Air quality indices

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Task 2.2 - Air Quality Communication

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Introduction

This is a document on air quality indices (AQI-s) produced in the framework of the EGP project AirINFORM. It is a fairly general description of various types of AQI-s, strong and weak points and for which purposes they can be used. The information doesn't apply only to the situation in China, it is meant as background information. The examples provided (mainly in the annexes) do rely heavily on indices, websites and apps that are in use in and around China.

This document can be read independently from the main text (AQ Communication, Part I) and in that case it is simply a description of AQI-s and their role in air quality communication. This Part II occasionally refers to Part I if a specific Chinese issue is addressed. The communication objectives mentioned in this Part II were discussed more extensively in Part I (chapters 2 and 3).

Document Part III appears a year after Parts I and II. It applies Chinese monitoring data to the Chinese and other AQI-s. In Part III some of the issues discussed in this document are actually illustrated with real (unvalidated) Chinese monitoring data.

1. Why AQI-s

An air quality index, AQI, condenses complex information on the concentration levels of various pollutants into one or more numbers on a relative scale. This information reduction is considered necessary for communication purposes but it is not without problems. See box 1.

AQI-s can be made for various reasons and in many different ways. Shooter and Brimblecombe (2009) mention two reasons for making an index: linking air quality to health effects to inform the public of poor air quality and provide information on possible remedial action; condense complex information to provide an information overview for policy development or monitoring and/or to check compliance with standards. Access to environmental information obligations (e.g. the Aarhus convention) can also be met by providing easy to understand summary information in the form of an AQI. Garcia et al. (2002) mention that AQI-s are part of an air quality management strategy, they play a role in the communication of such a strategy. This point is made more explicitly by Elshout et al (2008, 2012) giving an additional reason to provide air quality information: drawing the public's attention to air quality issues and raising awareness.

Box 1: Simplifying information to make it understandable or to create confusion?

Though indices are widely used for communication purposes, the assumption that it is necessary to reduce complex information for the consumption by the lay public has rarely been tested. Shooter and Brimblecombe (2009), in a review article on air quality indices, mention (citing Burden and Ellis, 1996) that in Australia, public confidence in reporting on air pollution fell following the introduction of an index. Johnson (2003) observed that different versions of the US AQI did not particularly well at increasing public knowledge or changing people's behaviour in case of episodes. A nice recent example of the confusion an AQI might create can be found in the FAQ section of the http://aqicn.org/?faq website. In this case the user mistakes the iAQI for the concentrations. (Website publishing monitoring data from China and other Asian countries; accessed on 30-5-2013.)

February 2nd 2013
We got a very good and relevant question this week from Severine P., who asked about pm2.5 concentrations versus pm10 concentrations.
What Severine asked in her mail was:

I don't understand why pm2.5 concentrations are often higher than pm10 concentrations. Aren't PM smaller than 2.5 micro included in PM smaller than 10 micro? Thank you for your answer

Severine's question is totally correct: $PM_{2.5}$ are, by definition, particulates smaller than 2.5 micrometers, so indeed, they should also be included as smaller than 10 micrometers. But the assumption about concentration is not correct: $PM_{2.5}$ concentration can be smaller than PM10, but yet, the converted AQI value can be higher.

This shows that it is important, like in Johnson's study, to properly test all communication messages.

There are several ways of making an AQI. The reason for making an AQI determines to some extent how it is best made. I divide AQI-s in two main types: 1. those aimed at providing behavioural and health recommendations in case of pollution episodes (risk communication); and 2. those aimed at providing general information based on policy considerations. AQI-s aimed at raising awareness are a special case of the latter.

Usually the two can easily be told apart: Type 1 AQI-s use health descriptions in the labelling of their bands and provide advice, whereas Type 2 AQI-s speak about high and low pollution or good/bad air quality. The second major difference is that the concentration bands in Type 1 are usually much higher than those in Type 2. Short-term exposure is mainly a risk at very high concentrations hence the very wide concentration rage needed in Type 1 AQI-s.

Table 1: Typical example of the SO_2 concentration ranges in the two types of AQI-s

SO2 (µg/m^3)	(very) Low	Moderate/ Medium	High	Very High
Type 1, health based: UK-index	0-286	267-532	533-1064	>1065
Type 2, policy based: CAQI	0-100	101-350	351-500	>500

Type 2 AQI-s, linked to standards, often also relate somehow to long-term exposure and therefore tend to have a narrower range. See table 1 for an example of the UK AQI (COMEAP, 2011) and the CAQI (Elshout, 2012, 2014). The US EPA AQI is a typical example of a type 1 index aimed at providing short-term health and behavioural advice. It spans a very wide concentration range.

1.1. Type1: health and behavioural advice AQI-s

1.1.1. General properties

These AQI-s have an important communicational characteristic: they provide a link between air quality and health. Also from the point of view of raising awareness on air quality this is an advantage. However, they also have several conceptual problems and that is one of the reasons why the policy/standards based indices (see section 1.2) are popular as well. The main issues are

- The underlying science is still developing and as a consequence different AQI-s provide different health advice at the same pollutant levels. This is awkward form a communication point of view, and it doesn't aid in making the provided information credible (apart from climate sceptics, there are also air pollution sceptics). This is further complicated by the fact that air pollution is a complicated mixture and that it is often not clear which pollutant is exactly causing the health effect(s). Think about NO_2, which was first considered a health relevant pollutant, later more of an indicator for (traffic related) combustion aerosol (of which the exact toxic components were not known and not commonly monitored) and recently there is new epidemiologic evidence that NO_2 might be a health relevant pollutant after all.

- A second more important problem is the fact that air pollution has health effects at two time scales: short term effects at high concentration levels and long term effects at low or even any level of pollution. WHO provides recommendations for both exposure times for most pollutants, reflecting the different exposure times where one (the short-term exposure) guideline is much higher than the one for long-term exposure. This can lead to an absurd communication paradox: in a certain city the health based AQI, aimed at providing advice in case of short term exposure risks, could always signal that air quality is good. Interested or concerned citizens looking at the website at regular intervals would always see an air quality that is labelled good. However, at the end of the year the same city could be required to make an air quality action plan because the year average air quality does not meet the year average standards. Policy based AQI-s seek to avoid this paradox, for health based indices this is unavoidable. See box 2.

Box 2: Short-term / long term exposure communication paradox

Look at the UK iAQI for NO_2. If the NO_2 hourly concentration has been 50 µg/m^3 all year the lay public visiting the website, has seen that the air pollution was low throughout the year, labelled with the lightest colour green available. However from the year average point of view a year average of 50 µg/m^3 is unacceptable (standard to be met in the EU by 2015) and this can have severe implications. In the Netherlands this could lead to a ban of adding new economic activities (in the past widening of roads has been blocked by ambient NO_2 concentrations slightly over 40 µg/m^3). EU countries risk being fined by the commission if they don't meet the standard.

Table 2: NO_2 calculation grid in the UK AQI

Index	1	2	3	4	5	6	7	8	9	10
Band	Low	Low	Low	Moderate	Moderate	Moderate	High	High	High	Very High
µg/m^3	0-67	68-134	135 - 200	201 - 267	268 - 334	335 - 400	401 - 467	468 - 534	535 - 600	601 or more

The problem that a concentration of 50 can be good and bad at the same time can't be fully solved. The policy based indices address this somewhat by introducing bands like medium and high at much lower concentrations than the health based indices. This way people visiting the website will occasionally see that the concentrations are not always in the lowest bands, in the good/green.

- The short-term exposure to air pollution is no longer a major problem in most of the developed countries, for the majority of the population. However people with certain medical conditions do experience problems due to short-term exposure. One can question the usefulness of a communication strategy, using an AQI+website aimed at the general public that is mainly relevant to only a small part of the population. One might consider delivering different messages to different target groups, in different ways. A more general AQI (policy/standards based) for the general public + health relevant warnings (text messaging, apps) to those who really need to be informed/warned. In this way one can also overcome/minimise the paradox in the previous bullet.

- The timely relevance of the message is sometimes also an issue. Behavioural advice is useful when one is warned timely in advance else it is impossible to adapt one's behaviour. This implies that these kind of AQI-s should be derived from high quality predictive models, preferably one or two days ahead of an event (e.g. forecasts of Day +1, Day +2 or at minimum a nowcast (Day +0)). This should be accompanied by monitoring data with a short averaging time (preferably hourly). This is the only way that timely and relevant information can be delivered. Relying on 24 hour average data, or reporting yesterday's data (still quite common for AQI-s) is rather useless if providing health and behavioural advice are the main objectives.

- Consistency of the health messages is an issue. Epidemiological knowledge continues to evolve and hence the thinking about safe levels of pollutants evolves as well. Apart from the fact that knowledge evolves it is also, apparently, interpreted in different ways. This can easily be seen by comparing the health advice given at different concentration levels for different AQI schemes. Since the AQI approaches are different it is hard to make this comparison. Hence we compare the concentrations for the first index band where the advice to 'reduce activity' is given and for the concentration where the worst AQI category starts. See table 3.

Table 3: Health effects seemingly occur at different concentrations in different countries

	AQI value or band number		Pollutant concentration (μg/m^3)					
			O_3 8-hour			$PM_{2.5}$ 24-hour		
	US, China	UK	China	US	UK	China	US	UK
No behavioural advice	0-100	1-3	0-200	0-245	0-80	0-75	0-35	0-35
First advice to reduce physical activity:	>100	>3	>200	>245	>80	>75	>35	>35
Worst category starts at:	300-500	10	>800	>733	>241	>350	>350	>70

(NB: US AQI breakpoints originally defined in ppm were converted for comparison purposes)

Table 3 shows that the appreciation of the risk of a certain concentration differs considerably between the US, the UK and China. Apart from the lower end $PM_{2.5}$ concentrations, the US and the Chinese indices agree fairly well. For the interested lay person comparing these indexing schemes this lack of consistency is awkward. It might contribute to a general sense that the provided information is flawed (see also box 1 where, amongst others, the whole principal of indexing is questioned) or in the case of China, that the government is 'cheating' while doing the calculation. This problem is discussed in chapter 4 of the Part I document.

