells generate a current as they either oxidise or reduce the target gas. Their temperature dependence is provided by sensor manufacturers but rapid temperature changes cause transients that can take hours to restabilise. Hot temperatures (>35°C) create high background currents which is very troublesome when measuring ppb concentrations. Importantly, humidity affects the sensor electrochemistry and rapid humidity changes generate excess current from the sensor, like a supercapacitor, resulting in large current transients6. These transients are difficult to model and are the largest source of data variance when using AQ sensor systems in a dynamic climate. Atmospheric pressure changes are usually slow and have negligible effect, but sudden air flow changes (e.g. ventilation systems) can cause transients which recover in a few minutes.

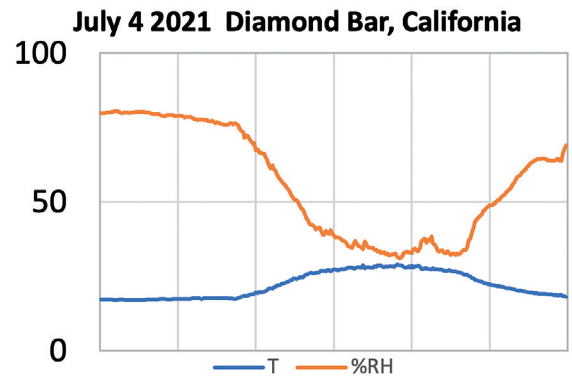
Metal oxide (MOx) sensors change resistance as the target gas interacts with the metal oxide surface. MOx sensors are relatively free of ambient temperature effects because they should operate at fixed high temperatures, but humidity has a significant effect by changing the surface chemistry, especially with n-type MOx sensors such as SnO_2 based sensors. Applying RH correction algorithms are only partially successful because the sensors drift with time, away from the correcting algorithm. MOx sensors are used in lowest cost AQ networks, but due to their humidity dependence and drift, are mostly avoided in the higher quality AQ sensor systems. Again, pressure has a small effect and can be easily corrected.

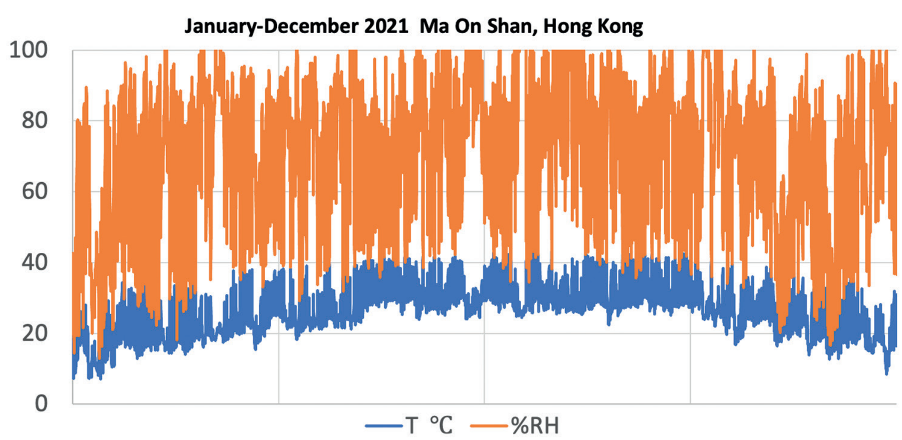
Class	Definition	Cities (Potential field test site)	Coldest Month °C	Average Month °C	>1 month max temp °C	Rainfall	Winter: Summer
TROPICAL							
Af	Tropical rainforest	Kuala Lumpur, Singapore		>18		>60 mm rain	aseasonal
Am	Tropical monsoon	Miami, Jakarta		>18		<60, mm rain	Dry after 21/12
As	Dry savannah	Mombasa, Ghana, Hawaii		>18		<60 mm rain	Dry season
Aw	Wet savannah	Lagos Mumbai Rio West Key		>18		>60 mm rain	
DRY							
BSh	Hot semi-arid	Honolulu, Diamond Bar	>0	>18		Little precip.	Steppe
BSk	Cold semi-arid	Denver, Casper	<0	<18		Little precip.	steppe
BWh	Hot desert	Las Vegas, Phoenix, Karaachi	>0	<18		Little precip.	Very dry
BWk	Cold desert	Xinjang, Damascus	<0			Little precip.	Very dry
TEMPERATE							
Cfa	Humid sub-tropical	Toulouse, Milan, Bologna	>0	0 to 18	>22	No dry season	dry: wet
Cfb	Temperate oceanic	London, Paris, Karlsruhe	>0	0 to 18	<22	No dry season	same
Cfc	Polar island	Rejkevik					
Csa	Hot summer Mediterranean	LA, Barcelona, Rome	>0	0 to 18	>22	<30	wet: dry
Csb	Warm summer Mediterranean	San Francisco, Pacific coast	>0	0 to 18	<22	<30	wet: dry
Cwa	Dry winter humid sub-tropical	Hong Kong	>0	0 to 18	>22		dry: wet
Cwb	Subtropical Highland	Nairobi, Mexico City	>0	0 to 18	<22		dry: wet
CONTINENTAL (NORTHERN HEMISPHERE ONLY)							
Dfa	Hot summer humid continental	Boston, Toronto, Minn.	<0	>10	>22	No dry season	same
Dfb	Warm summer continental	Helsinki, Oslo	<0	>10	<22	No dry season	same
Dsa	Hot, dry summer continental	Salt Lake City	<0	>10	>22	<30	3x
Dwa	Monsoon influenced hot summer humid continental	Beijing	<0	>10	>22		dry: wet
Dwb	Cold moderate	Vladivaskof	<0	>10	>22	Dry winter	

