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Modified Gaussian plume model and K-transport and diffusion model efficiency in the same atmospheric conditions

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The aim of this paper is to compare the modified Gaussian plume model and K-model for continuous emission sources in weakly orographically developed regions. Parametrization of input variables is based on the physical methods using similarity theory.

The results show that, when strong winds and stable atmosphere are present, ground level concentrations take similar values. In contrary, when weak winds and unstable atmosphere are present, K-model overestimates values given by Gaussian model due to exclusion of plume rise in the process of diffusion parametrization.

Efikasnost modificiranog Gaussovskog i K-modela transporta i difuzije u jednakim atmosferskim uvjetima

U ovom radu uspoređeni su modificirani Gaussovski i K-model transporta i difuzije za kontinuirani izvor emisije u orografski slabo razvijenom području. Parametrizacija ulaznih veličina se zasniva na fizici procesa uz uporabu teorije sličnosti.

Rezultati pokazuju sličnost vrijednosti prizemnih koncentracija pri pojavljivanju jačih vjetrova i stabilne atmosfere. No, pri pojavljivanju slabijih vjetrova i labilnije atmosfere, K-model precjenjuje vrijednosti u usporedbi s Gaussovskim modelom što je uzrokovano neuključivanjem dizanja perjanice prilikom parametrizacije procesa difuzije.

Introduction

Planetary boundary layer, as a part of atmosphere with very strong friction influence, is very hard to model. In past, several groups of models have been developed, but nowadays three basic groups of models are used:

1) models which use numerical integration of differential equations (K-transport and diffusion models),

2) models which use statistical methods for description of movements of large number of individual particles (Monte Carlo models),

3) models which use analytic solutions of differential equations (Gaussian models).

K-models are based on the law of conservation of mass, and it often needs respectable computer time for numerical integration (Nanni and Tagliazucca, 1982). Their advantage is time dependency, while Gaussian models are stationary. The advantage of Gaussian models is that they require very little computer time because of their analyticity, but the approximations are so rough that they can produce nonrealistic field of ground level concentrations of pollutants. The greatest problem is how to model the diffusion processes, which are very variable in time and space.

In this paper a comparison has been made of the ground level concentrations calculated by K-model (Nanni and Tagliazucca, 1982; Vilibić, 1994) and by the modified Gaussian plume model for continuous sources (Vilibić, 1994). They both assume time independence, although K-model is basically time dependent. Input data consist of five sets of values for different weather conditions – from stable through neutral to unstable. In the work of Vilibić (1994) numerical methods for preparing the stability nomograms (Smith, 1979; Vogt et al., 1971) have been converted for the computer use. Further parametrizations necessary for describing processes in both models in the planetary boundary layer are made using the similarity theory (Panofsky and Dutton, 1984; Smith, 1979).

Gaussian plume model

Guassian plume model has got the name from the shape of equation which describes the field of ground level concentrations:

$$c = \frac{Q}{2\pi\, u\, \sigma_y\, \sigma_z}\, e^{-y^2/2\sigma_y^2} \left[e^{-(z-h_e)^2/2\sigma_z^2} + e^{-(z+h_e)^2/2\sigma_z^2} \right] \tag{1}$$

where:

Q – source strength (kg/s)

z – the height above the ground (m)

y – the distance from the plume axis (m)

h_e – effective plume height (m)

u – wind speed at height h_e (m/s)

σ_y, σ_z – dispersion parameters (dependent upon the distance x from the source and upon the turbulence intensity) (m)

c – ground level concentration (kg/m^3)

This equation is an analytic solution of the K-model differential equation with the following approximations (Šinik, 1981):

1) stationary wind field
2) homogeneous wind field
3) no chemical reactions and no deposition
4) no ground absorption
5) interval of at least 10 minutes, to avoid instantaneous peaks
6) wind speed in x-axis different from zero, so the diffusion in the x-axis may be neglected.

For parametrization of the wind speed the exponential law is used (Weil and Brower, 1984), dispersion parameters are described by the Briggs curves (Gifford, 1978) which have been modified using the urban factor (Vilibić, 1994), and the effective height is calculated from other sets of Briggs equations (Briggs, 1978; Weil and Brower, 1984). For all parametrizations the use of similarity theory (Panofsky and Dutton, 1984) and the parametrization of radiation are also necessary (Penzar and Penzar, 1991).

In the paper by Vilibić (1994) the basic equation (1) has been improved by the inclusion of horizontal plume turning in the model. In the case with the mixing layer height z_i greater then the effective plume height h_e the developed equation is given as:

$$c = \frac{Q\,\varepsilon}{\pi\, u\, \sigma_y\, \sigma_z}\, e^{-y^2/2\sigma_y^2}\left[e^{-h_e/2\sigma_z^2} + \sum_{i=1}^{5}\left(e^{-(2mz_i - h_e)^2/2\sigma_z^2} + e^{-(2mz_i + h_e)^2/2\sigma_z^2}\right)\right], \qquad (2)$$

while in the case $z_i < h_e$ the developed equation is given by:

$$c = \frac{Q\,\varepsilon}{\pi\, u\, \sigma_y\, \sigma_z}\, e^{-y^2/2\sigma_y^2}\left[e^{-h_e/2\sigma_z^2} + \sum_{m=1}^{5} e^{-(2mz_i - h_e)^2/2\sigma_z^2}\right] \qquad (3)$$

The parametrization of z_i is given by the nomogram of Pasquill and Smith (1983) which is here transformed into the set of equations (Vilibić, 1994). Factor of condensation ε shows the value of horizontal plume turning, and it's defined as a ratio of areas attached to non-curved and curved plume (Vilibić, 1994). Expressions after the signs of sum define the plume reflection from ground and mixing layer (Šinik, 1981).

