Assessing air pollution risk potential: case study of the Tohoku district, Japan

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Abstract

The main purpose of the study was to propose the index of air pollution risk potential K_p, to prove its acceptability and to demonstrate the results of its application in a case study of the Tohoku district, Japan. K_p reflects climatic conditions, which are typical for a given area and determine both accumulation and dispersion of pollution in the atmosphere. Important applications of the index K_p are urban planning, industrial location in relation to sensitive areas and air quality management. The results of an index application can be easily interpreted, the number of the elements taken into account is quite small, however, it reflects the basic factors of the air pollution risk potential.
Keywords: air pollution, risk potential index, climatological analysis, weather appearance distribution.

1 Introduction

The worldwide evidence on airborne particulate matter and its impact on public health consistently shows adverse effects to exposures that are currently experienced by populations in both developed and developing countries. The epidemiological evidence shows impacts following both short-term and long-term exposures. Air pollution is caused by both natural and man-made sources. Major man-made sources of ambient air pollution include industries, automobiles, and power generation.

The pollution levels at any place and time represent balance between the rates of emission from their sources and the rate at which they are removed from the atmosphere [1]. The assimilative capacity of the atmosphere determines the dilution and dispersion of the pollutants. From the other hand, air pollutants can

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subsequently be deposited on the underlying surface and become a source of soil and water contamination [2].

The main purpose of the study was to analyze the role of climatological factors in the dispersal or diffusion of air pollutants released into the atmosphere of the Tohoku district of Japan and to propose the index of air pollution risk potential K_p in order to assist in industrial zoning as well as city/state or country industrial planning.

For air pollution transport with sources such as traffic, power station plumes, industrial plumes or plumes from accidents, most transport interest is within the atmospheric boundary layer (ABL). The ABL is the lower (500 to 1000 m) layer of the earth's atmosphere, which is influenced by the earth's surface shearing and heating effects.

Air pollution climatology explains the ability of the atmosphere to dilute or stagnate pollutants over a region at any time [3]. The principal meteorological variables important in the dispersion, transformation and removal of air pollutants, among others, are temperature, horizontal and vertical wind components, water vapor mixing ratio, precipitation, surface flux and boundary layer depth [4]. The majority of these variables change rapidly in the atmospheric boundary layer (ABL). On this basis (ABL) has a significant role in self-purification ability of the atmosphere. ABL controls the vertical extension, concentration and transformation of atmospheric pollution to some extent.

Dispersion of pollutants within the ABL is controlled by turbulence which varies strongly with stratification. Maximum mixing depth that is the height in which pollutant can have a vertical movement up to and partially into inversion layer, has a direct relation with ABL [5]. In other words, mixing depth is a critical parameter in determining air pollution concentrations near the ground which represents the depth through which pollutants are vigorously mixed. This parameter is highly important because using such data and the wind speed profiles, the corresponding "ventilation properties" can be calculated [4].

Dry air expanding adiabatically cools at a rate of 9.8°C/km or ~l°C/100m. This is known as "dry adiabatic lapse rate" (DALR) that is the reference lapse rate by which the "ambient lapse rate" is compared. A "neutrally stable" atmosphere occurs when the ambient lapse rate (ALR) is equal to the dry adiabatic lapse rate (DALR); i.e. the rate of cooling with altitude is ~ 1°C/100 m. An "unstable" atmosphere occurs when the ambient lapse rate exceeds the dry adiabatic lapse rate, i.e. the rate of cooling with altitude is > l°C/100m. This steeper temperature gradient encourages greater thermal turbulence. This ambient condition is said to be "unstable" with a "superadiabatic" lapse rate. A "stable" atmosphere occurs when the ambient lapse rate is less than the dry adiabatic lapse rate, i.e. the rate of cooling is < 1°C/100m. The temperature gradient is less steep and thus responsible for less turbulent activity. The ambient condition is said to be "stable" with a "subadiabatic" lapse rate [6].

A "stable inversion" condition is a variant of the stable atmosphere. Here, the temperature increases with altitude. An inversion temperature condition is a very stable condition, forcing air pollutants to remain trapped in the atmosphere for long periods [7].

Under stable atmospheric conditions the mixing height can drop to less than a hundred meters. This can trap pollutants in a very thin layer near the ground and result in high concentrations. Pollutants trapped above the mixing height also can cause high concentrations when the mixed layer at the ground lifts and suddenly brings the pollutants to the ground.

It is obviously important in predicting pollutant dispersion to know the speed and direction of wind. The variation of the horizontal wind speed with height is important in evaluating diffusion of pollutants [8].