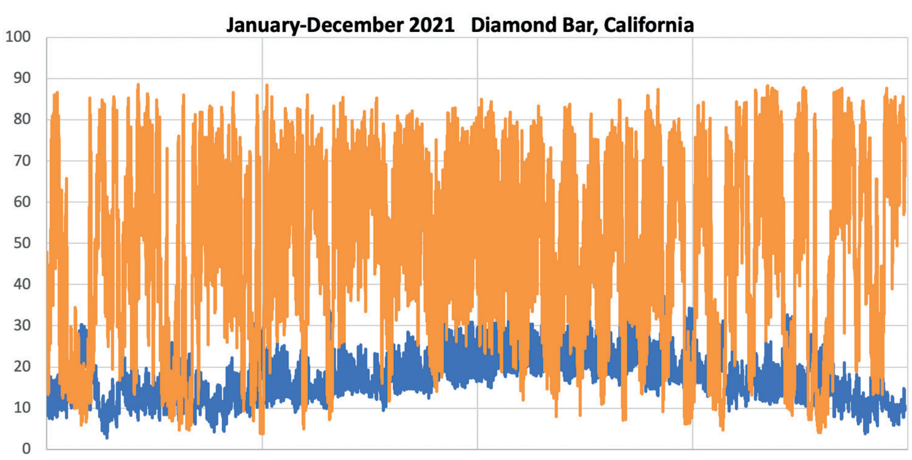


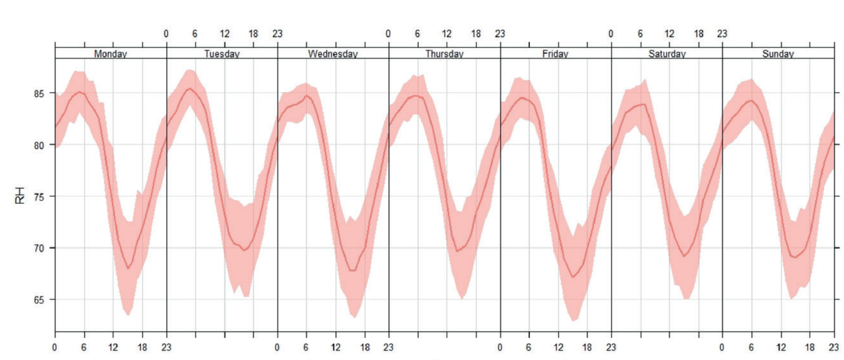


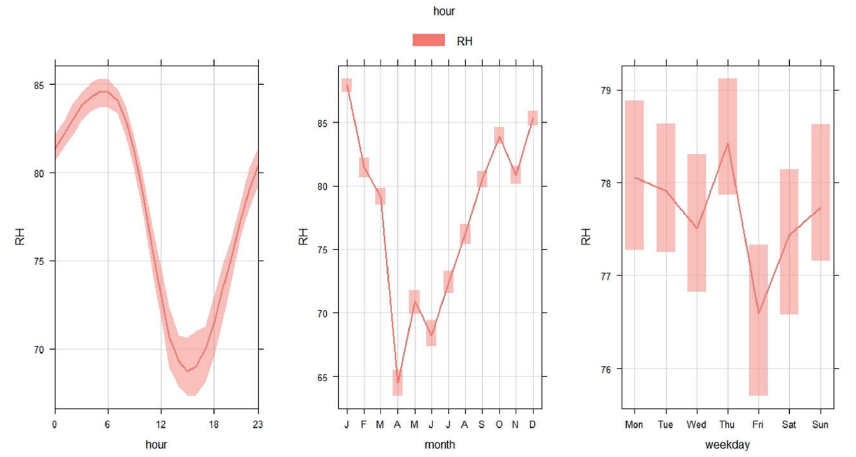












Particles are detected with laser scattering to measure PM_1, $PM_{2.5}$ and PM_{10}. Scattered light is measured either from single particles (Alphasense, Particle Plus), providing real time particle diameter distributions or scattering from an entire ensemble, calibrated to correlate with $PM_{2.5}$ (Plantower, Sensirion, Tera, Shinyea…). Both methods have a temperature dependence which can be compensated, but at humidity above 60 %RH the particles adsorb water[7], swelling to a larger apparent diameter. Equivalent grade PM instruments (typically $10,000) include high power inlet heaters to dry particles, but this is missing from low cost PM monitors due to power and cost restrictions, Tera being an exception. Climates with high humidity require either particle heating or humidity correction algorithms with their limitations; if not corrected, PM values will be seriously overestimated at high humidity, especially above 85%RH. Pressure variations are not a direct problem but the air flow rate must be controlled and ambient pressure will slightly affect the air flow rate.

Non-dispersive infrared (NDIR) spectroscopy is the most popular technology for measuring CO_2, a critical gas for climate warming and a product of combustion. Temperature compensation is critical, but most manufacturers take care of this by expensive factory multipoint temperature calibration. Humidity does not directly affect NDIR at the CO_2 wavelength, but fog and rain can condense on the optics causing errors. Pressure has a linear effect on the observed NDIR light absorbance, so must be corrected, usually with a low cost absolute pressure sensor. If there is no pressure correction then measurements are referenced to the ambient pressure at the time of factory calibration and should be post-process corrected.