Special case of spreading of the Gaussian plume occurs when the mixing layer goes over the effective height (where the maximum concentrations are present). This process is called fumigation which usually occurs in the morning after the night with strong stable conditions (Šinik, 1981). In that case equations given in Vilibić (1994) are used.

K-transport model

K-model is based on the law of mass conservation:

$$\frac{\partial c}{\partial t} + V\nabla c = \frac{\partial}{\partial x_i} K_{ij} \frac{\partial c}{\partial x_j} + S + D; \qquad \forall i, j = 1, 2, 3 \tag{4}$$

where:
V – wind speed
K_{ij} – components of tensor of diffusion
S – source strength, and
D – deposition rate.

If we assume that there is no vertical wind component ($w = 0$), deposition ($D = 0$) and non-diagonal terms of diffusion tensor ($K_{ij} = 0$, $i \neq j$), equation (4) may be transformed into:

$$\frac{\partial c}{\partial t} = -u \frac{\partial c}{\partial x} - v \frac{\partial c}{\partial y} + \frac{\partial}{\partial x} K_x \frac{\partial c}{\partial x} + \frac{\partial}{\partial y} K_y \frac{\partial c}{\partial y} + \frac{\partial}{\partial z} K_z \frac{\partial c}{\partial z} + S \tag{5}$$

This equation can be separated into a set of equations (Nanni and Tagliazucca, 1982) that are numerically integrated by improved methods of Runca and Sardei (1975). In this paper the numerical integration has been performed in space with dimensions 10 km × 10 km × z_i. The horizontal grid spacing is 500 metres, while the vertical one is $h_s/4$, where h_s is source height (Vilibić, 1994). Vertical changes of the wind speed at grid points are calculated using the exponential law (Weil and Brower, 1984) for u and v wind components. Parametrization of diffusion tensor is based on the relations given by Shier and Shieh (1974) for vertical diffusion, and by Nanni and Tagliazucca (1982) for horizontal diffusion. Source strength S is modelled such that in the source point concentration is Q and in all other points plume is transported by diffusion and transport processes.

Results

Both models (K- and modified Gaussian) have been applied to the same atmospheric conditions and compared using five sets of input data for various stability conditions in the planetary boundary layer (Table 1) in orographically weakly developed region. Technological parameters of the source (volume flux and temperature of smoke at stack exit, stack height, source strength) have been estimated using the data from some stacks in the Republic of Croatia *e.g.* Plomin 1 and 2, Rijeka and Zagreb.

Tables 2 to 6 illustrate numerically all the cases (A, B, C, D and E). Horizontal grid spacing is 500 metres. Numbers in the tables represent rela-

Table 1. Input data for cases A, B, C, D and E

CASE	A	B	C	D	E
Month	3	1	6	6	1
Hour	10	13	13	13	6
Cloudiness (in 1/8)	0	0	0	2	8
Wind at station 1 (ms^{-1})	2	1	1	4	3
Wind at station 2 (ms^{-1})	2	1	1	4	3
Atmospheric temperature at stack height (K)	280	290	300	300	270
Declination of Earth (^{o})	0	–15	20	20	–15
Roughness (m)			0.5		
Distance from source to station 1 (m)			3000		
Distance from source to station 2 (m)			8000		
Urbanization factor			0.5		
Angle between winds at stations 1 and 2 (^{o})			45		
Source height (m)			150		
Gas temperature at stack height (K)			470		
Volume flux (m^3s^{-1})			200		
Source strength (kgs^{-1})			1		

tive concentrations from 0 to 10000. Exact concentration can be calculated if every number is divided by 10000 and multiplied by the C(CG) or C(CK) which represent Gaussian and K-model maximal concentrations, respectively.

Figures 1 to 5 show graphically the distribution of ground level concentrations for all cases. Figures (a) represent three dimensional view of concentration fields, while Figures (b) and (c) represent the Gaussian and K-model concentrations, respectively. The concentrations are proportional to the area of the circles (the smallest edge points of the plume represent 0.1 % of the maximal concentration). Better understanding of graphical presentation will be achieved by consulting the table presentation.

Case A represents morning situation when fumigation occurs (Fig. 1, Table 2). Analysis of the results lead us to the conclusion that the Gaussian plume model gives very high concentrations close to the source, while farther concentrations decrease rapidly. This is in agreement with the fumigation theory (Šinik, 1981). Meanwhile K-model gives ten times smaller concentrations because here it has been applied as time independent model which is not temporaly related to the previous situations and does not include a fumigation process.

Case B describes unstable situation in winter with weak winds (Fig. 2, Table 3). Maximal concentration is 2.5 smaller in K- than in the Gaussian model and its distance from the source is greater (in K-model about 2500 m, in Gaussian about 500 m); so both models give similar concentrations at distances larger than 2000 m from the source. Closer than 2000 m the K-model gives lower values. Yet it should be mentioned that the plume is more

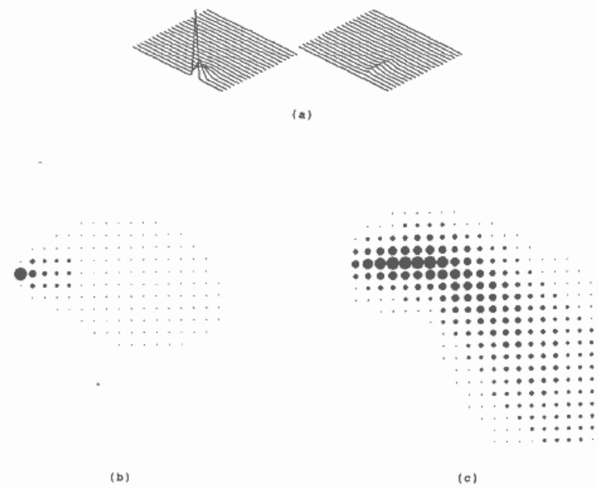

Figure 1. Ground level concentrations for case A. (a) 3D view (Gaussian left, K-model right); (b) 2D view (Gaussian model); (c) 2D view (K-model)

