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INTERNAL BOUNDARY LAYER ON THE WEST COAST OF ISTRIA

Interni granični sloj na zapadnoj obali Istre

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Abstract - In this paper the application of Venkatram's model for internal boundary layer (IBL) height evaluation containing the mechanical and thermal causes of IBL forming, has been given. The model has been chosen because of its theoretical base and the fact that its input parameters can be valued on a measured data base in our coastal area. Venkatram's model has been applied to the Istrian peninsula and tested by radiosounding data in Pula. We have estimated IBL height at the meteorological station in Pula (using both model and measurements) for the summer months when this layer is especially explicit in the coastal area. The diurnal change of IBL height for a certain period of time (1000-1700 LST) when the seabreeze is more likely to blow, has been evaluated in Pula, also in the summer months (based on the model, a presumption of a synusoidal land temperature dependence on time (0700-2100 LST) and on measurements).

Key word index: Internal boundary layer, Venkatram's model, Pula, Istria.

Sažetak - Ovaj rad daje proračun visine internog graničnog sloja prema modelu Venkatrama koji u sebi sadrži mehanički i termički uzrok formiranja IBL-a. Model je odabran zbog svoje teoretske osnove kao i zbog toga što se njegovi ulazni parametri mogu procijeniti na osnovi mjernih podataka u našem obalnom području. Model Venkatrama primijenili smo u Istri i testirali ga pomoću radiosondažnih podataka u Puli. Za ljetne mjesece, kada je ovaj sloj u obalnom području osobito izražen, procijenili smo visinu IBL-a u Puli (primjenom modela i mjerenja). Dnevni hod visine IBL-a za vremenski period (10-17 SEV) kada se zbog termičkih razlika kopna i mora razvije obalna cirkulacija, procijenili smo u Puli u ljetnim mjesecima (na osnovi modela, pretpostavke sinusoidalne ovisnosti temperature tla u vremenu (07-21 SEV), te primjenjujući mjerenja).

Ključne riječi: Interni granični sloj, Venkatramov model, Pula, Istra.

INTRODUCTION

Pollutant dispersion processes take place in the planetary boundary layer, PBL. In this layer wind shear is very strong, the flow is turbulent and the heat, received from the sun, is transferred from the earth's surface to the air by means of turbulent fluxes. The top of the planetary boundary layer can often be seen from airplanes as the upper limit of a reduced visibility region caused by the mixing of smoke, dust and aerosols through the boundary layer (Panofsky and Dutton, 1986). Gaseous pollutants cannot penetrate the inversion that exists at the top of the planetary boundary layer. Therefore, meteorological situations with the decreased height of the planetary boundary layer may cause serious air pollution events in urban area.

During night and in the morning hours, the coastal atmosphere is stable. Several hours after sunrise, the land warms up faster than the sea water, a coastal circulation develops and a seabreeze begins to blow. It carries away the stable air from above the smooth colder sea surface and brings it above the rough and warmer coastal land. Here this air grows unstable with developing turbulence and an "internal boundary layer" forms. The internal boundary layer (IBL) grows with fetch because turbulent fluxes develop firstly in the lower and then in the upper layers of the atmosphere. Thus the IBL grows parabolically inland up to several kilometers from the coast, where it gradually loses its peculiarities and becomes part of the convective PBL.

The internal boundary layer is caused by the differences in surface roughness (mechanical cause) and surface temperature (thermal cause). It means that the IBL can develop during the onshore flow when a difference in either temperature or roughness between land and sea surface exist. Although the thermal cause is mostly greater than mechanical one, in some recent papers (Nicholls and Readings, 1979, Ogawa and Ohara 1984) the importance of the mechanical cause in IBL formation near the shore is emphasized. For that reason an IBL can develop during both seabreeze circulation and gradient onshore flow.

Several definitions exist of IBL height. The IBL is best defined by the intensity of turbulence. Lyons (1975) defined the IBL height as the average maximum height which turbulent convective elements can still reach. He also recorded a sharp change in turbulence across the top of the IBL. Venkatram (1977) defined IBL height as the point where a jump in potential temperature occurs. It is the point of transition from neutral or unstable to stable atmosphere. Turbulence is generated by the roughness and temperature difference between two surfaces and the IBL, detected by the intensity of turbulence, is 1.4 times higher than the height defined by temperature (Gamo, 1982).

