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Air quality indices: a review

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National directives on air quality oblige nations to monitor and report on their air quality, otherwise require the public to be informed on the state of the ambient pollution. The last is the reason for the always increasing interest, in recent years, in air quality/pollution indices. The interest is demonstrated by the number of publications on this topic.

In this paper we will give an overview about the Air Pollution Indices proposed in literature and/or adopted by Governments, trying also to categorize them into homogeneous groups. For the classification different approaches can be followed. Since in real life exposure to mixtures of chemicals occurs, with additive, synergistic or antagonistic effects, here we will distinguish between indices that consider the conjoint effect of pollutants and indices that are only based on the actual most dangerous pollutant.

Keywords: Air quality indices; Pollution indices

1 Introduction

"Clean air is considered to be a basic requirement of human health and well-being. However, air pollution continues to pose a significant threat to health worldwide. According to a WHO assessment of the burden of disease due to air pollution, more than 2 million premature deaths each year can be attributed to the effects of urban outdoor air pollution and indoor air pollution." (WHO, 2006)

"Air quality indices 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. [...] 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. [...]". Moreover, "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" (Shooter and Brimblecombe, 2009).

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In the following sections we will try to categorize into homogeneous groups most of the Air Pollution Indices proposed in literature and/or adopted by Governments. All the indices here reviewed follow a data-driven approach, the most common in literature, but a model based approach that, modelling the data by a stochastic process, allows for missing value imputation and forecasting could be followed as well. Lagona (2005), for example, has proposed to follow a Hidden Markow Model approach that, even if it could appear a promising way to deal with the problem, lacks of simplicity and interpretability.

Even if air quality indices are updated every now and then published material risks to be outdated very soon, we think that a review on this subject can be useful for both scientists and local governments. The period spanned by the reviewed articles is 1999-2009.

For the classification different approaches can be followed. One could be that proposed by Mayer et al. (2004), who divides indices into Air Stress Indices (ASIs) and Air Quality Indices (AQIs, sometimes called, both in literature and in this paper, Air Pollution Indices - APIs). The former are based on an arithmetic summation of relative concentrations of air pollutants or relative numbers of exceedences of air pollutant specific short-term standards. They can be considered a summary assessment of the ambient air pollution and have not direct relation to the well-being and health of human beings. Their typical structure is:

$$ASI = \sum_{p=1}^P \left[\frac{C}{R} \right]_p \text{ or } ASI = \frac{1}{P} \sum_{p=1}^P \left[\frac{C}{R} \right]_p ,$$

where C is the mean concentration (mostly over one year) and R is a reference value for the air pollutant p . If a short-term air pollution stress is being assessed, C is the annual number of actual exceedences of air pollutant specific standards and R is the corresponding annual number of exceedences permitted in directives or guideline, e.g. of the European Union (EU).

AQIs, on the other side, are impact related with respect to people well being and, differently from what stated in Makra et al. (2003, pg. 87), actually are the most diffused.

“In general, the guidelines address single pollutants, whereas in real life exposure to mixtures of chemicals occurs, with additive, synergistic or antagonistic effects. In dealing with practical situations or standard-setting procedures, therefore, consideration should be given to the interrelationships between the various air pollutants” (WHO, 2000). That is why we do not think the distinction between ASI and AQI is the most appropriate and useful. In our opinion, a more useful approach consists in distinguishing between indices that consider the conjoint effect of pollutants and indices that are only based on the actual more dangerous pollutant (section 3). This is the kind of classification we will follow in this review; nevertheless, Table 1 will classify the indices that will be described in this paper according to other important statistical issues like spatial aggregation, the availability of uncertainty measures for the index, being/not-being health based, purpose, accounting for low level exposure. Moreover, we will try to give an overview about what Governments do (section 2). Section 4 will introduce the more general context of sustainability indices, even if this is not the main object of this review. Finally some conclusions will be illustrated in section 5.

Along the whole paper, whenever it will be necessary, we will refer to a data matrix \mathbf{X} , whose generic element, x_{tps} , represents the concentration of the pollutant p recorded in a site s at time t (usually a daily synthesis obtained by aggregating hourly data). The reported url have been accessed on may 5th 2010.

2 What governments do

A fundamental reference is WHO “Air quality guidelines for Europe”, published for the first time in 1987, and updated in 2000 (WHO, 2000) and 2006 (WHO, 2006). “The WHO air quality guidelines (AQGs) are intended for worldwide use but have been developed to support actions to achieve air quality that protects public health in different contexts. Air quality standards, on the other hand, are set by each country to protect the public health of their citizens and as such are an important component of national risk management and environmental policies. National standards will vary according to the approach adopted for balancing health risks, technological feasibility, economic considerations and various other political and social factors, which in turn will depend, among other things, on the level of development and national capability in air quality management. The guideline values recommended by WHO acknowledge this heterogeneity and, in particular, recognize that when formulating policy targets, governments should consider their own local circumstances carefully before adopting the guidelines directly as legally based standards.” (WHO, 2006).

The United States Environmental Protection Agency (EPA) started to use an Air Quality Index (AQI) in 1976 (the original name was Pollutant Standard Index - PSI) for use by States and local agencies on a voluntary basis. The aim was to create a certain homogeneity among the 14 different indices used by more than 50 urban areas in USA and Canada at that time. The Clean Air Act (the law that defines EPA’s responsibilities for protecting and improving the nation’s air quality), which was last amended in 1990, requires EPA to set National Ambient Air Quality Standards (NAAQS) for wide-spread pollutants from numerous and diverse sources considered harmful to public health and environment. The Clean Air Act established two types of national air quality standards. Primary standards set limits to protect public health, including the health of “sensitive” populations such as asthmatics, children and elderly. Secondary standards set limits to protect public welfare, including protection against visibility impairment, damage to animals, crops, vegetation and buildings. The Clean Air Act requires periodic reviews of the science upon which the standards are based and the standards themselves.