The UK recently revised and updated their AQI (COMEAP, 2011) and the document underlying the revision provides a good review of recent knowledge about short-term exposure to air pollution and health. The US tightened the lower bands of the $PM_{2.5}$ iAQI early 2013, making them consistent with the lower $PM_{2.5}$ bands in the UK.[1]

1.1.2. Sub-types of health and behavioural advice AQI-s

The health and behavioural advice AQI-s can be further subdivided into two[2] sub-types:

a) A single pollutant determines the index (the highest iAQI); interaction between pollutants is disregarded. This type is more common and the UK and US indices are prominent examples. Especially the US AQI is influential as it is wholly or partly copied in several other countries. See Annex A1.1 for a description.
b) Indices that take pollutant interaction into account are for example the South African DAPPS (Cairncross et al., 2007) and the Canadian AQI (Stieb et al. 2008). See annex A1.1 for a description. Hong Kong revised their index and is now (since 2014) using an AQHI (air quality and health index) following the Canadian example (Wong et al. 2013). See also section 2.2.

Type 1.a: The AQI-s that don't take interaction into account follow the same principle as almost all AQI-s, for each pollutant a sub-index or individual AQI (iAQI) is calculated. The pollutant with the highest iAQI at a given time determines the overall index or AQI. The information that is communicated to the public is usually the AQI + the name of the pollutant determining the AQI.

Type 1.b: The indices that take pollutant interaction into account are theoretically better than those that don't. Pollutant interactions do occur. However, given all the uncertainty surrounding the exact relation between air quality and health, devising such a complex AQI can be seen as being overly ambitious, suggesting a level of accuracy that in reality can never be met. This is aggravated by the fact that air quality tends to vary within cities or areas, whereas monitoring only takes place at a few locations and often the AQI is provided as one, or a few numbers per city/area. So the seeming precision gained in the exposure calculation is often not matched by the spatial detail. Unless a particular air quality situation exists that makes it necessary to take pollutant interaction into account, I don't recommend this approach. The calculations are complicated which is a disadvantage from the viewpoint of other communication objectives (accountability, transparency). Secondly, if the Canadian approach is taken, dose response relations have to be derived locally: e.g. the Canadian urban population. The results cannot be easily transferred to places/countries where public health is completely

[1] http://www.epa.gov/pm/2012/decfsstandards.pdf (accessed 24-5-2013).
[2] Some authors (e.g. Ruggieri and Plaia 2012) are not happy with the simplification of one pollutant determining the index. Without taking full pollutant interaction into account they propose to add a second characteristic to indices that shows if only one or more pollutants are (almost equally) high. In my view this leads to overly complicated indices, whilst the purpose of the index is to simplify the information.

different and dose response functions are likely to be different.[3] For a good discussion of this conceptually interesting approach see Stieb et al (2008).

1.2. Type 2: policy/standards based AQI-s

In the previous section a number of issues with health and behavioural advice AQI-s were mentioned. They are an important reason why policy/standards based AQI-s are popular in many countries. These indices avoid the multiple complicated issues mentioned in the previous section and mainly serve as a tool to reduce complex monitoring information into a simple relative measure of the amount of pollution. This can be used for communication purposes such as policy monitoring, for being accountable and for providing access to environmental information and raising awareness.

Also the paradox that air quality is safe from a short-term exposure perspective but unhealthy from a long-term perspective can be avoided, simply by not interpreting pollution in terms of health impacts in the AQI banding. Air quality ranges from good to bad (or pollution from low to high). Which pollution level is good and what is bad is largely arbitrary and can be decided locally. The bands are usually derived from local legislation, policy targets, WHO guidelines, etc. Sometimes bands are tweaked in such a way that there is a good frequency distribution of the classes over time. Though this might sound odd (and completely arbitrary) it is an approach well worth considering: e.g. if one provides an internet presentation with an AQI that is always the same (same band) the chances that such a website gets repeatedly visited is small. If one wants to use an AQI as a communication tool one has to make sure that it is attractive and informative. In this chapter the policy/standards based indices in general will be called type 2.a, those specifically aimed at raising awareness type2.b.

Many European AQI-s are standard/policy based and they all slightly differ. Sometimes even within a country different indices are used. This is the consequence of regionally different air quality standards (dating from before common EU legislation) or local adaptations due to prevailing conditions. At some point countries have harmonised the use of AQI-s within their country (e.g. the French ATMO forcibly replaced local initiatives). At the EU level no common index exists. A bottom-up initiative to come to an EU index was the CITEAIR project, proposing a common AQI (CAQI). See annex A1.2. Though it is used in several EU projects it is not enforced by the EU. A Chinese example of a policy/standard based AQI is the RAQI used in the Pearl River delta area. See annex A1.2.

Type 2.a indices are less demanding on their delivery time (e.g. need for forecasting) and communication channel. Though many operate in near-real time, providing yesterday's AQI is still a good way of informing the public, NGO-s, or policy makers about air quality as well as a way of showing that one is accountable. AQI-s aiming at raising public awareness have to be

[3] This also makes the index unsuitable as a tool to compare the air quality in different cities in different countries. The AQHI as the index is called was not meant for that purpose but it could be a useful side objective of having an index.

made in such a way that they not only report information but also allow the public to understand what drives air pollution. This implies for example separate indices for regional and urban background, for urban background and traffic; a short time resolution or time series to make sure that people can relate what actually happens (e.g. morning rush-hour to concentration developments); etc.

1.3. Issues related to all AQI types

In the previous sections I distinguished health and policy based AQI-s. This provided a framework to explain some specific characteristics of the AQI-s from a communication perspective. Despite these differences several issues apply to both AQI types and these are discussed here.

In fact, many air quality policies or standards are ultimately motivated by public health concerns. If looked at in another way the differences between the various AQI-s are not that big and even policy/standard based indices can be used to alert the public in case of high air pollution. The issues in common are:

1.3.1. The balance between continuity and being up to date

It is important to avoid frequent changes to an AQI. All AQI-s need occasional maintenance but this should not happen too often. Especially major changes that lead to a different perception of the air quality (e.g. fundamental changes to the calculation grid) should be minimised. Reasons for maintenance can be new epidemiological evidence, changed pollution levels, new legislation, etc. However, the index is a communication tool so people get used to its readings, its colours, etc. If changes are made they have to be clearly communicated. Many people don't bother to understand all the details behind the AQI (and indeed that is why AQI-s are used to communicate complex information!) so if they are used to it but the underlying properties change, misinformation is a result. Before an update is made one should consider what is worse: that the AQI doesn't reflect the latest views or that the public gets confused by the update. One of the reasons that many European AQI-s were not updated when common EU legislation came into force is precisely this reason. People were used to their AQI and that was more important.

1.3.2. Time averaging

Time averaging is mainly an issue for PM. Since most legislation is based on 24-h average concentrations AQI-s tend to work with these daily averages. If hourly updates are provided, they tend to use a moving 24-h average. Daily average information has a number of disadvantages: it is dull and one can hardly relate events in the real world to the concentrations or iAQI or AQI reported; if it is used for alerting people, the message arrives too late and stays too long (see box 3). For the CITEAIR CAQI an hourly calculation grid was developed in addition to the daily average grid.[4] In the recently revised UK AQI calculation another approach is taken: when concentrations start to rise, a trigger value is introduced. The trigger alerts people that the concentrations are high a few hours before the AQI would reach the same conclusion, avoiding that the alert by the AQI is too late. Though this is an important improvement, it doesn't resolve the problem of a moving average AQI being too high for too long. The US uses a different approach: their website AIRNOW does present hourly PM AQI maps. They are not a proper moving average but use a weighting that gives more weight to the past 4 hours if they differ considerably from the 12 hours before. This way a surrogate 24-hour average is calculated that avoids essentially lagging 12 hours behind. Deriving a corresponding calculation grid for hourly values appears to be the simplest way to capture rapidly changing situations, making an interesting AQI and providing appropriate (health) alerts.

In the course of 2014 some EMC-s in China started using hourly PM concentrations in their AQI. We recommended and encourage this. It was a response to comments made by various EMC-s (a.o. Shanghai) that the AQI is sometimes out of sync with what the people see and experience (swift improvement or deterioration of the air quality). The only step left to take is to develop a proper hourly grid for PM to calculate appropriate iAQI-s. Currently they are occasionally far too high (which might undermine the switch to hourly PM data in the iAQI).

Box 3: averaging times for PM

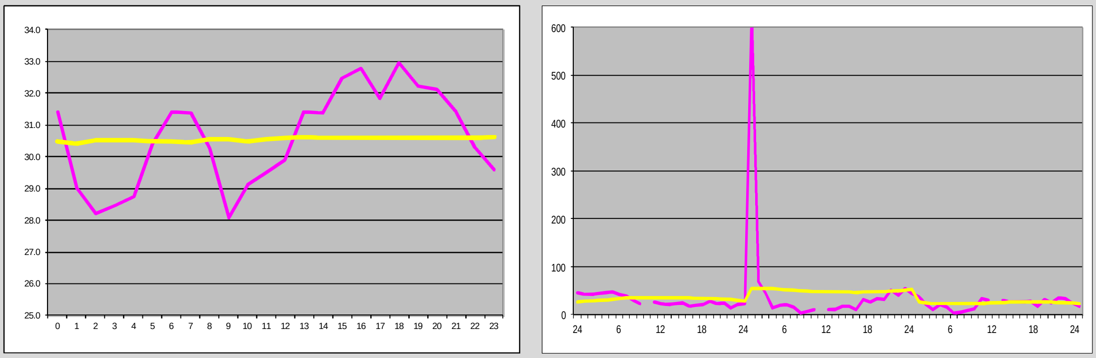

Figure 1: Presentation issues with daily PM values

On the left: hourly PM concentrations versus 24-hour moving average. The latter is flat line while the former clearly shows peaks related to the morning rush-hour and the built-up towards the evening rush-hour. On the right hand side: new year's eve fireworks: the hourly data shows a short sharp peak, the moving average shows a moderate increase, that stays elevated long after the hourly concentrations have returned to normal. The 24-hour moving average data often display wrong (wrongly timed, too high or too low concentrations).

[4] The US use both 8-hour and 1-hour O_3 AQI calculation grids for those areas where the shorter averaging time is more appropriate/more informative. Likewise corresponding hourly and daily calculation grids for PM were developed for the CAQI.

