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PREDICTION OF STABILITY AND MIXING HEIGHT IN THE COMPLEX OROGRAPHY

Prognoza stabilnosti i visine sloja miješanja na orografski kompleksnom području

AMELA JERIČEVIĆ, KORNELIJA ŠPOLER ČANIĆ and SONJA VIDIČ

Meteorological and Hydrological Service
Grič 3, 10000 Zagreb, Croatia
jericevic@cirus.dhz.hr
spoler@cirus.dhz.hr

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Abstract: The aim of this study is to investigate the possibilities of using the numerical weather prediction (NWP) model ALADIN to calculate input parameters, stability and mixing height (MH), for the Gaussian dispersion model. Since dispersion parameters were not a part of the routine model output, the methods for their calculation were tested. The model characteristics were analysed on the complex orography of the Rijeka area, the most developed industrial part of the Croatian coast. This was also done for the episode of elevated SO_2 concentrations due to fumigation processes. It was shown that the ALADIN model could be used for calculations of the dispersion parameters. The model unreliability in 2 m temperature prediction relates to days with fog or mizzle and there is also an indication of night-time 2 m temperature underestimation.

Key words: Numerical Weather Prediction model, stability classes, mixing height

Sažetak: Analizirana su svojstva i mogućnosti numeričkog prognostičkog modela ALADIN u proračunu ulaznih parametara, stabilnosti i visine sloja miješanja (VSM), za gausovski disperzijski model. Budući da operativni izlaz modela ne uključuje disperzijske parametre, bilo je nužno pronaći najpogodniju metodu za njihov proračun. Karakteristike modela analizirane su na orografski kompleksnu području Rijeke, industrijski najrazvijenijem dijelu hrvatske obale. Proučavane su i mogućnosti primjene modela u slučaju povećanja koncentracije SO_2 zbog fumigacije. Osim u danima s maglom ili rosuljom kada model precjenjuje temperaturu na 2 m, a noću je uglavnom podcjenjuje, pokazano je da se ALADIN može koristiti u proračunima disperzijskih parametara.

Ključne riječi: numerički prognostički model, klase stabilnosti, visina sloja miješanja

1. INTRODUCTION

Air pollution models are useful tools for evaluating emission rates and quantifying adverse pollutant effects in certain region. Air pollution models can be Lagrangian, Eulerian or Gaussian. The Gaussian dispersion models are still often used in practice. Stability and mixing height (MH) are two important dispersion parameters for those models. Ideally, hourly input parameters in dispersion models should be calculated from measurements. Unfortunately, radio sounding, which provides data for stability and MH calculations, in Croatia is performed only in Zagreb and Zadar twice a day. In practice, Numerical Weather Prediction (NWP) models are used to provide the meteorological input required by air pollution diffusion models.

The basic purpose of this study was to find the best methods to calculate mixing height and stability from the limited-area NWP model ALADIN.

Pasquill stability classes describe the intensity of turbulence by dividing it into six categories (from extremely unstable to moderately stable). Those categories are required as a common input to the Gaussian dispersion model. The International Atomic Energy Agency (IAEA) safety guide (1980) summarises the methods for the determination of stability classes and it is frequently used (e.g. Synodinou et al., 1996; Embaby et al., 2002; Essa et al., 2003). According to available NWP model output data, two methods were selected: one based only on the vertical temperature gradient (VTG) and the other on VTG and mean wind speed.

The MH represents the vertical extent over which turbulence decays and laminar flow becomes a dominant process. There are different ways to estimate MH (Seibert et al., 2000). The method using vertical turbulent diffusion coefficient for momentum, K_M, can be applied (Jacobsen et al., 1995) on the High Resolution Limited Area Model (HIRLAM) output. The 'mechanical' MH is defined as the lowest level where K_M is less than 1 m^2s^{-1} and K_M is determined by the Blackadar (1979) method from the Richardson number. Another method is based on friction velocity, u_*, from the ECMWF model (Wotawa et al., 1996) and MH is computed as $MH=c_1u_*/f$ where the proportionality factor c_1=0.07 is chosen, and f is the Coriolis parameter. The most frequently applied method for MH calculations is the method of the bulk Richardson number, R_{iB} (e.g. Sørensen, 1996). It is the ratio of the vertical potential temperature gradient and wind shear, and it is based on the assumption that turbulence vanishes at some previously defined critical value R_{iBc}. The height of the level at which R_{iB} reaches R_{iBc} is taken as MH. The R_{iBc} used in practice deviates from the theoretical value 0.25 (e.g. Taylor, 1931; Stull, 1988; Grisogono, 1994). Different authors employ different values of R_{iBc}, Hanna (1969) has 0.33–0.56 and Sørensen et al. (1996) take R_{iBc} in the interval 0.14–0.24. Here, based on measurement analyses, the model was tested for different R_{iBc} values in the interval 0.1–0.3.

This work will show that predicted stability and MH have seasonal and daily variations and that the ALADIN model can be used as a data provider for the Gaussian dispersion model.

2. METHODS AND INPUT DATA

Stability classes describe the intensity of atmospheric turbulence in six categories: A - extremely unstable, B - moderately unstable, C - slightly unstable, D - neutral, E - slightly stable and F - moderately stable. For the stability calculation from the NWP model two methods are employed. One method (M1) determines stability based on the VTG between two model levels, while the other method (M2), besides VTG, includes the mean wind speed in the layer. The M1 and M2 properties for stability determination are represented in Table 1 and Table 2, respectively. The modified Pasquill method, developed by Lončar in 1974 (according to Cividini and Šinik, 1987), is used for stability calculation from measurements. The stability classes calculated from measurements are then compared with the stability determined from the NWP model. The Pasquill method (Pasquill, 1961) works with 2m temperature, wind speed data at 10 m, insolation during the day and cloud cover during the night. Further, the modified Pasquill method also includes meteorological phenomena (hail, fog, thunder) and treats differently the cold and warm part of the year. This method is commonly used for dispersion studies in the Croatian Meteorological and Hydrological Service.

Table 1. Method M1 for Pasquill stability classes determination based on VTG (modified Table V in IAEA (1980)) A-extremely unstable, B-moderately unstable, C-slightly unstable, D-neutral, E-slightly stable, F-moderately stable.

Tablica 1. Metoda M1 za određivanje Pasquillovih klasa stabilnosti na temelju VTG (modificirana Tablica V u IAEA (1980)) A-ekstremno nestabilno, B-jako nestabilno, C-slabo nestabilno, D-neutralno, E-slabo stabilno, F-jako stabilno.

