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Air quality indexing

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Abstract

Air pollution data is complex. Nevertheless there is a widespread desire, and often a requirement, to report it to the public. Surprisingly little attention is paid to how this information is to be used by the public, or the realisation that many monitoring networks may be ill equipped to provide the appropriate information to the public. People's understandings tend to be localised within their immediate physical, social and cultural landscape. There is a tendency for trust to be derived from personal experiences and perceptions rather than numerical data. In an attempt to meet the public's needs for information on air quality a variety of indexes have been developed and they continue to evolve. To show the complexity and the diversity of such indices, a variety of current air quality indices are described here and compared in regard to their performance and ability to deliver quality information to the general public. A number of characteristics seem desirable for an index. Foremost it should provide timely information in an understandable and relevant form, and to be based on a sound understanding of public health and the underlying science. Other characteristics such as consistency, simplicity, versatility and flexibility are also important. In terms of their ongoing development, an AQI also needs to be useful for forecasting, and the method of calculation needs to be sufficiently flexible to allow for pollutants to be added or subtracted as changes to their health impact are revealed. Current AQIs potentially contribute to public understanding by providing information that is easily accessible and allows them the opportunity to modify their behaviour appropriately in response to changes in air quality. However, much progress is still to be made, mainly through more careful consideration of the combined impact of multiple pollutants, consideration of low level exposure, and with more timely transfer of usable information to the public. Air quality data may need to be more tuned to personal or health interests of individuals at the locations they will occupy if it is to meet expectations. Given a growing list of requirements it is difficult to convey appropriate information to the public in a simple way.

Key words:
Air quality index, alert, synergistic, public perception, air quality categories, pollution index

1. Introduction

Many countries have developed descriptors in an attempt to quantify air quality in a manner suitable for public use and action. By 2002, at least 30 countries had internet information on air quality (Garcia et al 2002). The developments have been driven by an understanding that the concentration of individual substances is often regarded as confusing, so it is best to express concentration measurements in terms of an air quality index (AQI). This approach to describing air quality has become increasingly popular, yet as observed many years ago by Babcock (1972) evaluating overall air pollution can be a complex undertaking.

Air quality indices (AQIs) aim at expressing the concentration of individual pollutants on a common scale where effects, usually health effects, occur at a value that is common to all pollutants. Such transformations may make air pollution data seem more accessible, yet this often seems to be done with little understanding of how this information is to be used by society, or how well it is understood.

This essay aims to review the properties of AQIs and discuss how these affect the ability of AQIs to convey information.

Communicating air pollution information

An AQI can be defined as a communication tool (Stieb et al., 2005), but the effective communication of air quality information still needs improvement (Krzyzanowski et al., 2005) and monitoring networks may be ill equipped to provide the appropriate information (Bush et. al., 2001). Public understandings tend to be localised within their immediate physical, social and cultural landscape (Bickerstaff, 2001), which is often far more localised than the spacing of individual monitoring sites. Trust in data is more likely to derive from personal experiences of local air quality than the accuracy of validated numerical data. Air quality data and information requires links to personal or health interests of individuals to meet public expectations. In Australia public confidence in reporting air pollution was observed to fall following the introduction of an index, (Burden and Ellis, 1996).

It is important that air quality information suggests actions that the recipient might take. In this way it usually needs to be forward looking and give pollution for the next day rather than the previous. The ability to forecast air pollution has much improved over the last decade (Termonia and Quinet, 2004), but it is still difficult to get the information to the public. Such a requirement might be possible via a web-based interrogation, although even this would often fail to pick up short-term excursions on a very local level. Furthermore some people relate air pollution to the way they feel. Thus they are dissatisfied when data provided by monitoring networks does not relate to their individual experiences or feelings (Bush et al., 2001).

Determining an AQI

Instrumental measurements of selected pollutants made in urban areas are used for the calculation of an air quality index (AQI) or air pollution index (API). The monitoring data is converted into the index with a variety of transformations. This means that indexing systems and air pollution descriptors often differ from one country to another. The range of indexing and associated reporting continues to increase, with both local and regional indexing now being reported in several countries along with forecasting up to 24 hours or more in advance.

There are normally three distinct phases in the calculation and distribution of an AQI: (1). Measurement of the concentration of potential pollutants, with real time instrumentation being used to obtain data on a 15 minute, hourly or daily basis. The pollutants chosen are those currently known to have short-term health effects with averaging time from 1 hour (e.g. NO_2) to 24 hours (e.g. PM_{10}) while those with long term effects are not yet included in the determination of many APIs (Garcia et al., 2002), and have low prominence in the UK Air Quality Archive (e.g. UK archive, 2005). (2). Determination of the API from the instrumental measurements, usually by reference to local or national standards, and the application of equations or set concentration points to convert the concentration measurements into index values. 3. Provision of the API to the public through a variety of media.

As stated by Longhurst (2005) APIs are subject to ongoing change and modification in parallel with changing technology, developing science, evolving risk assessment and conflicting political jurisdictions.

Uses of an AQI

Once generated an air quality index can: (1) help link air quality and health effects by being used to inform the general public of air quality and possible remedial actions. (2) simplify and condense air quality data hence it can also be a convenient means of providing an information overview for development of policy and regulation, optimise resources allocation and assess compliance with standards (Khordagui and Al-Ajmi, 1996). However, AQIs may not accurately reflect our current understanding of the adverse health effects of ambient air pollution. They typically fail to recognise low level exposure and additive contribution of multiple pollutants (Stieb et al., (2005).

Although AQIs can be used at a research level, the original quality-assured data is often more appropriate. Thus the main rational for AQIs remains as a tool to provide air quality information to the public. When available on the internet, they can display current information and background material on air quality. For example the UK Air Quality Archive (UK archive, 2005) now includes a full description of its air quality objectives for nine pollutants, indexing and banding, current air pollution levels, air pollution forecasts, health advice and the boundaries between index points.

