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Vsebina - Contents **Stran/Page**

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A METHOD OF ESTIMATION OF THE INFLUENCE OF A COOLING TOWER WITH NATURAL VENTILATION ON THE ENVIRONMENT

METODA OCENJEVANJA VPLIVA HLADILNEGA STOLPA NA NARAVNI VLEK NA OKOLJE

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SUMMARY

In the process of choosing the location, of the optimisation of technical equipment etc. for the power plant which is planned to be constructed, one of the factors is also the possible influence of the cooling tower on the environment. The present article deals with the estimation of possible influences of the cooling tower with natural ventilation. A numerical model describing dynamics and thermodynamics of the cloud above the tower is used to estimate the frequency of the cloud appearance in different weather conditions, characterised with the meteorological data relevant for the task. Reductions of insolation, of precipitation amount and its distribution around the tower, as well as of the solid deposition, are simulated with separate models. The frequency of appearance and the distribution of certain hydrometeors is estimated on the basis of the results of numerical models.

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The study has been done for the potential location of the nuclear power plant Prevlaka southeast from Zagreb. According to the used models and the available meteorological data (mostly the radiosonde ones), the estimated influences can spread over larger areas in the studied location only in certain weather situations, but in average they are rather small. Clouds can appear above the tower in up to 50 % of time, but their spreading into some of 16 directions can generally occur with frequency of less than 5 % and never with frequencies greater than 20 %. These clouds are several hundred meters high and long, but only occasionally high up to 1500 or long up to 100 km. Longer and higher clouds are rare. Precipitation increase, temperature and humidity changes can only be very small, below the accuracy of measurements. Sunshine duration can be diminished for more than 10 % in average up to a distance of 2 km in summer and 4 km in winter, while the reduction of insolation energy for 10 % is limited to a distance of 1 km the from tower. Also, light snow from stratus cloud and/or fog can be expected, causing slippery roads in the neighbourhood. Other influences can be estimated as being negligible.

POVZETEK

Prikazan je način določanja možnega vpliva hladilnega stolpa termoelektrarne na okolico že v fazi priprave na projektiranje oz. na gradnjo. Za to je bil izbran običajni način: uporabili smo numerični model za simuliranje pojavljanja oblaka nad stolpom na naravni vlek, s posebnima modeloma smo določali tudi količino in razporeditev padavin in trdne snovi v okolici stolpa. S še enim numeričnim modelom pa smo računali, za koliko je zmanjšano trajanje in energija sončnega obsevanja v okolici stolpa.

Vhodni podatki so tako tehnični podatki stolpa kot tudi meteorološki podatki. Glavni vir meteoroloških podatkov so radiosondna merjenja, kajti za pojavljanje oblaka so bistvene razmere v višjih plasteh ozračja, vsaj kakih 500 m od tal. Iz teh podatkov so bile izračunane empirične frekvence pojavljanja posameznih vremenskih stanj in za ta stanja so bili uporabljeni omenjeni numerični modeli. Na osnovi izračunov so bile tudi ocenjene pogostnosti in količine nekaterih pojavov kot so megla, rosa, slana, itd.

Vpliv hladilnega stolpa na okolico utegne biti znaten v posameznih vremenskih situacijah, ki so že same ugodne za pojavljanje oblačnosti. V teh primerih se utegnejo nekateri učinki, npr. dež, pojaviti nekaj prej oz. trajati nekaj dlje, kot bi sicer, po količini pa je povečanje majhno, tako da ga z merjenji sploh ni mogoče potrditi.

V poprečju so vplivi hladilnega stolpa na okolje majhni. Oblaki, ki se pojavljajo imajo sicer skupno pogostnost do 50 % časa, vendar pa po posameznih smereh (analiza je delana za 16 sektorjev vpliva) v splošnem pogostnosti pojavljanja ne presegajo 5 %, in v nobenem primeru 20 % z posamezni sektor ali mesec. Oblaki so v glavnem kratki: nekaj sto metrov v višino in daljino od stolpa, včasih so kakih 1500 m visoki ali 1000 m dolgi. Daljši in višji oblaki so le redki. Povečanje padavin in sremembe temperature in vlažnosti so zelo majhne, pod pragom natančnosti merjenja. Še najmočneje stolp in oblak nad njim vplivata na trajanje in energijo sončnega obsevanja. Na preučevani lokaciji lahko pride do zmanjšanja trajanja sončnega obsevanja do 10 % tja do oddaljenosti 2 km od stolpa poleti in do 4 km od stolpa pozimi (tik ob njem je za stolpom vpliv seveda še močnejši). Zmanjšanje energije sončnega obsevanja za 10 % pa se lahko razteza do okrog 1 km daleč.