$\frac{\Delta T}{\Delta z}$ (K/100 m)	$\frac{\Delta T}{\Delta z} \leq -1.9$	$-1.9 < \frac{\Delta T}{\Delta z} \leq -1.7$	$-1.7 < \frac{\Delta T}{\Delta z} \leq -1.5$	$-1.5 < \frac{\Delta T}{\Delta z} \leq 0.5$	$-0.5 < \frac{\Delta T}{\Delta z} \leq 1.5$	$\frac{\Delta T}{\Delta z} > 1.5$
Pasquill stability class	A	B	C	D	E	F

Table 2. Method M2 for Pasquill stability classes determination based on VTG and mean wind speed in the layer (modified Table VII in IAEA (1980) and reference therein: Vogt, K.J. et al.,1971: *Ausbreitung und Ablagerung*, Kernforschungsanlage Jülich, FRG Report Jül-807-ST)

Tablica 2. Metoda M2 za određivanje Pasquillovih klasa stabilnosti na temelju VTG i srednjeg vjetra u sloju (modificirana tablica VII u IAEA (1980) s referencom: Vogt, K.J. et al., 1971: *Ausbreitung und Ablagerung*, Kernforschungsanlage Jülich, FRG Report Jül-807-ST)

wind speed v (ms^{-1})	Stability class with ΔT/Δz (K/100 m), measured between 20 i 120 m height, of:						
	$\frac{\Delta T}{\Delta z} \le -1.5$	$-1.5 < \frac{\Delta T}{\Delta z} \le -1.2$	$-1.2 < \frac{\Delta T}{\Delta z} \le -0.9$	$-0.9 < \frac{\Delta T}{\Delta z} \le -0.7$	$-0.7 < \frac{\Delta T}{\Delta z} \le 0$	$0 < \frac{\Delta T}{\Delta z} \le 2$	$\frac{\Delta T}{\Delta z} > 2$
$\mathbf{v} < 1$	A	A	B	C	D	F	F
$1 \le \mathbf{v} < 2$	A	B	B	C	D	F	F
$2 \le \mathbf{v} < 3$	A	B	C	D	D	E	F
$3 \le \mathbf{v} < 5$	B	B	C	D	D	D	E
$5 \le \mathbf{v} < 7$	C	C	D	D	D	D	E
$7 \le \mathbf{v}$	D	D	D	D	D	D	D

The MH is the fundamental parameter in dispersion modelling. The bulk Richardson method is the most frequently used procedure to derive MH from the NWP model. This method is based on the bulk Richardson number, a dimensionless parameter, which is the ratio of the main turbulence production sources, buoyant and mechanical:

$$R_{iB} = \frac{\Delta\phi}{\overline{\theta}} \frac{\Delta\theta}{(\Delta u_j)^2 + (\Delta v_j)^2} \tag{1}$$

where ϕ is the geopotential height, θ is potential temperature and u,v are wind components (e.g., Sørensen et al., 1996).

This method assumes that the transition of two different flow conditions, from turbulent to laminar and vice versa can be determined by the critical value of the bulk Richardson number, R_{iBc}.

Starting from the first, lowest model level, the calculated R_{iB} number is compared with the previously defined critical value R_{iBc}. The level at which the critical value is reached is assumed to be MH.

The methods for stability and MH determination were applied to four 15-day periods representative for winter (25 January 2002–8 February 2002), spring (7–21 May 2002), summer (7–21 August 2002) and autumn (7–21 October 2002.) at eight selected grid points corresponding to Ljubljana, Rijeka-town, Rijeka-airport, Udine, Zadar, Zagreb-airport, Zagreb-Maksimir and Zagreb-Grič. These specific locations differ according to their geographical and topographical characteristics and they are used to analyse the spatial variability of stability and MH. The stability classes and MH were also analysed for a pollution episode, which occurred in the Rijeka (φ=45.3° N, λ=14.4° E) area on 3–5 February 2002, when SO_2 exceeded its critical value. Furthermore, with the modified Pasquill method, the stability classes were determined from measured data at climatological terms (0700, 1400 and 2100 LST), at Rijeka, for the period 1981–2001.

3. RESULTS AND DISCUSSION

3.1. Stability and MH

The comparison between the observed and modelled stability classes for the different locations is shown in Figure 1. The observed stability classes frequencies at different locations, determined with the modified Pasquill method, are small. They are 5 – 10 % for classes C, D and E between Zagreb, which is a continental location, and Zadar, which is on the coast. For these locations, the spatial difference for classes A, B and F is less than 5%. Note that for Rijeka, which is on the northern coast, the stability frequencies are more similar to Zagreb than to Zadar. The stability determined with M2 shows better agreement with the observed stability than the one determined with M1. Generally, M1 tends to produce more stable classes and underestimate