2. Design issues

There are a range of technical and communication issues in the design of AQIs. Since AQI systems tend to replace one number by another, when the pollutants are normalised to a single scale, it means that the public need a good explanation of the meaning of the scale. They need to know, which way the scale runs (i.e. is one or ten best?), how the numbers are scaled, is this with respect to concentration or the effects the pollutants have, do the indices account for the different averaging times required for the health effects of different pollutants, does the index allow for synergisms between pollutants? Many indices seem to be based on a linear scale, yet this may not be sensible. Some have argued that the boundaries between air pollution categories should be crossed frequently under conditions typically experienced, so that the public are aware of changes and that the air quality does not appear to remain at a single value often indicating good air quality (van den Elshout et al., 2005). Relatively constant values may not reflect the longer term air quality trends and create a sense that the monitoring network is not functioning appropriately.

Averaging times

When we present information on different pollutants to the public it often covers data that have widely different averaging times from a yearly running mean for benzene to a 15 minute average for sulfur dioxide. The notion of averaging times is not well understood by either the public or politicians, which can lead to misunderstandings, especially when different countries use different averaging times such that there are complaints that some regulations appear lax because they are relevant to a different averaging time. For example in Finland ozone in air is in the ‘acceptable’ category up to 225 µg m^{-3} (1 hour average), whereas in the Czech Republic ozone concentrations >120 µg m^{-3} (8 hour running average) are classified as exceedences. A casual comparison (225:120) would lead to a negative view and suggest lax air quality indexing in Finland, where as a comparison of 1 hour and 8 hour ozone standards (Garcia et al., 2002) in countries that have both a 1 hour and 8 hour standard would suggest that the AQIs of Finland and the Czech Republic are rather similar (1 hour:8 hour standards (µg m^{-3}); Italy 200:110, Philippines 140:60, Singapore 235:120, New Zealand 150:120).

Siting issues

Both Cogliani (2001) and Roberts (2003) have pointed out that there are problems associated with location of monitoring sites, with the choice of location having a significant influence on an index and any forecasting outcome. The spacing and density of monitoring stations in a network has been discussed by Wu and Chan (1997), while Bruno and Cocchi (2002) suggest that there is a need to consider how the order in which monitoring sites and pollutants are considered when information is aggregated to form an AQI, with time, site spacing and pollutant type also being of importance. While increasing the number of urban observation stations may result in an increase in the reliability of forecasts, a dense network also has the benefit of representing the pollution in an inhomogeneous environment, although networks can rarely achieve a density that can represent the spatial distribution of pollutants in a city. This probably has to be done using computer output from models of urban air pollution distribution.

Furthermore it is likely that the design of networks fails to provide the type of information the public want. They might prefer these to reflect the pattern of their daily lives and choices they make. These may be strategic i.e. “what route should my child generally take to school” (e.g. Hopley and Brimblecombe, 2002) or short term “what should our outdoor activities be today”. Air quality information is needed at a spatial resolution that allows the public to modify behaviour in a way that improves the quality of the air they breathe, even though air pollution is often seen as a problem that is caused by others, rather than something that is of individual control.

Single pollutant indices

One significant problem is that air pollution is not a single entity, yet indices frequently aim to represent the data in terms of a single index or number. This is often done by reporting the air quality as the index associated with the pollutant that has the highest index value and hence the most likely to create a serious effect. This seems a simple and logical approach yet it is immediately obvious that it avoids potential interactions or synergisms between pollutants. However, there may be other approaches to minimise this problem e.g. considering when more than one pollutant is close to a critical level.

When only a single pollutant is used an AQI can be misleading. The index value may depend on the choice of averaging times, absolute and changes in concentration, effects in specific areas and over an entire region, and the percentage of time for which one pollutant has higher concentrations than another. The complexity of air quality may not be fully described by simple descriptors, and thus information conveyed to the public depends on the choice and complexity of the variables chosen (Bell et al., 2005).

Attempts to solve this problem have been made (Bell et al., 2005), but often in a rather simple way. Bezuglaya et al. (1993) suggested an integral air pollution index (IAPI) for Russian cities that was simply the sum of a pre-selected number of the highest individual pollutant indices calculated by comparison with reference concentrations. Swamee and Tyagi (1999) have criticised this addition of sub-indices, concluding that it is ambiguous in that it can lead to an index in the hazardous category, which may be a false alarm. Hence they suggest a non-linear aggregation of sub-indices.

Another consideration is whether or not pollutants other than the priority pollutants should be included in any AQI determination. Borrego et al. (2000) suggest that volatile organic compounds play such an important role in photochemical pollution that they should be considered when making judgements about present and future air quality. Bezuglaya et al. (1993) included many toxic compounds and heavy metals when considering their proposed AQI system. Incorporation of additional pollutants in an AQI may not be practical as significant monitoring resources would be required and in some cases, for example with benzo(a)pyrene. It may not be able to provide the necessary information in the required time frame because of analytical restraints and additionally benzo(a)pyrene has long term rather than short term effects.

Reporting time

Timing is also a problem with the presentation of data. For example the most up to date ozone data may not be as relevant as the daily maximum that is likely to occur at the middle of the day. People often look at values in the evening when home from work, so the mid-day measurements can seem out-dated information. Giving the current value, but stressing the importance of the daily maximum overcomes this. The matter remains confusing because there is not a wide understanding of the differences between primary and secondary pollutants. Ideally the public should be informed regularly of both the current and future air quality. Canada, in particular the province of Ontario, and the UK, attempt to meet this requirement by reporting every two hours and every hour respectively; by contrast New Zealand does not provide any reports.

Pollutants to report

It has been argued (e.g. Cogliani, 2001) that consideration of particulate matter and benzene as well NO_2, CO and O_3 will increase characterisation of total urban air pollution as well as improve forecast reliability. However, this raises the question as to the optimum number of pollutants needed to convey air quality to the public. Large number may only serve to confuse and reduce the possibility of the public using the information in a practical manner. The current use of approximately 5 pollutants (see Table 1 for examples) has been widely adopted. There are also problems in reporting indices for particles, which may be of different composition and thus have different health effects. There are also problems whether the health effects are short term or a function of the long-term carcinogenicity of compounds such as benzo(a)pyrene. The difficulty is particularly acute in countries of South East Asia. Here forest fire smoke is a frequent problem, but it is reported on the same scale as other urban particles, although we have little idea of the relative toxicities of particles from biomass burning and other sources.