When pollutant concentration is low and precipitation is high, the air pollution level is low since the rain will be able to thoroughly wash all the pollutants away. When aerosol concentration is high and precipitation is high, the air pollution is still manageable since the rain will still have enough moisture to wash most of the aerosol away from the atmosphere. It is when aerosol is high and precipitation is low, the condition of air pollution will be the worse.

Based on the results of the previous studies [9–11] we propose the index or air pollution risk potential K_p. The index includes both favorable and unfavorable meteorological conditions that determine the air pollution risk.

Unfavorable for atmospheric ventilation meteorological conditions are wind velocity of V < 1 m/sec; vertical temperature gradient in the lower (500 m) layer of the atmosphere of $\gamma^{0.5} \leq 0.4°/100$ m and amount of precipitation of Q ≤ 1 mm. In contrast, favorable meteorological conditions are V > 3 m/sec, $\gamma^{0.5} \geq 0.8°/100$ m and Q ≥ 3 mm.

The associations between $\gamma^{0.5}$ and surface temperature differences at 6 and 9 p.m. $(\Delta T_{18,21})$, at 9 p.m. and daily minimal temperature $(\Delta T_{21,\min})$, daily maximum and minimal temperatures $(\Delta T_{\min,\max})$ were investigated [10]. The highest correlation was obtained between $\gamma^{0.5}$ and $\Delta T_{\min,\max}$, $r = 0.64$.

Thus, in the proposed index of air pollution risk potential (APRP) the probability $P(\gamma^{0.5} \leq 0.4°C/100m)$ was replaced with the probability $P(\Delta T_{\min,\max} \geq 9°C)$, and the probability $P(\gamma^{0.5} \geq 0.8°C/100m)$ was replaced with the probability $P(\Delta T_{\min,\max} \leq 5°C)$. Then the equation for calculation of the APRP index (K_p) is looking as follows:

$$K_p = \frac{P(V \leq 1.0) + P(\Delta T_{\min,\max} \geq 9.0) + P(Q \leq 1.0)}{P(V \geq 3.0) + P(\Delta T_{\min,\max} \leq 5.0) + P(Q \geq 3.0)} \quad (1)$$

The probabilities P in the given equation can be replaced with the number of days with the mentioned values of variables under consideration.

Then, the APRP index is looking as follows:

$$K_p = \frac{N_w + N_t + N_q}{M_W + M_t + M_q} \quad (2)$$

where N_w is the number of days with calm wind (V≤1 m/s); N_t is the number of days with daily temperature gradient ≥ 9ºC; N_q is the number of days with precipitation ≤ 1 mm; M_w is the number of days with wind speed ≥3 m/s; M_t is the number of days with daily temperature gradient ≤ 5ºC; M_q is the number of days with precipitation ≥ 3 mm.

The values of K_p reflect climatic conditions, which are typical for a given area and which determine both accumulation and dispersion of pollution in the atmosphere. The following index rates were calculated: K_p = 0.3 – 1.0 is a low risk potential, K_p = 1.0 – 2.0 is moderate, K_p = 2.0 – 5.0 is high, and K_p > 5.0 is very high. The higher is the K_p value the worse conditions are for the pollution dispersion and removal. If the value of K_p < 1 then the self-purification process exceeds the accumulation of pollutants in the atmosphere.

Index K_p was applied for defining the potential air pollution risk zones in the Tohoku district, Japan. The following section briefly describes the weather variables distribution in the Tohoku region with the special focus on those included into the index of air pollution risk potential.

2 A climatological analysis of the weather variables distribution in the Tohoku district

Tohoku is a geographical area of Honshu, largest island of Japan. This region is also called Ou and is even referred as Michinoku. The region occupies about one - fifth of the total area of Japan. It is located on the northeastern part of Honshu. Tohoku comprises of six prefectures - Akita, Aomori, Fukushima, Iwate, Miyagi and Yamagata Prefectures.

The topography of the Tohoku district is very complicated. The Ou mountains as the backbone range run through the district north to south, dividing it into the Pacific side and the Japan Sea side. On the Japan Sea side, the Dewa hills and the Echigo mountains run north to south parallel with the backbone range, making may basins between them. On the Pacific side, the Kitakami mountains and Abukuma mountains run parallel with the backbone range. According to the land feature, weather distribution shows complicated pattern in the Tohoku district.

