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Geoinformation Technologies and Spatial Analysis of Carbon Dioxide Transport Through Border Line

Geoinformation technologies and methods of spatial analysis of emissions in the border regions have been developed and GIS based software has been created for estimating mass of carbon dioxide (CO_2) emissions that goes through border line. Described mathematical models of processes of CO_2 emissions in the energy sector in the border regions take into account the meteorological data. Spatial analysis of carbon dioxide transport processes has been done for Ukrainian – Polish border zone in consideration with wind rose.

Introduction

It is very important to have full information about country's greenhouse gases (GHG) emissions for participating in new international obligations concerning reducing and monitoring emissions, verification and fulfillment of economical and ecological commitments. Main sources of emissions/absorptions processes are located very irregularly on country territory. Analysis of spatial distributions of GHG emissions from different sectors of human activities on regional level is useful and valuable for projecting effective nature protecting tools, study the ways of reducing emissions and uncertainties of GHG inventories.

Already existed mathematical models of processes of GHG emissions in the energy sector do not consider atmospheric diffusion and influence of wind profile. So development of mathematical models that will take into account these factors is relevant task. **The aim of research** is to develop mathematical models of processes of GHG emissions in Energy sector in the western regions bordering Ukraine, taking into account gas transportation, to be more detailed – models, that will give an opportunity to calculate the amount of carbon dioxide that goes through fixed border line.

Carbon dioxide (CO_2) properties

CO_2 is a naturally occurring gas in the atmosphere and one of the main greenhouse gases as it transmits visible light but absorbs strongly in the infrared and near-infrared. CO_2 is also a pollutant, as it is toxic in higher concentrations: 1 % (10,000 ppm) will make some people feel drowsy. Concentrations of 7 % to 10 % cause dizziness, headache, visual and hearing dysfunction, and unconsciousness within a few minutes to an hour.

The behavior of dense gases such as CO_2 can be quite different than for passive tracers (with neutral buoyancy) due to density effects. For example, a plume of CO_2 will spread laterally over flat terrain even in the absence of wind because it is denser than the surrounding air [1]. A concentrated CO_2 plume will generally hug the ground and cross terrain contours to reach the lowest elevation. Driven by density effects, a CO_2 plume will spread more quickly than a neutrally-buoyant gas which spreads only through diffusion, giving the counter-intuitive result that ground level concentrations can drop more quickly for a dense gas than for a passive gas tracer under calm conditions [2]. The dispersion of CO_2 is highly dependent on ambient winds. In weak winds, density (buoyancy) effects dominate the dispersion process; in high winds, the gas begins to act more as a passive pollutant, with the ambient wind overwhelming density effects. Topographic depressions inhibit the movement of the CO_2 plume under weak winds. At wind speeds of greater than 2 m/s, the plume is quickly swept out of the domain and diluted, even for rolling hills of amplitude 50 m [1].

Mathematical background

Mathematical model that consider physical properties of carbon dioxide has been built. It involves two cases: windy and calm conditions.

Data required:

- meteorological data including annual average wind rose;
- emission data (mass of carbon dioxide in Gg, source coordinates);
- border line divided into elementary line type objects and their coordinates.

At any point and any time moment wind can be represented as a vector having a direction and value (speed). Although the wind has three dimensions, it is common only to consider the horizontal components of the wind. The wind direction is the direction from which the wind comes. The wind is considered in meters per second, m/s, and at the vertical height of 10 meters about ground.

The mass of carbon dioxide that goes through border line is directly proportional to the emission rate. It is therefore important to use emission rates that are as accurate as possible. Calculated emissions in Energy sector from every elementary area object of investigated regions are used as sources of emission [3].

Using digital map the Ukrainian – Polish border line was divided into elementary line objects. In order to estimate mass of carbon dioxide that transports through border line there were made assumptions [2], [4]:

- Mass that is emitted from the source is assumed to remain in the atmosphere. None of the gas is removed through chemical reaction nor is lost at the ground surface through reaction, gravitational settlings, or turbulent impaction.
- Steady – state conditions: meteorological conditions are assumed to persist unchanged with time, over the time period of transport from the source to elementary line object of border line.
- The average mass profiles at any distance in the crosswind direction, horizontal (perpendicular to the pass of transport) are well represented by a Gaussian, or normal distribution.
- Mass of gas that goes through border line is assumed to be direct proportional to concentration on border line.
- Surface roughness is not considered.