Confusion and information loss

Information is lost in deriving an index by banding or grouping measurement data together. Averaging is also included through the use of running averages. In the UK system a large amount of data is reduced to just four bands (very high, high, moderate and low) hence a considerable amount of information is lost.

Confusion could also arise from the wide range of AQI systems being used in different countries. For example the USA uses a maximum index number of 500, Canada 100, Australia (New South Wales) 50 and the UK 10. To complicate matters even further other countries indicate air quality using words such as ‘good’, ‘poor’ and ‘awful’ (Poland, Holland) while others use colours (Portugal, Italy). Some countries such as Finland and Belgium include an index, words and colours. Currently movement from one country to another requires knowledge of a new indexing system to be acquired (see also van den Elshout et al, 2005).

Short term and long term exposure to air pollutants

While short term exposure is the concern of current air quality indexes, there remains the issue of low level long term exposure. This issue still needs to be addressed with respect even to the common air pollutants (Kyle et al., 2002). It is probably relatively easy to assign an index to benzene for example where the carcinogenic risk is relatively well known, but it is harder to grasp how to combine a lifetime risk from benzene with the short term risks from exposure to SO_2 or particles. It would seem sensible given the very different health outcomes that long and short-term indices be kept separate.

Synergistic effects of air pollutants

Little is currently known regarding the combined health effects of a combination of atmospheric pollutants. As observed by Krzyanowski et al. (2005) we still have limited understanding of the toxicity of individual components, let alone as part of a complex mixture. It is generally accepted that the effects of toxic substances are at least additive, and this is also believed to be the case for air pollutant. However Zeliger (2003) points out that chemical mixtures of differing lipophilicity may produce greater than anticipated effects, namely more severe symptoms, unpredicted effects on organs not known to be affected by the individual components, and effects at concentrations much lower than those known to be harmful for the individual components. Zeliger (2003) also suggests that toxicities should be determined for mixtures rather than for individual chemicals, and that standards for water and air quality may require revision as a result. Murena (2004) briefly discusses this issue of synergistic effects, but points out that knowledge of the effects of a mixture of air pollutants on human health is rather limited.

Concern has been expressed that synergistic effects are not taken into account in the determination of air quality indices (Murena, 2004; Stieb et al., 2005). Several attempts have been made to include such effects, (for example Murena (2004), and references therein). As mentioned above Bezuglaya et al. (1993) has suggested an integral air pollution index (IAPI) for Russian cities but this only addresses the issue of multiple pollutants rather than synergisms between them. Khanna (2000) has investigated the differences between the USA's AQI where the index is determined by the pollutants with the highest index value, and an air pollution index (API) based in part on the ambient concentrations of all pollutant gases simultaneously. A significant difference was noted; on occasions the API values contradicted the AQI values.

As can be seen these approaches often attempt to combine mathematically concentrations of two or more pollutants into an index, with the schemes to do this being simple additive ones through to complex non-linear transformations. Such operations are not especially difficult to undertake, but inevitably, as noted by their proponents, demand more health information, because sufficient data to validate the effectiveness of such schemes never seems to be available. This is understandable as health effect data is difficult enough to gather for individual pollutants, thus it is even more laborious to gather it for the larger number of potential combinations of pollutants

Given the lack of understanding of synergistic effects, it is hard to know how many single pollutant indices should be incorporated in an AQI, and how they should be combined. The lack of knowledge of cumulative toxic effects suggests a need for further research. Simply adding sub-indices, although an obvious solution, may not be the best solution.

The design of AQIs needs to consider characteristics relevant to aiding public understanding of air quality (Khanna, 2000; Stieb et al., 2005)). We assess the importance of these attributes in the sub-sections below.

Generalized requirements

Clearly an index needs to be derived from good monitoring data obtained from monitoring stations representative of the community it purports to represent. It needs to be trusted and understandable. Value laden terms should be avoided e.g. 'excellent 'can be replaced by 'low' (see examples in Table 2). Additionally there is a need to deal with the difficult problem of recognising that pollutants have different averaging times relevant to health impacts.

Indices should avoid giving false impressions of the magnitude of changes in air pollution. This can be particularly noticeable when a small change in concentration, for example a change in ozone concentration from 49 to 50 ppb, gives the impression that there has been a significant change in the potential impact of air pollution on health (i.e. a change in descriptor in the UK indexing system from 'low' to 'moderate'; see Table 1).

The index should be easy to associate with health effects and provide additional information relating to potential health symptoms and advice as to what action to take. The health impacts of the pollutants incorporated into the index should be similar in magnitude at each of the assigned index values.

The index must not demean public understanding and recognise issues in the public perception of air quality. Most particularly be aware of localised understandings of air quality.

There are a number of other characteristics worthy of considering because indices may need to be:

- usable in alert systems and provide the potential to be adopted to forecasts of air quality and associated health effects and actions.
- applicable to a wide range of pollutants and be able to incorporate additional pollutants as they become important.
- able to provide an opportunity to assess pollutant impact on vegetation and ecosystems.
- relate to atmospheric visibility
- handle long term health impacts of air pollution.
- adopted by a range of countries, municipalities, local bodies, states etc.

3. Comparing indices

Here we use some indices to compare their characteristics, with the systems from USA/Canada UK, and New Zealand selected for numerical comparison. The USA has developed an AQI which runs from 1-500 and has been adopted, sometimes with modifications, by a number of other countries (Garcia et al., 2002). The UK, is unique in having both an index (number), and bands which are an attempt to simplify the index such that it links directly to health outcomes, and the 1-10 scale resembles that of the sunburn or pollen indices familiar to the public. New Zealand does not have a conventional indexing system, but rather relies on guidelines and categories as a means of focusing local authority and, indirectly, public attention on air quality. Canada has AQI system similar to that of the USA but with an index of only 1-100, but it adopts five named bands. Tables 1 and 2 give a summary of the characteristics of indices from these four countries.