Two primary factors influence Tohoku's climate: a location near the Asian continent and the existence of major oceanic currents. The climate of Tohoku is influenced by the monsoon, especially in winter. The winter monsoon out of Siberia is characterized by high pressure and polar continental air that is greatly modified by the warm Japan Sea in its eastward progress. Frequent snow and cloudy conditions, therefore, are the norm in the windward Tohoku Japan Sea side, while sunny, dry weather prevails on the Pacific side. Dominant weather factor for most of the country during summer is the Ogasawara High, a lower tropospheric anticyclone, associated curved trade winds from the tropics which constitute the summer monsoon. In fact, 70 to 80 percent of the annual precipitation falls in the period between June and September [12].

Two major ocean currents affect this climatic pattern: the warm Kuroshio Current (Black Current; also known as the Japan Current); and the cold Oyashio (Parent Current; also known as the Okhotsk Current). The Kuroshio Current flows northward on the Pacific side of Japan and warms areas as far north as Tokyo; a small branch, the Tsushima Current, flows up the Sea of Japan side. The Oyashio Current flows southward along the northern Pacific, cooling adjacent coastal areas.

The characteristics concerning the weather appearance are described according to five regions. They are as follows [13]:

1) The coastal region along the Japan Sea and 2) coastal region along the Pacific Ocean. The side of the country which faces the Sea of Japan has a climate with much rain and snow, produced when cold, moisture-bearing seasonal winds from the continent are stopped in their advance by the Central Alps and other mountains which run along Japan's center like a backbone. In winter, the Japan-Sea coast is exposed to the northwestern monsoon with the mountain in the background. It is, therefore, considered that the distribution of the amount of precipitation in proximity to the Japan Sea coast is not yet complicated by landform but correlates with circulation patterns in the Far East.

The Pacific Ocean side of the Tohoku region belongs to the temperate zone and its summers are hot, influenced by seasonal winds from the Pacific.

Temperature differences between the Japan Sea and the Pacific sides of the Tohoku district exist not only because of weather conditions, but coastal configuration and the effect of ocean currents as verified by sea surface temperatures as well. Indeed, coastal configuration and ocean currents may be of primary significance in affecting temperatures.

3) The western slopes in Echigo mountains and in the northern part of the Ou mountains. These regions have highest frequency of snowy weather throughout the Tohoku district. As these regions are fully exposed to the W-NW monsoon, snowy weather is frequently seen in every flow-pattern in the winter type pressure pattern. Cloudy weather is not so frequent that the number of fine days in the slopes is larger than in the Japan Sea coast. In these slopes, it snows always when it snows anywhere in the western side of the backbone range, because almost all of the snowing in this side appears as the extension of the snowing in each of the slopes. In this sense, both slopes form the original areas of snowy weather in the Tohoku district.

4) The group of basins in the western side of the backbone range. The appearance frequency of every kind of weather varies with basins, because the topographical conditions of each basin is different each other. The cloudy or snowy weather of the Japan Sea coast tends to spread over the Hirosaki basin and seldom spreads to the basins of Yamagata, Yonezawa and Aizu. Anyway it is frequently snowy and seldom fine in the basins of Shinjo and Obanazawa and in the Aomori region, and in both the basins of Yokote and Yonezawa only in the winter-type pressure pattern. It is less snowy and more fine in both the basins of Yamagata and Aizu.

5) Inland regions on the eastern side of the backbone range. In these regions, on the leeside of the backbone range, snowy or cloudy weather with wide

extension is rarely seen in mid-winter, because the backbone range interrupts the eastward extension of the weather. They have more of fine weather than the opposite side of the range.

Since the shelter-effect by the back born range does not work at the lowered saddles in the back born range, snowy or cloudy weather on the western side extends occasionally eastward through the parts. The regions at such a location are the region around Okunakayama, the regions of Hanamaki and Mizusawa, Sempoku plain the Fukushima basin, and the Koriyama basin. The frequency distribution of snowy weather appearance, which is characterized by the pattern that snowy weather is comparatively frequent in these region when the weather is seen in any place (here Fukushima) leeward of the saddle-like part.

There have been several studies of the observed air temperature profiles over mountain slopes compared with nearly free-air temperatures [14, 15]. According to these reports, temperature differences between mountain-air and free-air exhibit considerable variability as related to season, the type of air mass (i.e., wind direction, wind speed), the time of day (i.e., radiative and turbulent heat exchanges), cloud amounts, and the existence of snow-cover. The primary control of the temperature difference between free-air and summit-air appears to be the atmospheric temperature structure related to the lapse rate and adiabatic lapse rate.