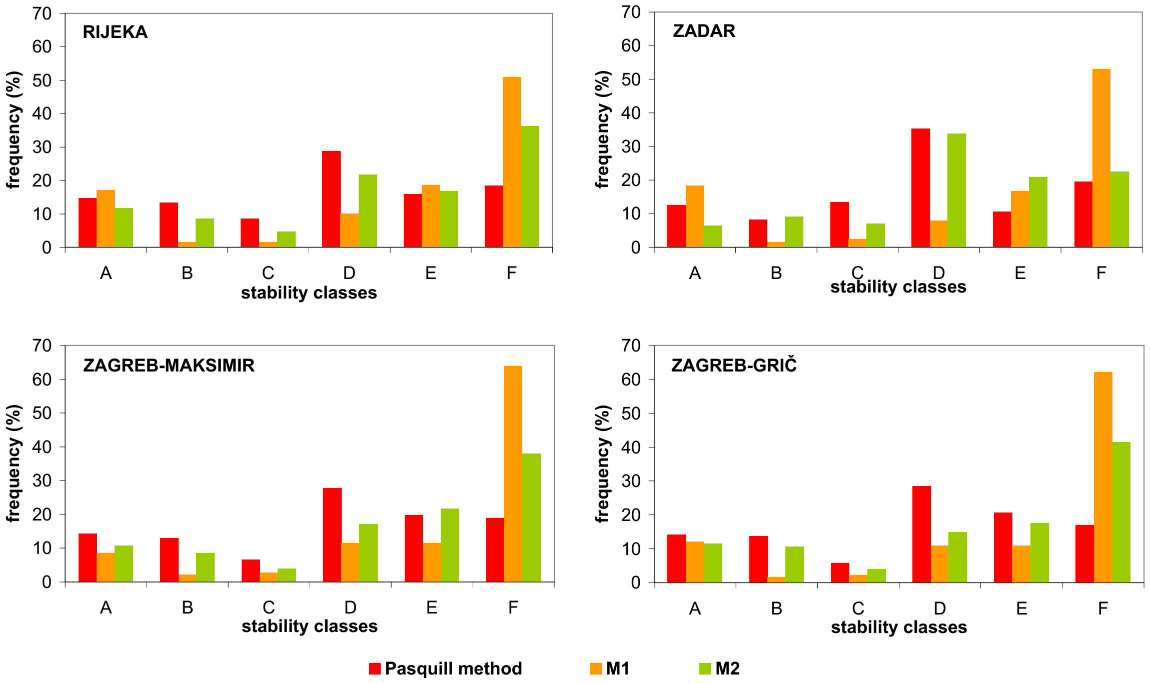
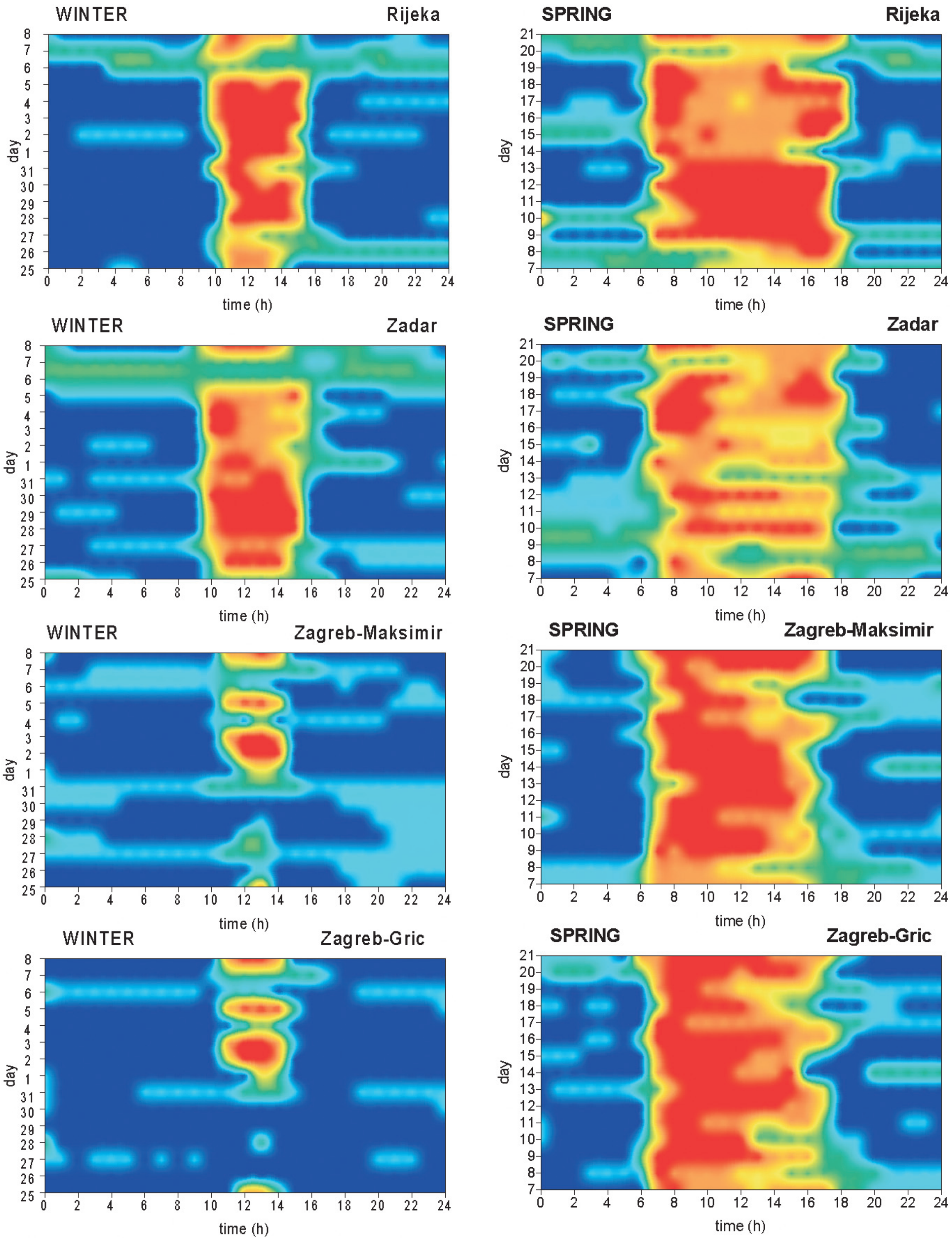


Figure 1. Comparison between the observed stability classes, determined with the modified Pasquill method, and data in climatological terms (0700, 1400 and 2100 LST) in the period 1981–2001 at the Rijeka, Zadar, Zagreb-Maksimir and Zagreb-Grič meteorological stations and stability classes determined with the M1 and M2 methods from modelled data for the same locations. The classes go from extremely unstable, A, to moderately stable, F.

Slika 1. Usporedba klasa stabilnosti određenih modificiranom Pasquillovom metodom iz meteoroloških podataka u klimatološkim terminima (0700, 1400 i 2100 LST) u razdoblju 1981–2001. na meteorološkim postajama Rijeka, Zadar, Zagreb-Maksimir i Zagreb-Grič klasama stabilnosti određenim metodama M1 i M2 iz podataka modela za te lokacije. Podjela klasa stabilnosti je od ekstremno nestabilno, A, do umjereno stabilno, F.