EPA AQI (<http://www.epa.gov/air/urbanair/>) is an index for reporting daily air quality. It tells how clean or polluted air is, and what associated health effects might be a concern for you. The AQI focuses on health effects you may experience within a few hours or days after breathing polluted air.

EPA has set NAAQS for six principal pollutants, which are called “criteria” pollutants: CO, Pb (not included in the computation of AQI), NO_2 , O_3 , PM and SO_2 (<http://epa.gov/air/criteria.html>). Six categories corresponding to different level of health concerns (and symbolized by different colors) are considered.

Subindices are calculated according to a table (<http://www.epa.gov/ttn/naaqs/standards/nox/fr/20100209.pdf> pg 65) by linear interpolation between the 6 class borders:

$$AQI_p = \frac{I_H - I_L}{BP_H - BP_L}(C_p - BP_L) + I_L$$

where:

- AQI_p is the index for pollutant p ;
- C_p is the concentration (daily synthesis) of the pollutant p ;
- BP_H is the breakpoint $\geq C_p$;
- BP_L is the breakpoint $\leq C_p$;
- I_H is the AQI value corresponding to BP_H ;
- I_L is the AQI value corresponding to BP_L .

The final index, ranging in $[0, 500]$, is obtained as the largest or “dominant” AQI_p value and usually communicated (<http://www.airnow.gov/>) together with the “dominant” pollutant; an AQI value of 100 generally corresponds to the national air quality standard for each pollutant.

Canadian Government, through the Meteorological Service of Environment Canada, provide an AQI computed in the same way as EPA’s one, but considering 4 categories only. Recently, a new Air Quality Health Index (AQHI) has been added to AQI. The AQHI is based on the relative risks of a combination of common air pollutants which are known to harm human health: O_3 , PM and NO_2 . The AQHI is measured on a scale ranging from 1 to 10. The AQHI values are also grouped into 4 health risk categories helping to easily and quickly identify the actual level of risk (<http://www.ec.gc.ca/cas-aqhi/default.asp?lang=En&n=065BE995-0>).

At European level, the last air quality directives came into force in June 2008 and will be transposed into national legislation by June 2010 (Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF>). This directive lays down measures aiming at, among others, “assessing the ambient air quality in Member States on the basis of common methods and criteria”. Actually this directive has not been applied yet, and each state follows (when it is done) its own method. The European Environment Agency (EEA, <http://www.eea.europa.eu/>) is the agency of the European Union (that came into force in late 1993) whose task is to provide sound, independent information on the environment; it represents a major information source for who is involved in developing, adopting, implementing and evaluating environmental policy, and also for the general public. Currently, the EEA has 32 member countries.

The Department for Environment, Food and Rural Affairs (DEFRA) is the government department responsible for environmental protection in the United Kingdom. Here, most OF air pollution information services use the index and banding system approved by the Committee on Medical Effects of Air Pollution Episodes (COMEAP). The system uses an index ranging from 1 to 10, divided

into four bands to provide more details about air pollution levels in a simple way. The overall air pollution index for a site or region is calculated from the highest concentration of the five pollutants NO_2 , SO_2 , O_3 , CO and PM_{10} . The sub index for each pollutant again is computed by linear interpolation between the 10 class borders, according to a table (<http://www.airquality.co.uk/standards.php>).

The French Environment and Energy Management Agency (ADEME), in cooperation with the Ministry of Ecology and Sustainable Development and in accordance with its public health objectives, publishes the Bulletin de l’Air based on Atmo indices calculated by certified air-quality monitoring agencies (AASQA). The Atmo index, symbolised by a giraffe, represents the mean urban air quality using a single figure scale. The Atmo ranges from 1 to 10 (1 = very good air quality, 10 = very bad air quality) and bases its calculation on four subindices characterising the four pollutants NO_2 , SO_2 , O_3 and PM . The thresholds used to define subindex levels were set basing on regulatory criteria on air quality (<http://www.atmoauvergne.asso.fr/en/index/calculation.htm>). The final Atmo index is equal to the highest of the four subindices.

In Germany, at our knowledge, no Air Quality Index has been introduced. One-hour-averages of NO_2 , SO_2 , O_3 , CO and PM_{10} are available at <http://www.env-it.de/umweltbundesamt/luftdaten/index.html?setLanguage=en> and the values are hourly updated. For each pollutant 11 classes (10 for CO and 7 for O_3), symbolized by different colors, are considered. Information on air quality can also be found at http://db.eurad.uni-koeln.de/index_e.html?/prognose/index_e.html. An AQI, defined as:

$$AQI = \max \left(\frac{SO_2(24h)}{125}, \frac{NO_2(24h)}{90}, \frac{PM_{10}(24h)}{50}, \frac{O_3(24h)}{100}, \frac{CO(24h)}{10000} \right) * 50,$$

is computed by the Rhenish Institute for Environmental Research at the University of Cologne. The index assumes values in 6 classes, from Very Good ($AQI < 10$) to Very Poor ($AQI > 80$).

The Air Monitoring Networks of Flanders, Brussels and Wallonia compute and communicate air pollution through an index scaled from 1 (excellent air quality) to 10 (awful quality). The computation is performed by using data obtained from the telemetric networks that measure continuously the air quality in the 3 Regions. The index is based on the concentrations of NO_2 , SO_2 , O_3 and PM_{10} . A “characteristic value” is computed every day for these 4 pollutants and then compared to a concentration scale. The concentration scales are based on the European guidelines concerning the assessment and management of the ambient air quality and reported in a table (http://www.irceline.be/~celinair/english/homeen_java.html) that shows, for each pollutant, the relation among the measured concentrations, the index value and the corresponding scale, symbolized also by different colors.