Air quality indices obtained from systems used in USA, UK and New Zealand have been compared by calculating their values using the same set of data obtained from the UK archive. There are obviously dangers in this as the systems might be more attuned to working in their home countries than on a foreign data set, given that they are applied to across many cities nationally.

Hourly data for NO_2, O_3 and PM_{10} for 2003, was taken from a relatively polluted UK site, Leamington Spa. This was downloaded from the UK National Air Quality Archive database. In keeping with the pollutant averaging times normally used in the calculation of AQI's, the hourly measurements for NO_2 were used without modification. Eight hour running averages were calculated for O_3, and both 8 hour and 24 hour running averages for PM_{10}. When an hourly measurement was missing, the missing value was added by interpolation, when more than one consecutive measurement was missing running averages were not calculated for the missing data. The resulting concentrations for each hour were then converted into the appropriate index (UK and USA) or category (New Zealand). Table 3 shows the comparison for O_3, NO_2 and PM_{10} for these three countries.

There are clearly some significant differences in the various indices calculated for the Leamington Spa data. However all three show a high frequency of acceptable air quality

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PM_{10}: New Zealand 91% acceptable or better, UK 98% low, USA 98% good.
O_3: New Zealand 80% acceptable or better, UK 95% low, USA 99% good.

NO_2: New Zealand 100% acceptable or better, UK 100% low, USA no index.

The New Zealand system does however suggest some significant atmospheric pollution approximately 20% of the time for O_3 and 9% for PM_{10}, whereas the UK the comparable figures are 5% and 2% and the USA 1% AND 2%. In the New Zealand system his translates into 1699 hours of excessive O_3 and 634 hours of excessive PM_{10} concentrations during 2003 in Leamington Spa. Using the UK system the comparable number of hours are 480 and 169 hours, and for the USA 81 and 168 hours respectively. Obviously the New Zealand system is more stringent than those of the UK and USA. This may reflects the perception that overall better air quality exists in New Zealand allowing stricter air quality guidelines. The guidelines were revised in 2002 after consideration of the current air pollution levels in New Zealand and by adopting a ‘no observable adverse effect level’ or ‘lowest observable adverse effect level’ approach (Ministry for the Environment, 2002). Unfortunately the use of guidelines rather than standards has allowed exceedences to occur for many years during winter in Christchurch, a major South Island city of 300,000 inhabitants. Over recent years there have been over 30 PM_{10} exceedences per year in Christchurch (Spronken-Smith et al., 2002).

The AQIs of the USA, UK and Canada don’t as yet meet all of the general criteria listed towards the end of Section 2. Nevertheless they are based on significant monitoring data and the number and health impacts have been taken into consideration by all three countries in formulating the indices. However, the small number of bands or categories, a maximum of 6 (USA) means these are prone to give a misleading impression in going from one band to another as a result of a small change in pollutant concentration, e.g. from ‘moderate’ to ‘high’ (UK system). They do not allow for synergistic effects between pollutants, and all have a tendency to oversimplify the complexities of air quality, for example with respect to issues such as averaging times.

As AQIs still need development air quality managers often introduce improved versions. However, a study of public response to the USA’s PSI and the newer format, the AQI, found neither format particularly effective at increasing public knowledge of air pollution or decreasing outdoors activity during high episodes (Johnson, 2003). Such conclusions do not give much confidence in the current approach to quantifying and transferring air quality information to the public.

Synergisms

This situation is represented in Table 4 where we can see two pollutants represented as their bands, and summarises the O_3 and PM_{10} data for Leamington Spa in 2003. Here a simple numerical index as is adopted in the UK or France for example. The non-shaded cells denote the non-controversial situation. The situation of concern is denoted by the shaded cell, which we will here term the sub-critical cell. Here both pollutants are only slightly below the effect level (high), so the air pollutant situation may well be misrepresented in this small number of cases.

Because of the way indices are set up to represent pollutants on the same scale the sub-critical cell lies in the diagonal of the matrix, so there are only a few sub-critical cells. This immediately suggests that this sub-critical situation may be rare. However, if pollutants were to be highly correlated with a one to one relationship, this would not be true. There are possibilities for pollutants to be correlated, perhaps because they come from the same source or that the meteorological controls that affect them as similar. However, it not obvious that their indices would have a 1:1 relationship and be essentially equal. One should also note that in general individual pollutants in urban atmospheres are rather weakly correlated given the very large number of factors that affect their concentrations. Thus our initial expectations are that these sub-critical situations should not be especially frequent.

Alerts

Many air pollution guidelines consider the importance of alerts when air pollution becomes serious (see Elsom, 1994). The notion was embodied in the Council Directive 96/62/EC on ambient air quality assessment and management of the European Union which states: "harmful air pollutants should be avoided, prevented or reduced and limit values and/or alert thresholds set for ambient air pollution levels". Alerts are typically seen as situations where air pollution has reached dangerous levels well above guideline values, where some kind of drastic action needs to be taken. In terms of 96/62/EC the view is "'alert threshold` shall mean a level beyond which there is a risk to human health from brief exposure and at which immediate steps shall be taken". This might be closing factories and large point sources imposing restrictions on traffic or urging people to reduce domestic fuel use.

The New Zealand ambient air quality guidelines (Ministry for the Environment, 2002) use the term 'Alert' in a seemingly different way by referring to when levels become elevated pollution levels, that are nevertheless still below the guideline value. It is not clear why New Zealand has adopted this terminology. It has been suggested that the New Zealand alert or warning level (between 66% and 100% of the guideline for a pollutant) is meant to indicate that the guideline value could be exceeded if upward trends are not curbed. Such an alert would indicate to managers, administrators and policy makers that it may be necessary to develop policies aimed at curbing a potential upward trend or enhancing air quality. However there appears to be no evidence of this having any influence in New Zealand.

Inaction

The most serious concern raised by AQIs relates to the subsequent transfer of information to the public. It appears that they have limited affect on the public; there is little evidence that the public take AQI's seriously as they do not appear to modify their behaviour noticeably in response to warnings about pollutants (Johnson, 2003).