Table 2. Numerical presentation of ground level concentrations for case A

MODIFIED GAUSSIAN MODEL :

0	0	0	0	0	1	1	3	4	5	6	6	6	5	5	5	4	3	3	2
0	0	0	0	1	4	6	9	11	12	12	12	11	10	9	8	7	6	5	4
0	0	0	1	6	16	19	21	24	24	22	21	18	16	14	12	10	9	7	6
0	0	0	10	29	45	45	46	44	40	36	32	28	24	20	17	15	12	10	9
0	0	18	62	91	99	87	79	78	60	52	44	38	32	27	23	19	16	14	11
0	41	180	224	207	176	138	115	95	79	66	55	47	39	33	28	24	20	17	14
167	899	705	484	339	247	184	144	115	93	77	64	54	45	38	32	28	23	20	17
MAXS	2500	1111	625	400	277	204	156	123	99	82	68	58	49	41	36	30	26	22	19
167	899	705	484	339	247	190	147	118	96	80	68	58	50	43	37	32	28	24	22
0	41	180	224	207	176	152	124	103	85	74	63	55	49	42	37	33	28	26	23
0	0	18	62	91	99	105	95	83	73	64	57	51	45	40	36	32	29	26	23
0	0	0	10	29	45	64	66	63	59	54	49	45	41	38	34	31	28	25	23
0	0	0	1	6	16	35	44	47	46	44	42	40	37	34	31	29	27	24	22
0	0	0	0	1	4	18	29	34	36	36	35	34	33	30	29	27	25	23	21
0	0	0	0	0	1	9	19	25	28	29	29	29	27	27	26	25	23	22	20
0	0	0	0	0	0	4	13	19	23	24	25	24	24	24	23	23	22	20	19
0	0	0	0	0	0	3	10	15	18	19	19	20	21	21	21	21	20	19	18
0	0	0	0	0	0	3	8	12	15	15	17	18	18	19	19	19	18	17	17
0	0	0	0	0	0	3	7	10	11	13	14	15	16	17	17	17	17	16	15
0	0	0	0	0	0	3	6	7	9	11	12	13	14	15	15	15	15	15	14
0	0	0	0	0	0	4	5	6	8	9	11	12	12	13	13	14	14	14	13
0	0	0	0	0	0	3	4	5	7	8	9	10	11	12	12	12	12	12	12
0	0	0	0	0	0	2	3	5	6	7	8	9	10	10	11	11	11	11	11
0	0	0	0	0	0	2	3	4	5	6	7	8	9	9	10	10	10	10	10

K-MODEL :

0	0	0	0	1	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	2	2	3	2	1	1	0	0	0	0	0	0	0	0	0	0
0	2	4	7	11	15	18	12	8	5	3	1	0	0	0	0	0	0	0	0
4	13	25	41	59	78	94	64	44	27	16	8	4	1	0	0	0	0	0	0
25	74	140	215	294	371	431	299	206	130	76	41	20	9	4	1	1	0	0	0
147	396	699	1004	1282	1522	1672	1180	813	516	304	168	86	41	18	8	5	2	1	0
781	1884	2590	3879	4508	4917	5036	3608	2453	1600	963	543	288	142	66	30	18	10	6	3
3181	6233	8483	9631	MAXS	9955	9501	7161	5147	3460	2187	1298	722	376	184	89	52	31	19	10
925	2089	3201	4051	4628	4995	5281	5902	5431	4388	3195	2126	1304	746	394	201	124	76	47	27
193	485	818	1133	1408	1637	1954	3462	4160	4113	3516	2672	1839	1160	669	372	241	155	100	60
36	98	177	264	350	432	638	1776	2715	3241	3239	2816	2177	1516	961	586	397	267	179	111
6	18	35	55	77	100	186	843	1606	2384	2645	2614	2265	1744	1215	799	569	400	276	176
1	3	6	10	15	21	55	386	894	1492	1983	2215	2138	1817	1382	978	728	532	379	248
0	0	1	2	2	4	17	174	478	926	1358	1750	1872	1745	1444	1099	853	643	477	321
0	0	0	0	0	0	6	79	250	554	942	1309	1550	1569	1486	1146	926	723	547	381
0	0	0	0	0	0	2	35	129	322	612	941	1214	1333	1293	1129	965	760	590	424
0	0	0	0	0	0	1	16	65	183	386	653	913	1086	1133	1049	912	757	605	445
0	0	0	0	0	0	0	7	33	102	238	440	667	858	953	936	840	719	591	447
0	0	0	0	0	0	0	3	16	56	144	291	478	656	778	887	746	653	552	429
0	0	0	0	0	0	0	1	8	31	86	189	332	485	616	674	639	573	495	396
0	0	0	0	0	0	0	0	4	16	55	120	225	355	471	540	535	490	432	355
0	0	0	0	0	0	0	0	2	9	29	73	148	248	346	423	433	404	366	309
0	0	0	0	0	0	0	0	0	4	15	42	92	162	243	311	324	310	288	250

MAXS(CG)= 3.362E-06
MAXS(CK)= 1.417E-07

narrow in the K-model, especially when weak winds and unstable atmosphere are present. This is due to additional modelling of horizontal diffusion and plume rise in the Gaussian model (Briggs, 1978; Weil, 1979) and the influence of edge walls in the K-model.