Še en vpliv je omembe vreden: pozimi lahko pride do povečanja rahlega sneženja iz stratusnih oblakov ali megle, kar utegne povzročiti spolzke poti v okolici zaradi tanke plasti zglajenega snega na njih. Drugi vplivi na okolje pa so v poprečju zanemarljivi.

INTRODUCTION

Cooling towers of thermoplants are of three main types: moist with natural ventilation, moist with forced ventilation and dry ones, each having the advantages and disadvantages as regards energy consumption, outflow of moisture and dry matter, dimensions etc. Here we deal with the influence on the environment of the moist cooling tower with natural ventilation and with an effective droplets eliminating system.

Many studies have been made on the same topics, the one of Hanna (1977), being among the first . He estimated that the main effect of the tower (of 1 MW power) are the clouds above it, being several hundred meters high. Later investigations confirm this finding with the constatations of the cloud with vertical dimension of up to 700 m, width of 400 m, and spreading of about 1500 or 2000 m downwind from the tower (Egler and Nester, in the Abwaermekommission, 1981). Schatzmann and Policastro (1984) made a statistics of the observed clouds above three towers of different power plants. They found that 80 % of clouds do not reach the height of 400 m and 95 % are lower than 700 m. About 60 % of clouds do not spread more than 700 m, and almost 80 % less than 1000 m from the tower. But in certain weather situations also very high and long clouds can be observed: in a project Climod in Switzerland, clouds with horizontal extent between 4 and 5 km were observed

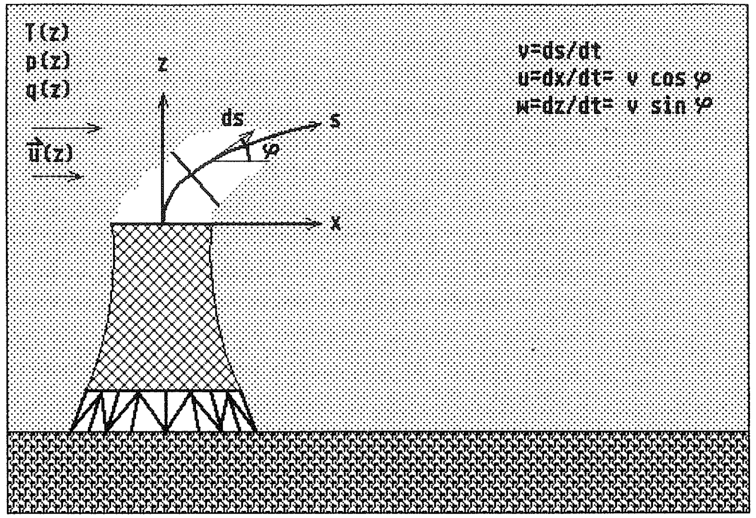

Figure 1: Schematic presentation of the model geometry and variables

Slika 1: Shematična predstavitev geometrije modela in njegovih spremenljivk

in 16 % of the time (reported in EKM, 1981). A great part (70 %) of these extremely long clouds are formed above the tower in a cloudy and/or rainy weather, and so they only contribute to the already existing cloudiness or rain.

The measurable effect of these clouds is on the insolation; close to the tower this effect is important, while the effect on air- and soil-temperature is so small that it cannot be proved by measurements (EKM, 1981; RWE AG, 1981). The common opinion is that precipitations caused by towers with effective droplet eliminators, are limited to the cases of precipitation weather, and so the towers support only slightly the precipitation processes (in the amount of up to 1 % and a little in duration) (RWE AG, 1981), while the operation of towers in general does not act as a trigger for convective clouds and/or precipitation (EKM, 1981).