1.3.3. Spatial representativeness

Most information on AQI-s deals with the calculation grid and when trying to find information on the spatial representativeness of the AQI it is usually hard to find. However it is a detail that merits careful thought. An AQI can be calculated for an (administrative) area such as a city or a region. In that case area averaging has to take place. If this is not done and AQI-s are reported for individual monitoring sites it is left to the receiver of the information to decide what is the appropriate monitoring station providing information that is relevant for him or her. If one is in an area with little or no local gradients the nearest station is the most representative. However if local sources dominate the occurring concentrations it highly depends on whether or not one is exposed to these local sources. This is information the lay public might not have/might not understand. It is one of the reasons why the CITEAIR project characterises a city by two indices: one for people in/near busy roads and one in the city background. If someone lives in a city background situation but the nearest monitoring site is a traffic station, it is better to disregard that information and rather look at a background site even if it is further away. Doing no averaging – even if one seems to provide more information in that case – might not be the best (the most informative) approach.

There are several ways to handle area averaging:

- The easiest is not to average and report each station. The disadvantages are as mentioned: it still leaves the public with a lot of information to digest and interpret, and it makes it hard to compare one city to another.
- In the US they report one index figure per city, this is also common in many other countries. In this case one has to decide if the city average is used or the highest value. If averages are used one has to decide if the pollutant concentrations are averaged before the AQI is calculated or if the AQI per station is calculated and subsequently the AQI-s are averaged. If the highest value is used - at least for the AQI-s where the highest iAQI determines the AQI - the highest iAQI at any given time determines the index. On the other hand, if a time series of AQI-s is presented the AQI can alternatively be based on different monitoring sites making the time series harder to interpret.
- Averaging can be done per pollution/exposure type, e.g. averaging for traffic exposure, for urban background, for industrial zones, etc. This makes it easier to compare situations/cities as the result is less dependent on the local monitoring strategy.

Other approaches are special cases of the three mentioned above. They mainly involve some kind of weighting e.g. by population numbers. In my view this makes sense for year average AQI-s that are used for policy monitoring. See section 3.1. It was proposed by Žujić et al (2009) for real time monitoring as certain monitoring sites were in busier areas than others. I think that the averaging by type (previous bullet) is more useful. Even if population weighting is applied it still depends heavily on where the monitoring sites happen to be located and not on how the population is exposed and for which part of the population the number is relevant.

If spatial and temporal averaging takes place one has to be clear on the order in which this is done. In particular for the indices where the highest iAQI determines the AQI, and where the highest AQI in an area determines the area AQI (e.g city AQI), the order in which things are done may impact the outcome and which pollutant determines the AQI. E.g. average every hour across all the monitoring sites for each pollutant and subsequently determine a daily average before determining iAQI-s or determine daily average iAQI-s at each site and subsequently determine the area AQI.

1.3.4. The choice of pollutants in the AQI

The choice of pollutants to be included in an AQI varies considerably. Most provide calculation grids for ozone, nitrogen dioxide and PM_{10}. Lately several AQI-s have added $PM_{2.5}$. Other pollutants such as sulphur dioxide, carbon monoxide and benzene occur as well. To some extent the pollutant mix in the AQI depends on the air pollution history of the area. In Europe, the old monitoring networks dating back to the 1960ies and 70ies tended to have SO_2 included, whilst the younger networks (dating from a time when industrial air pollution has largely been replaced by traffic related air pollution) typically included CO instead of SO_2. Which pollutants to include should be based on the actual nature of the prevailing air pollution. As a general rule the index should include at least O_3 and PM_{10} and/or $PM_{2.5}$. Both are health relevant, occurring fairly universal, transported over large distances and wholly or partly formed in the atmosphere. For local combustion sources including traffic, NO_2 (or NO_x, though I'm not aware of any AQI that uses it) is a suitable indicator and it appears in most if not all, AQI-s.

How to treat missing pollutants is an issue that is hardly ever treated explicitly. The fact that for most AQI calculations individual iAQI-s per pollutant are determined implicitly suggests that all pollutants are equal and carry a similar weight. It suggests that if one of the pollutants is missing one can still calculate the AQI, after all the highest available iAQI determines the AQI. Technically this is correct but does this AQI based on only a few or even one pollutant have the same meaning?

The CAQI was specifically intended to make air quality comparable in different cities in different countries and for that purpose a minimum set of pollutants was specified to be able to calculate the CAQI. The developers felt that without a minimum set of common indicators comparability could not be assured (Elshout et al, 2013, 2008). The US AQI takes the view that every pollutant 'has its own AQI'. Even if not all pollutants are available an AQI is presented. In one way this is a valid consideration: if one pollutant is high, one would want to alert the public and not withhold that warning simply for the administrative reason that the information is not complete. Not doing so would be a mistake.

On the other hand, if several pollutants are missing and the AQI is low providing that information one might mistakenly send a reassuring signal. In short, the selection of a minimum set of pollutants to be included in the index needs careful thought and analysis of available data. This also applies to the question of how to treat missing values of pollutants, and the need to adapt the messages accompanying the AQI, in this case.

For the health based AQI-s that take pollution interaction into account, a missing pollutant leads to AQI values that are too low[5]. This is obvious. For the AQI-s where the highest pollutant determines the AQI the same might happen. Practical results from the CAQI (see box 4) demonstrate this. Results from data analysis on Chinese data shows that in its current form both PM fractions would be needed. This is discussed more extensively in document part III.

Box 4: Sensitivity of an AQI to the pollutants included

The CAQI index requires that at least three pollutants are available to be able to calculate an AQI. The table presents the frequency of the distribution of each index class if the CAQI is calculated according to the existing calculation rules or if it had been based on one of the individual AQI-s. As can be seen this would have led to a completely different outcome. For this sample of 31 European urban background monitoring stations at least the data for PM_{10} and O_3 would have to be available ('CAQI minimum set' - blue column).

Table 4: Sensitivity of the CAQI index for the pollutants included

Index class	**CAQI -Index (current)**	iAQI			**CAQI minimum set(?)**
		PM_{10}	NO_2	O_3	**PM_{10}+O_3**
0-25	**32**	55	92	64	**33**
25-50	**52**	32	8	33	**51**
50-75	**13**	10	0	3	**13**
75-100	**3**	3	0	0	**3**
" >100"	**0**	0	0	0	**0**

If one takes seasonal aspects into account the differences are even bigger. Leaving out PM for example leads to completely wrong wintertime AQI values. (Elshout et al, 2013).

[5] Note that including pollutants that are strongly correlated could lead to AQI values that are too high in these additive health effects AQI-s. This depends on the way the Relative Risks were determined (single versus multi-pollutant models).

2. Recent developments – health based indices

2.1. Introduction

Looking at the scientific literature there have been a number of publications on AQI-s. Most of them tend to stress the importance of a sound health base, e.g. Sicard et al. (2012), Chen et al. (2013), Dimitriou et al. (2013) and Wong et al. (2013). The more sophisticated health indices aim to address a few issues that exist with other AQI-s. E.g.:

a) If the AQI class is bad, or high, what does it mean? How bad is it, what can I expect?
b) If more than one pollutant is high, is there an extra risk?
c) If the AQI for PM_{10} is x and the AQI for NO_2 is also x, do the two pose the same health risk?

Though many of these indices are published as they make interesting research material, **few of them are actually used.** In earlier sections we discussed that health based indices have several communication issues and the more sophisticated indices suffer from high complexity. Often index bands are explained in terms of relative risks or excess risks. Though these concepts are familiar to epidemiologists, they are very hard to understand for the lay-public. If the index is mainly used for exposure monitoring then these complex indices are the best solution.

Recently Hong Kong actually implemented a complex health based index taking pollutant interaction into account following Canada, where it was implemented as well. In these cases relative risk is used to determine index classes that can be communicated more easily to the public. To my knowledge Canada and Hong Kong are the only places where a sophisticated health based index is actually used.

In the Netherlands the existing air quality index is under review and is likely to be replaced by a simple health based index. In the Netherlands pollutant interaction won't be taken into account but the above 3 questions are addressed in a simplified way.

In the next two sections these two recent developments are briefly presented. Some more info on the Canadian index is available in Annex A1.1.

2.2. The Hong Kong AQHI

In Hong Kong the air quality and health index or AQHI is operational since 2014. It replaces an API (Air pollution index) that strongly resembles the US and Chinese AQI-s. The AQHI follows closely the Canadian index. Local epidemiological studies were conducted to study the Relative Risks associated to air pollution exposure. Hospital admissions were chosen as health endpoint. SO_2 was included in Hong Kong (not in Canada) to reflect local air pollution problems. The index now includes NO_2, O_3, PM_{10} and SO_2.

The authors have also established relative risk factors for $PM_{2.5}$ and this pollutant could have been included in the AQHI as well. However, preference was given to PM_{10} because it is monitored at more stations and it is more relevant during (coarse dust storms). Including both at the same time would exaggerate the risk because both species are highly correlated.

The total excess risk is calculated as:

$$\text{Excess Risk} = \Sigma((RR_j-1)*C_j)$$

The AQI is based on 3 hour moving averages. This is a good compromise between real-time information and getting stable results. Based on Hong Kong monitoring data the ER would range from 0 to 19.37%. This is then converted into 10 bands, each associated with a risk band, plus an additional band '10+' covering even higher risks (concentrations), should they arise. The bands can be arbitrarily chosen (Canada) or partly linked to policy standards or WHO guidelines. In Hong Kong they tied band 8 to the WHO short-term guidelines and arranged the rest accordingly. The highest band occurs rarely (2.7% of the time) which is excellent to avoid message fatigue. For more information see Wong et al (2013).

The AQHI addresses the three issues in 2.1 in the following way:

- Relative criteria such as 'low' … 'high' are tied to epidemiologically determined risks. Though risk is a difficult concept for lay people, the approach provides a factual basis for the relative categories.
- Risk are used in an additive way. So if two pollutants are high the risk increases. Whether it is fully correct to simply add the risk is somewhat doubtful. However, since the risks are only used to provide a science base for what is still a relative measure for the severity of the pollution, this approach is sufficiently correct.
- The AQHI doesn't provide iAQI-s for individual pollutants so this question doesn't arises with this AQI. At the fundamentals of the AQI calculation, the true relative risk per 10 $\mu g/m^3$ for each pollutant is used. In that sense the AQI gives each pollutant the appropriate health weight.

The fact that there is no table with grids and that it is not easily possible to identify the pollutant that contributes most to the pollution risk at a given time is a (small) disadvantage from a communication and educational point of view. If this AQHI is meant to monitor public exposure over time it is a very good option.

2.3. The Dutch AQI revision project

In the Netherlands the existing smog warning is being overhauled to be replaced by a modern AQI (Dusseldorp et al. forthcoming). Health effects of individual pollutants are chosen as the basis. The AQI is constructed in such a way that it also takes into account the three issues mentioned in 2.1.