Case C represents a very unstable situation in summer with strong convection and weak winds (Fig. 3, Table 4). Ground level concentration field calculated by K-model gives thousand times larger values than the Gaussian model. The reason for this disagreement lies in the modelling of vertical diffusion processes without inclusion of plume rise in K-model. This produces much smaller effective height of the source in K-model, as strong convective eddies bring more plume gases to the ground.

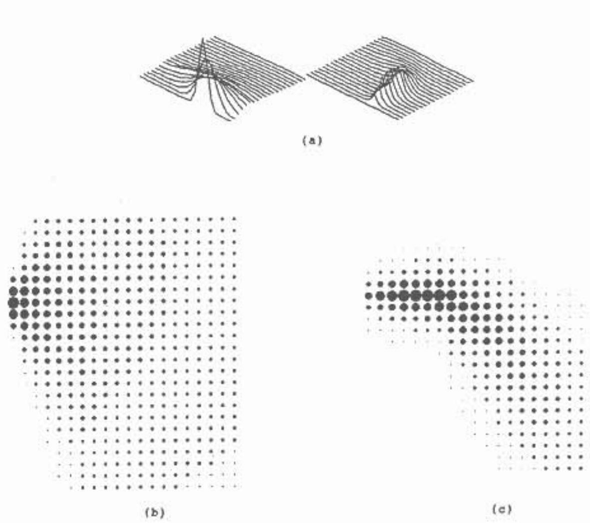

Figure 2. Ground level concentrations for case B. (a) 3D view (Gaussian left, K-model right); (b) 2D view (Gaussian model); (c) 2D view (K-model)

Case D shows unstable situation in summer with strong winds (Fig. 4, Table 5). A trend of horizontal plume shrinking can be noticed in both models, which is caused by dominant influence of transport processes rather than diffusion. Maxima of concentrations are shifted to the distances between 2000 and 3000 m from the source, and their values are 5 and 2 times smaller than in the cases B and C, respectively.

Case E describes nightly situation with strong winds and cloudy sky (Fig. 5, Table 6). It can be noticed that the maxima, especially the Gaussian one, are shifted to about 5000 m from the source with farther horizontal shrinking of plumes. Values of both maxima are smaller than in the case D and the concentration fields are similar for the same reasons as in the case D (dominant transport processes).

Table 3. Numerical presentation of ground level concentrations for case B

MODIFIED GAUSSIAN MODEL :

0	24	361	812	1081	1187	974	966	948	903	859	814	766	720	677	635	595	558	523	491
0	107	704	1183	1376	1403	1145	1107	1056	997	936	876	817	764	712	665	620	578	542	507
0	378	1237	1626	1687	1617	1316	1241	1161	1081	1003	929	862	798	740	686	639	596	556	518
8	1063	1963	2189	1993	1815	1478	1366	1255	1153	1056	972	893	824	759	701	651	604	562	526
183	2372	2812	2582	2269	1987	1628	1470	1333	1206	1097	1000	911	837	769	710	654	609	567	527
1691	4210	3634	2984	2489	2119	1747	1555	1386	1243	1119	1012	919	839	769	709	656	607	565	525
6413	5939	4238	3254	2631	2202	1842	1612	1420	1262	1138	1013	919	832	763	702	646	598	556	519
MAXS	6661	4461	3350	2680	2231	1983	1644	1432	1260	1122	999	905	820	747	687	632	585	544	508
6413	5939	4238	3254	2631	2202	1922	1642	1421	1240	1097	977	881	798	726	665	615	569	529	522
1691	4210	3634	2984	2489	2119	1905	1619	1388	1202	1059	938	846	767	698	639	592	548	532	495
183	2372	2812	2582	2268	1987	1859	1569	1331	1149	1005	895	803	728	664	612	567	539	502	468
8	1063	1963	2109	1993	1815	1772	1456	1262	1086	950	840	754	685	629	580	543	507	474	443
0	378	1237	1626	1687	1617	1675	1465	1182	1010	881	785	706	642	590	546	509	477	447	419
0	107	704	1183	1376	1403	1568	1363	1050	931	809	722	655	600	541	508	477	448	421	396
0	24	361	812	1081	1187	1432	1188	987	842	738	663	602	535	505	475	448	422	397	375
0	4	167	526	819	979	1302	1064	839	756	667	605	527	498	471	445	420	397	375	354
0	0	70	322	597	786	1158	931	770	670	600	515	489	464	440	417	395	374	354	335
0	0	26	185	428	616	1026	800	671	595	500	478	455	433	412	391	371	352	334	317
0	0	8	101	285	470	858	677	586	483	464	444	425	405	386	367	349	332	316	301
0	0	3	52	186	349	687	576	464	448	431	414	396	379	363	345	329	314	299	285
0	0	0	25	117	253	563	443	431	417	402	386	371	355	344	323	318	296	283	270
0	0	0	11	71	179	421	412	401	388	375	361	347	333	320	306	293	288	268	257
0	0	0	5	41	123	351	383	373	362	351	338	326	313	301	289	277	265	254	244
0	0	0	2	23	82	364	357	348	339	328	317	306	295	284	273	262	252	241	232

K-MODEL :