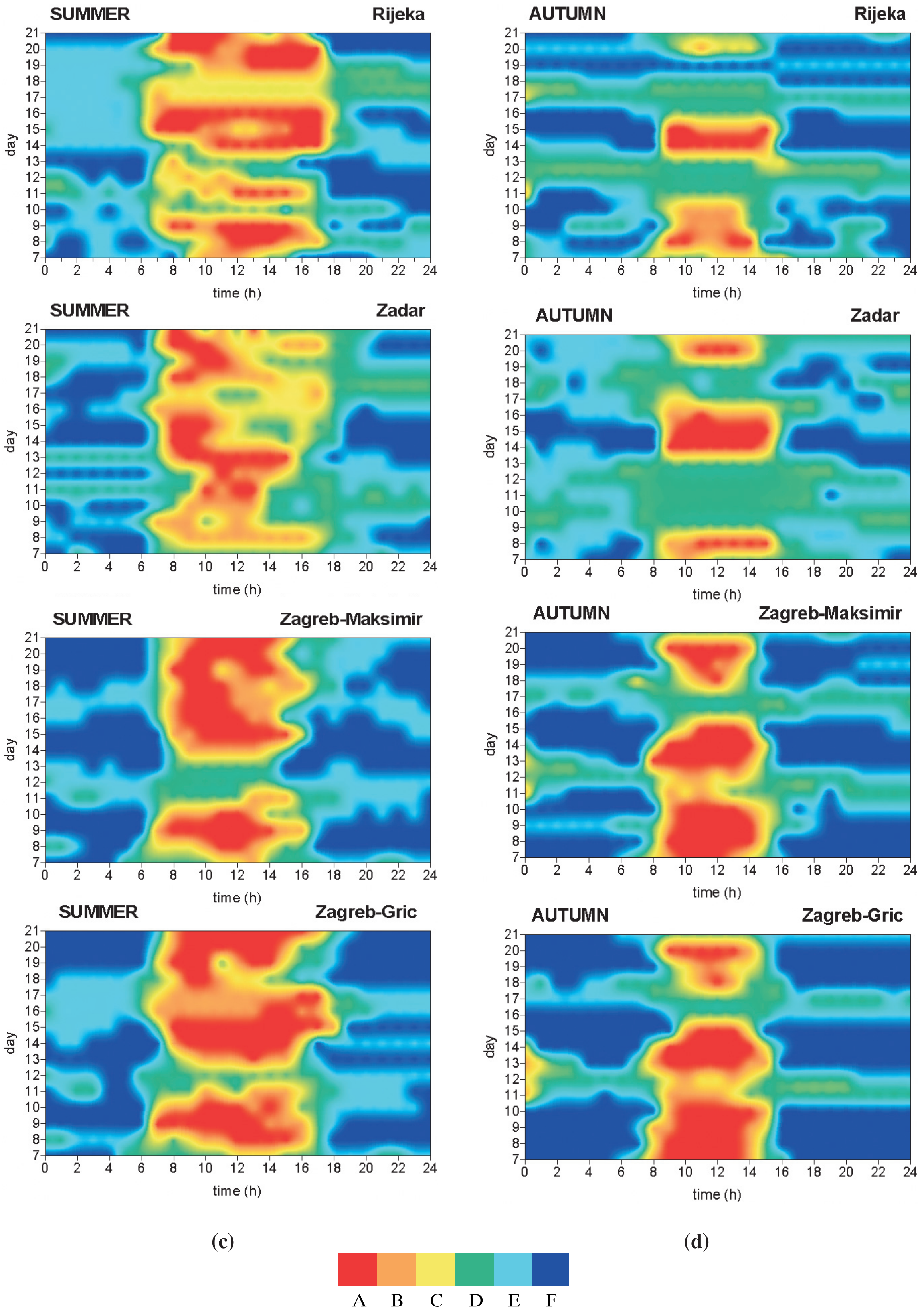
the lability in the atmosphere. On the other hand, M2, besides vertical temperature variations, includes the mean wind in the layer, related to the mechanical turbulence production term, and thus the stability representation is more realistic. In Figure 2, daily and seasonal variations of stability for the same four locations are represented. During the day, instability classes dominate mainly due to an intensified VTG. Stable and neutral situations, occurring during night-time, are usually connected with a negative surface VTG. There is more spread in the unstable classes daily interval during the longer spring and summer duration of the day. Although a greater spread was expected during summer, the calculation has shown it in spring. The reason could be the more frequent cyclones that dominated the weather conditions at the beginning of the studied summer period, which increased precipitation especially in the Adriatic region. Climatologically, May 2002 was very warm and August was very wet compared with 30-year average values (DHMZ, 2003). Neutral classes are frequent during whole day in this autumn period, especially for the Rijeka and Zadar coastal stations, shown in Figure 2(d). The reason is increased precipitation decreasing the temperature gradients, which is usual for this time of year. For Zagreb-Maksimir and Zagreb-Grič, the spatial difference in stability is most intense in winter, with periods of stable classes lasting the whole day. (Fig. 2(a)). This stable, stagnation periods are characteristic of winter anticyclone situations in the continental part of Croatia.



(a) (b)

Figure 2. The daily and seasonal course of stability classes determined with M2 from the ALADIN model for Rijeka, Zadar, Zagreb-Maksimir and Zagreb-Grič, Croatia, for (a) winter, (b) spring, (c) summer and (d) autumn.

Slika 2. Dnevni i sezonski hod klasa stabilnosti određenih pomoću metode M2 iz modela ALADIN za Rijeku, Zadar, Zagreb-Maksimir i Zagreb-Grič, Hrvatska za (a) zimsko, (b) proljetno, (c) ljetno i (d) jesensko razdoblje.



(c) (d)

Figure 2. continued.

Slika 2. nastavak.