Instead of using a local study (as in Canada, Hong Kong) a WHO study for the whole of Europe was used to select the relative risks (WHO, 2013). For each pollutant the relative risk is used to align the pollutant classes (point c. in 2.1). In this approach, each AQI band, whether it is for

PM, for O_3 or for NO_2, has the same health effect. If all four pollutants are in the highest subclass the AQI moves up one class (see table 5.)

Like the Hong Kong and Canadian AQI-s this approach is based on relative risk but it retains the communicatively more common approach of AQI classes for each pollutant. Potential additive effects are treated in a very basic way that is not fully correct if one wants to estimate true risk. However, as a basis for providing warnings through an AQI it is good enough.

Like the Hong Kong and Canadian AQI-s, it uses a short averaging time also for PM (1 hour). This provides true real-time information to the public. Pollutants included are NO_2, PM_{10}, $PM_{2.5}$ and O_3. SO_2 is no issue in the Netherlands. The spacing of the grid is arbitrarily chosen (10 classes in 4 groups). In each group the risk of hospitalisation doubles. In the resulting grid the highest class doesn't occur frequently (on average 3% depending on the monitoring site).

Table 5: Netherlands tentative AQI approach

	Good			Moderate			Bad			Very bad
	1	2	3	4	5	6	7	8	9	10
Mortality ER (%)	0-0.5	0.5-1	1-2	2-3	3-4	4-5	5-7	7-9	9-10	>10
Hospital admission ER (%)	0-1.5	1.5-3	3-3.5	3.5-5	5-6.5	6.5-8	8-11	11-14	14-15	>15
NO_2, O_3, PM_{10}, $PM_{2.5}$			All 4 →			All 4 →			All 4 →	

2.4. Common characteristics of recently revised AQI-s that are in use

In this section we specifically look at indices that are actually used, assuming that the authorities that use them have made a deliberate choice between practical, communicational and conceptual characteristics of an AQI.

- Short averaging time (1h, 3h): CAQI – EU, Canada, Hong Kong, the Netherlands and the UK introduced hourly 'triggers' for their moving average pollutants. (See annex A.1).
- Health based, all the above mentioned except the CAQI;
- All except the CAQI have paid attention to carefully worded behavioral advice, often even tested on the public if it is well understood.
- Pollutant interaction Canada, Hong Kong, the Netherlands (though in a simplified way); not in the UK and the CAQI. The ones that do use interaction acknowledge that due to lack of independence between the pollutants, this could be an overestimation of the risk. This is particularly true if both PM species are included (as in the Netherlands).
- Highest class shouldn't occur too often: all the above.
- Explicit mention of which pollutants should be available to be able to calculate an index: this is very important for the additive health indices but also for the UK index and the CAQI. Hong Kong decided to use PM_{10} in its index instead of $PM_{2.5}$ as the two show high correlation but PM_{10} data is more available than $PM_{2.5}$.

- Consistency between the PM species: explicitly implemented in the grids in the UK and the CAQI, implicitly implemented by using the relative risk in the health based AQI-s.

Should the Chinese AQI get a stronger foundation in health as this seems to be a trend? In my opinion this is, for the time being not a good idea. Technically it is unnecessarily complicated. Practically the current concentration levels are very high (unhealthy by most international standards - see comparison in document Part III) and even without a conceptually correct link to health effects, the public can easily be warned with an AQI with a more policy based grid.

Other lessons to be learned are more important: improve and test the wording of the recommendations; make the PM grids more consistent; avoid message fatigue by avoiding that the highest class occurs too often and use short averaging times. Considering the latter an important first step was taken in 2014.

3. AQI properties & communication objectives

In chapter 1 the reasons to make an AQI and several design consequences were discussed. In section3.1 we briefly touch on some other design issues and in 3.2 two summary tables are presented linking AQI properties to communication objectives.

3.1. How to condense information

AQI-s are about condensing complex concentration information of multiple pollutants in awkward units of measure, sometimes different averaging times, into (usually) one number on a relative scale. The scale is often accompanied by qualifying statements (good, bad, high, low, etc.). Usually this is visually reinforced with colours and or smiley-s.

Some AQI-s are only qualitative and numbers are not even mentioned (they are needed in the background however to decide to which category the measurements belong). Most have a limited number of broad classes (3 to 5) and subcategories in each class. Sometimes a numerical value is attached and the scale can run from 1 to 5 up to 1 to 500. The conversion of actual measurements to AQI numbers can be linear, non-linear or linear in each class (often the case). Garcia et al (2002) provide a non-exhaustive overview of various conversion methods. One method is not necessarily better than the other. A point to consider is how the classes relate to the wording used and the health advice given. Remember that close to class borders a minor change of 1 $\mu g/m^3$ can cause a change of class and hence another message. The risk perception of a situation can therefore dramatically change at an insignificant change of the air quality. That is the disadvantage of a discrete indexing system. The US EPA commissioned a study to analyse the risk perception of the messages when they changed their index (Johnson, 2003). This a good paper on risk communication and indices. The UK also studied the message in the course of their recent index review (COMEAP, 2011).

On the length of the scale (e.g. 1 to 5 or 1 to 500) different views exist. Some say the AQI is an enormous generalisation of information and in addition, the spatial coverage is not well defined so anything more than a few broad categories is overly pretentious and not backed by serious science. Elshout et al (2008) argue that to raise awareness and entice repeated visits to a website the information should be dynamic. This calls for a long scale that favours differentiation and changes in the course of the day and from one site to another.

The point to be stressed here is that one should be aware of the implicit message that colours[6] or numbers may send. This largely depends on local context and culture. For example the French ATMO runs from 1 to 10 with 10 designating the worst air pollution. However in school 10 is the highest grade one can obtain and there a 10 refers to a job very well done. Likewise in many countries red is associated with alerts and hence the colour is often used for the

[6] Colours also present a challenge for colour blind people. The (culturally) best colours for those with complete colour vision might not be the best for those with a degree of colour blindness. The use of numbers and smiley-s is therefore recommended. On index maps (see section 3.3) this is not possible. If these are envisaged as well, the colour coding merits attention right from the start.

highest AQI band referring to poor air quality. However, in China red symbolises good fortune and joy.

3.1. Linking AQI properties & communication objectives

Many AQI properties have been discussed and this section aims to put them in the perspective of the communication objectives mentioned in chapter 3 of the part I document. Table 5 summarizes the points discussed in chapter 1 in relation to the communication objectives. The table shows that the choice for one type of index doesn't mean that other uses are no longer possible (see for example figure 2). It is meant to underline that careful thinking about the main communication issues might lead to different design choices.

Table 6: AQI types and communication objectives

Communication objective (see Part I document)	Health and behavioral advice		Policy/standards based relative scale	
	Highest iAQI (Type 1.a)	Pollutant interaction (Type1.b)	General (Type2.a)	Raising awareness (Type 2.b)
Make / monitor air quality policy	+ (too much focus on short term exposure – situations that (should be) are unlikely to occur regularly)	+/++ (detailed focus on exposure assessment that can be useful for policy monitoring if the long term aspect is covered as well)	++ (all types are suitable but this can be easily adjusted to easily fit the purpose)	+ (as such suitable but has additional requirements not needed for this purpose)
To be accountable / to provide access to environmental information	+	+	++ (all types are suitable but this can be easily adjusted to easily fit the purpose)	+
Raising awareness	0 (too much focus on short term exposure, in particular the long-term short-term paradox)	0 (too much focus on short term exposure, in particular the long-term short-term paradox)	+	++ (better suited than 2.a; additional characteristics are added to achieve this purpose)
Risk communication short-term exposure	++ (Benefits from easy straightforward approach, examples are ample and can be copied)	++ (Better/best assessment of health risks; laborious to set up correctly)	0/- (not designed for this purpose but crude warning for high pollution levels is possible)	0/- (not designed for this purpose but crude warning for high pollution levels is possible)

Table 7 further details desirable properties of the AQI and its dissemination form in relation to communication objectives. This table is to some extent subjective and reflects the ideas of the author. It also serves as an example on how to identify desirable properties of an AQI once the communication priorities are set. Both the characteristics to assess as well as their weighting can be done in a session with relevant stakeholders in order to identify desired AQI properties.

Table 7: Communication objectives and AQI characteristics

Characteristics	Make / monitor air quality policy	To be accountable / provide access to environmental information	Raising awareness	Risk communication short-term exposure
Short averaging time (1 hour)			xx	xxx
PM_{10} or $PM_{2.5}$ **and** O_3	x	x	x	xxx
Ease to add different additional pollutants depending on local relevance	xx	xx	xx	x
Easy to calculate and trace back from AQI to concentration		xxx	xx	
Near real time data, nowcast forecast		x	x	xxx
Yesterday's AQI	x	xx	x	
Highest site determines the AQI		xx	xx	x
City averages (per exposure type)	xx			
AQI for each pollution/exposure type	xx	xx	xxx	?
AQI per monitoring site	x	x		?
Comparison to other cities/areas	x		xx	
AQI time trend (diurnal variation)	x		xx	
Paper reports	x	x		
Internet or other passive publications (newspaper)	x	xx	xx	x
TV/radio in case of high AQI		x	x	xxx
Txt messaging service, apps with personalised alerts		x	x	xxx
Behavioural advice				xxx
Integration with other info like weather info		x	xx	
Numerical index with a long scale			xxx	x
.....				

(a)

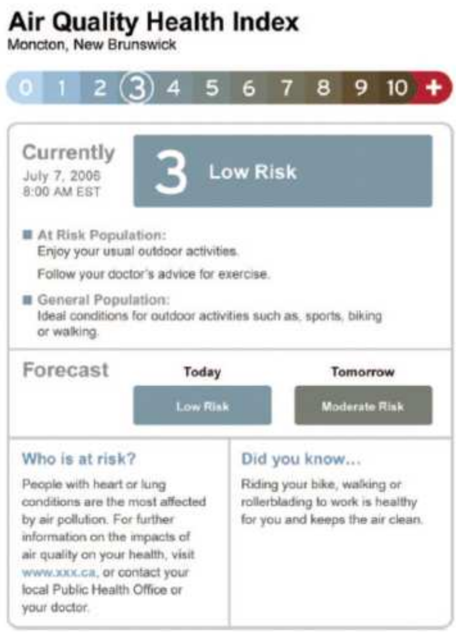

Figure2: Canadian messaging: an AQI aimed at risk communication combining awareness messages (what can you do yourself); Source: Stieb et al (2008).