IBL height is a very important quantity in the coastal modelling dispersion. Gaseous pollutants which might previously have accumulated at a given height in the stable atmosphere of the morning planetary boundary layer, may be suddenly drawn down to the surface by means of turbulent eddies in the developing IBL-and than a shore fumigation with rather high pollution take place. Pollutants, once emitted from stacks into the onshore air flow can move inland and at some point arrive to the IBL growing inland so that fumigation may take place. For that reason, it is definitely very important to understand the IBL physics and to use a theoretical model, which might estimate its development in relation to local meteorological characteristics.

This paper presents an application of Venkatram's (1977) model for IBL height evaluation on the west coast of Istria. We also simulate, in a very simplified way, the possible diurnal change of IBL height, according to land-surface temperature.

METHOD

The leading parameters in almost all existing IBL models are: the difference between the sea-surface and land-surface temperature and land-surface roughness. Venkatram (1977) suggested a physically realistic model of internal boundary layer height by using the Tennekes mixed layer model in a Lagrangian framework. In a coastal area it is very important to include the advective effects that occur with the onshore flow. Raynor et al. (1975) presented essentially the same empirical model and showed good agreement between the predicted and observed IBL heights. We have made use of Venkatram's well-known theoretical model of IBL evaluation and have applied it to west coast of Istria. This model was chosen because of its simplicity and possibility of application to our coastal area.

The model preedicts an increase in IBL height, h, getting away from the coastline downwind seabreeze:

$$h(x)=\frac{u_*}{u}\left[\frac{(T_l-T_w)}{\gamma}x\right]^{1/2} \qquad (1)$$

where $h(x)$ is the IBL height (m), u_* is a friction velocity (m s^{-1}), u is a wind speed (ms^{-1}), T_l and T_w are land-surface and sea-surface temperature (^oC), γ is the temperature gradient in the capping inversion layer (^oC), and x is the inland distance in the seabreeze direction (m). Figure 1 shows a typical IBL structure. Equation (1) includes both causes of IBL generation. The ratio u_*/u refers to the mechanical forcing and the tempe-rature difference (T_l - T_w) to the thermal one. The ratio u_*/u appears to be almost constant, so that the model is mostly sensitive to the thermal cause. The surface friction u_* can be determined by the similarity formula (Panofsky and Dutton, 1986):

$$u_*=\frac{k\,u}{\left[ln\left(\frac{z}{z_0}\right)-\Psi_m\left(\frac{z}{L}\right)\right]} \qquad (2)$$

where k is the von Karman's constant (k = 0.35), z is the height above the ground (m), z_o is the roughness lenght (m), Ψ_m is the integral universal similarity function and L is the Monin-Obukhov lenght (m).

The horizontal extent of the model over which (1) can be used is about 6 km (Venkatram, 1977). This model for the estimation of IBL height in a coastal area has been applied and tested as described in the next section. The essential assumption of the model is that land - surface temperature does not change with time

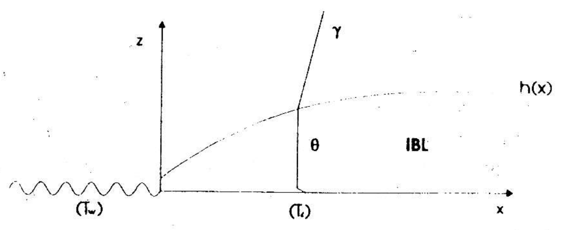

Figure 1. Typical structure of an internal boundary layer.
Slika 1. Tipična struktura internog graničnog sloja.

(stationary state, time scale of the model about 3h) and that land temperature, wind direction and wind speed do not change with growing distance from the coast. Because of intensive turbulent mixing uniform profiles of potential temperature and wind inside the IBL (except in the shallow surface layer) are assumed. The required input data for the application are radio-sounding measurements of temperature, wind and pressure as well as land-surface and sea-surface temperatures. In cases when radio-sounding measurements have not been performed, it is possible, based on surface data (wind, land and sea temperature), to estimate IBL height with the additional assumption of a constant lapse rate above the IBL.