0	0	0	0	1	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	2	2	3	2	1	1	0	0	0	0	0	0	0	0	0	0
0	2	4	7	10	14	18	12	8	5	3	1	0	0	0	0	0	0	0	0
4	12	25	40	58	77	93	63	43	27	15	8	4	1	0	0	0	0	0	0
35	72	137	211	289	367	426	296	204	129	75	43	20	9	4	1	1	0	0	0
145	391	693	995	1271	1509	1659	1171	806	511	302	166	86	41	18	8	4	2	1	0
783	1886	2989	3872	4492	4894	5009	3586	2475	1588	955	539	285	141	65	30	18	10	6	3
3233	6297	8539	9660	MAXS	9931	9462	7121	5113	3435	2170	1287	716	374	183	91	54	31	18	10
930	2093	3201	4042	4611	4969	5250	5866	5395	4357	3171	2010	1254	739	393	211	129	77	46	26
192	481	811	1124	1396	1623	1937	3438	4131	4085	3492	2655	1830	1154	669	380	246	157	98	57
35	96	174	260	345	427	632	1764	2697	3220	3218	2799	2166	1510	960	600	406	268	172	104
6	18	34	54	76	98	183	837	1596	2230	2629	2598	2250	1733	1204	865	572	393	264	167
1	3	6	10	15	20	54	383	888	1483	1970	2198	2119	1800	1363	971	716	515	361	237
0	0	1	1	2	3	17	173	476	921	1390	1739	1855	1726	1424	1077	825	621	452	305
0	0	0	0	0	0	6	78	269	551	940	1305	1528	1546	1386	1123	908	697	526	370
0	0	0	0	0	0	2	35	128	321	611	937	1199	1318	1271	1104	920	738	575	414
0	0	0	0	0	0	1	16	65	183	385	646	905	1079	1119	1033	894	740	593	437
0	0	0	0	0	0	0	7	33	102	237	437	668	856	948	923	838	709	583	442
0	0	0	0	0	0	0	3	16	56	144	293	479	661	781	804	741	649	545	427
0	0	0	0	0	0	0	1	8	31	86	190	348	500	621	676	637	573	496	397
0	0	0	0	0	0	0	0	4	16	58	121	232	362	480	544	534	487	432	357
0	0	0	0	0	0	0	0	2	8	29	76	152	254	354	426	429	402	367	332
0	0	0	0	0	0	0	0	0	4	16	43	94	166	250	320	325	310	289	256

MAXS(CG)= 7.577E-07
MAXS(CK)= 2.983E-07

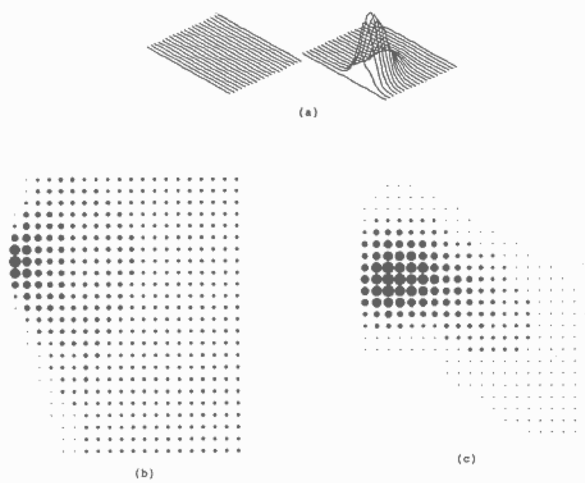

Figure 3. Ground level concentrations for case C. (a) 3D view (Gaussian left, K-model right); (b) 2D view (Gaussian model); (c) 2D view (K-model)

Table 4. Numerical presentation of ground level concentrations for case C

MODIFIED GAUSSIAN MODEL :

0	81	485	754	862	885	710	696	675	650	623	596	569	543	519	496	473	453	433	414
0	257	818	1012	1041	1010	811	738	742	705	669	634	601	572	543	517	493	469	449	428
2	686	1271	1299	1222	1129	909	855	803	754	709	667	630	595	564	534	508	484	461	440
50	1527	1824	1594	1393	1237	1008	926	857	797	741	695	652	614	579	547	519	493	470	449
511	2847	2416	1868	1543	1327	1086	985	902	828	767	714	666	626	589	557	526	501	477	454
2667	4443	2953	2092	1659	1396	1153	1034	933	852	783	725	675	631	594	561	532	504	480	457
7186	5882	3330	2240	1733	1439	1208	1067	955	865	793	730	679	633	595	562	531	503	479	458
MAKS	6342	3467	2291	1759	1454	1246	1088	965	868	793	726	676	630	591	558	527	500	475	455
7186	5882	3330	2240	1733	1439	1261	1091	963	861	783	719	667	622	583	550	522	495	472	477
2667	4443	2953	2092	1659	1396	1258	1083	949	845	767	702	652	605	572	539	513	486	485	463
511	2847	2416	1868	1543	1327	1240	1060	932	820	744	683	633	592	557	527	503	490	469	449
50	1527	1824	1594	1393	1233	1201	1024	887	790	716	656	610	572	540	512	492	472	453	435
2	686	1271	1299	1222	1129	1151	977	846	751	681	629	586	550	521	493	474	455	438	421
0	257	818	1012	1041	1010	1091	923	799	711	645	598	560	529	491	473	456	439	423	407
0	81	485	754	862	885	1021	860	745	665	608	568	533	487	470	454	438	423	408	394
0	21	266	536	693	761	947	792	688	620	572	536	481	466	451	436	422	408	394	381
0	4	134	365	541	640	867	719	629	575	535	472	459	446	433	419	406	393	380	368
0	0	62	237	410	528	781	647	576	533	462	451	439	427	415	403	391	379	367	356
0	0	27	147	302	427	681	579	529	469	441	431	420	410	399	388	377	366	355	344
0	0	10	87	316	338	585	523	435	425	421	412	403	393	383	373	363	353	343	332
0	0	3	49	150	263	515	420	415	410	403	395	387	378	369	359	350	340	331	321
0	0	1	26	101	200	403	401	397	392	386	379	371	363	355	346	337	328	319	311
0	0	0	13	56	149	385	383	380	375	370	363	357	349	341	333	325	317	309	300
0	0	0	6	42	145	368	361	364	360	355	349	343	336	329	321	314	306	298	290