In Italy air monitoring should be coordinated by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale). Actually, through its site (http://www.apat.gov.it/site/it-IT/Servizi_per_l'Ambiente/Dati_di_Qualita_dell'aria), it is possible to see what some cities or some regional agencies do. Some of them communicate only the observed daily concentrations of pollutants, others (Puglia, Emilia-Romagna, Piemonte, Toscana) transform concentrations in subindices, even if usually the number of categories is not the same from a region to another. Subindices for each pollutant are usually obtained by dividing observed

concentration by a reference value and multiplying by 100. The final index is equal to the highest of the determined subindices.

3 Literature review

3.1 Single-pollutant indices

A very simple, but widely applicable indicator is proposed in Kassomenos et al. (1999), which considers neither an aggregation by pollutant nor by space. The authors define a set of limit values, pollutant specific and sometimes also site-specific (Table 2).

The choice of one of the alternatives in Table 2 depends on the domain where monitoring stations are located, since in urban domain population risk should be mainly addressed, while in a semi-urban or rural domain the effects on flora and fauna should be accounted for.

According to these limits, for each site and each pollutant an air quality indicator, that assumes values in 7 classes, is considered (Table 3), where C is the observed concentration.

Bruno and Cocchi (2002; 2007), consider explicitly the three dimensions upon which air quality data are defined: time, space and type of pollutant. The authors describe the aggregation steps that have to be followed in order to get a final index from a matrix of elementary data x_{tps} . The first aggregation step concerns usually time, allowing to get a daily synthesis starting from hourly data. Very often, in order to get a daily synthesis for each pollutant at each monitoring site, a researcher can refer to the guidelines of the national/international environmental agencies (that usually, given a pollutant, consider the same function as time synthesis). A second step, necessary at least before aggregating by pollutants, concerns standardization: a first possibility lies in a simple ratio (eventually multiplied by 100) between the pollutant concentration and its specific threshold value. Alternatively, a segmented linear function can be considered. In the more recent paper (Bruno and Cocchi, 2007) the first possibility is preferred, considering the choice as more coherent with the recent EU directives.

After standardizing, a choice is necessary: if aggregating first by pollutant and then by space or contrariwise. The results usually depend on this choice. The authors consider both the possibilities, comparing the results.

- Monitoring site - pollutants aggregation.

Here the spatial dimension is first eliminated (through a function $g()$), then the standardized values $f(g())$ are aggregated by pollutants (function g^*), getting the final index:

$$I1_{g^*,f,g} = g_p^* f(g_s(x_{ps}))$$

$I1$ will depend on the three functions f, g, g^* .

- Pollutant - Monitoring sites aggregation.

Here the standardized values ($f()$) need to be computed as a first step, then the aggregation by pollutant (through a function $g^*()$) and finally the spatial dimension is eliminated (function g), getting the final index:

$$I2_{g^*,f,g} = g_s(g_p^*(f(x_{ps})))$$

$I2$ will depend on the three function f, g, g^* .

About the two functions $g()$ and $g^*()$ the authors propose two order statistics: the median (m) and the maximum (M). In this way, given the type of standardization chosen, 8 different indices can be obtained, 4 $I1$ -type and 4 $I2$ -type. Actually, two of these are the same, $I1_{MM}$ and $I2_{MM}$, as the result obtained by using the maximum is not influenced by the order of aggregation. A measure of dispersion for each of the two series of indices, $I1$ and $I2$ type, is proposed.

Among all the proposed indices, $I1_{MM} = I2_{MM}$ is considered in (Bruno and Cocchi, 2007), the choice being supported by the well-known EPA AQI.

Bodnar et al. (2008) present an interesting application of two of the indices proposed by Bruno and Cocchi (2002) in the perspective of defining a European common index methodology which makes air quality comparable in time across different countries. $I2_{MM}$ and $I2_{mM}$ have been computed for a synthetic communication of daily health risk related to air pollution 2005 data collected in Piemonte and Lombardia (Italy), Berlin and Brandenburg (Germany) and Masovian Province (Poland). A comparison of the two indices, as proposed by Bruno and Cocchi (2002), has been also used to assess the spatial or network variability.

The paper by van den Elshout et al. (2008) presents the results of a European project, CITEAIR, initiatives of the cities of Leicester, Paris, Prague, Rome and Rotterdam (<http://citeair.rec.org>). The paper proposes a Common Air Quality Index (CAQI) which allows to compare air quality for different cities in different countries in real time. CAQI, that is computed both as a daily value and as an hourly index, is calculated according to a grid in a table (5 classes heavily inspired by EU legislation and based on a compromise among the participating cities) by linear interpolation between the class borders. The final index is the highest value of the sub-indices for each component. The index is computed by separating traffic monitoring sites from urban background sites and considering NO_2 , PM_{10} and CO in the first case and NO_2 , PM_{10} , O_3 , CO and SO_2 in the second. The EyeOnEarth site (<http://eyeonearth.cloudapp.net>) provides daily CAQI values across Europe.

In (Mayer et al., 2002, 2004) an index developed and tested by the Research and Advisory Institute for Hazardous Substances, Freiburg, Germany, and the Meteorological Institute, University of Freiburg, Germany, is reported. It is an impact-related index applicable for the information of people in Internet on the daily integral air quality. For each pollutant a linear interpolation between single index classes is computed:

$$DAQx_p = \left[\left(\frac{DAQx_{up} - DAQx_{low}}{C_{up}^p - C_{low}^p} \right) * (C_{inst.}^p - C_{low}^p) \right] + DAQx_{low},$$

where: $C_{inst.}^p$ is the daily maximum 1-h concentration of NO_2 , SO_2 , and O_3 , the daily highest 8-h running mean concentration of CO or the daily mean concentration of PM_{10} ; C_{up}^p and C_{low}^p are the upper and lower thresholds of pollutant p concentration range (according to a table which considers 6 classes); $DAQx_{up}$ and $DAQx_{low}$ are the index values corresponding to C_{up}^p and C_{low}^p , respectively. The final value of the index, $DAQx$, is the maximum among the five $DAQx_p$.