Air pollution forecasting

Air quality forecasting has advanced in recent years adding a new dimension to the use of air quality indexing, although in most instances, the forecasting of air quality for periods more than a day is still in still at an early stage of development. In terms of benefit to the public, forecasting is of equal importance to stating the current air quality; in fact it can be argued that it is of greater importance since it potentially allows members of the public to make a choice regarding their future activities in relation to air quality.

A number of forecasting systems have been proposed or are currently in use. Cogliani (2001) proposed a daily air pollution forecast method using daily thermic-excursions, the previous days measured air pollution, and the daily average wind speed. It was claimed that a correlation coefficient of 0.85 was achieved for Milan, Italy, using this approach.

In the UK a forecast of air pollution for the following 24 hours is prepared each afternoon, for inclusion in a 16:00 air pollution bulletin. A revised forecast is also issued at 11:00 if high air pollution (i.e. index >=7) is being measured or is expected. A new or revised forecast may be issued at any hour of the day in the event that the situation is changing rapidly. In making predictions the UK forecasting system draws upon the combined effort and experience of air quality experts from the Meteorological Office and The National Environmental Technology Centre (NETCEN). The predictions are presented to the public in the same way as the UK air pollution index with an index number (1-10) and banding category.

Canada now provides a two-day air quality forecast in terms of the band names in their Quality of Air Index. The existence of a significant number of air quality monitoring stations in Canada, especially in the province of Ontario (Canada, Air Quality, Ontario, 2005), gives Canada an advantage over countries such as New Zealand where monitoring of the surrounding oceanic regions is much more difficult. South Australia is implementing an air quality forecasting system (SA AQSF) designed to provide the residents with a twice-daily 24-36 hour forecast. It is argued that by accurately forecasting tomorrow's air quality, a community can be alerted on days where high air pollution is expected, allowing people to take steps to avoid it; by avoiding using cars and wood heaters when poor air quality is forecast.

Research on the development of a new generation of air quality forecasting systems also continues (Termonia and Quinet, 2004; Brandt et al., 2003; Seaman 2003; Tory et al., 2003; Wang et al., 2003; Pudykiewicz and Koziol, 2001; Slini et al., 2002). Neural networks have been used to predict aspects of air quality; however some associated difficulties have been highlighted such as not having a sufficient number of training patterns (Jiang et al., 2004; Niska et al., 2004). Interestingly Hooyberghs et al. (2005) using a neural network tool to forecast daily average PM_{10} concentrations one day ahead found the most important input variable to be boundary height layer, and that such concentrations were driven by mainly by meteorological conditions rather than anthropogenic sources.

Hicks (2003) suggests that the over-riding need is not for accurate prediction of some quantifiable air quality component, but rather a forecast of the probability of harmful consequences to exposure. Concentrations are not required as much as the probability that concentrations will be harmful. However expressing probabilities rather than naming bands or an index may serve to confuse rather than enlighten the public. Overall forecasting may be better received by the public than indexing, as it provides the opportunity to take action, and in a sense provide the public with a means of being in control through determining the atmospheric environment to which they are exposed.

Alternative AQIs.

In addition to the many operational air quality indexing systems, a significant number of alternatives have been offered in the literature, for example Trozzi et al. (1999) have suggested a specific AQI applicable to Italy. Cheng et al. (2004) proposed a revised (USA) pollution standard index (PSI) by combining the original PSI with an entropy function. Kahanna (2000) has proposed an index of pollution based on the epidemiological dose-response function associated with each pollutant and the welfare losses due to exposure to pollution. In one instance the different climatic conditions characteristic of different parts of the world have been recognised (Murena, 2004).

Roberts and Martin (2005) focused on the adverse health effects of multiple pollutants rather than a single pollutant, and discuss ways in which relevant data can be analysed. They make the interesting point that, with respect to the association between health and an air pollutant, a single pollutant may in fact be a proxy for another air pollutant or a mixture of air pollutants, hence the need for multiple pollutant studies to resolve this issue. Such studies can assist with the setting of air quality standards resulting in health benefits to the public. Recent papers on the adverse health effects of multiple pollutants are given by Roberts and Martin (2005).

The motivation for suggesting such alternatives is often that they are considered an improvement on the USA EPA AQI, which is often used as a de-facto standard. There is no evidence that indicates that alternatives are suggested as a result of any public concern over the current AQI's.

Finally, some consideration should be given to possible use of significantly different ways in which air quality can be described and information transferred to the public. Hunova (1998, 2003) has used 'ambient air pollution, 'ground level ozone' and wet atmospheric deposition to describe air quality in the Czech Republic, with each of these factors containing 5 quality categories (best, better, medium, worse, worst). This was an attempt to avoid the current debate regarding AQI's with their emphasis on single pollutants. A consideration of data from the Czech Republic (1996-1999) led to the overall conclusion that in the southern part of the country was impacted by ground level ozone, while the northern part was impacted by ambient air pollution, with wet atmospheric deposition and ground level ozone being factors at higher elevations. Zellner and Capurro (1997) have described an index for Buenos Aries, Argentina, which combined urban topography (construction height, street width) with meteorological variables and traffic flow as an indicator of pollutant exposure and the atmospheres capacity to dilute contaminants. A website has been proposed for India for displaying the nation-wide air quality index where the calculated index value is displayed in the form of an 'air quality meter' with a pointer, (Indian Air Quality index, 2005).

4. Discussion and conclusion

At present AQI's, representing current ambient air quality are a popular means of transferring air quality information to the public. However the apparent reluctance of the public to react to air pollution and modify their behaviour suggests that AQIs may not be performing as expected. More work is required to understand how best to report air pollution to the public.