K-MODEL :

6	24	40	40	35	29	20	10	6	3	1	0	0	0	0	0	0	0	0	0
11	45	73	74	64	52	37	19	11	6	3	1	0	0	0	0	0	0	0	0
49	164	238	236	197	152	108	56	31	17	9	4	2	1	0	0	0	0	0	0
188	538	696	660	561	460	305	162	93	52	28	15	7	3	1	0	0	0	0	0
593	1521	1819	1671	1438	1126	798	453	276	160	90	49	24	11	5	2	1	0	0	0
1658	3325	3785	3513	3075	2549	1888	1105	681	411	244	131	67	33	15	7	4	2	1	0
3383	5886	6627	6118	5528	4826	3564	2180	1380	864	511	287	149	75	36	19	12	7	4	2
3645	7526	9193	8739	7943	6922	4910	3158	2065	1369	878	532	291	151	81	46	31	20	12	6
4498	8695	MAKS	9434	8384	7249	5227	3638	2540	1785	1212	769	470	273	159	100	68	45	29	15
4188	8313	9257	8152	7081	6061	4647	3589	2736	2041	1433	968	636	400	253	166	114	77	51	29
2540	5217	5847	5334	4615	3887	3218	2844	2318	1839	1404	1033	722	480	323	226	162	114	78	50
1163	2473	2786	2475	2137	1635	1618	1657	1549	1374	1167	918	691	487	352	260	194	143	105	78
449	842	912	843	722	561	607	810	898	912	840	723	566	440	339	264	206	159	122	84
160	261	274	254	228	178	217	371	484	555	571	525	451	371	304	248	201	161	127	90
54	79	81	75	66	62	75	161	249	322	363	366	339	308	257	219	184	152	123	89
17	23	23	22	19	19	25	71	124	182	224	244	245	231	208	184	159	135	112	84
5	7	6	6	5	5	9	33	64	100	132	156	168	178	162	149	132	115	98	75
1	2	1	1	1	1	3	15	31	53	76	96	111	121	123	117	107	95	83	65
0	0	0	0	0	0	1	6	15	29	44	59	74	86	93	92	83	77	69	56
0	0	0	0	0	0	0	2	8	15	25	37	50	61	68	70	66	61	56	46
0	0	0	0	0	0	0	1	4	8	15	24	34	43	50	53	51	48	45	37
0	0	0	0	0	0	0	0	2	5	9	15	23	30	36	39	39	37	35	30
0	0	0	0	0	0	0	0	0	3	5	9	14	20	25	28	27	26	25	23

MAKS(CG)= 2.226E-07
MAKS(CK)= 1.921E-04

Conclusion

Processing different cases of planetary boundary layer stability, it can be noticed that the Gaussian plume model gives lower concentrations than K-model when weak winds and unstable atmosphere are present. This occurs because the plume rise is not included in the K-model, so theoretically the plume reaches the ground faster and produces larger concentrations. In the Gaussian model this problem has been smoothed with additional modelling of plume rise. Also, because of comparison with the Gaussian model, K-model is here time independent, so it couldn't describe the fumigation process (forced time independence). K-model is, basically, a prediction model and, when this characteristic is taken into account, it gives better description of the time variations of

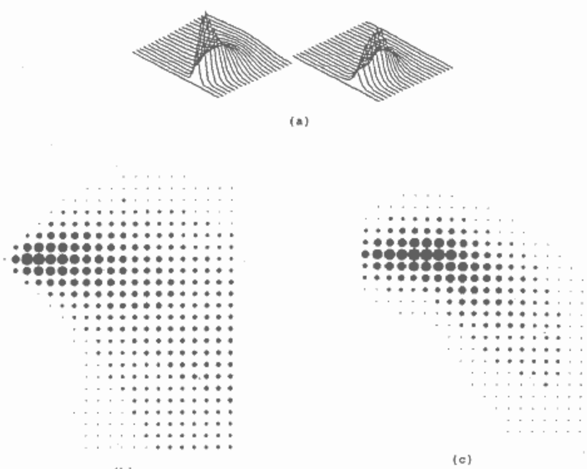

Figure 4. Ground level concentrations for case D. (a) 3D view (Gaussian left, K-model right); (b) 2D view (Gaussian model); (c) 2D view (K-model)

planetary boundary layer parameters as well as concentration fields than the K-model as forced in this paper. In the stable conditions and also when strong winds are present, both models give similar ground level concentrations. That similarity is caused by dominance of transport rather than diffusion processes, which are easier to model.

From the results it can be concluded that the Gaussian plume model is more applicable when the ground level concentration for continuous stationary sources is of interest, while the K-model is not effective in the stationary situations. Its advantage is the description of instantaneous sources of emission (time dependence). Further improvements of both models would be possible if measuring of input meteorological parameters could be more effective. Then the better parametri-

Table 5. Numerical presentation of ground level concentrations for case D

MODIFIED GAUSSIAN MODEL :