The same authors (Mayer and Kalberlah, 2009) propose a Long-term Air Quality index ($LAQx$) that follows the same approach of $DAQx$, but it is not a simple average of $DAQx$ values added up over a whole year. $LAQx$ considers annual mean values of NO_2, SO_2, PM_{10} and benzene, as well as the annual number of days, n , with $DAQ^* \geq 4.5$ (4.5 corresponds to EU standards and DAQ^* is the $DAQx$ computed without PM_{10}):

$$LAQx_p = \left[\left(\frac{LAQx_{up} - LAQx_{low}}{C_{up}^p - C_{low}^p} \right) * (C_{inst.}^p - C_{low}^p) \right] + LAQx_{low},$$

where: $C_{inst.}^p$ is the annual mean value of pollutant p or the number of days $DAQ^* \geq 4.5$; C_{up}^p and C_{low}^p are the upper and lower thresholds of pollutant p concentration range or DAQ^* ranges respectively; $LAQx_{up}$ and $LAQx_{low}$ are the index values corresponding to C_{up}^p and C_{low}^p respectively.

$LAQx_p$ is computed for each pollutant and the highest value is called $LAQx_{ifs}$, where ifs stands for index forming substance.

Up to three modifying substances can be considered, satisfying the following condition: $LAQx_p \geq LAQx_{ifs}$ and they will influence the final index which is computed as:

$$LAQx = LAQx_{ifs} + \sum_{p=1}^N \left[\frac{1}{3} (LAQx^p - 0.75 * LAQx_{ifs}) \right]$$

with N the actual number ($N \leq 3$) of modifying substances.

Similarly to $DAQx$, 6 classes are considered for $LAQx$.

3.2 Multi-pollutant indices

Several attempts considering the conjoint effect of more than one pollutant to formulate an air quality index can be found in literature.

A dated, but always interesting, paper on this subject is the one by Swamee and Tyagi (1999). In that paper the concepts of “ambiguity” and “eclipsicity”, introduced for the first time by Ott (1978), are reported, where the former describes situation when unnecessary alarm raises by declaring a less polluted air to be highly polluted, and the latter describes situations where a false sense of security is provided by indicating highly polluted air as less polluted. The paper proposes, for the first time, an aggregating function that will be considered again in other papers (Khanna, 2000; Zhou et al., 2006; Kyrkilis et al., 2007):

$$I = \left(\sum_{p=1}^P s_p^{1/\rho} \right)^\rho,$$

where $s_p = s_s (q/q_s)^m$ is the subindex relative to pollutant p , q is its observed concentration, q_s is a standard concentration (threshold value) for pollutant p , s_s is a scaling coefficient (500 for NAAQS) and m is a constant computed and reported in the paper for each pollutant. This aggregating function includes both the sum of all the subindices, when $\rho = 1$, and the maximum among the subindices, when $\rho \rightarrow 0$.

The proposed index I results to be free from eclipsicity, and the authors assure, by extensive studies not reported in the paper, that for $\rho = 0.4$ the

aggregation includes the effect of all the subindices (i.e. all the pollutants) and ambiguity is minimized.

The same aggregating function is proposed by Kyrkilis et al. (2007), who consider the same standardization to get subindices AQI_p as Swamee and Tyagi (1999), except for the constant m that is assumed equal to 1. The overall Air Quality Index is written as:

$$I_s = \left(\sum_{p=1}^P (AQI_p)^\rho \right)^{1/\rho} \quad \rho \in [1, \infty[.$$

The authors here propose $\rho = 2.5$ (that corresponds to $\rho = 0.4$ in (Swamee and Tyagi, 1999)), without motivating this choice.

In this paper a spatial aggregation is also proposed: in order to get an index referable to the whole city, the median of the I_s for all the monitoring sites is considered.

Khanna (2000) proposes an index of pollution based on the epidemiological dose-response function associated with each pollutant, together with the welfare loss due to exposure to pollution. The welfare loss provides the common metric that allows the ambient concentration of different environmental indicators to be aggregated into an overall pollution index.

Once defining, for each pollutant p , a threshold X_p^{min} below which damages from exposure to it are not significant, a region s is polluted if at least 1 pollutant exceeds its threshold. The index for a region s is defined as $I_s = f(A_p^s)$, where $A_p^s = g(x_{ps})$ is a particular attribute (air quality, water quality ...) for a region depending on P indicators (individual sources of pollution). That is:

$$I_s = \begin{cases} f(g(x_{ps}, x_{p's})) > 0 & \\ \quad \text{if } x_{ps} > X_p^{min}, x_{p's} > X_{p'}^{min}, & p \neq p' \\ f(g(x_{ps})) > 0 & \\ \quad \text{if } x_{ps} > X_p^{min}, x_{p's} \leq X_{p'}^{min}, & p \neq p' \\ 0 & \text{if } x_{ps} \leq X_p^{min} \quad \forall p \end{cases}$$

The proposed index appears more general than the previous ones, allowing to compute intermediate measures of environmental quality A_a , such as air or water quality, each aggregating different indicators.