The Gaussian distribution is used to describe the crosswind and vertical distributions that result from turbulent mixing that causes dispersion [4], [5]. The height of this curve is described by following function:

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp[-\frac{(x-\mu)^2}{2\sigma^2}], \tag{1}$$

where μ is the *x* position where the center of the distribution occurs. The magnitude of the peak of the distribution is $\frac{1}{2\pi}$. The shape of the distribution in the horizontal, whether narrow or broad, is determined by the magnitude of standard deviation, σ. The principle disadvantage of the Gaussian distribution is that it extends from $-\infty$ one side to $+\infty$ on the other. Real plume spreading will be finite. However, from a practical standpoint, the height of the Gaussian distribution is very small beyond the limits of $\pm 4\sigma$ [4].

It is assumed that *x* axis is oriented in the wind direction The *y* axis is oriented in crosswind direction.

As mass rate of CO_2 that passes through border line is directly proportional to gas concentration, the next formula takes place:

$$M(x, y) = K_v * c(x, y), \tag{2}$$

where *M* (*x, y*) is the distribution of mass in crosswind direction, g/m; K_v is the coefficient which value depends on effective volume of gas plume, m^2; *c*(*x,y*) is the gas concentration in crosswind direction, g/m^3.

Instantaneous gas concentrations in crosswind direction can be described by formula:

$$c(x, y) = \frac{2M_E}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} e^{-\frac{y^2}{2\sigma_y^2}}, \tag{3}$$

where M_E is the total mass of emissions in g; σ_x is the standard deviation of concentration distribution in the puff in the upwind-downwind direction; σ_y is the standard deviation of concentration distribution in the crosswind direction, m, at the downwind distance *x*; σ_z is the standard deviation of concentration distribution in the vertical direction, m, at the downwind distance *x* [4].

The speed of the wind mainly serves to give the download position of the center of the puff. Wind speed may influence the dispersion indirectly because the dispersion parameters $\sigma_x, \sigma_y, \sigma_z$ may be functions of wind speed. Much less is known of dispersion in the upwind-downwind direction than is known of lateral and vertical dispersion. In general, one should expect the σ_x to be the same as σ_y.

For calculation of σ_y and σ_z parameters based on measurements of atmospheric turbulence over flat plains are used. As it has been observed when air is stable, vertical mixing is inhibited, and when there is strong solar heating of the surface, there may be strong convective activity with large vertical motions. There have been produced empirical results for the variation of σ_y and σ_z for six stability classes: A – extremely unstable, B – moderately unstable, C– slightly unstable, D – neutral, E – slightly stable, F – moderately stable.

Guidelines are given for estimating the stability class from wind speed, cloud cover and time of day in Table 1.

Table 1 – Guidelines for determining Pasquill – Gifford stability classes [4]

Surface wind speed, m/s	Day with insolation			Night	
	Strong	Moderate	Slight	Overcast $\geq 4/8$ low cloud	$\leq 3/8$ cloud
2	A	A – B	B	–	–
2 – 3	A-B	B	C	E	F
3 – 5	B	B – C	C	D	E
5 – 6	C	C – D	D	D	D
6	C	D	D	D	D

Approximate power-law functions (4) can be specified for quasi-instantaneous sources corresponding to the Pasquill stability classes [4] (Table 2).

$$\sigma_y = ax^b, \sigma_z = cx^d. \tag{4}$$

Table 2 – Quasi-instantaneous Power Functions [4]

Pasquill stability	a	b	σ_y 100 m	σ_y 4 km	c	d	σ_z 100 m	σ_z 4 km
A	0,18	0,92	12,45	371	0,72	0,76	23,8	393
B	0,14	0,92	9,69	288	0,53	0,73	15,3	226
C	0,1	0,92	6,92	206	0,34	0,72	9,4	133
D	0,06	0,92	4,15	124	0,15	0,70	3,8	50
E	0,045	0,91	2,97	85	0,12	0,67	2,6	31
F	0,03	0,90	1,89	52	0,08	0,64	1,5	16
“G”	0,02	0,89	1,21	32	0,05	0,61	0,8	8

If to substitute the valuable *c* (*x, y*) (formula (3)) into formula (2):

$$M(x,y) = K_v * \frac{2M_E}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} e^{-\frac{y^2}{2\sigma_y^2}}. \tag{5}$$

The area under curve $M(x,y)$ is assumed to be equal to M_E, total mass of emissions (see Figure 1):

$$M_E = \int_{-\infty}^{\infty} M(x,y)dy$$

or

$$M_E = \int_{-\infty}^{\infty} K_V * \frac{2M_E}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}. \tag{6}$$