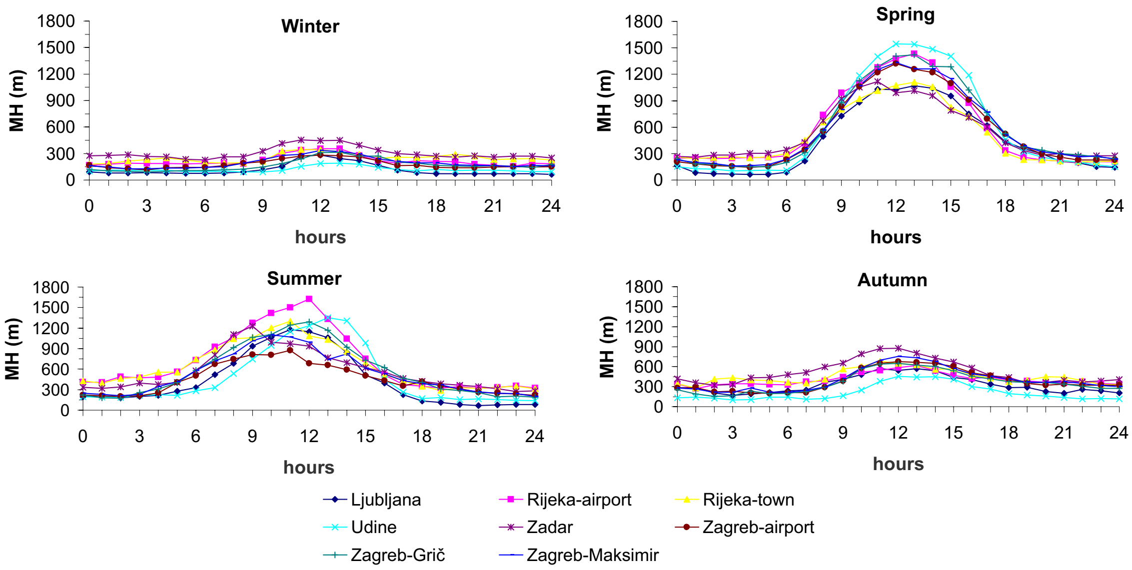


Figure 3. The daily and seasonal course of the averaged mixing height (MH) estimated from the ALADIN model with the bulk Richardson number method with $R_{iBc} = 0.1$ for eight different locations in the model that correspond to: Rijeka-airport, Rijeka-town, Zadar, Udine, Ljubljana, Zagreb-airport, Zagreb-Grič and Zagreb-Maksimir.

Slika 3. Dnevni i sezonski hod srednje visine sloja miješanja (VSM) proračunate iz modela ALADIN bulk-Richardsonovom metodom uz $R_{iBc} = 0.1$ na osam različitih lokacija u modelu koje odgovaraju: Rijeka-aerodrom, Rijeka-grad, Zadar, Udine, Ljubljana, Zagreb-aerodrom, Zagreb-Grič i Zagreb-Maksimir.

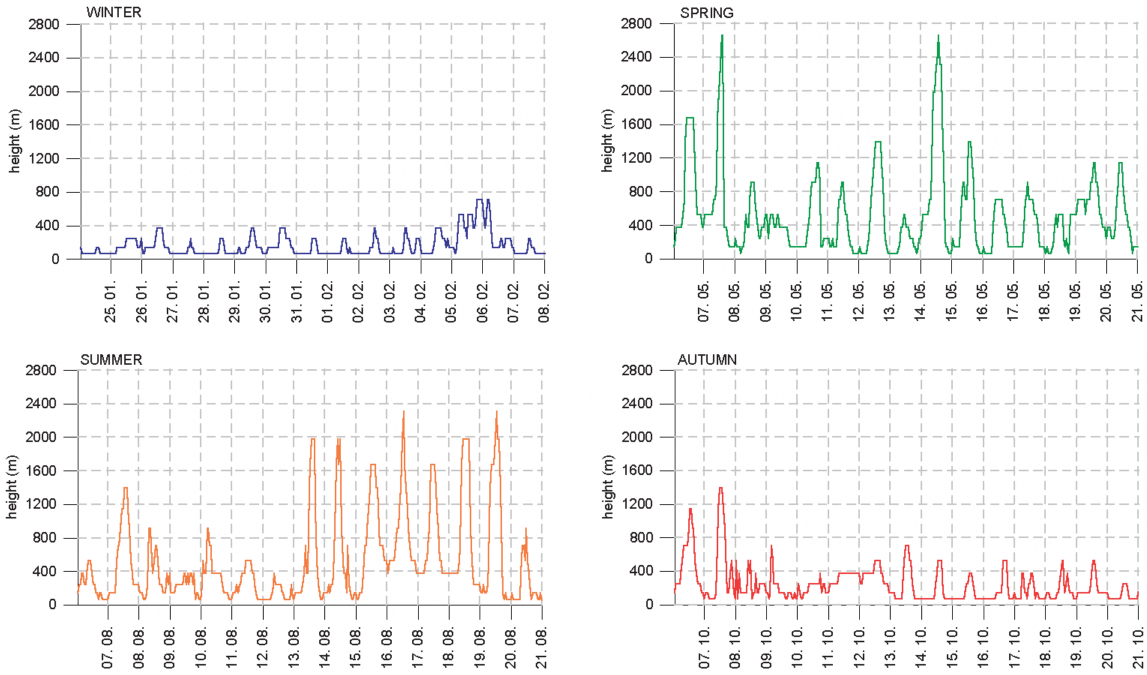


Figure 4. The daily and seasonal course of MH estimated from the ALADIN model with the bulk Richardson number method with $R_{iBc} = 0.1$ for Rijeka, Croatia.

Slika 4. Dnevni i sezonski hod VSM-a proračunate iz modela ALADIN bulk-Richardsonovom metodom uz $R_{iBc} = 0.1$ za Rijeku, Hrvatska.

The spatial and seasonal variation of MH determined from the NWP model is also represented. Figure 3 shows the seasonally averaged MH calculated with $R_{iBc} = 0.1$ for all chosen locations. In the winter period, the average MH did not exceed 600 m. Long-lasting stable conditions suppressed turbulence and the average MH shows only a slight shift at noon hours. In spring, the atmospheric processes became more intense, increasing instability and consequently making the turbulent boundary layer thicker. This can be seen in the daily course of the predicted MH when the average maximum at times reached 1600 m. In summer, the buoyancy term is the dominant turbulence generator and the average MH in summer has maximum values ranging from 800 to 1800 m. Although it is reasonable to expect higher MH values during summer, the beginning of this analysed summer period showed lower MH values (Fig. 4). This is because the convective processes were disturbed by an unstable synoptical situation and frequent cyclone formations that influenced the weather situation. In autumn, MH was again lower, depending on the cold air mass breach frequency and stagnating periods. It is obvious that the determined MH varies spatially, showing a larger spread during the colder part of the year.

Figure 4 presents the daily and seasonal course of MH calculated from the ALADIN model with $R_{iBc}=0.1$ for Rijeka. The optimal critical value $R_{iBc}=0.1$ for the Rijeka area was found based on a comparison study (not shown here). The ALADIN has seasonal and daily variations of MH with low values during stable boundary layer (SBL) conditions and in the colder part of the year (winter and autumn) and higher MH in convective boundary layer (CBL) conditions and during spring and summer.

Stability describes turbulence intensity in the atmosphere, and MH determines its vertical range. Hence, these two parameters jointly give an interpretation of the dispersion processes in the boundary layer. It is reasonably to expect a coincidence between MH and stability, having the smaller MH for stable classes and the higher for unstable ones. Therefore, Figures 2 and 4 show good agreement between stability and MH and their corresponding daily and seasonal variations. Note that there is a seasonal MH variation for the corresponding stability class. For example, the difference between the summer and winter MH, that corresponds to class A - extremely unstable - is around 1000 m.