More particularly, f and g functions are specified as the constant elasticity of substitution (CES) function:

$$I_s = \begin{cases} \left\{ \sum_{a: A_{sa}(\bullet) > 0} \delta_a \{A_{sa}(\bullet)\}^{-\rho_1} \right\}^{(-\nu_1/\rho_1)} > 0 & \forall s \\ 0, & \text{if } A_{sa}(\bullet) = 0 \quad \forall a, s \end{cases}$$

and

$$A_{sa} = \begin{cases} \left\{ \sum_{p: D_p(\bullet) > 0} \omega_p \{D_p(x_{ps})\}^{-\rho_a} \right\}^{(-\nu_2/\rho_a)} > 0 & \forall s \\ 0, & \text{if } D_p(\bullet) = 0 \quad \forall p \end{cases}$$

and

$$\begin{aligned} D_p(x_{ps}) &> 0 \text{ if } x_{ps} > X_p^{min} & \forall p, s \text{ such that } D(\bullet) > 0 \\ D_p(x_{ps}) &= 0 \text{ if } x_{ps} \leq X_p^{min} & \forall p, s \end{aligned}$$

where

$$\begin{aligned} \sum_a \delta_a &= 1, & \delta_a &\geq 0, & \nu_1 &\geq 1, & -\infty < \rho_1 < -1 \\ \sum_p \omega_p &= 1, & \omega_p &\geq 0, & \nu_2 &\geq 1, & -\infty < \rho_a < -1 \end{aligned}$$

Here $D_p(\bullet)$ represents the society-wide dose-response function and ω_p the marginal damage due to pollutant p . The elasticity of substitution ρ_a is the same for all the pollutants that make up attribute A_a . If we focus only on air quality (that is a single value for a), as the same author does in the last part of the paper, an Air Pollution Index is obtained considering a society-wide dose-response function D (similarly to EPA AQI) of the form:

$$D_p(x_{ps}) = \begin{cases} 5 + \frac{x_{ps} - x_p^{min}}{x_p^{max} - x_p^{min}} & \text{if } x_{ps} > x_p^{min} \\ 0 & \text{if } x_{ps} \leq x_p^{min} \end{cases} \quad \forall p, s,$$

where $x_p^{min} = 50\%$ of NAAQS and x_p^{min} is, for each pollutant, the concentration corresponding to AQI = 500. The final index will be:

$$AQI = \left\{ \sum_{p: D_p(\bullet) > 0} \omega_p \{D_p(x_{ps})\}^{-\rho} \right\}^{(-1/\rho)}.$$

The pollutant space is divided into 5 areas characterized by an increasing value of the elasticity of substitution ρ . This means that, as a region becomes more polluted, decreasing value of 1 pollutant can be more hardly substituted by an increasing value of another pollutant, maintaining at the same time the level of the air quality. It is important to notice that, excluding the last hypothesis of varying value of ρ , the proposed index is almost the same as the one in (Swamee and Tyagi, 1999) and (Kyrkilis et al., 2007).

A completely different approach is presented by Cairncross et al. (2007), where a novel air pollution index, based on the relative risk of the increased daily mortality associated with simultaneous exposure to common air pollutants, is presented.

The approach is based on the availability of appropriate mortality relative risk values, RR_p , for each pollutant. The overall AQI is defined in terms of the sum of the mortality risks:

$$AQI = \sum_p PSI_p = \sum_p a_p * C_p,$$

where C_p is the time-averaged concentration of pollutant p and a_p is a coefficient directly proportional to the incremental risk value ($RR_p - 1$) associated to pollutant p (their value, for each pollutant, is computed and reported in the paper). Differently from what usually happens by standardizing pollutant concentrations, that are equally weighted with respect to damage, here the alignment among pollutants is based on their mortality relative risk: that is, the consistency between pollutant exposure metrics is assured by assigning to the same relative risk (the reference value is the one corresponding to 1-h maximum O_3 concentration of $100\mu g^{-3}m$) the same sub-index value.

The proposed AQI assumes values in 11 classes $[0; 10]$ aggregated into 4 (Low, Moderate, High, Very High) macro-classes. API results to be self-consistent, as

a sub-index value for any pollutant included in the index reflects the same increment in relative risk of daily mortality.

A modified version of EPA-AQI is proposed by Murena (2004), assuming additive effects of monitored pollutants. A reference scale of the AQI with the corresponding pollution categories for each pollutant is reported: according to EPA table, 5 categories are considered, but here breakpoints are based on EC directives and WHO's guidelines. Pollution in a monitoring site s is computed as:

$$PI_s = PI_{b_c} \sum_{p=1}^P \frac{C_p}{BP_{p,c}},$$

where C_p is the daily concentration of pollutant p , $BP_{p,c}$ is the bottom breakpoint concentration corresponding to each category c for pollutant p , and PI_{b_c} is the bottom value of PI corresponding to the highest pollution category c for which $\sum_{p=1}^P C_p / BP_{p,c} \geq 1$. Considering that additive effects among pollutants can be assumed only if they belong to the same category and have similar effects on human health, the proposed index may produce an overestimation of the actual pollution.

The author proposes also an aggregation by space, both considering a single pollutant and after aggregating by pollutants. A Urban Pollution Index (UPI) is computed:

- for the single pollutant p as:

$$UPI_p = \sum_{s=1}^S PI_{ps} W_{ps} = \sum_{s=1}^S PI_{ps} \frac{Area_{ps}}{Area},$$

where PI_{ps} is the standardized (by linear interpolation like EPA AQI) value of pollutant p in station s and W_{ps} is a weight representing the proportion of the urban area surface represented by sensor measuring p in station s ;

- for the whole set of pollutants as:

$$UPI = \sum_{s=1}^S PI_s W_s = \sum_{s=1}^S PI_s \frac{Area_s}{Area},$$

where PI_s is the aggregated index proposed in the paper and W_s is a weight representing the proportion of the urban area surface represented by station s .