Weather, Climate and Environmental Conditions

Daily weather will affect low cost sensors with hot or cold temperature, or dry or high humidity. We cannot predict weather weeks ahead, but we do know the climate which is the average weather behaviour for any location on this planet. In the long term, climate with high temperatures, frequent and rapid humidity changes or long term high humidity will affect the overall performance of AQ networks. But climates are also defined by their seasons[7].

Away from the equator there are four seasons, but when discussing environmental conditions both Spring and Autumn are considered to be equivalent: the average temperature will start from either high or low and finish the season either low or high; pressure, temperature and humidity fluctuations are frequent. Winter and Summer have more stable conditions with less fluctuations. Equatorial locations have either no seasonal differences or simply wet and dry seasons.

Climate can be classified in many ways, the Köppen–Geiger climate classification is the most common classification. The table above lists the 20 classifications which are habitable.

How do climates compare?

Let us look at three very different climates: very humid Glasgow (Cfb: courtesy Ricardo plc), Hot and humid Hong Kong (Cwa: courtesy Dane Westerdahl) and hot Mediterranean Los Angeles (Csa: courtesy Raul Dominguez SCAQMD). Diurnal patterns for Hong Kong and Diamond Bar in Los Angeles both show expected midday temperature rises but the average temperature and range of humidities are quite different. Likewise, there are clear seasonal differences between January and July.