3.2. SO_2 episode in Rijeka

A pollution episode occurred in Rijeka on 3 February 2002 when the concentration of SO_2 increased approximately by 300% reaching a measured daily concentration of 225.5 µg m^{-3}. This high daily concentration continued during the next two days and on 4 February 2002 a warning was sent out to the public not to expose outdoors it being a health risk. The daily averaged SO_2 concentrations from 1 to 15 February 2002 are represented in Figure 5. This significant increase in daily concentrations is obvious for the period 3–5 February 2002. The refinery and other industrial sources of SO_2 claimed that they did not increase emissions in this period and city traffic was also of usual intensity. If this is accurate, these higher concentrations are the consequence of specific meteorological conditions. Rijeka is a coastal industrial city and also the most polluted part of Croatia. It is situated on the coast with mountains right behind it and with two local circulations: the sea breeze and mountain slope circulation which superpose and may produce higher pollution in this complex area. The synoptical situation of that winter period was characterized by a surface anticyclone centred over the continental part of Croatia, and a NW and W warm flow from the Atlantic ocean at higher altitudes, originating from the Island Cyclone, as shown in Figure 6 for 25 January 2002 at 1200 UTC, and this situation remained during the most of the analysed

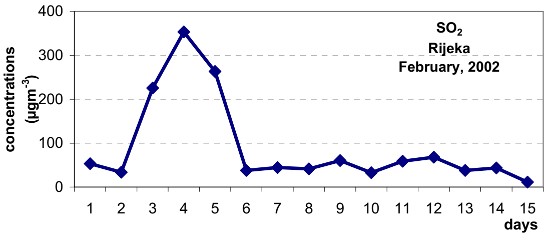


Figure 5. The daily averaged SO_2 concentrations measured in Rijeka in the period from 1 to 15 February 2002.

Slika 5. Dnevne osrednjene koncentracije SO_2 izmjerene u Rijeci u razdoblju od 1. do 15. veljače 2002.

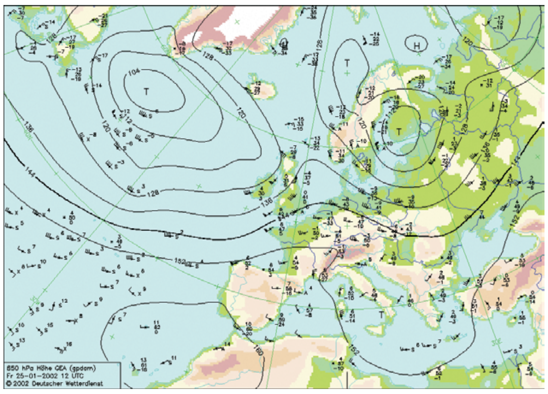
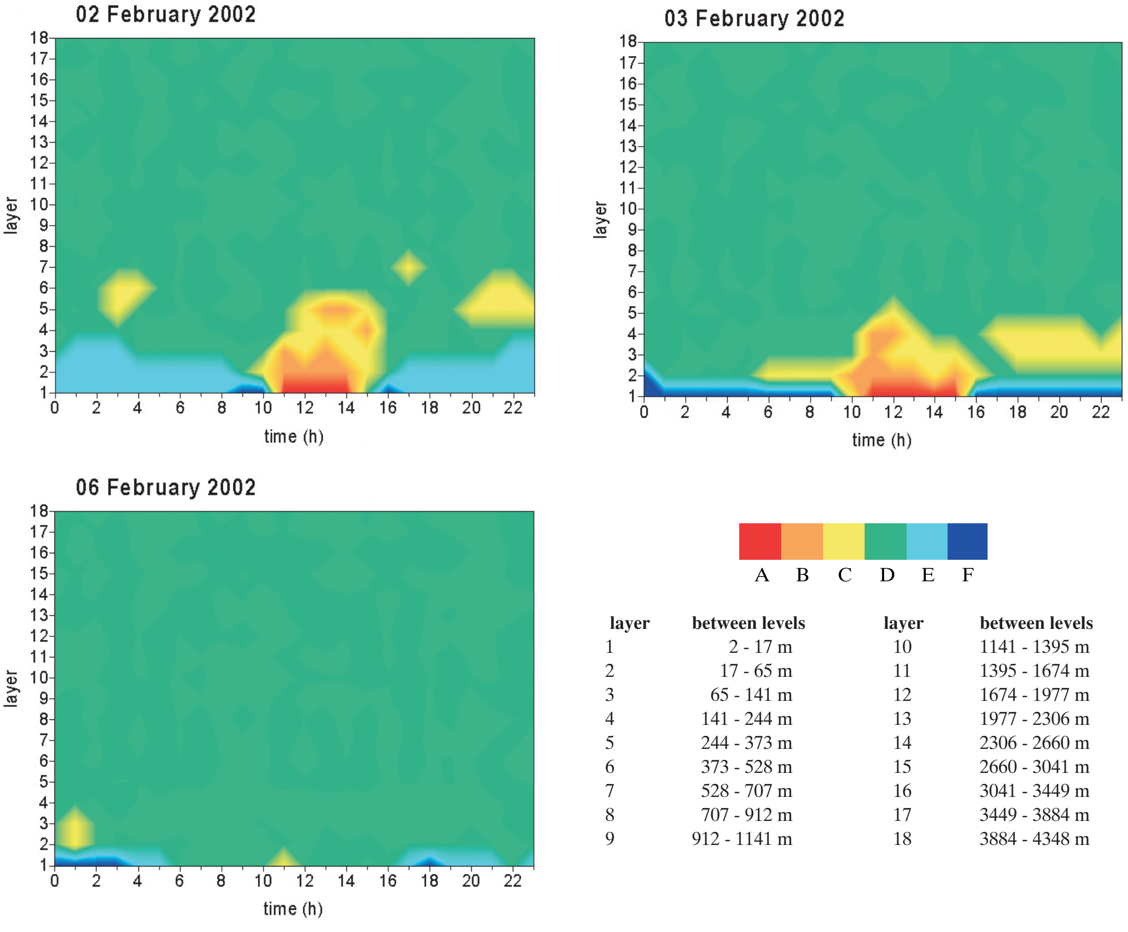


Figure 6. The synoptical situation at 850 hPa over Europe on 25 January 2002 at 1200 UTC (from the Europäische Wetterbericht, 2002)

Slika 6. Sinoptička situacija na 850 hPa plohi nad Europom 25. siječnja 2002. u 1200 UTC (iz Europäische Wetterbericht, 2002).

winter period. The weather was stable. It was a long-lasting stagnation period characterized by fog and low stratified cloudiness and the surface wind was week.