0	0	0	0	0	0	2	7	15	23	31	35	39	39	36	33	29	25	21	17
0	0	0	0	0	0	21	45	69	90	103	109	108	100	91	79	68	58	46	38
0	0	0	0	11	67	122	192	245	274	281	273	250	224	194	165	138	113	92	74
0	0	0	14	121	357	493	612	668	663	627	564	496	425	361	301	247	202	163	130
0	0	16	250	784	1316	1428	1491	1427	1301	1147	998	842	706	588	484	398	322	260	209
0	13	574	1942	2964	3336	3055	2781	2432	2085	1766	1483	1239	1030	853	703	576	470	381	308
1	1087	4786	6638	6582	5831	4824	4037	3354	2788	2325	1931	1612	1340	1116	927	766	631	517	421
101	4718	9705	MAXS	8587	7024	5705	4655	3812	3165	2656	2218	1881	1584	1333	1124	942	787	654	541
1	1087	4786	6638	6582	5831	5311	4316	3664	3116	2680	2307	1995	1720	1478	1267	1086	923	780	698
0	13	574	1942	2964	3336	3545	3325	3030	2722	2448	2181	1955	1739	1536	1348	1182	1025	924	798
0	0	16	250	784	1336	1949	2139	2225	2167	2068	1941	1802	1661	1513	1371	1231	1121	993	876
0	0	0	14	121	357	877	1282	1502	1618	1655	1636	1590	1522	1439	1341	1246	1140	1033	930
0	0	0	0	11	67	337	677	967	1163	1280	1348	1372	1362	1329	1270	1208	1132	1048	962
0	0	0	0	0	0	115	354	615	828	983	1093	1165	1204	1185	1180	1150	1102	1041	974
0	0	0	0	0	0	39	154	406	603	763	890	986	1014	1063	1084	1080	1056	1017	965
0	0	0	0	0	0	14	119	287	454	605	735	795	884	948	987	1003	999	980	947
0	0	0	0	0	0	7	88	222	361	496	531	638	769	842	893	924	937	933	916
0	0	0	0	0	0	5	77	186	302	376	439	579	669	745	804	846	871	881	877
0	0	0	0	0	0	11	77	165	227	313	405	497	583	659	722	731	805	825	832
0	0	0	0	0	0	22	80	125	188	262	344	427	508	582	643	700	748	768	786
0	0	0	0	0	0	34	63	104	158	222	293	369	444	515	579	634	678	712	735
0	0	0	0	0	0	29	53	88	133	189	252	319	388	455	518	573	620	657	685
0	0	0	0	0	0	25	45	75	114	162	217	278	341	403	463	517	565	605	637
0	0	0	0	0	0	21	39	64	98	139	188	242	299	357	414	467	514	556	590

K-MODEL :

0	1	3	5	7	9	10	7	4	3	1	1	0	0	0	0	0	0	0	0
0	1	5	7	10	15	15	10	7	4	2	1	0	0	0	0	0	0	0	0
3	11	20	31	43	54	61	40	28	17	10	5	2	1	0	0	0	0	0	0
17	47	85	129	173	216	239	161	110	69	39	21	10	4	2	0	0	0	0	0
71	193	336	489	635	766	828	571	393	246	142	77	38	18	7	3	1	0	0	0
287	740	1212	1662	2050	2365	2458	1734	1185	748	437	238	121	58	25	11	5	3	1	0
1068	2502	3711	4635	5388	5898	5842	4187	2889	1835	1050	607	316	154	71	31	16	8	4	2
3067	5999	7739	8837	9569	MAXS	9411	7071	5039	3327	2059	1195	651	332	158	73	38	20	11	5
1259	2756	3937	4866	5544	6027	6129	6108	5221	3970	2746	1746	1028	563	285	139	76	42	23	12
378	902	1403	1858	2237	2539	2816	3835	4030	3609	2849	2025	1310	777	436	223	127	73	43	23
101	257	425	595	750	884	1086	2040	2616	2755	2688	1984	1420	921	547	308	186	112	64	39
25	67	117	171	223	271	380	987	1524	1872	1925	1719	1361	968	625	379	242	154	98	58
6	16	30	45	60	75	126	452	828	1172	1363	1357	1186	925	650	426	287	192	128	88
1	4	7	11	15	19	41	201	438	691	902	998	960	818	627	445	318	224	157	102
0	0	1	2	3	4	14	88	215	398	568	694	733	682	568	436	330	246	183	125
0	0	0	0	0	1	5	38	105	213	344	463	536	544	492	408	327	257	208	145
0	0	0	0	0	0	2	16	51	114	203	299	379	420	411	368	313	259	212	163
0	0	0	0	0	0	0	7	24	60	117	190	263	317	336	333	285	252	218	175
0	0	0	0	0	0	0	3	11	31	67	119	181	236	270	277	261	239	217	183
0	0	0	0	0	0	0	1	5	16	38	75	124	175	214	234	231	222	211	185
0	0	0	0	0	0	0	0	2	8	22	47	84	128	168	195	201	201	199	181
0	0	0	0	0	0	0	0	1	4	13	30	57	93	130	160	178	177	181	170
0	0	0	0	0	0	0	0	0	2	7	18	37	64	95	122	132	140	148	142
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

MAXS(CG)= 9.888E-08
MAXS(CK)= 7.289E-08

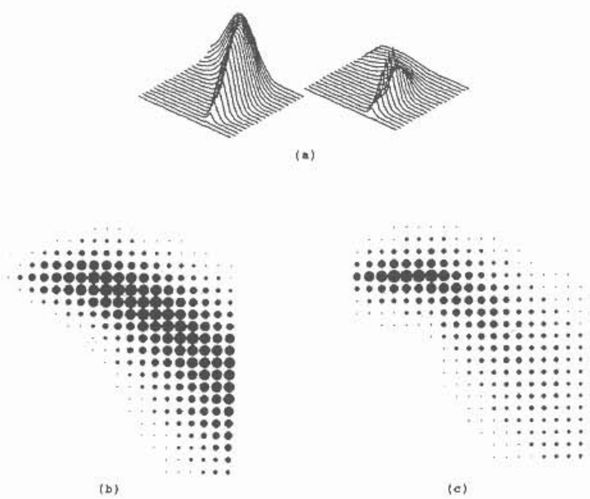

Figure 5. Ground level concentrations for case E. (a) 3D view (Gaussian left, K-model right); (b) 2D view (Gaussian model); (c) 2D view (K-model)