Most of the mountain-air temperatures exhibit larger variations than the free-air temperatures. The sequence of temperature differences (mountain-air minus free-air) of each mountain can be divided into three groups which have a positive, negative and mixed sense of the temperature difference. When the Ogasawara high extends over Japan, large positive temperature differences are found in the central part of the mountainous region.

With respect to the spatial variations of the differences, they appear to clearly change with latitude. Negative or small differences are predominant in the higher latitudes, near the coast of the Japan Sea, and in the lower latitudes, close to the Pacific Ocean. In the central mountainous region, however, the sense of the difference is positive. It appears that heating of the mountain surface plays an important role in this temperature distribution pattern, since this pattern becomes sharper under the conditions of the well-developed Ogasawara high.

3 Calculation of air pollution risk potential index in the Tohoku district

Numerous climatological studies of Japan stress monsoonal influences on self-purification ability of the atmosphere in winter and in summer as well. The most unfavorable for air self-purification are summer climatic conditions with Ogasawara High as dominated weather factor for most of the country and associated stable stratification and curved trade winds from the tropics which constitute the summer monsoon.

To calculate the air pollution risk potential index we used daily minimum and maximum surface air temperature, wind velocity and amount of precipitation data in January and August at 18 weather stations in the Tohoku district, compiled by the Japan Meteorological Agency (JMA), 1978-1998 [16].

In winter the Japan Sea side of the Tohoku district are characterized with low APRP index values K_p =0.3-1.0. These index values are presented in western, north-western and northern part of the district. The winter monsoon out of Siberia brings frequent snow and cloudy conditions to the windward Tohoku Japan Sea side, while sunny, dry weather prevails on the Pacific side. Since the cyclones developing in the Pacific polar frontal zone pass along the east coast of Asia to the northeast, the polar air out-breaks behind cyclones. In the season, therefore, the current from Siberia is not stationary, but the period of violent blow appears alternately. A cold, dry, continental polar air from Siberia is much modified over the Japan Sea, and becomes warm, moist and unstable after passing the Japan Sea.

Islands of Japan lie athwart the air-stream, the Japan Sea side of the Islands is exposed to it, and the Pacific side is sheltered by the relief of mountains. In winter the moderate APRP index is presented on the Pacific coast of Tohoku K_p =1.0-2.0. In winter it snows frequently on the former wind-ward side, but it is usually dry, sunny and fine on the latter leeside with high daily temperature gradients. As it was already marked, high daily temperature gradients result in increasing of stability of stratification of a ground layer of an atmosphere, and consequently, in increasing of potential of air pollution.

There are two regions of the Tohoku district with high APRP index in winter K_p >2. These are the areas of Yamagata City and the basin of Abukuma river.

Very high values of the APRP index in winter (K_p >5) appear also on the Pacific Ocean side near Miyako City. The temperature in Miyako City and the regions north of this city tend to drop due to effects from the cold current Oyashio which results in a more stable stratification of the atmosphere. Also, this region is located in the basins of Kawaki river, sheltered with Kitakami mountains from NW air masses.

Summer weather conditions of the Tohoku region are less favorable for self-purification of the atmosphere than winter weather because of the influence of Ogasawara High that is characterized with high thermal stability and low wind velocities.

In summer the low values of risk potential are shown for the Japan Sea coast K_p =0.3-0.1. Summer season on the Japan Sea coast is characterized with a high amount of precipitation (Q = 100 мм). On the Pacific Ocean side of the district the major part of Miyagi prefecture is characterize by low values of the APRP index in summer.

Low APRP index values are also presented in the plain Mutsu that occupies most of the Shimokita Peninsula. It has a cold maritime climate characterized by cool summers and cold winters with heavy precipitations (Q =130 mm) resulted from Ogasawara High influence.

The major part of the Pacific Ocean side in summer is characterized with moderate values of the APRP index (K_p =1.0-2.0). These values are the results of the combination of stable stratification of the atmosphere and large amount of precipitations.