APPLICATION

We have applied the model for IBL evaluation in the Pula region. Equation (1) has been used to calculate IBL heights. Radio-sounding measurements in Pula, during the ALPEX Special Observation Period have provided input data together with the land-surface temperature measured in Poreč and the sea-surface temperature measured in Rovinj at 0700 h, 1400 h and 2100 h (LST). Figure 2 shows the Istrian peninsula (North Adriatic), the configuration of the coast, and the location of the meteorological stations where the model was applied. As the area of the west Istrian coast is not orographically developed, Pasquill's instability classes refer to the localities of small roughness length (z_o=5 cm).

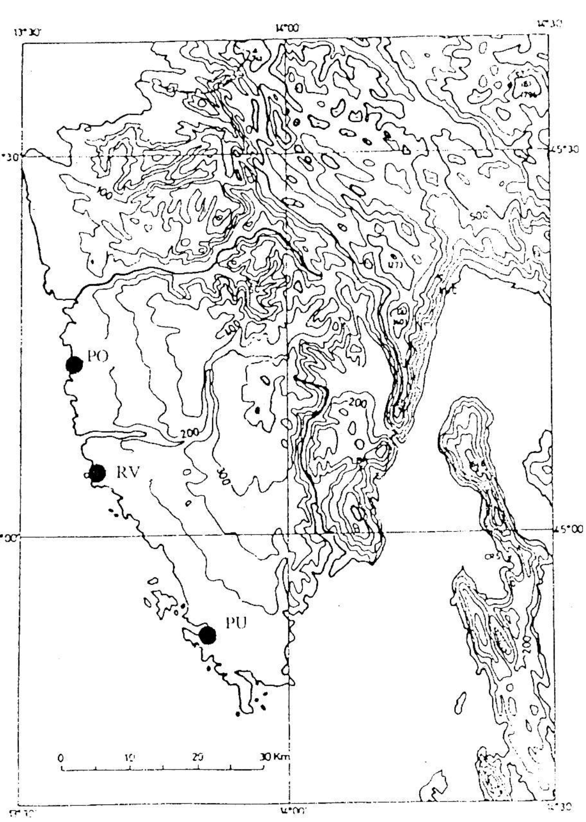

Figure 2. Map of the Istrian peninsula, showing the measurements sites (PU-Pula, RV-Rovinj, PO-Poreč).

Slika 2. Karta Istre s lokacijama mjernih postaja (PU-Pula, RV-Rovinj, PO-Poreč).

The IBL can develop in either seabreeze or gradient flow. For that reason, situations with onshore flows (wind direction 160°-290°) have been chosen in Pula. The IBL develops by day so we have used mid-day radio-sounding data to experimentally determine the IBL height (*h(EXP)*) from the potential temperature profile as the first level above the ground at which potential temperature gradient exceeds 1°C km^{-1}. The calculated IBL heights (*h(MOD)*) according to the model, the friction velocities (u_*) and the stability classes (according to Pasquill, needed for evaluation of *1/L*) for 23 selected cases are given in Table 1.

The stability classes refer to the layer of the first 100 m above the ground. Classes of B (moderately unstable) and C (slightly unstable) instability were the most frequent. The IBL heights determined from the model were the range of 69 m - 385 m and the heights determined from the potential temperature profiles ranged from 70 m - 517 m. The correlation coefficient between the measured and predicted value of IBL depth is 0.65 (Fig. 3). This means that the model, in spite of being so crude, corresponds rather well to the real IBL heights. The difference between the mean observed and predicted values of IBL heights is 17 m. This means that the model generally underpredicts the real IBL heights. The reason can be that the sea-surface temperature measured in Rovinj bay is higher because of the vicinity of the Rovinj hospital, and therefore not representative of the whole west coast of Istria. Another reason could be the neglecting of IBL height at the land-sea interface. The ratio (u_*/u) is in the 0.11-0.12 range and we shall take it as a constant in further consideration. That is also obvious from Equation (2) where we can see that u_* is proportional to u at constant roughness length in unstable stratification. For that reason the model is not sensitive to wind speed. In spite of the simplicity of the model and the problems of lack of simultaneous data (surface data and radio-soundings) the result for the 23 selected cases are reasonable good.