3.2. Adapting behaviour?

Shooter and Brimblecombe (2009) mention 'risk communication' as the principal reason to have an air quality index. However they note, citing the study by Johnson (2003) on the US AQI, that AQI information rarely succeeds in changing people's behaviour in face of the oncoming poor air quality. They argue that better forecasting, making a timelier alert might improve people's response in the case that the index is signalling adverse air quality. This is obviously an improvement.

On the other hand, I doubt that this would considerably change the general public's response to an alert. In large parts of Europe and the US the air quality has to be extremely poor before it poses an acute danger to the population in general. With busy agenda's full of obligations it is unlikely that the average person will cancel his sports game, that a school outdoor activity that was planned long ago (involving many volunteers) is postponed at short notice to avoid exposure, that work is suspended, etc. Whilst in China the pollution levels are occasionally substantially higher, the possibilities to adjust one's plans, even if warned a day or so in advance, is probably equally limited. This seriously questions the rationale of providing health and behavioural advice using an AQI via media with a broad audience like tv or the internet.

People/patients that are truly affected by air pollution that can and do take measures (reducing their exposure, taking additional medication) because they have to, could be warned in specific ways. By particularly addressing this more limited target group using specific communication means, the general communication via websites and the AQI to a broader audience could be framed in the context of raising awareness/being accountable.

Current day technology facilitates these targeted ways to inform the select group of people concerned. For example AirAlert provides a messaging system that those in need of this kind of information can subscribe to (see www.airalert.info/Sussex/Default.aspx). This exists already several years and a very nice feature is that those without mobile phones (e.g. some of the elderly likely to be in the target group for this services) can get a voice message on their ordinary phone. The latest development is made possible by smartphone apps. Instead of a government deciding which pollution level is harmful or not, everyone can set his/her own alarm level based on experience or advice from the own physician. The recently launched Dutch air quality app (www.luchtkwaliteitmetingen.nl/ - in Dutch language only) is, as far as I know, the first to include this facility to personalise alarm levels in addition to general AQI based information.

4. Other AQI-products (year average, maps, etc)

4.1. Year average AQI-s.

All AQI-s discussed in this document so far refer to AQI-s with an hourly or daily averaging time and communication messages aimed at short term exposure situations. Year average AQI-s are rare though quite regularly the occurrence of the daily AQI is summarized and reported at the end of the year. This is a useful way of providing an annual overview, particularly if one or more AQI bands are related to standards. In this way one can indicate which percentage of the time the air quality met the set standards. For AQI-s aimed at health and behavioural advice this summary at the end of the year is less obvious (the AQI was made specifically for short-term exposure) but it is nevertheless informative to see which percentage of the time certain conditions occurred.

The main advantage of this approach (summarizing daily data) is that it ties short- and long-term exposure together in one presentation. The disadvantage is that the results are hard to interpret for lay people: instead of having one figure that indicates the status of the air quality one gets a percentage of occurrence per index class. See box 5 for an example. A possible solution to further simplify the message is to include in the presentation, the percentage of time the standards were met. In that case the main information collapses into a single figure.

A different approach is to develop a separate year average AQI, using for example the 'distance to target' principle, where the target is an air quality standard (local legislation, WHO recommendation, etc.). For each pollutant the year average concentration is divided by the standard or target value. A value > 1 means that the standards are not yet met. The CITEAIR project proposed such an index (see box 5). The advantage is that it is very easy to see if the air quality is improving over time and if standards are met. The disadvantage is that due to the averaging a pollutant that is doing well compensates pollutants that still exceed the standard. A careful selection of critical pollutants is needed! A second disadvantage are standards that are based on discrete occurrences rather than year average concentrations: e.g. an ozone concentration that should not occur more than x times a year (as in the EU legislation). These are computationally more complicated. Solutions exist of course but the easy to understand transparency – the very purpose of making an index – can easily be compromised.

Box 5: Year average AQI-s

The US EPA website (www.epa.gov/airdata/ad_rep_aqi.html) lets you generate year average AQI summaries. Below an excerpt from the 2012 report. Often the year average summaries contain the statistics on the occurrence of each band (the grey columns). The US EPA provides several additional statistics such as the median AQI, and the number of days each pollutant dominated the AQI. The interpretation difficulties of the core table start when one wants to compare the situation in two cities, or in the same city over time. Look at the top 2 cities: the first has more good days, but also 10 unhealthy days: which city is better? The AQI median value can provide some guidance: it is the same for both cities. Similar interpretation problems occur with the other three stations: without the median AQI it would be difficult to judge whether one city is better than another or not.

County	Good	Moderate	Unhealthy for Sensitive Groups	Unhealthy	Very Unhealthy	AQI Median
Inyo	228	115	9	4	10	45
Sacramento	218	106	37	5	.	45
Kings	134	190	38	4	.	60.5
Madera	110	198	54	4	.	61
San Diego	74	270	21	1	.	61.5

County	# Days CO	# Days NO2	# Days O3	# Days SO2	# Days PM2.5	# Days PM10
Inyo	.	.	265	.	12	89
Sacramento	1	24	268	.	72	1
Kings	.	1	185	.	149	31
Madera	.	.	165	.	188	13
San Diego	.	19	95	.	220	32

The Year Average CAQI (Elshout, 2012, Elshout and Léger 2007) uses the distance to target approach. Each pollutant is divided by the year average standard and when the result is <= 1 the standard is met. For the core pollutants the average is calculated (“city index”). The presentation provides both an easy average ranking (city index) as well as the details per pollutant. It is easy to see if air quality is improving, which pollutants are doing well, and which not. As with the hour by hour CAQI, the calculation is done for traffic and city background monitoring sites.

Year	NO2 Year average	PM10 year average	PM10 exceedences daily average	O3, # of days with 8-hour average >=120µg/m3	SO2 year average	Benzene year average	City Index
2006	1.03	0.83	1.11	1.84	0.35	-	1.2
2007	0.98	0.75	1.2	0.72	0.25	-	0.91
2008	0.95	0.78	0.97	0.96	0.25	0.2	0.91
2009	0.95	0.83	1.11	1.28	0.2	0.2	1.04
2010	0.88	0.7	0.71	1.44	0.1	0.2	0.93

Sample data shown: www.airqualitynow.eu/comparing_city_annual.php?lyon

4.2. Policy indicators

The year average AQI-related products are particularly useful for monitoring the evolution of air quality over years or for assessing the impact of air quality policy over time. It summarizes for the lay public and for public authorities (often no air quality specialists) the status of the air quality and the results of measures taken. For this purpose it is quite relevant to not only use the results of the monitoring sites but to generalise the results to make them more representative.

This can be done by weighting the results of individual monitoring sites as was proposed by Žujić et al (2009) for hourly/daily observations. The better method in my view is to categorise the results according to land use, to exposure type, etc. Combined with the number of inhabitants in each category a measure of 'environmental pressure' or 'environmental comfort' can be designed that could be used for trend monitoring. The most detailed way of doing this is by using modelling as a sophisticated kind of interpolation between the monitoring sites.

There are many ways of devising such an indicator and again one is not necessarily better than another. Bell et al (2011) present a few examples and stress the point that the design of the indicator has a major impact on the outcome and the relative ranking of the cities that were studied. The main point is that the same method has to be applied each year in the same way, after all these year average AQI-s are relative indicators as well. Their main use is in comparing situations (over time).

Policy indicators and the year average AQI-s are relevant to the authorities making policy but are also an excellent communication tool towards the public, showing that the relevant authorities are accountable. A selection of easy to understand indicators can be made for this purpose.

4.2.1. The EEA Environmental indicators

The EU's environemental agency, EEA, has developed a large set of indicators that is annually monitored and for which the memberstates obligatory deliver annual data. This covers all kinds of environementla domains,including air quality. The air quality indicators can be found at: www.eea.europa.eu/themes/air/indicators#c7=all&b_start=0&c5=air+quality.

They cover emissions but also exposure data. See for example: www.eea.europa.eu/data-and-maps/indicators/exceedance-of-air-quality-limit-1/exceedance-of-air-quality-limit-5.

The data is annually published by EEA (see www.eea.europa.eu/publications/air-quality-in-europe-2013) but every indicator also has its webpage (as the "exceedance of air quality limit" example shows) elaborating how the data are collected, time series of results, etc. Often even access to underlying raw data is possible.

The indicators have been developed and refined over the past decades and are now cornerstones of EU policy development/monitoring. Check this part of the EEA website for useful examples of indicators with a longer (longer than hours/days) averaging times.

Above we discussed ways concentration or AQI maps can be population weighted. There are two schools of thought. One is, as described above, trying to relate as good as possible spatial concentration information to population numbers. The second approach in this is taken by EEA, and it is probably relevant to most of the medium sized EU cities, assuming that one concentration figure for a city is good enough because people don't always stay at home but rather move around. In fact if one bases exposure only on residential address the true exposure could indeed be underestimated as during the day people tend to move to industrial areas or the city centre for their employement, school or other services.

4.3. AQI maps

AQI maps can be made in near real-time by interpolating between monitoring sites or by running models. The AQI maps are increasingly common. In the past it was not always evident that the departments responsible for monitoring also had the modelling expertise to make real-time maps and the work was also computationally demanding, making it uncertain that an hourly updated map could be produced. Computational problems are generally solved by the ever increasing computer power, and many websites and apps have map presentations.

If the maps are meant to warn the public of adverse air quality it suffices to make a map showing the AQI only. If the presentation is also used for raising awareness one would like to see at least also which pollutant determines the index at a given time and space. This implies providing two types of information in a single map. This can be achieved by combining index colours which different hatchings for each pollutant. If this is done with transparent colours (to be able to see the geographic features on the base map) the result is likely to be a rather messy image that is hard to interpret. In one EU project it appeared that the AQI map often had the same colour throughout the area. It so happened that areas with different pollution problems still produced the same AQI as the highest pollutant determines the AQI. They dropped the idea of making AQI maps. In the US they present an AQI map and one can toggle between the AQI and the $PM_{2.5}$ and O_3 iAQI maps. This is a nice way of solving this problem and it works well with these two pollutants (a sensible selection both from a health and a communication perspective).