An interesting approach, that aims at reducing both ambiguity and eclipsicity, is the one followed in (Cheng et al., 2004). The authors propose a correction to EPA AQI, based on Shannon entropy. Starting from the consideration that if we consider, for example, two scenarios where the (standardized via a segmented linear function) values of the five common pollutants are: $A = (100, 100, 100, 100, 100)$ and $B = (100, 10, 10, 10, 10)$, the air quality is different, but EPA AQI would not distinguish between them, the new index RAQI is proposed as:

$$\begin{aligned}
RAQI = & \text{Max}[I_1, I_2, I_3, I_4, I_5] \times \\
& \times \frac{\sum_{p=1}^5 \text{Ave}_{daily}[I_p]}{\text{Ave}_{annual}[\sum_{p=1}^5 \text{Ave}_{daily}[I_p]]} \times \\
& \times \frac{\text{Ave}_{annual}\{\text{Entropy}_{daily}[\text{Max}[I_1, I_2, I_3, I_4, I_5]]\}}{\text{Entropy}_{daily}[\text{Max}[I_1, I_2, I_3, I_4, I_5]]} .
\end{aligned}$$

Here the first factor is EPA AQI, as I_p , $p = 1, \dots, P$, are the standardized values, by a segmented linear function, of the concentrations of the 5 main pollutants. The second factor accounts for the individual contribution of each sub-index pollutant to the RAQI: it serves to reduce AQI's ambiguity and eclipsity where levels of pollutants are more serious than indicated by the index value. The entropy function present in the third factor, defined as the \log_{10} of the maximum function of the I_1, \dots, I_p , is a modifier serving to prevent numerical divergence to excessively large values. When the RAQI value approaches the average value, the entropy value is large, indicating low pollution levels. When the index value is diffuse, entropy values are high, indicating high levels of pollution.

According to the classification proposed in (Mayer et al., 2004), examples of ASI are reported in (Mayer et al., 2002, 2004). These are two indices developed by the Office for the Environmental Protection, Urban Climatology Section, City of Stuttgart, Germany:

$$ASI_1 = \frac{1}{4} \left(\frac{C(SO_2)}{20\mu g/m^3} + \frac{C(NO_2)}{40\mu g/m^3} + \frac{C(PM_{10})}{40\mu g/m^3} + \frac{C(benzene)}{5\mu g/m^3} \right),$$

where C are the arithmetic annual means of pollutant concentrations, and the denominators refer to EU long-term standards;

$$ASI_2 = \frac{1}{4} \left(\frac{N(SO_2)}{24} + \frac{N(NO_2)}{18} + \frac{N(PM_{10})}{35} + \frac{N(CO)}{1} \right),$$

where N is the annual number of actual exceedences of air pollutant specific short-term EU standards and the denominators represent the number of exceedences permitted.

The papers present also an index developed by the Federal State Institute for Environmental Protection Baden-Wuerttemberg, Germany, defined as:

$$ASI_{BW} = \frac{C(SO_2)}{350\mu g/m^3} + \frac{C(CO)}{10mg/m^3} + \frac{C(NO_2)}{200\mu g/m^3} + \frac{C(PM_{10})}{50\mu g/m^3} + \frac{C(O_3)}{180\mu g/m^3},$$

where $C(SO_2), C(NO_2), C(O_3)$ are the air pollutant specific highest daily 1-h mean values, $C(CO)$ is the highest daily running 8-h mean value of CO and $C(PM_{10})$ is the daily mean value of PM_{10} , while again the denominators refer to EU standards.

All these indices consider the pollution due to all the pollutants, even if, being of the ASI type, they do not have a direct relation to human health.

A multipollutant index is proposed by Coglian (2001). The index is based only on the hourly highest concentrations in the day of NO_2 , CO and O_3 . According to a table reported in the paper, the observed concentration are transformed into a score I_p assuming value 1 (low concentration), 4 (acceptable

concentration) and 13 (high concentration), 0 being the score corresponding to a missing value. The final index I is obtained as sum of the three scores (subindices) and therefore ranges in $[1, 39]$ or, better, in $[1, 3]$ (low pollution for all the subindices), $[4, 12]$ (acceptable pollution for at least 1 subindex, the others being good) and $[13, 39]$ (high pollution for at least one subindex). Starting from this index I , another “calculated” index I_c is proposed as a linear function of I computed the day before, the daily average wind speed and the daily thermic excursion. I_c shows a high correlation with I , and therefore is proposed in order to forecast I .

A multipollutant index based on the combined levels of three pollutants, PM , SO_2 , NO_2 , respecting WHO guidelines for air quality, is presented in (Gurjar et al., 2008). The index has been proposed thinking principally to the comparison of air quality in megacities and assumes the following form:

$$AQI = \frac{1}{2P} \left[\sum_{p=1}^P \left(\frac{AC_p - GC_p}{GC_p} \right) + \sum_{p=1}^P \left(\frac{AE_p - GE_p}{GE_p} \right) \right],$$

where AC_p is the atmospheric concentration of pollutant p , GC_p the corresponding WHO recommended threshold, AE_p the atmospheric emission (per year, per capita, etc.) of pollutant p and GE_p the corresponding guideline. The index is not computed for each site, but for the whole mega city, since AC_p and GE_p refer to the ambient air of the mega city. Since no information are available about GE_p , the index reduces to the first part only, with $1/P$ substituting $1/2P$.

Chelani et al. (2002) present an index depending on two parameters assuming different values considering residential vs. industrial areas, and a 24 hourly vs. an annual basis. The general expression is:

$$AQI = \left[a \times \sum_{p=1}^P I_p \right]^b,$$

where a and b are the two parameter cited above and computed and reported in the paper, while I_p s are the subindices obtained dividing the observed concentration by threshold values for each pollutant.

Five categories are considered in order to classify the final value of the index.