EVALUATION OF DIURNAL INTERNAL BOUNDARY HEIGHTS IN THE SUMMER MONTHS OVER THE WEST COAST OF ISTRIA

The IBL forms mostly during the seabreeze flow. The seabreeze occurs most frequently in summer due to the significant temperature difference between sea and land surfaces. The strength of the seabreeze depends on the temperature difference between the two surfaces. When the temperature difference is greater, the seabreeze is more intensive. During the day, the air over the land gets heated while the sea-surface temperature hardly changes. The cooler air from the sea can typically penetrate 10 - 20 km inland but this dis-

Table 1. Summary of conditions for 23 cases (T_l - land surface temperature, T_w - sea-surface temperature, γ - potential temperature gradient above IBL, *h(MOD)* - IBL height according to the model, *h(EXP)* - IBL height determined from potential temperature profile).

Tablica 1. Pregled meteoroloških uvjeta u 23 slučaja (T_l- prizemna temperatura iznad tla, T_w - prizemna temperatura iznad mora, γ - gradient potencijalne temperature iznad IBL, *h(MOD)* - visina IBL dobivena modelom, *h(EXP)* - visina IBL određena iz profila potencijalne temperature).

Date	Time UTC+1h	Stability clas	Wind direction	Wind speed [ms⁻¹]	T_l [°C]	T_w [°C]	γ [°Cm⁻¹]	Friction velocity [ms⁻¹]	h (MOD) [m]	h (EXP) [m]
3. 3. 82.	1215-1319	B	250	3.0	13.4	9.0	0.002	0.35	246	156
12. 3. 82.	1215-1302	A	240	3.0	12.8	9.3	0.007	0.37	114	70
15. 3. 82.	1215-1329	A	240	3.0	9.8	9.0	0.002	0.37	102	90
16. 3. 82.	1220-1342	A	240	2.0	13.4	9.2	0.006	0.24	135	170
25. 3. 82.	1515-1615	B	250	3.0	16.5	9.6	0.010	0.35	138	150
26. 3. 82.	1215-1312	B	240	2.0	18.5	9.7	0.010	0.23	146	211
1. 4. 82.	1215-1313	A	290	2.0	18.9	10.9	0.010	0.24	69	82
3. 4. 82.	1215-1315	A	270	2.0	21.2	13.0	0.010	0.24	86	75
10. 4. 82.	1215-1313	B	240	3.0	14.2	11.4	0.003	0.35	150	230
17. 4. 82.	1215-1325	B	250	5.0	18.8	11.6	0.007	0.59	169	197
19. 4. 82.	1215-1316	C	240	5.0	21.0	11.6	0.003	0.55	258	370
21. 4. 82.	1215-1307	C	240	4.0	20.2	11.5	0.002	0.44	304	217
22. 4. 82.	1215-1329	A	240	2.0	17.0	11.4	0.002	0.24	293	350
24. 4. 82.	1515-1616	A	270	2.0	20.0	11.4	0.002	0.24	219	289
28. 4. 82.	1215-1330	C	250	6.0	22.9	11.4	0.004	0.66	264	200
9. 3. 82.	1215-1304	A	180	2.0	14.5	9.4	0.006	0.24	170	245
10. 3. 82.	1215-1317	C	160	3.0	13.5	10.2	0.005	0.33	177	396
5. 4. 82.	1215-1316	B	180	3.0	22.4	12.2	0.004	0.35	272	115
11. 4. 82.	1215-1310	A	220	2.0	22.2	12.2	0.005	0.24	238	250
18. 4. 82.	1215-1311	B	170	5.0	21.4	11.7	0.010	0.59	168	223
24. 4. 82.	1215-1317	B	160	4.0	20.0	11.4	0.003	0.47	385	517
26. 4. 82.	1215-1327	B	200	4.0	23.5	11.5	0.005	0.47	223	100
29. 4. 82.	1520-1608	D	190	3.0	20.2	11.4	0.004	0.33	197	200

tance is determined by the topography of the underlaying surface. Near the surface there is an onshore flow and in the upper layer (roughly about 500 m) there is a return flow. The IBL depth is confined to the height of the onshore flow, because it grows in the stable maritime air that flows from the sea and causes IBL formation (Lyons and Olson, 1973).