The complexity of air pollution and its science has created problems for both the public and policy makers. There are many pollutants to consider with some being secondary products of atmospheric transformations. The science is often so sophisticated that it becomes hard for politicians and the public to interpret. However there is a continuing desire for better communication between the scientists and society at large. It is likely that air pollution information will continue to be represented in simple forms such as indices in spite of numerous technical issues, and how to best relate indices derived from pollutant measurements to health or environmental outcomes and issues such as averaging times, synergisms in air pollution indices, and low level exposure. Further work is required on the statistical structure and effects of the step function property of air pollution bands, the nature of the scale (1-10, 1-100, 1-500) and the multi-pollutant problem. These make the design of air pollution indices a task that involves a great deal of thought and clarity of thinking, most particularly about their purpose.

Increased relevance of AQI’s is achieved through their use in air pollution forecasting. Current efforts to develop reliable forecasting may make AQI’s more acceptable and useful to the public. The importance of forecasting is critical in taking actions to avoid or lessen air pollution. Weather forecasting is very prominent on television networks, so it may be time for air quality forecasting to be more widely presented with weather forecasting.

Much has to be done in terms of effective reporting air pollution data and addressing the severe difficulties of averaging times and spatial scales. Nevertheless it is probable that even then these will not necessarily meet with public acceptance unless we can grapple with the way in which people perceive and currently react to the air pollution that surrounds them.

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References

Babcock, L.R. Jr., 1972. A combined index for measurement of total air pollution: Effects of changing air quality standards. In “Determination of Air Quality”, Eds Mamantov, G., Shults, W.D. Plenum Press, New York.

Bell, L.B., Hobbs, B.F., Ellis, H., 2005. Metric matters: Conflicting air quality rankings from different indices of air pollution. Journal Air and Waste Management 49, 97-106.

Bezuglaya, E.U., Shchutskaya A.B., Smirnova I.V., 1993. Air pollution index and interpretation of measurements of toxic pollutant concentrations. Atmospheric Environment 27A, 773-779.

Bickerstaff K., Walker G., 1999. Clearing the smog? Public responses to air-quality information. Local Environment 4, 279-294.

Borrego, C., Gomes P., Barros N., Miranda A.I., 2000. Importance of handling organic atmospheric pollutants for assessing air quality. Journal of Chromatography 889:271-279.

Brandt., J., Christensen, J.H., Frohn, L.M., Berkowicz, R., 2003. Air pollution forecasting from regional to urban street scale—implementation and validation for two cities in Denmark. Physics and Chemistry of the Earth Parts 28, 335-344.

Bruno, F., Cocchi, D., 2002. A unified strategy for building simple air quality indices. Environmetrics 13, 243-261.

Burden, F.R., Ellis, P.S., 1996. Air pollution indices for Victoria. Clean Air 30, 26-30.

Bush, J., Moffatt, S., Dunn, C.E., 2001. Keeping the public informed? Public negotiation of air quality information. Public Understanding of Science 10, 213-129.

Canada, Air Quality, Ontario, 2005, http://www.theweathernetwork.com/features/airq/pages/indexON.htm (Accessed 1-10-05).

Chelani, A.B., Chalapati, Rao C.V., Phadke, K.M., Hasan, M.Z., 2002. Formation of an air quality index for India. International Journal of Environmental Studies 59, 331-342.

Cheng, W., Kuo, Y., Lin, P., Chang, K., Chen, Y., Lin, T., Huang, R., 2004. Revised air quality index derived from an entropy function. Atmospheric Environment 38, 383-391.

Cogliani, E., 2001. Air pollution forecast in cities by an air pollution index highly correlated with meteorological variables. Atmospheric Environment 35, 2871-2877.

Elsom, D., 1994. ‘Smog Alert, Managing Urban Air Quality’ Earthscan.

Garcia, J., Colosio, J., Jamet, P., 2002. Air-quality indices. Elaboration, uses and international comparisons. Les Presses de l’Ecole des Mines, Paris.

Hicks, B.B., 2003. Planning for air quality concerns of the future. Pure and Applied Geophysics 160, 57-74.

Hooyberghs, J., Mensink, C., Dumont, G., Fierens, F., Brasseur, O., 2005. A neural network forecast for daily average PM_{10} concentrations in Belgium. Atmospheric Environment 39, 3279-3289.

Hopley, E., Brimblecombe, P., 2002. Diurnal cycles of carbon monoxide and nitric oxides near schools. Clean Air and Environmental Protection 32, 75-77.

Hunova, I., 1998. Ambient air quality for the territory of the Czech Republic in 1996-1999 expressed by three essential factors. Science of the Total Environment 2003;303:245-251.

Hunova, I. Sparial interpretation of ambient air quality for the territory of the Czech Republic. PhD Thesis. Praha: CGU, (98pp in Czech).

Indian Air Quality Index, 2005, http://home.iitk.ac.in/~mukesh/ (Accessed 1-10-05).

Jiang, D., Zhang, Y., Hu, Z., Zeng, Y., Tan, J., Shao, D., 2004. Progress in developing an ANN model for air pollution index forcast. Atmospheric Environment 38, 7055-7064.

Johnson, B.B., 2003. Communicating air quality information: Experimental evaluation of alternate formats. Risk Analysis 23, 91-103.

Khanna, N., 2000. Measuring environmental quality: an index of pollution. Ecological Economics 35, 191-202.

Khordagui, H.K., Al-Ajmi, D.N., 1996. Application of indices for air quality management in Kuwait. Environmental Management 20, 151-158.

Krzyzanowski, M., Vandenberg, J., Stieb, D., 2005. Perspectives on air quality policy issues in Europe and North America. Journal of Toxicology and Environmental Health 68, 1057-1061.

Longhurst, J., 2005. 1 to 100: Creating an air quality in Pittsburgh. Environmental Monitoring and Assessment 106, 27-42.

Liu, C.M., 2002. Effects of $PM_{2.5}$ on AQI in Taiwan. Environmental Modelling and Software 17, 29-37.

Munn, R.E., Phillips, M.L., Sanderson, H.P., 1977. Environmental effects of air pollution: implications for air quality criteria, air quality standards and emission standards. The Science of the Total Environment 8, 53-67.

Murena, F., 2004. Measuring air quality over large urban areas: development and application of an air pollution index at the urban area of Naples. Atmospheric Environment 38, 6195-6202.