From (6):

$$K_V = \pi\sigma_x\sigma_z.$$

Final formula for mass distribution in crosswind direction is:

$$M(x,y) = M_E * \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2\sigma_y^2}}.$$

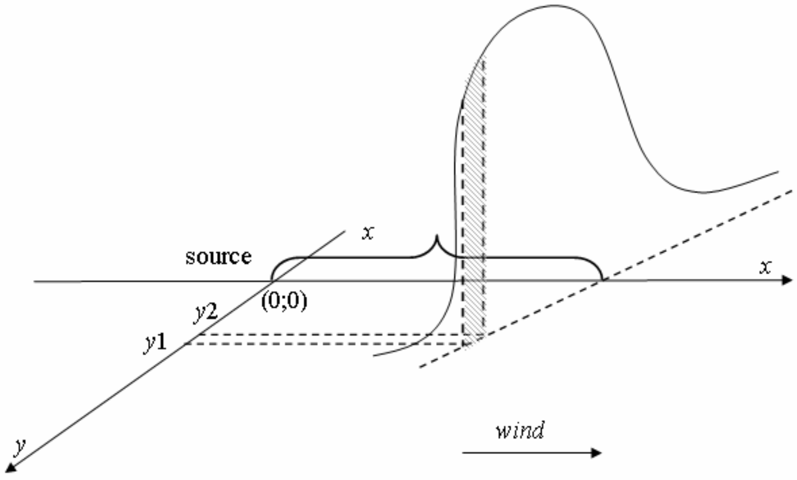

Figure 1 – Mass distribution in crosswind direction

Mass that goes through elementary line object $M_{gas}(x,y_1,y_2)$ (see Figure 1) can be estimated by following formula:

$$M_{gas}(x,y_1,y_2)=\int_{y_1}^{y_2} M_E * \frac{1}{\sqrt{2\pi\sigma_y}} e^{-\frac{y^2}{2\sigma_y^2}}. \tag{7}$$

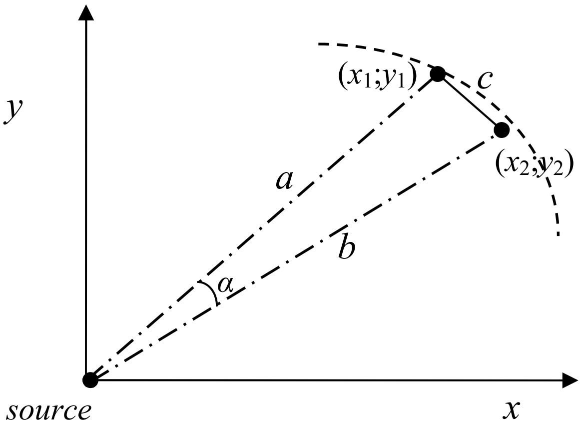

Figure 2 – Mass distribution in case of calm conditions

In case of calm conditions the average mass profiles at any distance in any direction cannot be represented by a Gaussian curve. So it is assumed that mass of gas has even distribution in all directions.

Mass of carbon dioxide that passes elementary line object is directly proportional to the value of angle α (in radians) that is created by two radii drawn from the ends of line object to source as it is shown in Figure 2. Using cosine rule, here the formula (8) for estimating rate of mass:

$$M_{gas}^{calm}(a,b,c)=M_E \frac{\arccos\left(\frac{a^2+c^2-b^2}{2ac}\right)}{2\pi} \tag{8}$$

where M_{gas}^{calm} is the mass of gas in calm conditions; *a,b* are the radii connected source centre and ends of elementary line object, *m*; *c* is the length of elementary line object, *m*.

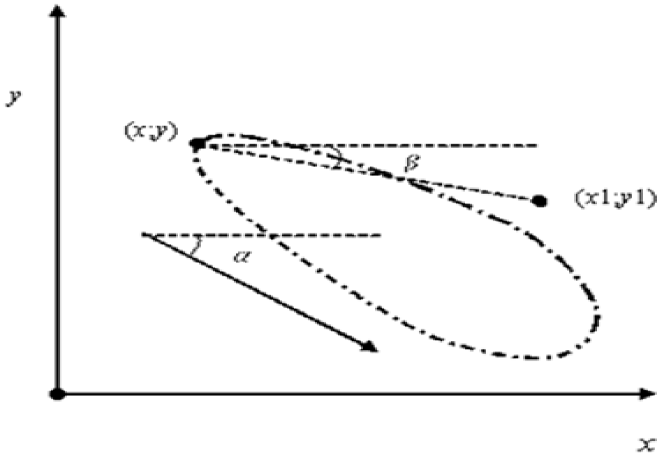

Figure 3 – Moving from coordinate system of digital map to another one with centre in the source of emissions and *x* axis oriented in the wind direction

As in practice there is a need to work with big number of sources of carbon dioxide emissions and different wind directions, so there were developed formulas below (9) – (10) for moving from one coordinate system of digital map to another with center in source of emissions and x axis oriented in the wind direction.