Modelled maps have one problem that is awkward for AQI-s aimed at alerting the public. The chemical transport models that are used to calculate these maps tend to work with fairly large gridcells averaging all pollution within the grid. Typical cell sizes in operational applications range from 5x5 to 20x20 km in the EU. The smaller the cell the more demanding the computations are **and** smaller cells are only viable if spatially detailed emissions are available. The larger cells are more common. Averaging emissions over an area of 20x20 km can easily obscure locally relevant sources and even make cities below one million in habitants disappear in the general background. In several EU applications the few cities with sizes from 5-10 million can be seen and others can't. In reality also the smaller cities experience higher concentrations of primary pollutants than the surrounding countryside. Grid averaging, by definition, reduces the spatial variability and hides/underestimates areas with high concentrations. There are ways to prevent this but practical applications are not common yet. So the warning here is that modelled AQI maps often paint a better picture than the true situation: they underestimate high concentrations (and inflate low concentrations - but this is less important). They are most suited for situations where large scale atmospheric phenomena determine the AQI (O_3, $PM_{2.5}$ episodes).

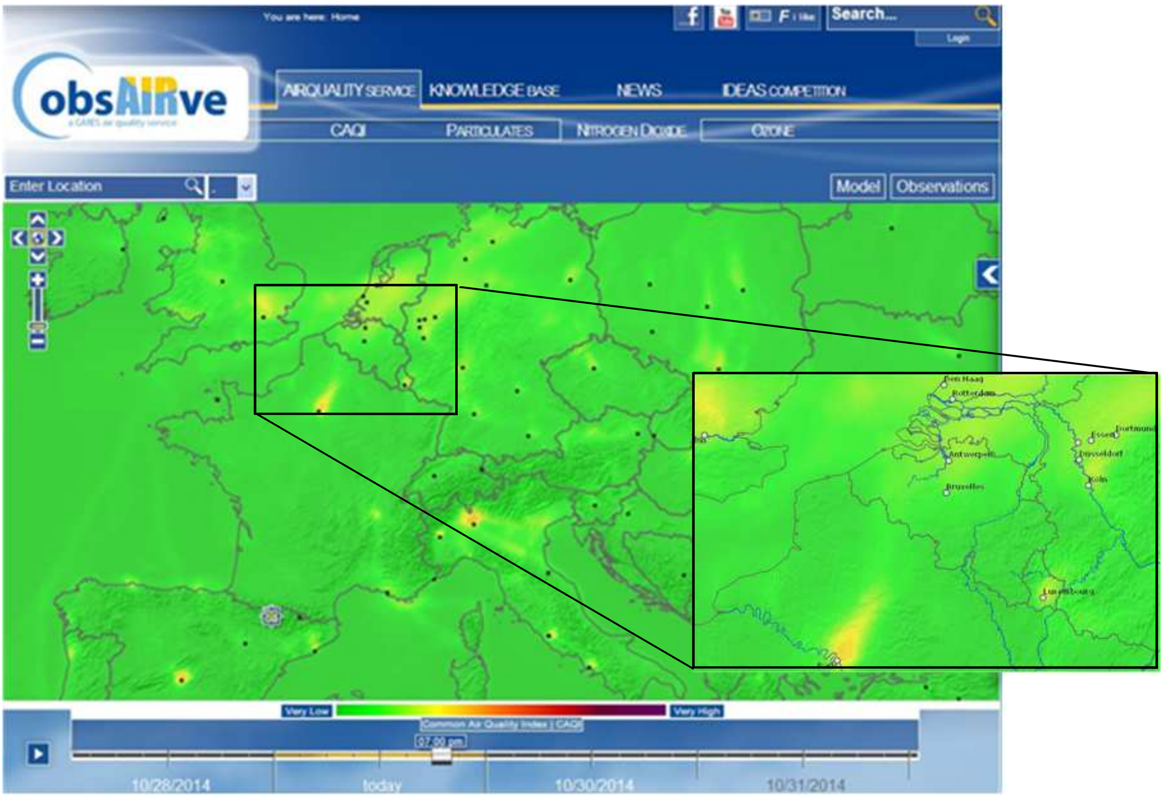

Figure 3: www.obsairve.eu website/app, showing air quality in Europe.

The NO2 map shows elevated concentrations in the very big cities (London, Paris, Madrid), the industrial zone in northern Italy is visible but smaller with a million inhabitants or less, that should nevertheless show higher NO2 concentrations than their surroundings are not visible.

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Annexes

A1. Selected air quality indices

This annex details the calculation of a few air quality indices. It is far from complete as there are a few dozen air quality indices. **A few documents contain overviews of air quality indices (Elshout and Léger, 2007; Garcia et al, 2002 and Wikipedia, 2013) but beware: AQI-s are sometimes updated to accommodate new pollutants, to be in line with new regulations, etc.** Please **always** check the original sources to verify what the actual state of an index is. The indices presented hereunder were correct on June 2013.

A1.1 Indices aimed at providing behavioural/health advice

Here we compare indexing systems having the same communication ambition: providing advice to reduce short-term exposure to air pollution. **Firstly the Type 1.a (in the main text) AQI-s where the highest iAQI determines the AQI. The US and UK AQI-s are given as an example.**

First the US AQI (see Document Part I section 4.1.2, here only the break points are given) and the UK AQI. Notice the differences between the two AQI-s. For the UK AQI See: http://uk-air.defra.gov.uk/air-pollution/daqi. (Accessed June 3, 2013).

Table A.1: US-AQI breakpoints[7] for AQI bands ($\mu g/m^3$)

US-AQI**		SO_2 1h	NO_2 1h	PM_{10} daily	$PM_{2.5}$ daily	CO 8h (mg/m^3)	O_3** 1h	O_3** 8h
1	50	90	100	54	12	5.1		120
2	100	200	190	154	35	10.8	250	150
3	150	480	680	254	54	14.3	320	190
4	200	800*	1220	354	150	17.7	400	230
5	300	1580*	2350	424	250	35.0	790	730
6	400	2110*	3100	504	350	46.5	990	Use hourly O3
	500	2630*	3850	604	500	58.0	1180	Use hourly O3

*Daily averaged concentrations are used
** The higher of the two parameters is used. For the first two bands only 8-hour averages are used.
Source: www.epa.gov/airnow/aqi-technical-assistance-document-sep2012.pdf. The three lower bands for $PM_{2.5}$ are based on www.epa.gov/pm/2012/decfsstandards.pdf (Accessed June 3, 2013).

Table A.2 UK AQI breakpoints ($\mu g/m^3$)

Index Band	1 Low	2	3	4 Moderate	5	6	7 High	8	9	10 Very High
O3 8h	33	66	100	120	140	160	187	213	240	241 or more
NO2 1h	67	134	200	267	334	400	467	534	600	601 or more
SO2 15 min.	88	177	266	354	443	532	710	887	1064	1065 or more
PM2.5 24h	11	23	35	41	47	53	58	64	70	71 or more
PM10 24h	16	33	50	58	66	75	83	91	100	101 or more

[7] Note that US breakpoints are given in PPM for the gasses. Here they were converted to $\mu g/m^3$.

Table A.3: UK AQI description of bands

How to use the Daily Air Quality Index

Step 1: Determine whether you (or your children) are likely to be at-risk from air pollution. Information on groups who may be affected is provided on the Additional information on the short-term effects of air pollution page. Your doctor may also be able to give you advice.
Step 2: If you may be at-risk, and are planning strenuous activity outdoors, check the air pollution forecast.
Step 3: Use the health messages corresponding to the highest forecast level of pollution as a guide.

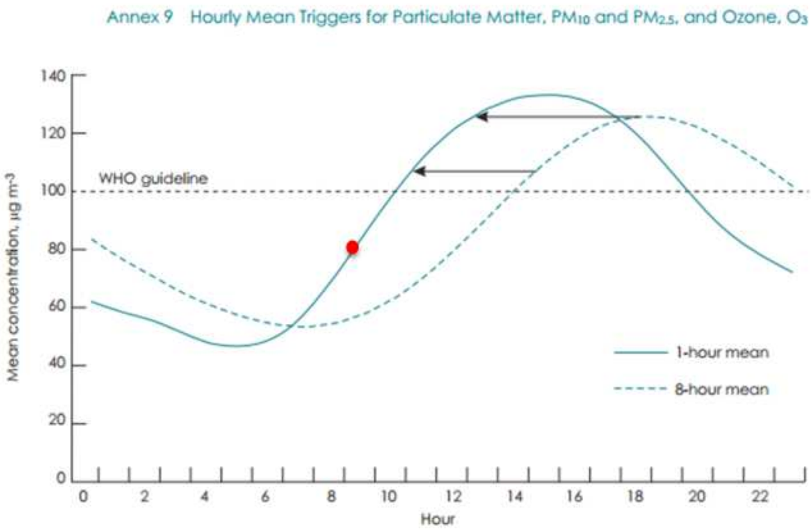
Air Pollution Banding	Value	Accompanying health messages for at-risk groups and the general population: At-risk individuals*	General population
Low	1-3	**Enjoy** your usual outdoor activities.	**Enjoy** your usual outdoor activities.
Moderate	4-6	Adults and children with lung problems, and adults with heart problems, **who experience symptoms**, should **consider reducing** strenuous physical activity, particularly outdoors.	**Enjoy** your usual outdoor activities.
High	7-9	Adults and children with lung problems, and adults with heart problems, should **reduce** strenuous physical exertion, particularly outdoors, and particularly if they experience symptoms. People with asthma may find they need to use their reliever inhaler more often. Older people should also **reduce** physical exertion.	Anyone experiencing discomfort such as sore eyes, cough or sore throat should **consider reducing** activity, particularly outdoors.
Very High	10	Adults and children with lung problems, adults with heart problems, and older people, should **avoid** strenuous physical activity. People with asthma may find they need to use their reliever inhaler more often.	**Reduce** physical exertion, particularly outdoors, especially if you experience symptoms such as cough or sore throat.

*Adults and children with heart or lung problems are at greater risk of symptoms. Follow your doctor's usual advice about exercising and managing your condition. It is possible that very sensitive individuals may experience health effects even on Low air pollution days. Anyone experiencing symptoms should follow the guidance provided below.

The UK AQI uses triggers for the components with moving average concentrations to assure that warnings are better timed. For a full description see the COMEAP rapport (http://comeap.org.uk/images/stories/Documents/Reports/comeap review of the UK air quality index.pdf; Accessed 23-7-2012). The next figure (from annex 9 of the report) provides the explanation of how the triggers work:

- The moving average reacts quite late to the rising hourly values and the public might be informed rather late.
- Don't wait until the 8-hour average reaches a value of 80 µg/m3 but use a trigger at 82 µg/m^3. If the hourly concentration reaches 82 and if the subsequent hour is even higher: issue a warning.