To determine the increase in IBL height, getting away the downwind seabreeze from the coast line at a given time of day, we had to modify Venkatram's model before applying it to the west coast of the Istrian peninsula. Some input terms in Equation (1) could not be evaluated without radio-sounding data. For that reason, we assigned typical values to the variables (u_*/u) and (γ) in (1). We used the mean value of γ for the 23 cases examined in section 3 (γ = 0.01), as a typical value of the potential temperature lapse rate above IBL for the region of Pula. The ratio (u_*/u), usually called friction coefficient, was almost constant in the 23 examined cases. If we assume that the coastal land surface is characterized by a constant roughness length, we may take the friction coefficient as a constant (u_*/u = 0.12). Equation (1) becomes

$$h(x) = 0.12\left[\frac{T_l - T_w}{0.01}\, x\right]^{1/2} \tag{3}$$

We are now able to evaluate IBL height by using only surface observations. The modelling of diurnal variation of IBL depth needs the inclusion of temporal dependence in Equation (3) i.e. of the value $h(x,t)$. During the time period from 1000 h to 1700 h when the seabreeze usually blows, the sea-surface temperature hardly changes while the land-surface temperature changes considerably. For this reason we have taken a seawater temperature constant ($\overline{T}_w$) and calculated it by means of 3 daily sea-surface temperature measurements:

$$\overline{T}_w = \frac{T_w(7)+T_w(14)+T_w(21)}{3} \quad (4)$$

where $T_w(7)$, $T_w(14)$ and $T_w(21)$ are sea-surface temperatures measured at 0700 h, 1400 h and 2100 h, respectively.

In order to determine the diurnal variation we parameterized the land-surface temperatures:

$$T_l(t)=\left[T_l(14)-T_l(7)\right]\sin\omega(t-7)+T_l(7) \qquad 7\,h<t<14\,h \quad (5a)$$

$$T_l(t)=\left[T_l(14)-T_l(21)\right]\sin\omega(t-7)+T_l(21) \qquad 14\,h<t<21\,h \quad (5b)$$

where $T_l(7)$, $T_l(14)$ and $T_l(21)$ are the land-surface temperatures at 0700h, 1400h and 2100h, respectively, and ω is the frequency determined by assumption of the maximal land-surface temperature at 1400h ($\omega=\pi/14$). The land-surface temperatures measured at 0700h, 1400h and 2100h are input terms for Equations (5a) and (5b), so that the diurnal variation of the land temperature is modelled by two sinusoidal functions. We have used two sinusoidal functions because the land-surface temperature is not equal at 0700h and 2100h.

By introducing (4), (5a) and (5b) into (3) we obtained:

$$h(x,t)=0.12\left[\frac{T_l(t)-\overline{T}_w}{0.01}x\right]^{1/2} \quad (6)$$

where time variations of $h(x,t)$ follow the function $T_l(t)$ given by (5a) and (5b). Equation (6) was applied for IBL detection in Pula during the period 1 Juny - 31. August 1982 (Fig. 3). We used climatological data (wind, sea-surface temperature and land-surface temperature) measured at standard climatological terms during the summer months in 1982. The data were selected according to the following criteria (based on climatological data at 1400 h):

a) data were included only for wind directions from NW, SE and SW (corresponding to the most frequent seabreeze directions in Pula)

b) the temperature difference between land and sea surfaces had to exceed 7°C.

Britvić (1990) used the statistical comparison scheme presented by Stunder and Sethuraman (1985) and found that the model worked better under conditions of greater temperature difference between the land and sea surfaces, $\Delta \geq 7°C$ (and a greater stability above IBL as well). Figure 4 illustrates the maximal and minimal IBL height at 1400 h in relation to distance from the coast (according to Eq. 3).