In the Rijeka area, the highest emission sources are approximately 200 m above the ground and obviously they were above MH since there was no increase in the daily SO_2 concentration before 3 February 2002. This led to an accumulation of pollutants in the elevated stable layer. This long-lasting stagnation period was broken the day before a smog increase, when weather conditions changed. It was sunny and calm on 2 February 2002, and the buoyant processes elevated MH which reached the stable polluted layer. When the MH reaches a stable layer intensive mixing occurs, this process is known as fumigation, and the pollutants are drawn into the turbulent layer.



layer	between levels	layer	between levels
1	2 - 17 m	10	1141 - 1395 m
2	17 - 65 m	11	1395 - 1674 m
3	65 - 141 m	12	1674 - 1977 m
4	141 - 244 m	13	1977 - 2306 m
5	244 - 373 m	14	2306 - 2660 m
6	373 - 528 m	15	2660 - 3041 m
7	528 - 707 m	16	3041 - 3449 m
8	707 - 912 m	17	3449 - 3884 m
9	912 - 1141 m	18	3884 - 4348 m

Figure 7. The time representation of the vertical stability classes determined from the ALADIN model with the M2 method for 2, 3 and 6 February 2002 in Rijeka, Croatia.

Slika 7. Vremenski prikaz vertikalnih klasa stabilnosti proračunatih iz modela ALADIN metodom M2 za 2, 3. i 6. veljače 2002. u Rijeci.

This is probably the main reason for the measured increased SO_2 ground concentrations on 3 February 2002. The stagnation period ended with the Genoa Cyclone approaching on 6 February 2002, which brought rain and stronger winds, so the SO_2 concentrations decreased.

The prognostic values of MH from 25 January to 5 February 2002 are low (see Figure 4) having daily maxima less then 400 m. On 6 February 2002, with the weather change, MH was higher. However, we can conclude that this predicted MH was too high, even with R_{iBc}=0.1, to describe this fumigation process. The calculated stability also confirms that ALADIN over-predicted the near-surface stability. The vertical representation of the predicted stability is shown in Figure 7 for 2, 3 and 6 February 2002. These specific days were selected because they were characterized with different atmospheric conditions. On 2 February 2002 it was sunny and calm and the buoyant processes are well described in the model, having unstable classes during the day. However, the next day was also calm but cloudy and there was fog, and the model representation was similar as the day before. This continued until 6 February. As long as there was fog, the model showed unstable conditions. On 6 February, the model gave nearly-neutral conditions through all vertical layers, and that day it was raining.

The main reason for this is that ALADIN has large deviations from 2m temperature for days with fog. A seasonal comparison between ALADIN and the measured 2 m temperature in Figure 8 confirms this. During spring and summer, the measured and modelled temperature curves fit, which is also the case for winter and autumn when there is no fog or mizzle. Nevertheless, when there is fog the measured temperature does not have a daily course while the 2 m temperature in the model does.

The unrealistically predicted 2 m temperature during fog occurrence reproduces more turbulent conditions in the atmosphere with higher MH and more unstable classes.

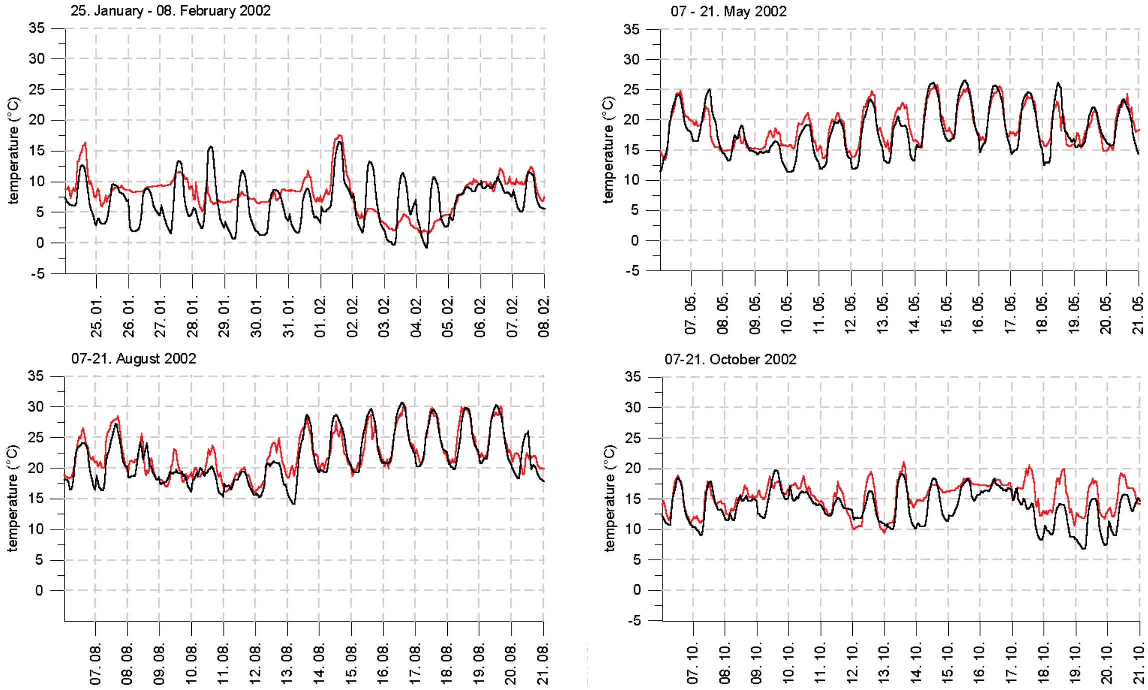


Figure 8. The daily and seasonal comparison between the measured (black curve) and modelled (red curve) 2 m temperature in Rijeka, Croatia.

Slika 8. Dnevna i sezonska usporedba izmjerene (crna krivulja) i modelirane (crvena krivulja) temperature na 2 m u Rijeci.

4. CONCLUSION

The main goal of this research was to find the methods for stability and MH calculation from the NWP model ALADIN which were then applied and tested in different topographical conditions and used as input parameters in the Gaussian dispersion model.