We can see that there are differences in both the average temperature and humidity and the daily fluctuations. Annual profiles for the year of 2021 (below) for the two locations show the wide range and variations of temperature and relative humidity, with Hong Kong on the average 15°C hotter and 30% higher humidity.

It would be surprising if an AQ sensor system network that was calibrated in one climate remained accurate in another climate. The red plots to the left show diurnal, weekly and monthly relative humidities in Glasgow in 2021. It is best to visit in the spring. While diamond Bar in Los Angeles averages about 50% RH, Glasgow averages between 65% and 85% RH.

When we look at the time traces of temperature and relative humidity, it is clear that some climates can present severe environmental conditions for low cost AQ sensor systems.

Are field trials in one climate valid?

Dozens of peer reviewed papers have published results from field trials of low cost AQ sensors systems, although there have been

Temperature	Humidity/ precipitation	Season Extreme	Season Mild	Classification Extreme	Classification mild
Hot	Dry	Summer	Summer	Bwh	Csa, Bsh
Hot	Wet	Summer	Winter	Af, Aw	Cfa
Cold	Wet	Winter	Not summer	Dfa	Dfb
Changeable	Changeable	Spring, Autumn	Spring, Autumrn	Am, Cfa	Cfb, Dfb

few published results for entire AQ sensor system networks; Breathe London, a long running AQ network field trial is the exception. The locations for sensor system field trials have been in various climates: Finland, London, Delhi, Nairobi, Boston, Los Angeles, Belgium, Stuttgart, Beijing are just a few sites, each with their own climate and resultant environmental conditions. Results have been inconsistent for several reasons: different quality sensors, different sensor system constructions, various ML and regression analysis correction algorithms and different climates. The results are variable with the best performance from field trials in mild climates during winter or summer months.

Concern about the data quality from low cost AQ sensor systems is driving standards committees to set Data Quality Objectives (DQOs) for these sensor systems. To achieve the DQO, sensor systems must be tested in the laboratory, in the field, or in both environments. CEN standard committee TC264 WG42 has set two paths for DQO validation: either by extensive field trials or by both shorter field trials and laboratory testing (TS 17660-1:2021). This Technical Specification demands field trials in at least two sites (four sites for the extended field trials) during two seasons, confronting this climate variation problem. ASTM D22.03 is writing a similar Practice Standard (WK64899), also demanding field trials. However, neither document specifies that sensors are tested in extreme climates, so the result is that sensor systems (not sensor networks) can be tested in milder climates and manufacturers can claim they meet the DQO in all climates, although TS 17660 does warn about climate limitations.

Can we do better?

We can do better. It is assumed that if a sensor system passes in a climate with a certain temperature/ humidity regime, it will perform adequately when the temperature and humidity ranges in another climate are less extreme than the test site. Field trials in climates with severe temperature and humidity extremes during field trials should qualify the sensor system for use in less severe climates.

We can view climates in the Köppen table more simply as mixtures of hot/ cold and wet/ dry. These can be combined to provide four climate scenarios: hot/ dry, hot/ wet, cold/ dry and cold/ wet. We consider cold/dry to not be as severe as cold/ wet, so three climate categories should be tested. In addition, rapid weather changes also stress test sensor system performance, so a fourth climate of changeable weather should be included. The above table lists possible extreme and mild climates in the four categories.

Discussions are beginning amongst certifying bodies, national laboratories and test houses to set up global test sites for validating sensor systems in different climates, ensuring they meet DQOs set by standards committees, following Directives and legislation. VACUUMS, a European project, tested many systems; Marylebone in London has been a test site for various sensor systems; and the current AQ-SPEC program, operated by South Coast Air Quality Management Division (SCAQMD) in Los Angeles has tested many sensor systems, with all test results available on their website. Field trials can be run reliably in different climates, we need to expand to include test sites with more extreme climates.

Low cost AQ sensor systems and networks fulfil a needed requirement to monitor our air pollution in all major urban centres globally. Commercial sensor systems are available from many manufacturers, we now need to build the trust that they can provide good quality data. The first step is Test Specifications and Practice Standards from standards committees, the next step is globally recognised test sites that ensure data quality in all climates.