Due to the complicated coastline in the region of Pula, the air trajectory between the coastline and the position of the meteorological station in Pula appears

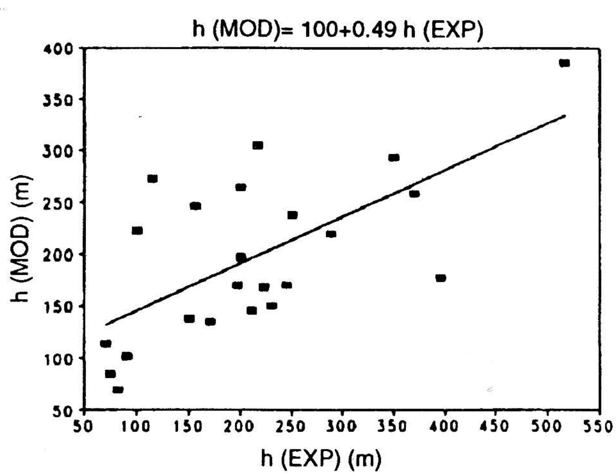

Figure 3. A comparison of IBL height determined by the model *(h(MOD))* with IBL height determined experimentally *(h(EXP))*.

Slika 3. Usporedba visine IBL *(h(MOD))* određene modelom s visinom IBL određenom eksperimentalno *(h(EXP))*.

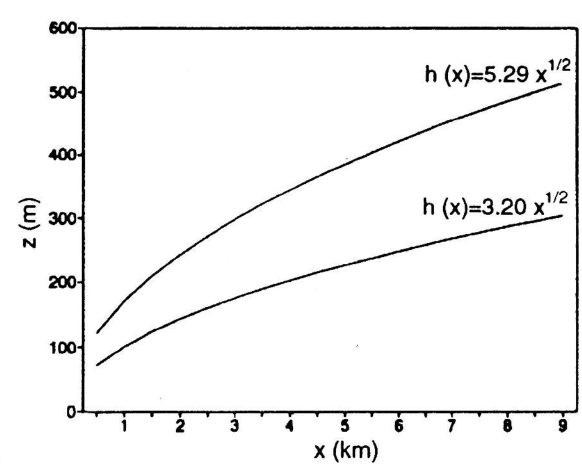

Figure 4. Maximal and minimal internal boundary layer (IBL) height at 1400 LST versus distance from the coast.

Slika 4. Maksimalna i minimalna visina internog graničnog sloja (IBL) u 1400 LST u odnosu na udaljenost od obale.

to be different for different wind directions (because the direction of the x axis is oriented according to the wind direction) so that a calculation of the advective distance (x) depends on wind direction. In Pula, sea winds can come from different directions. The most frequent onshore wind directions during summer are NW, SW and SE. We estimated the diurnal IBL depths in Pula according to Equation (6) for three wind directions. The results, shown in Figure 5, indicate that in the coastal zone of Pula the internal boundary layer grows by day from about 50 m at the onset of the seabreeze to 200 - 300 m in the early afternoon, when the seabreeze is the strongest - and then it slowly decreases again. The IBL decreases with the seabreeze (just after 1700 h) and the PBL decreases later, after sunset (Steyn and Oke, 1982; Carson 1973).

Figure 5 illustrates that for the NW wind in Pula, IBL heights and diurnal variations are the smallest and for the SE wind the IBL is the highest and has the largest diurnal variations. The mean temperature difference between the land and sea surfaces is almost the same for three wind directions (14.7 °C for NW, 14.2 °C for SW and 14.3 °C for SE wind). The maximal temperature difference during the three summer months was 20.5 °C. For the NW wind in Pula advective distance (x) is the smallest so that the influence of the stable maritime air is the largest. For the SE wind the advective distance (x) is about 6 km longer and the influence of the surface is dominant for IBL development.