Stability was calculated with two methods: one (M1) takes into account the VTG and the other (M2) both VTG and the mean wind in the layer. Comparing the results from the model with the observed stability, calculated with the modified Pasquill method, it was found that M2 is better. The seasonal and daily variations of stability classes calculated from ALADIN with M2 have a realistic representation. This method, M2, is more used in practice (e.g. Ferenczi, 2002). It is shown that the highest spatial variations in stability between the continental and coastal part are present during the colder part of the year (autumn and winter), which is also a climatological characteristic of Croatia (Gajić-Čapka and Zaninović, 2004; Zaninović and Gajić-Čapka, 2005).

Here, the bulk Richardson method has been used with R_{iBc}= 0.1 and it has been confirmed that it is practical for MH calculation from NWP models. Empirically determined R_{iBc} is dependent on seasonal variability and on local characteristics e.g. surface roughness (e.g. Telišman and Grisogono, 2002). Further, this value strongly depends on the NWP model characteristics (resolution, parameterisation used etc.), which is confirmed by other authors (Zilitinkevich and Baklanov, 2002). Our results confirm that a detailed analysis is needed when determining R_{iBc} from the NWP model and that R_{iBc} can vary from the theoretical value of 0.25 (e.g. Stull, 1988). The ALADIN model gives a realistic representation of daily and seasonal MH variations and shows that it is sensitive in different orographycal conditions.

Comparing stability and MH, good agreement has been found between the results. There are lower values of MH for stable classes (E, F) e.g. during the night, and higher MH for unstable ones (A, B and C), e.g. during daily convection.

The dispersion parameters for the Rijeka area are of special interest because this is an industrial region and its orography is complex. Unfortunately, here are only ground measurements in Rijeka, and thus the NWP model data are very important. The basic question is whether pollution episodes can be predicted based on the dispersion parameters, i.e. stability and MH, calculated from ALADIN? Naturally, this is important for emission control purposes, and concentration calculations would give a straightforward answer. Nevertheless, it is possible to expect higher pollutant concentrations in longer stagnation periods, having a stable atmosphere and low mixing.

Some characteristics of the model have been found through this analysis and it has been shown that in the days with fog or mizzle ALADIN overpredicts 2 m temperature. Further, the predicted stability and MH also describe more unstable conditions than the existing in days with fog and this should be taken into consideration.

The results have confirmed that the ALADIN model could be used over complex orography for the MH and stability calculation needed in the Gaussian dispersion models.

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REFERENCES

Blackadar, A.K. 1979: High-resolution models of the planetary boundary layer. *Advances in Environmental Science and Engineering.* Vol. 1 (ed. J.R. Pfafflin and E.N. Zeigler), Gordon and Breach, New York, 50–85.

Cividini, B. and N. Šinik, 1987: Climatic Analyses of Atmospheric Stability Horizontal Variations Over A Lowland. (in Croatian with English abstract), *Papers*, **22**, 51–58.

DHMZ, 2003: Climate monitoring and assessment for 2002. (in Croatian), *Reviews,* **12,** DHMZ**,** Zagreb**,** 41. pp.

Embaby, M., A.B. Mayhoub, K.S.M. Essa and S. Etman, 2002: Maximum ground level concentration of air pollutant. *Atmosfera*, **15** (3), 185–191.

Essa, K.S.M., S.M. Etman and M. Embaby, 2003: Air pollutant concentration and its location under different thermal stability classes. *Meteorol. Atmos. Phys*., **83** (1–2), 123–129.

Ferenczi, Z., 2002: Investigation of meso-scale transport processes by means of a puff model. *Proceedings of 8th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes,* Sofia, Bulgaria, 14–17 October 2002, Demetra Ltd., Sofija, 196–199.

Gajić-Čapka, M. and K. Zaninović, 2004: Climate conditions in the Sava, Drava and Danube rivers basins. (in Croatian), *Hrvat. vode,* **49**, 297–312.

Grisogono, B., 1994: A curvature effect on the critical Richardson number. *Cro. Meteor. Jour.,* **29**, 43–46.

Hanna, S.R., 1969: The thickness of the planetary boundary layer. *Atmos. Environ*., **3**, 519–536.

IAEA, 1980: A safety guide No 50 SG-S3: Atmospheric dispersion in nuclear power plant siting. IAEA, Vienna, 97 pp.

Jacobsen, H.A., E. Berge, T. Iversen and R. Skalin, 1995: Status of the Development of the Multilayer Eulerian Model. *EMEP/MSC-W Note*, **3/95**.

Pasquill, F., 1961: The Estimation of the Dispersion of Windborne material. *Meteorol. Mag.,* **90**, 33–49.

Seibert, P., F. Beyrich, S-E. Gryning, S. Joffre, A. Rasmussen and P. Tercier, 2000: Review and intercomparison of operational methods for determination of mixing height. *Atmos. Environ*., **34**, 1001–1027.

Synodinou, B.M., M. Petrakis, P. Kassomenos and S. Lykoudis, 1996: Atmospheric stability and atmospheric circulation in Athens, Greece. *Nuovo Cimento C.,* **19** (2), 245–255.

Sørensen, J.H., A. Rasmussen and H. Svensmark, 1996: Forecast of atmospheric boundary-layer height for ETEX real-time dispersion modelling. *Phys. Chem. Earth.*, **21**, 435–439.

Stull, R.B., 1988: An introduction to boundary layer meteorology. Kluwer Academic Publishers, 666 pp.

Taylor, G.I., 1931: Effects of variation in density on the stability of superimposed streams of fluids. *Proc. Roy. Soc. (Lond.), Ser. A,* **132**, 499–523.

Telišman, P.M. and B. Grisogono, 2002: Idealised numerical simulations of diurnal sea breeze characteristics over a step change in roughness. *Meteorol. Z*., **11**, 345–360.

Wotawa, G., A. Stohl, and H. Kromp-Kolb, 1996: Parameterization of the planetary boundary layer over Europe: A data comparison between the observation-based OML preprocessor and ECMWF model data. *Contr. Atmos. Phys*., **69**, 273–284.

Zaninović, K. and M. Gajić-Čapka, 2005: Climate conditions of Adriatic catchments. (in Croatian), *Hrvat. vode,* **50**, 1–14.

Zilitinkevich, S. and A. Baklanov, 2002: Calculation of the height of the stable boundary layer in practical applications. *Boundary-Layer Meteorol*., **105**, 389–409.