Table 6. Numerical presentation of ground level concentrations for case E

MODIFIED GAUSSIAN MODEL :

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	2	3	3	2	1	1	0	0	0	0	0
0	0	0	0	0	2	8	20	34	42	45	38	29	20	12	7	3	1	0	0
0	0	0	0	12	77	169	284	359	385	351	285	213	140	86	48	25	11	5	2
0	0	2	65	351	925	1419	1881	1959	1876	1629	1299	953	645	403	232	123	61	28	12
0	6	229	1125	2561	4092	5043	5600	5658	5269	4573	3726	2816	2000	1310	794	452	238	116	51
1	139	1063	2911	4963	6718	8039	8818	9129	8939	8243	7166	5811	4411	3120	2036	1241	701	365	175
0	6	229	1125	2561	4092	5864	7415	8743	9667	MAKS	9680	8711	7274	5626	4027	2651	1619	913	516
0	0	2	65	351	925	2066	3516	5272	7098	8670	9696	9934	9328	8028	6340	4591	3062	1879	1169
0	0	0	0	12	77	366	1016	2168	3798	5717	7614	9061	9706	9399	8267	6616	4996	3436	2226
0	0	0	0	0	2	36	156	666	1597	2068	4974	6853	8561	9389	9234	8297	6787	5341	3645
0	0	0	0	0	0	2	28	167	580	1447	2848	4706	6677	8287	9069	9008	8132	6762	5235
0	0	0	0	0	0	0	3	38	195	638	1523	2937	4771	6522	8035	8813	8744	7953	6706
0	0	0	0	0	0	0	0	9	68	278	786	1761	3086	4816	6541	7882	8557	8481	7768
0	0	0	0	0	0	0	0	2	26	126	410	961	1949	3326	4952	6522	7726	8308	8235
0	0	0	0	0	0	0	0	1	11	61	197	525	1158	2169	3528	5043	6474	7545	8070
0	0	0	0	0	0	0	0	0	5	26	95	276	662	1346	2369	3676	5100	6409	7315
0	0	0	0	0	0	0	0	0	2	11	45	140	364	800	1528	2543	3799	5131	6332
0	0	0	0	0	0	0	0	0	0	5	20	69	194	458	936	1681	2693	3896	5142
0	0	0	0	0	0	0	0	0	0	2	9	33	100	254	555	1067	1827	2822	3972
0	0	0	0	0	0	0	0	0	0	0	4	16	50	136	318	651	1191	1959	2922
0	0	0	0	0	0	0	0	0	0	0	1	7	25	71	177	387	750	1309	2018
0	0	0	0	0	0	0	0	0	0	0	0	3	12	36	96	222	457	843	1419

K-MODEL :

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	2	2	3	1	1	0	0	0	0	0	0	0	0	0	0	0
1	3	6	11	15	21	25	15	9	5	3	1	0	0	0	0	0	0	0	0
7	23	46	73	104	136	163	105	70	42	23	12	5	2	1	0	0	0	0	0
49	144	277	433	598	760	887	608	412	254	144	76	37	16	3	2	1	0	0	0
282	783	1426	2117	1786	3337	3784	2729	1867	1173	683	370	186	87	38	16	9	5	3	1
1261	3080	5066	6887	8385	9666	MAKS	7618	5406	3541	2158	1235	647	319	146	65	37	22	13	7
317	855	1527	2234	2906	3493	4083	5585	5532	4662	3420	2251	1346	738	336	181	108	66	41	23
59	168	316	485	660	829	1113	2932	4058	4325	3841	2962	2030	1257	709	379	240	155	99	68
9	28	55	87	123	158	268	1365	2511	3329	3534	3177	2492	1738	1092	644	434	295	198	124
1	4	8	14	20	26	69	610	1424	2288	2862	2971	2650	2075	1447	936	672	480	338	238
0	0	1	2	2	3	21	269	766	1461	2124	2523	2540	2220	1711	1213	923	692	507	347
0	0	0	0	0	0	7	119	399	887	1483	1996	2252	2185	1853	1429	1147	900	690	491
0	0	0	0	0	0	3	52	204	520	989	1499	1883	2014	1870	1565	1320	1082	863	635
0	0	0	0	0	0	1	23	103	298	639	1081	1504	1764	1785	1614	1428	1222	1009	771
0	0	0	0	0	0	0	10	51	168	403	737	1158	1484	1633	1589	1471	1305	1116	878
0	0	0	0	0	0	0	4	25	93	249	516	865	1211	1444	1508	1453	1336	1179	954
0	0	0	0	0	0	0	2	12	51	151	343	630	965	1244	1385	1386	1314	1196	997
0	0	0	0	0	0	0	0	6	28	90	224	454	753	1043	1239	1280	1248	1168	1002
0	0	0	0	0	0	0	0	3	15	53	146	322	534	859	1079	1146	1148	1102	971
0	0	0	0	0	0	0	0	1	8	31	94	222	431	609	922	999	1026	1007	909
0	0	0	0	0	0	0	0	0	4	13	57	146	304	516	728	812	853	853	787

MAKS(CG)= 7.478E-08
MAKS(CK)= 5.958E-08

zation of diffusion processes would be achieved. It is necessary to emphasize that the parametrizations should be based on the physical processes in the atmosphere rather than on the statistical methods (Weil and Brower, 1984; Vilibić, 1994).

To test the modified Gaussian and K-models it is necessary to organize an experiment where ground level concentrations would be measured at points determined from the results of both models. The comparison with the empirical data can be useful in further improvements in parametrization of diffusion processes included in both models.

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