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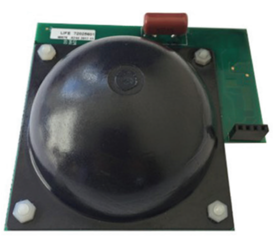
A simple and effective tool for fighting radon contamination

Over ten percent of cases of lung cancer are linked to an excess of exposure to radon, according to a report from the World Health Organisation.



Radon (Rn) is present from a wide variety of natural and man-made sources. This odourless, colourless radioactive gas is the immediate decay product of radium resulting from the radioactive decay of uranium that takes place naturally in rock and soil. Hence all people are exposed to Rn in varying degrees.

Most Rn in indoor air comes from soil and is proving to be more of a hazard than levels of Rn in the drinking water supply. The level of Rn inside a building is largely determined by its location and whether the ground on which it is located has significant levels of uranium present to create the gas. Once Rn reaches the open air, it will rapidly dissolve to a relatively harmless, low concentration. However, if it rises in to a home or commercial property, it can be trapped and build up to dangerous levels for people inside the building. The radioactive decay will then create alpha particles, which in turn can cause permanent damage to lung tissue.

To combat this danger, **Euro-Gas** have developed the Radon SS, a unique, high performance phototransistor gas sensor capable of detecting a field range of 0-65,000Bq/m^3 levels, with a standard range of 1750pCi/l Rn. This user-friendly technology can be easily integrated in portable and fixed air quality and gas detection instruments and offers operators complete data for current and average Rn alpha particle concentration.

More information online: ilmt.co/PL/o02B

email: 51267pr@reply-direct.com

New acoustic imager for fixed and mobile monitoring

Fluke Process Instruments have recently launched their new SV600 Fixed Acoustic Imager at the Hannover Fair. The new Fixed Acoustic imager enables users to detect, locate and track air or gas leaks before they become costly problems. Using an array of sophisticated sound sensors, a camera and Fluke's powerful SoundMap technology, SV600 visualizes sounds for asset monitoring, troubleshooting and quality inspection. It easily integrates with factory systems and enables 24/7 monitoring of compressors, pumps, pipes and other equipment with user-defined alarms. Remote evaluation options help minimize operator intervention, thus improving factory safety. Notably, the SV600 acoustic imager has already been integrated, as a payload, in Boston Dynamics' agile robot Spot for autonomous and remote-controlled surveillance in difficult-to-access or potentially unsafe environments.

For More Info, email: 58018pr@reply-direct.com

Reliable and precise oxygen measurement for combustion plants

LogiDataTech's MF-Oxy measures oxygen partial pressure directly in gas mixtures, to measure absolute oxygen content precisely and reliably in harsh in industrial locations. This device can also self-diagnose for hardware malfunctions, even during operation and its sensor can be calibrated without the use of reference gas.

The MF-Oxy was designed specifically for automatic control of combustion plants, and for taking precise oxygen measurements in difficult-to-reach areas or in self-contained locations such as ventilation tubes or containers. Its signals can be transmitted up to 300 meters and the data then transferred over great distances. There are two versions, with the capability of operating at maximum exhaust temperatures of +250°C and +350°C. A fail-safe system can be made operational via an additional, independent digital output.

MF-Oxy oxygen sensors are available with a measuring range from 0.1 to 25 Vol.-% or 0.1 to 100 Vol.-% oxygen. For use at temperatures of up to +250°C, there is a choice of probe tubes of 120 mm, 220 mm, 400 mm and 800 mm are available; for operation at process temperatures of up to +350°C, all probe sizes apart from the 120 mm are available. The instrument also includes an analogue interface with 4 - 20 mA or 0 - 10 V; it is also features an independent digital output. The MF-Oxy is equipped as standard with a full sinter cab; optionally, an inside sinter can be installed, to make the system more resistant to impurities, although this option would increase reaction times.

The MF-Oxy is complaint with DIN EN 50270: 2015-5 type1 and type2 and DIN EN 61326-1: 2013-07 and with EMC-directives 2014/30/EU.

More information online: ilmt.co/PL/agQj

For More Info, email: 58369pr@reply-direct.com