The spatial and temporal distribution of IBL heights is shown in Figure 6 In the first few kilometers of fetch growth of the IBL heights is faster than further on. This is due to the parabolic dependence of IBL height on fetch. At longer distances its diurnal variations are larger than at shorter distance from the coast.

The spatial and temporal distribution of IBL heights is a direct consequence of the dominant influence of the stable maritime air on the shorter fetch and a greater influence of the land-surface unstable air on the longer fetch.

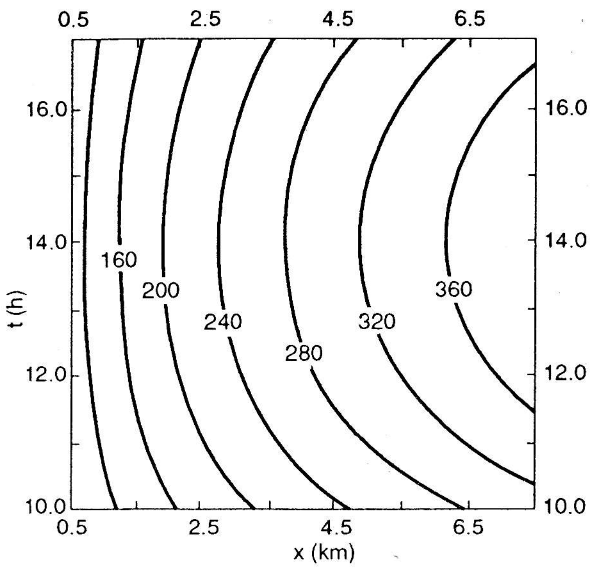

Figure 6. Spatial and temporal distribution of IBL heights in meters on the west coast of Istria (as a function of the land-surface temperature and downwind distance).

Slika 6. Prostorna i vremenska raspodjela visine IBL u metrima na zapadnoj obali Istre (kao funkcija prizemne temperature iznad tla i udaljenosti u smjeru vjetra).

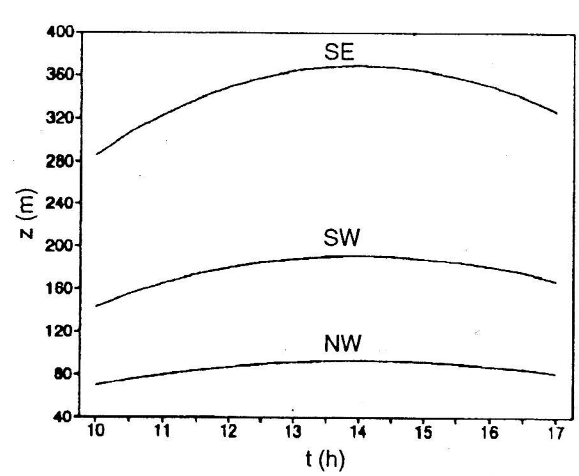

Figure 5. Diurnal variation of IBL heights in Pula for NW, SW and SE wind directions.

Slika 5. Dnevne promjene visine IBL u Puli za NW, SW i SE smjer vjetra.

CONCLUSION

The model proved successful in the Pula region. The application of the model to summer months shows that the IBL height is the lowest with the wind of NW direction. These are the cases when the appearance of local pollution in Pula is the most possible. The diurnal change of IBL height in the period of time from 1000 h to 1700 h points to an increase in IBL height till 1200 h and a slow decrease after 1500 h. From 1200 h till 1500 h the IBL height is almost constant and its diurnal value is maximal. The diurnal change of IBL height grows with the distance from the coast due to a greater influence of the land.

It is important to note that all the results presented in this work are based on a limited number of data. In order of better understand IBL physics and to prepare a more reliable theoretical model, we would need more measurements (especially radio-soundings and surface temperatures data) on the east Adriatic coast under a wide variety of meteorological situations. In spite of the simplicity of the model and the lack of both surface and radio-sounding data the model predicts IBL height reasonable well. We can apply this model over flat terrain, with an onshore flow and a significant thermal difference between land and sea surface temperatures. To improve the model it is necessary to include a parametrization of the mechanical effects in the model. An application in an orographically developed area would ask for significant modification of the model or even the application of a new model.

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