Niska, H., Hiltunen, T., Karppinen, A., Ruuskanen, J., Kolehmainen, M., 2004. Evolving the neural network model for forecasting air pollution time series. Engineering Applications of Artificial Intelligence 17, 159-167.

Pudykiewicz, J.A., Koziol A.S., 2001. The application of Eulerian models for air quality prediction and the evaluation of emission control strategies in Canada. International Journal of Environment and Pollution 16, 425-438.

Roberts, S., 2003. Combining data from multiple monitors in air pollution mortality time series studies. Atmospheric Environment 37, 3317-3322.

Roberts, S., Martin, M.A., 2005. critical assessment of shrinkage-based regression approaches for estimating the adverse health effects of multiple air pollutants. Atmospheric Environment 39, 6223-6230.

Seaman, N.L., 2003. Future directions of meteorology related to air-quality research. Environment International 29, 245-252.

Slini, T., Karatzas, K., Moussiopoulos, N., 2002. Statistical analysis of environmental data as the basis of forecasting: an air quality application. Science of the Total Environment 288, 227-237.

Spronken-Smith R.A., Sturman A.P., Wilton E.V., 2002. The air pollution in Christchurch, New Zealand – progress and prospects. Clean Air 36, 23-29.

Stieb, D.M., Smith Doiron, M., Blagden, P., Burnett, R.T., 2005. Estimating the public health burden attributable to air pollution: An illustration using the development of an alternative air quality index. Journal of Technology and Environmental Health Part A 68, 1275-1288.

Swamee, P.K., Tyagi, A., 1999. Formation of an air pollution index. Journal Air and Waste Management Association 49, 88-91.

Termonia, P., Quinet, A., 2004. A new transport index for predicting episodes of extreme air pollution. Journal of Applied Meteorology 43, 631-640.

Tory, K.J., Cope, M.E., Hess, G.D., Lee, S., Wong, N., 2003. The use of long-range transport simulations to verify the Australian Air Quality Forecasting System. Australian Meteorological Magazine 52, 229-240.

Wang, W.J., Xu, Z.B., Lu J.W., 2003. Three improved neural network models for air quality forecasting. Engineering Computations 20, 192-210.

Wu, H.W.Y., Chan, L.Y., 1997. Comparative study of air quality surveillance networks in Hong Kong. Atmospheric Environment 31, 935-945.

UK Archive, 2005. http://www.airquality.co.uk/archive/standards.php#band (Accessed 21-8-05).

van den Elshout, S., Leger, K., Nussio, F., 2005 Comparing urban air quality in Europe in real time – a review of existing air quality indices and the proposal of a common alternative, in Topcu, S., Yardim, M.F., Bayram, A., Elbir, T., Kahya, C. *Proceedings of the Third International Symposium on Air Quality Management at Urban, Regional and Global Scales*, Hava Kirlenmesi Arastirmalari ve Denetimi Turk Milli Komitesi, Izmir, Turkey, 1, 324-334.

Zeliger, HI. Toxic effects of chemical mixtures. Archives of Environmental Health 2003:58;23-29.

Table 1. Summary of air quality indices used in USA, Canada, UK and New Zealand (see Table 2 for band and category names).

Country	**Index Name**	**Index & Banding**	**Pollutants incorporated**	**Relevant Standard**
USA	Air Quality Index	1-500 5 named categories	O_3, $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2	National Ambient Air Quality Standards
Canada	Index of the Quality of Air Index	1-100 5 named categories	O_3, PM_{10}, CO, SO_2, NO_2,	Maximum tolerable values
United Kingdom	Air Pollution Index	Index: 1-10 4 named bands	O_3, PM_{10}, CO, SO_2, NO_2	National Air Quality Standards
New Zealand	Ambient Air Quality Guidelines	Percentage of the guideline for each pollutant 5 named categories	O_3, $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2, Pb, H_2S, benzene, 1,3 butadiene, formaldehyde, acetaldehyde, benzo(a)pyrene, mercury, chromium, arsenic	National Ambient Air Quality Guidelines

Table 2. Bands and categories names used in the USA, Canada, UK, and New Zealand. In the UK health advice is as follows: **Low**- effects unlikely to be notice even by those sensitive to air pollution, **Moderate**- sensitive people may notice mild effects but these are unlikely to need action, **High**- sensitive people may notice significant effects and may need to take action and **Very high**- the effects on sensitive people, described for high pollution, may worsen.

Country:	USA (categories)	Canada (categories)	UK (bands)	New Zealand (categories)
Band or category names:	Good	Very good	Low	Excellent
	Moderate	Good	Moderate	Good
	Unhealthy for sensitive groups	Moderate	High	Acceptable
	Unhealthy	Poor	Very high	Alert
	Very unhealthy	Very poor		Action
	Hazardous			

Table 3. The categorization of air quality by the air quality indicator systems for the USA, the UK and New Zealand for O_3, NO_2 and PM_{10}.

	USA		**UK**			**New Zealand**	
OZONE **(8 hour running averages from 8667 one hour measurements)**	Hazardous	0.0%	10	Very high	0.0%	Action	3%
	Very unhealthy	0.0%	9	High	0.0%	Alert	16%
	Unhealthy	0.1%	8	High	0.0%	Acceptable	43%
	Moderate	0.9%	7	High	0.1%	Good	25.7%
	Good	99.0%	6	Moderate	0.5%	Excellent	11.3%
			5	Moderate	1.5%		
			4	Moderate	3.5%		
			3	Low	20.5%		
			2	Low	44.7%		
			1	Low	29.3%		
NITROGEN DIOXIDE **(from 5815 one hour measurements)**	(Hazardous)	No AQI for any of the concentrations measured at Leamington Spa in 2003. (The index is only used above 1,332 µg m^{-3})	10	Very high	0.0%	Action	0.0%
	(Very unhealthy)		9	High	0.0%	Alert	0.2%
	(Unhealthy)		8	High	0.0%	Acceptable	10.3%
	(Moderate)		7	High	0.0%	Good	52.2%
	(Good)		6	Moderate	0.0%	Excellent	37.3%
			5	Moderate	0.0%		
			4	Moderate	0.0%		
			3	Low	0.0%		
			2	Low	1.5%		
			1	Low	98.5%		
PM_{10} **(24 hour running averages from 7082 one hour measurements)**	Hazardous	0.0%	10	Very high	0.0%	Action	2.4%
	Very unhealthy	0.0%	9	High	0.2%	Alert	6.6%
	Unhealthy	0.0%	8	High	0.4%	Acceptable	50.2%
	Moderate	2.4%	7	High	0.3%	Good	40.1%
	Good	97.6%	6	Moderate	0.3%	Excellent	0.7%
			5	Moderate	0.3%		
			4	Moderate	0.9%		
			3	Low	6.6%		
			2	Low	48.1%		
			1	Low	42.9%		