An approach based on factor analysis is proposed in (Bishoi et al., 2009). The proposed index, having no relation to the health of people and therefore of the ASI type, is obtained as a function of the first three principal components of the observed concentration matrix (no standardization is applied):

$$NAQI = \frac{\sum_{i=1}^3 P_i E_i}{\sum_{i=1}^3 E_i},$$

where P_1, P_2, P_3 are the first three principal components and E_1, E_2, E_3 are the associated eigenvalues.

As assessed at the end of the paper, the index can be only used in defining the state of air in relative terms, with respect to space (comparing different areas) or time (worsening or improving of quality in a region along time).

Three composite environmental indices (CEI) are listed by Zhou et al. (2006). In the three cases, starting from the elementary data x_{ps} (time is not considered), a normalizing transformation is considered:

$$r_{ps} = \frac{\min_s \{x_{ps}\}}{x_{ps}}.$$

This is the appropriate normalization among the ones proposed in the paper as pollutants satisfy “the smaller the better” condition.

Assigning a weight w_p to each pollutant p , an aggregated index for monitoring site s can be obtained according to one of the following functions:

SAW: Simple Additive Weighting

$$I_s = \sum_{p=1}^P w_p r_{ps},$$

WP: Weighted Product

$$I_s = \prod_{p=1}^P r_{ps}^{w_p},$$

WDI: Weighted Displaced Ideal method

$$I_s(\rho) = \left[\sum_{p=1}^P w_p^\rho r_{ps}^\rho \right]^{1/\rho},$$

where ρ is a distance parameter ranging in $[1, \infty[$.

The parameter ρ has the same role of $1/\rho$ in (Swamee and Tyagi, 1999) and ρ in (Kyrkilis et al., 2007). Nevertheless here the only value of $\rho \rightarrow \infty$ is considered.

A comparison of the behaviour of the three indices is possible in terms of difference of information in the data matrix X and in I . A measure is proposed with this aim, based on the Shannon entropy and the Spearman rank correlation coefficient. Introducing a normalization of X and I_s :

$$y_{ps} = \frac{x_{ps}}{\sum_{s=1}^S x_{ps}},$$

$$w_s = \frac{I_s}{\sum_{s=1}^S I_s},$$

the Shannon entropy, that measures the divergence of different sites with respect to each pollutant p and I , can be obtained by:

$$e_p = -\frac{1}{\ln S} \sum_{s=1}^S y_{ps} \ln y_{ps},$$

$$e = -\frac{1}{\ln S} \sum_{s=1}^S w_s \ln w_s.$$

At the same time, considering a reference rank sequence for the S sites, the Spearman rank correlation coefficient R_{ps} and R_s between X_p or I and this reference sequence can be computed. The measure of loss of information will be:

$$d = \left| \sum_{p=1}^P w_p (1 - e_p) R_{ps} - (1 - e) R_s \right|.$$

This measure, even if in the paper is applied only to the three indices proposed, has a wider applicability.

Very little we have found in literature about spatial aggregation. Only Bruno and Cocchi (2002, 2007) consider explicitly the problem, while some suggestions can be found in (Murena, 2004) and (Kyrkilis et al., 2007).

An interesting approach is presented in (Zujic et al., 2009), where a spatial aggregation of AQI (computed as proposed by Kassomenos et al. (1999)) for each pollutant p is considered. As stated by the authors, in order to estimate correctly population exposure, both the areas with maximum concentrations and the areas with high population density should be considered. By assuming that all stations considered together are representative of the area, then a statistical weight, W_{ps} , can be attributed to each station, based on the population density D_{ps} of the area represented by the station s measuring pollutant p :

$$W_{ps} = \frac{D_{ps}}{\sum_s D_{ps}}.$$

If, in a city K monitoring sites measure pollutant p , an overall index for pollutant p will be:

$$AQI_p^w = \sum_{s=1}^K AQI_{ps} \cdot W_{ps}.$$

The value of the index computed in this way will be lower than the Maximum among AQI_{ps} , since less polluted areas are considered, but probably with a low weight; at the same time, it will be greater than the average value of AQI_{ps} , as usually high polluted areas have a higher density of population (i.e. a higher weight).

4 Sustainability index

In the above sections we have considered stand alone air quality indicators: actually AQIs are sometimes considered as part of a more general Environmental Sustainability Index. We have anticipated this possibility while reviewing the paper by Khanna (2000), specifying that we were focusing only on air quality. A variety of sustainability indices can be found both in literature and on-line. A review is not the object of this paper but, as a reference, we only want to cite what is probably the most famous one: the Environmental Sustainability Index (now called Environmental Performance Index, <http://sedac.ciesin.columbia.edu/es/esi/>). It is a composite index tracking 21 elements of environmental sustainability, covering natural resource endowments, past and present pollution levels, environmental management efforts, contributions to protection of the global commons and a society's capacity to improve its environmental performance over time. It has

been proposed by Yale University's Center for Environmental Law and Policy, in collaboration with Columbia University's Center for International Earth Science Information Network (CIESIN), and the World Economic Forum. In 2006 it has been transformed into an Environmental Performance Index (<http://sedac.ciesin.columbia.edu/es/epi/>), that uses outcome-oriented indicators and can be more easily used by policy makers, environmental scientists and the general public.

5 Conclusions

This brief review on air pollution indices shows, on one side, the wide interest in the problem, on the other, the lack of a common strategy which allows to compare the state of the air for cities that follow different directives. The major differences between the indices in the literature are found in the number of index classes (and their associated colour) and related descriptive terms, in the pollutants considered, in class bounds, sometimes in averaging times, in update frequency. Although it was not the specific subject of this article, here we want also to stress that the guidelines themselves are sometimes consistently different from state to state, not only in indicating the pollutants to be monitored, but also in setting the threshold values and the number of allowed exceedances per year. While it is true that, as WHO said (WHO, 2006), "when formulating policy targets, governments should consider their own local circumstances carefully", that is the specificities of places must be taken into account, it would be desirable to have a greater harmonisation of AQIs. "The Air Quality Index (AQI) is a widely used concept to communicate with the public on air quality. A growing number of national and local environment agencies use the AQI for (near) real-time dissemination of air quality information. [...] Although the basic concepts are similar, the AQIs show large differences in practical implementation. [...] When applying the AQIs on a common set of air quality data [...], large differences in index value and the determining pollutant are found" (Leeuw de and Mol, 2005).