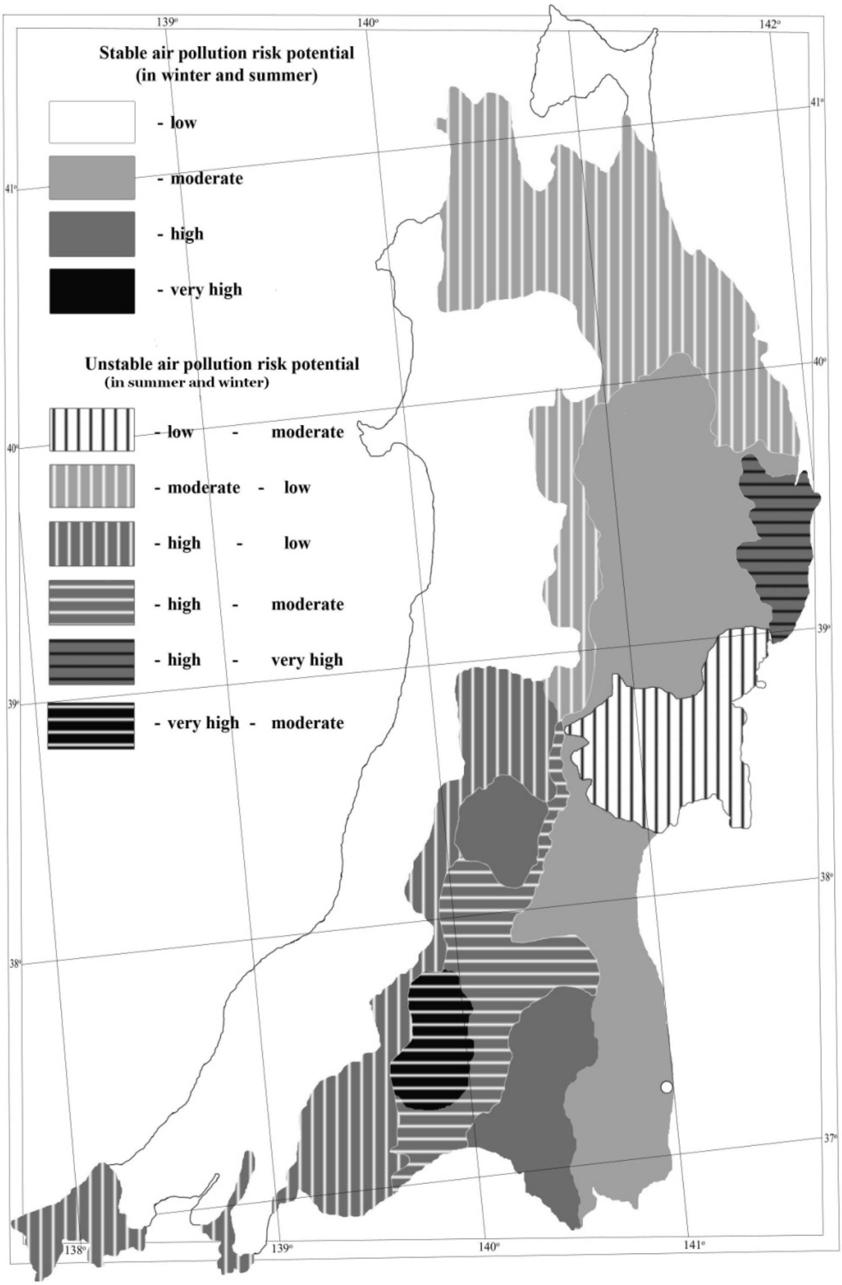

Figure 1: APRP index values, Tohoku district, Japan.

The central part of the Tohoku district in summer is characterized with high values of the APRP index ($K_p > 2.0$). This is the result of the combination of meteorological variables under study – stable stratification of the atmosphere, low wind velocities (V = 0.2–1.2 m/sec) and low amount of precipitation (Q=80 mm). In summer high values of the APRP index appear on the Pacific Ocean side near Miyako City.

Very high values of the APRP index in summer ($K_p \geq 5.0$) appear in Wakamatsu basin, first of all, because it is sheltered by the relief of mountains.

The combination of winter and summer APRP index values is presented in Figure 1. The regions with stable and unstable air pollution risk potential appear within the Tohoku district. The stable low APRP index values appear on the Japan Sea side of the Tohoku district and the Shimokita Peninsula. The stable moderate APRP index values appear on the northern part of the Pacific Ocean coast of Tohoku. The stable high APRP index values appear in the Yamagata and Koriyama basins.

The central and north-eastern parts of the Tohoku district are characterized with unstable APRP index values in winter and summer seasons. The summer values of the APRP index are marked with colors, the winter values are marked with shadings.

4 Conclusion

The assimilative capacity of the atmosphere determines the dilution and dispersion of the pollutants. The most important atmospheric conditions are wind speed, amount of precipitation and the vertical temperature characteristics of the local atmosphere.

The index of air pollution risk potential was proposed. It is calculated on the base of the unfavorable and unfavorable for air self-purification values of climatic variables.

Index K_p was applied for defining the potential air pollution risk zones in the Tohoku region, Japan. K_p reflects climatic conditions, which are typical for a given area and which determine both accumulation and dispersion of pollution in the atmosphere.

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