Variables in Figure 3: x,y are the coordinates of emission source in "old" coordinate system; x', y' are the new coordinates with centre in source of emissions and axis x oriented in the wind direction; (x_1,y_1) are the coordinates of ends of line type object in map coordinate system; α is the angle between wind direction and x axis; β is the angle between vector, connected source and receptor, with x axis.

$$x_1' = a\cos(\beta-\alpha), y_1' = a\sin(\beta-\alpha), \tag{9}$$

where (x_1', y_1') are the coordinates of ends of line type object in new coordinate system with centre in source point and axis x oriented in wind direction.

The value of angle β can be calculated using formulas (10):

$$\beta = \begin{cases} arctg\dfrac{y_1-y}{x_1-x}, x_1 > x, y_1 > y; \\ \pi - arctg\dfrac{y_1-y}{x_1-x}, x_1 < x, y_1 < y; \\ 2\pi - arctg\dfrac{y_1-y}{x_1-x}, x_1 > x, y_1 < y; \\ \pi - arctg\dfrac{y_1-y}{x_1-x}, x_1 < x, y_1 > y; \\ \dfrac{\pi}{2}, x_1 = x, y_1 > y; \\ \dfrac{3\pi}{2}, x_1 = x, y_1 < y; \\ 0, x_1 > x, y_1 = y; \\ 2\pi, x_1 > x, y_1 = y. \end{cases} \tag{10}$$

Numerical modeling

For estimating mass that goes through border line as input data there were used average annual wind rose for western Ukrainian regions (wind speed, and direction with frequency), and digital maps with information about carbon dioxide emissions in Energy sector of western regions in Ukraine on elementary objects level [1].

The tools of geoinformation system (GIS) MapInfo was used. Additional menu was created on the panel, based on developed mathematical model, and programmed on MapBasic. It gives opportunities to build border line, select border zone of fixed width with emissions sources, and calculate mass that passes through selected border line (see Figure 4).

For calculations the Ukraine – Polish border line was chose and border zone with 100 km width was selected. As a result the digital map with information about mass of carbon dioxide that goes through border line on elementary object level was created. Figure 5 shows the distribution of mass of carbon dioxide that goes through Ukraine – Polish border line on elementary line object level from south to north.