As Baldasano et al. (2003) stated, it is becoming a regular practice to present air quality information through a country- or city-specific air quality index, which makes comparison of values difficult and of limited usefulness. Internet is increasingly used for this purpose, but a review of existing websites and air quality indices shows that also the way air quality is interpreted differs considerably.

Although the complexity of air pollution and its science, there is a continuing desire for better communication between the scientists and society at large (Shooter and Brimblecombe, 2009).

Further work is required to achieve an harmonisation, considering issues as averaging times, synergisms in air pollution indices, and low level exposure.

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Table 1: AQIs reviewed

Author	Index	Uncertainty measures	Spatial aggregation	Pollutant aggregation	Health based	Purpose	Low Level exposure
Kassomenos et al. (1999)	See Table 3	NO	NO	NO	YES	Uniform indexing of air pollution over large metropolitan areas	YES
Bruno & Cocchi (2002)	$I1_{g*,f,g}$ or $I2_{g*,f,g}$	YES	YES	NO	YES	Recovering information from air quality indices	NO
van den Elshout et al. (2008)	CAQI	NO	NO	NO	NO	Comparing urban air quality in real time	YES
Mayer et al. (2002)	$DAQx_p$	NO	NO	NO	YES	Information of people in the Internet	YES
Mayer and Kalberlah (2009)	$LAQx$	NO	NO	NO	YES	To assess daily and long term air pollution	YES
Swamee and Tyagi (1999)	$\left(\sum_{p=1}^P s_p^{1/\rho}\right)^\rho$	NO	NO	YES	YES	Ambiguity-free Ecipsicity-free air quality function	NO
Kyrkilis et al. (2007)	$\left(\sum_{p=1}^P (AQI_p)^\rho\right)^{1/\rho}$	NO	YES	YES	YES	Estimating citizen exposure	NO

Continued on next page

Table 1 – continued from previous page

Author	Index	Uncertainty measures	Spatial aggregation	Pollutant aggregation	Health based	Purpose	Low Level exposure
Khanna (2000)	$\left\{ \sum_{p:D_p(\bullet)>0} \omega_p \{D_p(x_{ps})\}^{-\rho} \right\}^{(-1/\rho)}$	NO	NO	YES	YES	Evaluating human health benefits of reduced air pollution	YES
Cairncross et al. (2007)	$\sum_p PSI_p = \sum_p a_p * C_p$	NO	NO	YES	YES	Reflecting the overall air pollution health impact	YES
Murena (2004)	$\sum_{s=1}^S PIb_c \sum_{p=1}^P \frac{C_p}{BPb_{p,c}} W_{ps}$	NO	YES	YES		Accounting for local conditions	YES
Cheng et al. (2004)	$RAQI$	NO	NO	YES	YES	To produce an objective result in the long term	YES
Makra et al. (2003)	ASI_1, ASI_2 ASI_{BW}	NO	NO	YES	NO	To consider mean and short term Air Stress Indices	NO
Cogliani (2001)	I, I_c	NO	NO	YES	YES	To evaluate and rank air quality in megacities	YES
Gurjar et al. (2008)	MPI	NO	YES	YES	YES	Air pollution forecasting accounting for meteorological variables	YES
Chelani et al.	$\left[a \times \sum_{p=1}^P I_p \right]^b$	NO	NO	YES	YES	To assess air	NO

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Table 1 – continued from previous page

Author	Index	Uncertainty measures	Spatial aggregation	Pollutant aggregation	Health based	Purpose	Low Level exposure
(2002)						quality status in metropolitan cities	
Bishoi et al. (2009)	$NAQI$	NO	NO	YES	NO	To define the state of air in relative terms	NO
Zhou et al. (2006)	$\left[\sum_{p=1}^P w_p^\rho r_{ps}^\rho\right]^{1/\rho}$	YES	NO	YES	YES	To quantify the loss of information due to aggregating function	NO
Zujic et al. (2009)	$\sum_{s=1}^K AQI_{ps} \cdot W_{ps}$	NO	YES	NO	YES	To reflect effective population exposure	YES

Table 2: Limits for the scale of air quality indicators

Value	Alternative 1 (semi-urban or rural areas)	Alternative 2 (urban areas)
C_{UL}	Upper protection limit (greater health risk and worse air quality condition or double the value of C_{LL})	Upper protection limit (greater health risk and worse air quality condition or double the value of C_{LL})
C_{LL}	Lower protection limit (standard limit value for health protection)	Lower protection limit (standard limit value for health protection)
C_{TV}	Target value, set by standards	Short term target value
C_{AV}	Alert value, required by standards	Alert value, 0.85 of C_{TV} value
C_{IV}	Intermediate value, the limit for vegetation protection when it is lower than the one for health effects	Intermediate value, $(C_{TV} + C_{AM})/2$
C_{AM}	Annual mean limit specified by standards	Annual mean value from recorded data

Table 3: Air quality indicator scale

Index	Air quality indicator	Limits
7	Extreme	$C > C_{UL}$
6	Severe	$C_{UL} \geq C \geq C_{LL}$
5	Bad	$C_{LL} \geq C \geq C_{TV}$
4	Critical	$C_{TV} \geq C \geq C_{AV}$
3	Poor	$C_{AV} \geq C \geq C_{IV}$
2	Moderate	$C_{IV} \geq C \geq C_{AM}$
1	Good	$C_{AM} \geq C$