Note that this system works during rising concentrations but not during falling concentrations. Simply switching to hourly values and an hourly concentration grid is an easier solution that works both ways. Nevertheless this is an important step forward to improve real-time information.



Secondly the Type 1.b (in the main text) AQI-s where pollutant interaction is taken into account.

Lately many examples of sophisticated health based indices have been published. However few of them are actually in use. Apart from Canada, described here, Hong Kong is the only place where such kind of index was implemented. Examples from South Africa and Canada are given.

- The DAPPS uses relative risk (RR) values for individual pollutants, multiplies each concentration with their RR-1 and adds up the total to achieve a sum of RR-s. The total RR determines the degree of hazard the prevailing air presents. For a full discussion see the paper by Cairncross et al (2007).[8]

Here the sub-index bands are reproduced that allow a comparison between the DAPPS and the other indices (at iAQI level).

$$\text{Total Risk} = \Sigma((RR_j-1)*C_j)$$

where RR_j is the RR of pollutant j and C_j is the concentration of pollutant j at the averaging time corresponding to RR_j.

[8] Free download at: http://www.ehrn.co.za/publications/download/04.pdf (Accessed 6-6-2013)

Table A.4 DAPPS (South Africa) calculation grid for sub-indices

Pollutant sub-indices for DAPPS air pollution index (API) system

Relative risk (RR)	Sub-index value	Concentration corresponding to relative risk value						
		PM_{10}, 24-h average (µg m^{-3})	$PM_{2.5}$, 24-h average (µg m^{-3})	SO_2, 24-h average (µg m^{-3})	O_3, 8-h maximum (µg m^{-3})	O_3, 1-h maximum (µg m^{-3})	NO_2, 1-h maximum (µg m^{-3})	CO, 8-h rolling average (mg m^{-3})
1	0	0	0	0	0	0	0	0.0
1.015	1	21	10	38	30	33	51	3.9
1.031	2	41	20	77	60	67	102	7.9
1.046	3	62	30	115	90	100	153	11.8
1.061	4	83	40	153	120	133	204	15.7
1.077	5	104	50	192	150	167	256	19.7
1.092	6	124	60	230	180	200	307	23.6
1.107	7	145	70	268	210	233	358	27.5
1.123	8	166	80	307	241	267	409	31.5
1.138	9	186	90	345	271	300	460	35.4
>1.153	10	>207	>100	>383	>301	>333	>511	>39.3

The summing of the individual RR-s (implicitly) assumes that the effects of each individual pollutant is independent of that of the others, which is not true. One could say that whereas the 'highest iAQI determines the AQI' concept is likely to underestimate the impact, this approach somewhat overestimates the likely health impact. (Unless the RR-s are derived from multi-pollutant models.) Also note that the amount of pollutants included determines to some extent the outcome. For consistent application of the DAPPS everyone should monitor the same set of pollutants.

- The Canadian Air Quality Health Index (AQHI) has a similar approach as the DAPPS in that it sums the health effects of individual pollutants (Stieb et al, 2008). Relations between excess mortality and pollutant concentrations were not derived from WHO published RR-s (as in the DAPPs) but rather determined on the basis of Canadian urban air quality monitoring and mortality data. This is an important difference. Though the pure toxicity of pollutants can be regarded as constant and country or site independent, health outcomes of pollution episodes do differ depending on other factors, such as overall life expectancy, smoking habits and other life-style and environmental health factors. Likewise, the air pollution mixture can be rather site specific. The level of correctness achieved by the Canadian approach is therefore also a limitation: Stieb et al (2008) discussion their AQHI, mention that it is typical for Canadian urban environments and might not apply to rural areas. Hong Kong, intending to update their API with a Canadian style AQHI, will have to make their own epidemiological analysis to get the correct coefficients of for the AQHI calculation.

The Canadian AQHI cannot be summarised in concentration bands such as the other AQI-s discussed. Some important features of the AQI are summarised below (Stieb et al 2008):

- The AQHI is meant to enable the public to protect themselves from acute health effects of air pollution. The averaging time for all pollutants (including PM) was therefore set to the past 3 hours (being a compromise between stable results and the shortest possible averaging time).

- The AQHI should include at a minimum NO_2, O_3, and PM_{10} or $PM_{2.5}$. Since most pollutants are mutually correlated these three capture (in the Canadian situation) the health effects of the occurring pollutant mixtures.
- The communication material associated to the AQHI was developed and tested together with stakeholder groups. Categories were defined to take into account the relative frequency of the bands. **'An excessive frequency of days at higher levels was avoided to avoid saturation of individuals who might than be inclined to ignore the index.'**

Table A.5 health messages Canadian AQHI

Category	Numerical Value	Health Messages: At-Risk Population	Health Messages: General Population
Low risk	0–3	Enjoy your usual outdoor activities. Follow your doctor's advice for exercise.	Ideal conditions for outdoor activities: sports, biking, or walking.
Moderate risk	4–6	If you have heart or breathing problems, and experience symptoms, consider reducing physical exertion outdoors or rescheduling activities to times when the index is lower. Follow your doctor's usual advice about managing your condition.	No need to modify your usual outdoor activities.
High risk	7–10	Children, the elderly and people with heart or breathing problems should reduce or reschedule physical exertion outdoors to periods when the index is lower, especially if they experience symptoms. If you have heart or breathing problems, follow your doctor's usual advice about managing your condition.	Anyone experiencing discomfort such as coughing or throat irritation should consider reducing or rescheduling strenuous outdoor activities to periods when the index is lower.
Very high risk	Above 10	Children, the elderly and people with heart or breathing problems should avoid physical exertion outdoors. If you have heart or breathing problems, follow your doctor's usual advice about managing your condition.	Everyone should consider reducing or rescheduling strenuous outdoor activities to periods when the index is lower, especially if they experience symptoms.

A1.2 Policy/standards based indices

Policy & standards based indices set the class borders relative to air quality standards or other (policy) considerations.[9] The bands are to a large extent arbitrary (in the sense that they don't depend on epidemiological evidence linking concentrations to health impacts) and can therefore be adapted to the prevailing concentrations. This way certain communication objectives can be better served such as assuring a fair frequency distribution of the bands and avoiding that the worst category occurs to often; and more importantly avoiding that the air quality always looks good whilst this is not true from a long-term exposure perspective (this is often a problem with health based indices).

In the UK the public reported this issue (G. Fuller, p.c.) and in the Netherlands we also encountered this confusion. In the review of the UK AQI (section 3.9) some attention is given to the problems of averaging times (COMEAP, 2011). They conclude that no ready solution exists to solve this problem. However they also mention (section 2.3) that 'Health effects may occur even at low concentrations of particles and therefore an arbitrary index was devised.' So, in order to convey an appropriate message (particle pollution is never safe) a grid was devised that suits the information objective. The fact that the UK adopted (and maintained after the review) this approach in an otherwise health based short-term exposure AQI shows how serious the issue is.

Two examples are given (though many exist):

- Fist the EU CAQI that features the concept of mandatory pollutants and the traffic <> background approach (each area is represented by two AQI numbers)
- Second the Pearl River delta RAQI because it is regionally used in China.

[9] As a matter of fact some of the health and behavioural advice AQI-s also use a standard to fix one of the bands. If a short-term exposure standard exists it usually forms the difference between the 'good' and the 'medium' bands.

CAQI index

Table A.6: Pollutants and calculation grid for the CAQI hourly and daily grid (Elshout, 2012)

Index class	Grid	Traffic						City Background							
		core pollutants			pollutants			core pollutants				pollutants			
		NO_2	PM_{10}		$PM_{2.5}$		CO	NO_2	PM_{10}		O_3	$PM_{2.5}$		CO	SO_2
			1-h.	24-h.	1-h.	24-h.			1-h.	24-h.		1-h.	24-h.		
Very low	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	25	50	25	15	15	10	5000	50	25	15	60	15	10	5000	50
Low	25	50	25	15	15	10	5000	50	26	15	60	15	10	5000	50
	50	100	50	30	30	20	7500	100	50	30	120	30	20	7500	100
Medium	50	100	50	30	30	20	7500	100	50	30	120	30	20	7500	100
	75	200	90	50	55	30	10000	200	90	50	180	55	30	10000	350
High	75	200	90	50	55	30	10000	200	90	50	180	55	30	10000	350
	100	400	180	100	110	60	20000	400	180	100	240	110	60	20000	500
Very High*	> 100	> 400	>180	>100	> 110	>60	>20000	> 400	>180	>100	>240	> 110	> 60	> 20000	>500

NO_2, O_3, SO_2: hourly value / maximum hourly value in µg/m^3
CO 8 hours moving average / maximum 8 hours moving average in µg/m^3
PM_{10}, $PM_{2.5}$ hourly value / daily value in µg/m^3
* An index value above 100 is not calculated but reported as " > 100"

Table A.7: Calculation scheme for the year average CAQI

Pollutant	Target value / limit value	Calculation
NO_2	Year average is 40 µg/m^3	Year average / 40
PM_{10}	Year average is 40 µg/m^3	Year average / 40
PM_{10} daily	Number of daily averages above 50 µg/m^3 is 35 days	Log(number of days+1) / Log(36)
Ozone	25 days with an 8-hour average value >= 120 µg/m^3	# days with 8-hour average >=120 / 25
$PM_{2.5}$	Year average is 20 µg/m^3	Year average / 20
SO_2	Year average is 20 µg/m^3	Year average / 20
Benzene	Year average is 5 µg/m^3	Year average / 5
CO	-	Not calculated

RAQI index

The RAQI compares the prevailing daily concentrations to the set concentration targets for four pollutants. The four ratios thus obtained are summed. The RAQI therefore deviates from the often used 'highest iAQI determines the AQI' approach. See excerpts from: www-app.gdepb.gov.cn/raqi3/capi_ENG_detail.html

The RAQI is a measure of the aggregate level of major air pollutants. The RAQI for the Pearl River Delta (PRD) regional air quality monitoring network is derived from the concentrations of 4 major air pollutants, namely respirable suspended particulates (RSP or PM_{10}), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3). The higher the index value, the higher the overall level of regional air pollution.