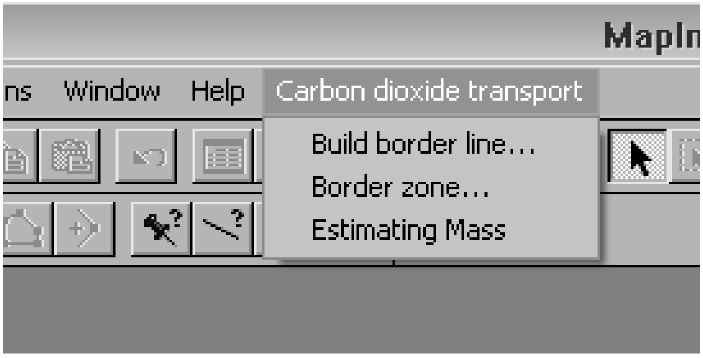

Figure 4 – MapInfo menu

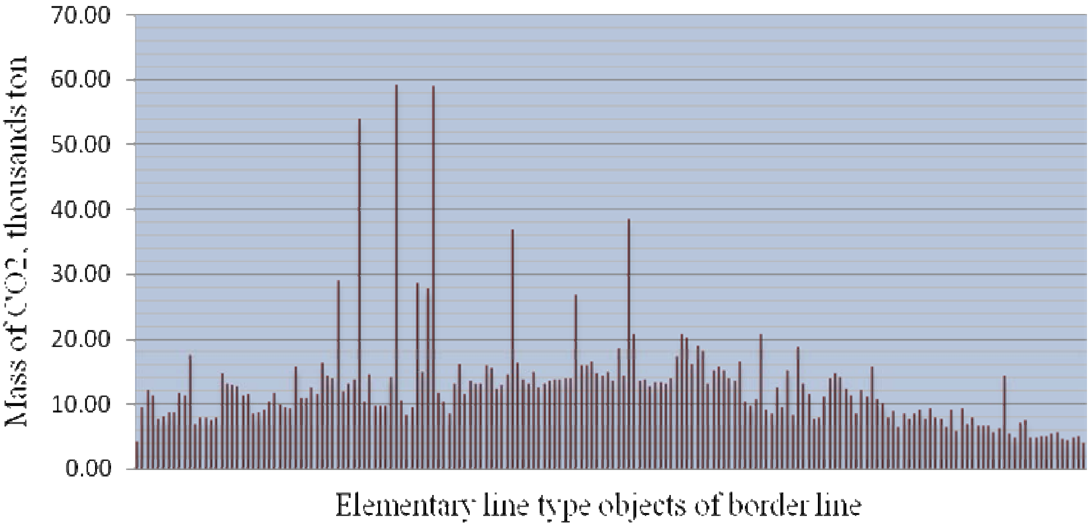

Figure 5 – Mass distribution of CO_2 across border line from south to north

Conclusions

Created mathematical model that takes into account meteorological data and is based on geoinformational technologies gives the opportunity to estimate rate of mass of carbon dioxide that goes through border line. Made estimations for Ukrainian – Polish border line and border zone with 100 km width show that only 15 % of CO_2 emitted in this zone are transported through border line from Ukraine to Poland. Creation of common geoinformation system for GHG spatial inventory, and formation of georeferenced databases with input data and inventory results for Ukrainian – Polish border regions is in perspective. Developed methods and geoinformation technologies can be used for estimating mass that transports through border line as well.

References

1. Chowa F.K. Modeling the effects of topography and wind on atmospheric dispersion of CO2 surface leakage at geologic carbon sequestration / Fotini K. Chowa, Patrick W. Granvolda, Curtis M. Oldenburgb // Greenhouse Gas Control Technologies 9 (GHGT-9), Energy Procedia. – University of California: Berkeley Published by Elsevier Ltd., 2009. – Vol. 1, Issue 1. – P. 1925-1932.

2. Good practice guide for atmospheric dispersion modelling / Prepared by the National Institute of Water and Atmospheric Research, Aurora Pacific Limited and Earth Tech Incorporated for the Ministry for the Environment. – Ministry for the Environment, 2004. – 142 p.
3. Hamal Kh. Geoinformation technology for spatial analysis of greenhouse gas emissions in Energy sector : thesis for a candidate's degree : 05.13.06 / Khrystyna Hamal. – Lviv : Lviv Polytechnic National University, 2009. – 246 p.
4. Turner D.B. Workbook of atmospheric dispersion estimates: an introduction to dispersion modelling / D. Bruce Turner. – Boca Raton, Florida, USA: CRC Press, 1994. – 194 p.
5. Markiewicz M. Mathematical modelling of heavy gas dispersion / M. Markiewicz / Models and techniques for health and environmental hazards assessment and management. Part 2. – Air Quality Modelling. – Institute of Atomic Energy, Otwock-Swierk, Poland, 2006. – P. 281-299.

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Геоинформационные технологии и пространственный анализ процессов переноса диоксида углерода через границу

Описаны геоинформационные технологии и методы пространственного анализа эмиссий парниковых газов в приграничных регионах и создано программное обеспечение для численного моделирования процессов переноса диоксида углерода через границу. Предложенные математические модели процессов эмиссии углекислого газа в энергетическом секторе западных регионов Украины для вычисления перемещения атмосферных масс учитывают метеорологические условия, а именно – розу ветров. Пространственный анализ эмиссий углекислого газа был сделан для украинско-польской пограничной полосы.

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Геоінформаційні технології та просторовий аналіз процесів переносу діоксиду вуглецю через кордон

Описано геоінформаційні технології та методи просторового аналізу емісій парникових газів в прикордонних регіонах та створено програмний засіб для числового моделювання процесів переносу діоксиду вуглецю через лінію кордону. Запропоновані математичні моделі процесів емісії вуглекислого газу в енергетичному секторі західних регіонів України для обчислення переміщення атмосферних мас враховують метеорологічні умови, а саме – розу вітрів. Просторовий аналіз емісій вуглекислого газу зроблено для українсько-польської прикордонної смуги.

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