Table 4. Occurrences of bands for PM_{10} and O_3 for Leamington Spa for 2003. Total number of hours when both pollutants were measured was 7378 hours, (maximum possible = 8760 hours). UK banding scheme. Sub-critical cell shaded.

		PM10 Band (24 hour running averages)				
		Low	Moderate	High	Very High	
O_3 Band **(8 hour running averages)**	Very High	0	0	0	0	0.0%
	High	8	0	0	0	0.1%
	Moderate	293	19	0	0	4.2%
	Low	6860	127	71	0	95.7%
		97.1%	2.0%	1.0%	0.0%	7378

Appendix.

Elements of AQI's of the USA, the UK and New Zealand as used in Section 3

USA

On any given day, an AQI (on a scale of 0-500) is calculated from field measurements for each of five pollutants; ozone (O_3, 8 hour and 1 hour average), particulate matter (PM_{10}, $PM_{2.5}$, both 24 hour averages), carbon monoxide (CO, 8 hour average), sulfur dioxide (SO_2, 24 hour average) and nitrogen dioxide (NO_2, 24 hour average). Figure A1 shows the non-linear relationship between the AQI and pollutant concentration for O_3 and PM_{10}.

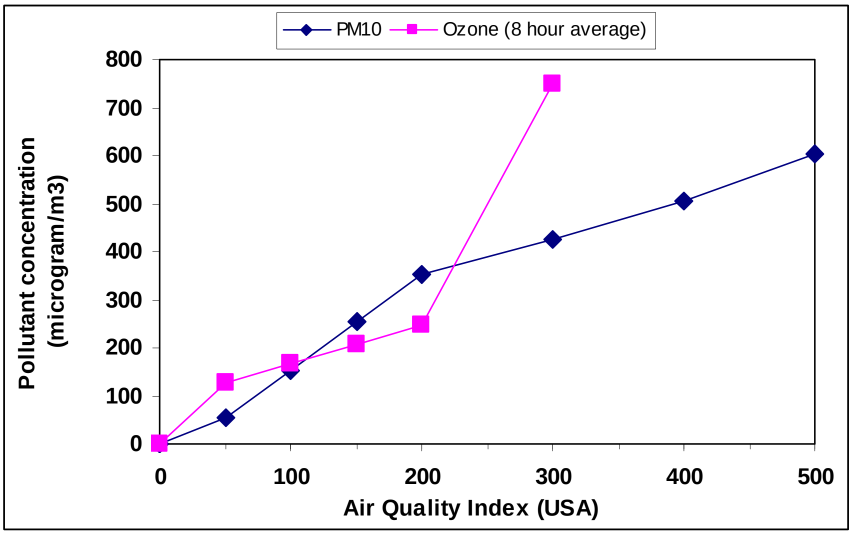

Figure A1. The relationship between the USA air quality index and concentration for O_3 and PM_{10}.

For each pollutant an AQI of 100 is equivalent to the NAAQA for that pollutant. For example for CO the AQI of 100 is equivalent to a concentration of 9 ppm (averaged over 8 hours). An AQI of 500 is equivalent to the Significant Harm Levels (SHL) as defined in USA EPA 40 CFR 51.151.

The AQIs for NO_2 do not start until 200 as there is no NAAQS for this pollutant under 200 $\mu g\ m^{-3}$.

UK

Table A1. Air quality bands in the UK for ozone, nitrogen dioxide and particulate matter. The units are are μg $m^{-3.}$ For ozone, the maximum of the 8 hourly and hourly mean is used to calculate the index value*

		O_3	NO_2	PM_{10}
		1, 8 hourly*	hourly mean	24 hour running mean
Low	1	0-33	0-95	0-21
Low	2	34-65	96-190	22-42
Low	3	66-99	191-286	43-64
Moderate	4	100-125	287-381	65-74
Moderate	5	126-153	382-477	75-86
Moderate	6	154-179	478-572	87-96
High	7	180-239	573-635	97-107
High	8	240-299	636-700	108-118
High	9	300-359	701-763	119-129
Very High	10	>=360	>=764	>=130

New Zealand

Some examples of the 2002 New Zealand ambient air quality guidelines are given in the Table A2. In 2005 these guideline values were adopted as standards without adjustment. New Zealand air quality guideline categories are given in Table A3.

These guidelines were designed to encourage local and regional authorities to exercise control over emissions and air quality in general, rather than to inform the public of the current ambient air quality. The guidelines were developed to reflect well-debated, expert, national and international best practice and knowledge, but carry no legislative requirements, and were derived from consideration of epidemiological studies, international guidelines and laboratory research, (Ministry of the Environment 2002).

Table A2. Examples of New Zealand Ambient Air Quality Guidelines (2002)

Contaminant	Guideline values	Averaging time
O_3	150 μg m^{-3} 100 μg m^{-3}	1 hour 8 hour
NO_2	200 μg m^{-3} 100 μg m^{-3}	1 hour 24 hour
PM_{10}	50 μg m^{-3} 20 μg m^{-3}	24 hour annual

Table A3. New Zealand air quality categories

Action	Exceeds the guideline value
Alert	Between 66% and 100% of the guideline value
Acceptable	Between 33% and 66% of the guideline value
Good	Between 10% and 33% of the guideline value
Excellent	Less than 10% of the guideline value