The RAQI is divided into 5 grades. The categorization of the RAQI grades, their corresponding index values and air quality conditions are as shown below:

Grade	Value	Air Quality Conditions in the Monitored Area
I	0-1	Concentrations of all pollutants are well within the National Ambient Air Quality Standards (NAAQS) [#]
II	1-2	Concentrations of all pollutants are generally within the NAAQS
III	2-3	Concentrations of individual pollutants may approach or exceed the NAAQS
IV	3-4	The NAAQS are generally exceeded
V	> 4	The NAAQS are significantly exceeded

[#] Refer to the Class 2 NAAQS (GB 3095 – 1996 – revised version), which are applicable to residential, mixed commercial/residential, cultural, industrial and village areas.

The formula for calculating the RAQI is as follows:

$$I_c = \sum_{i=1}^{4} \frac{C_i}{R_i}$$

where *Ic* stands for the RAQI, an indicator of the aggregate pollution level of four pollutants, namely, SO2, NO2, PM10 and O3. With respect to SO2, NO2 and PM10, *Ci* means the daily average concentration while *Ri* represents the daily average concentration limit of the corresponding pollutants as specified in the Class 2 NAAQS (GB 3095 – 1996 – revised version). With respect to O3, *Ci* means the highest hourly average of a day while *Ri* represents the 1-hour average concentration limit in the Class 2 NAAQS. The Class 2 NAAQS (GB 3095 – 1996 – revised version) apply to residential, mixed commercial/residential, cultural, industrial and village areas. The concentration limits for various pollutants in the standards are listed in the table below.

Standard for various pollutants		
Pollutant	Sampling duration	NAAQS (GB 3095–1996–revised version) Class 2 standards (ug/m3)
SO_2	Daily average	150
NO_2	Daily average	120
PM_{10}	Daily average	150
O_3	Hourly average	200

A2. Apps and websites some examples

Apart from the CNEMC and various EMC/city websites there are several other sources of air quality information. In this annex I discuss some of the websites and apps displaying information on China. This is not meant as an exhaustive review and whatever was not available in English (or could be translated by Google Chrome) isn't discussed anyway.

A2.1 Apps

At the time of writing the IOS app store had four (English language) air quality apps for China. The review was done on the versions available on May 29 2013.

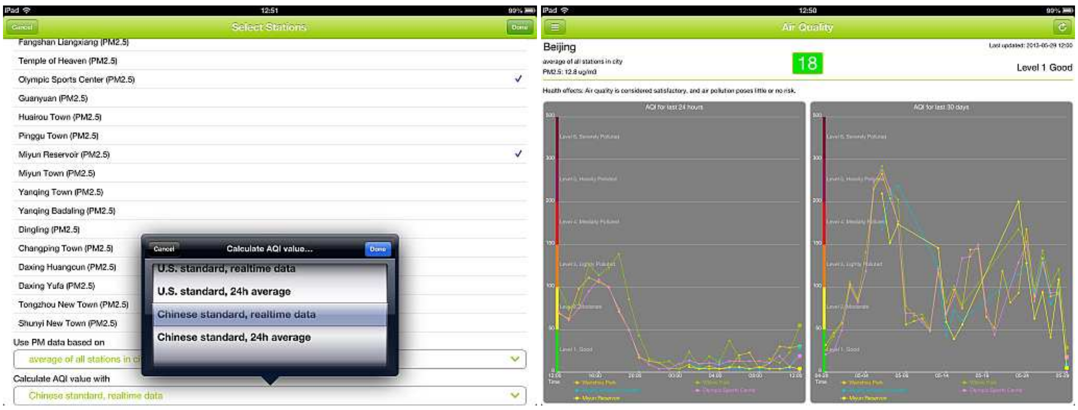
- The app **Beijing/Shanghai air quality** only presents data for either city in the name of the app. The data is obtained from the US consulate/embassy only and only covers $PM_{2.5}$. *Since other pollutants occasionally determine the index. So to present this as the AQI is wrong/misleading.* Access to the daily report of the BJEPB is offered as well. (In Chinese, functionality unclear to me). The AQI used (Chinese or US) is not clear but I suspect it is the US. In 2014 the access to BJEPB has disappeared.
- One app is simply called **$PM_{2.5}$** suggesting that it only deals with $PM_{2.5}$. However inside the app information is given for the full range of six pollutants (requires some navigation to find it) as a two day trend. [10] The trend information is accompanied by meteo information. The presentation is not very polished but is the most comprehensive combination of information that is released in all four apps. Data can be selected for a number of cities/monitoring sites. The fact that the background picture changes depends on the AQI level (from green park, blue sky, to muddy coloured scene with low visibility is a nice gimmick. The AQI used is not mentioned though I assume it is the US (brief check on levels and AQI). In 2014 the app has hardly developed and it doesn't work as smooth as it used to (with latest ipad OS?).
- **Air Quality** was an attractive app (2013) and currently (end 2014) is a very attractive and comprehensive app providing both MEP and US embassy/consulate data. All kind of selections are possible, cities can be compared; weather info is included. The app shows trends for the past hours, days and months. The app doesn't provide the calculation background so the user can't verify if the correct approaches were used for the hourly index calculation. A map with individual monitoring sites is provided and users can toggle between actual concentrations and the AQI.
  The fact that cities across china can be compared makes the app interesting, the possibility to access trends and see the situation in town for different pollutants makes the app interesting to play with. The app is useful for many of the communication objectives identified. It is also not clear which AQI is used (US or China). However it does provide background information for each pollutant, including health effects, and provides

[10] There seems to be a link to this app and the website http://www.aqicn.info/?map see next section. Perhaps the app taps into the website for information and graphics?

reference to both the Chinese and US AQI grids. Well documented. Some health advice is given (open windows, suitable for sports, etc.) though it doesn't follow the exact wording of the Chinese nor the US AQI[11]. *Very nice app, hard to beat!*

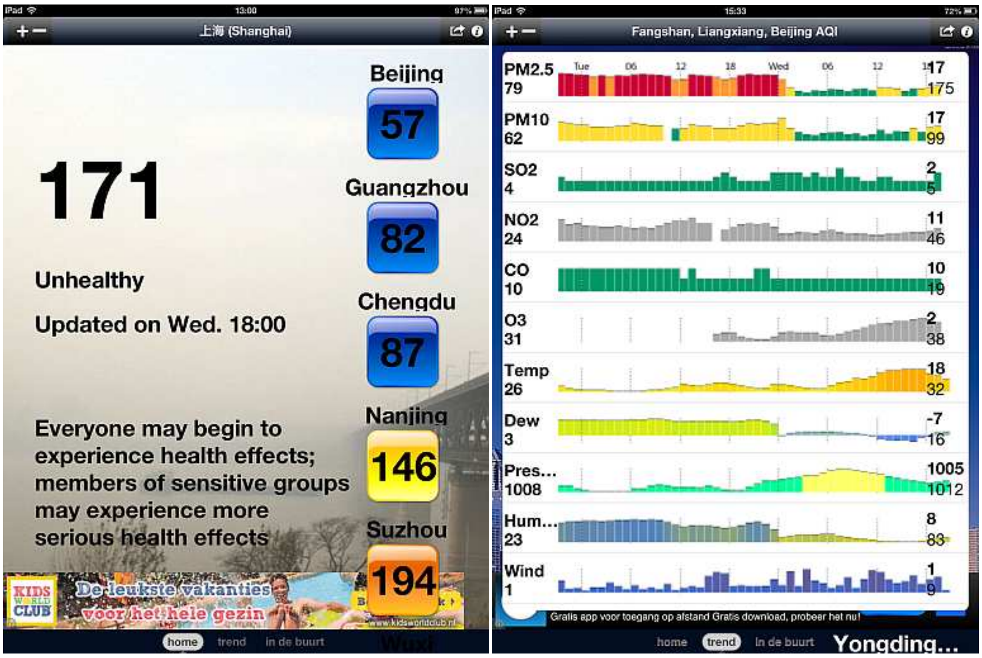
- **Air Quality China** is an attractive app providing both MEP and US embassy/consulate data. The user can select the cities and compare city averages to other Chinese cities. It shows nice graphs for monitoring sites for the last 24 hours and the last 30 days. You can select if the overall AQI shown is based on the city average, the average of your selection or the highest station in a city or the highest in your selection of monitoring sites. The app allows the user to select hourly and daily averaging times and the use of the US or the Chinese AQI (again a choice of four options). The displayed results don't show what AQI option was selected, so someone who wants to compare the two and switches settings often can be misled. Apparently the feature was not included to be used in this – interesting - way

The last two apps operate smoothly and have interesting features. NB: not all non-government apps are good/informative: I came across some dysfunctional and apps with a bad presentation and interface as well.



Air quality China: select your AQI options and the stations and city you want to see. Nice graphs with daily details and a monthly overview

[11] The ventilation advice is a risky as it might not be appropriate/correct. This was extensively discussed in the main text. Also the advice to wear/not to wear masks is questionable as only certain masks, and only if they are worn in the proper way, provide protection.



PM2.5: not the best interface but a very comprehensive set of data. Note that $PM_{2.5}$ drops sharply as humidity drops. This could be due to a change in wind direction (unfortunately not shown). Providing a whole range of information makes people understand what drives the occurring air pollution. The app apparently relies on bits of international code: some menu items (as well as the adds in the free version) are in Dutch.

Air Quality: rich in features, decide what you want to see on the map; relative rankings of cities and monitoring sites. Making cities comparable can be part of raising awareness. Health advice in this app is nicely displayed with text and graphics but the remarks on wearing masks and ventilation are not the official advice (and questionable in my view).

A2.2 Websites

- The website http://www.aqicn.info/?map allows the visitor to compare air quality in China to that in many other Asian countries in real time. This website (available since 2008?) used to have the Chinese API but has now switched to the US-AQI. The website has a FAQ section where questions received, are answered. You can leave comments, it has a poll, etc. so facilities for user interaction and feedback are available. All in all it is pretty complete in documenting what it does and where information comes from. The site is linked to the app $PM_{2.5}$ (see above).

It also provides information on a type of mask that is able to reduce $PM_{2.5}$ particles though it doesn't provide information on how to wear masks (as the US embassy website does).

The site is interesting as it allows the visitor to see air quality in Asia. By converting all raw measurement data that the site manages to obtain and presenting everything in the same AQI it assures that the data are comparable (assuming all calculations are done correctly and that true raw data is used). How the site manages monitoring data from areas where less than the full range of observations are used is not clear. As far as I know it is one of the few cross-border air quality comparison sites and the only one (?) covering Asia.

In 2014 this site now covers much of the world, including Europe and the US.

Other websites covering air quality in several countries at the same time:

- www.airqualitynow.eu (some 100 European cities - 2006)
- www.obsairve.eu (European monitoring data, supported by modelling - 2012)