The clouds from a cooling tower can cause the fog or stratus clouds to be more dense, while the frequency of looping or fumigation of these clouds to the ground is negligible (Spillane and Elsum, 1983). Also the emission of dry constituents is important only from the tower with forced ventilation (Kunaj, 1984), while from the towers with natural ventilation this emission is very small (RWE AG, 1981).

THE MODEL AND THE DATA

The common approach to investigate the potential influence of some future event or process is to simulate it numerically. Here the first task is to simulate the appearance of clouds above the cooling tower, the shape of such a cloud, its density and the eventual precipitation from it. When these characteristics are known for a certain set of typical or average meteorological situations, then the effects on insolation, precipitation at the ground, eventual depostion of solid matter etc. can be estimated.

The model of a cloud

The models for clouds above cooling towers are in general the so called integrated models (e.g. Jiin-lang Lee, 1976; Klug, reported in Abwaermekommission 1981, Schatzmann and Policastro, 1984), what means that they deal with an average cloud and precipitation water content inside a certain volume element. They are twodimensional, what means that the simulation proceeds through consecutive volume elements along the cloud axis, separately for different directions from the tower. The necessary data for these models are the technical data of the tower and its emissions, as well as meteorological data up to the height of 3000 or 5000 m from the ground.

The model we used is similar to the one of Jiin-lang Lee (1976), but modificated in some details, regarding the spectrum of cloud droplets and hydrometeor drops in the cloud. The domain is schematically shown in Fig. 1.

Independent variable is

s - the path along the axis of the cloud;

and dependent variables inside the cloud are

r - radius of the cloud,
v - velocity along the cloud's axis,
φ - the slope of the axis,
T - temperature,
p - pressure,
q - specific humidity,
q_c- specific amount of cloud droplets,
q_h- specific amount of hydrometeor droplets;

all are computed inside the cloud and along its axis.

All of these quantities must be known also for the top of the tower, at s=0, where they serve as initial conditions. There they depend mainly on technical characteristics of the tower, but, on the other side, they depend on the environmental conditions as well, while the operating regime of the tower depends on temperature, humidity and pressure of the neighbouring air.

The parameters of the environment (acting as a sort of boundary conditions), which should be known in all relevant heights, are

$T_e(z)$ - environmental temperature,
$p_e(z)$ - environmental pressure,
$q_e(z)$ - environmental humidity,
$u_e(z)$ - environmental wind velocity.

The equations which we use are:

The two equations of motion, for horizontal and for vertical direction:

$$\frac{\partial}{\partial s}(v^2 r^2 \sin(\varphi)) = gr^2[\frac{T}{T_e}\frac{R_s + q(R_v - R_s)}{R_s + q_h(R_v - R_s)} - q_c - q_e] \pm \frac{C_d}{\pi} r(u_e \sin(\varphi))^2 \cos(\varphi) \quad (1)$$

$$\frac{\partial}{\partial s}(v^2 r^2 \cos(\varphi)) = \frac{C_d}{\pi} r(u_e \sin(\varphi))^2 \sin(\varphi) \quad (2)$$

Here the first (vertical one) considers the unbalanced buoyancy due to temperature difference, due to different weight of humid air(R_s and R_v are specific gas constants for dry air and water vapour, resp., and q and q_e specific humidities of air inside of a cloud and in the environment), and due to extra load of cloud droplets and hydrometeor drops (characterised by q_c and q_h). Both of equations, the first for vertical and the second for horizontal direction, take into account also the drag, caused by the wind, where C_d is the drag coefficient.

Third equation is the mass conservation equation

$$\frac{\partial}{\partial s}(v^2 r^2) = 4\alpha v^* r \quad (3)$$
$$v^* = f(v, u_e)$$

The entrainment of the environmental air into the cloud is treated through v^*, which depends on velocities inside the cloud and in the environment, and serves as an empirical factor.

Next is the energy conservation equation

$$\frac{\partial}{\partial s}(\frac{T}{T_e} v^2 r^2) = \frac{wr^2}{T_e}[\frac{\partial T_e}{\partial z} + \frac{g}{c_p}] + \frac{L}{c_p T_e}(C_c + C_h) \quad (4)$$

which considers the unsaturated adiabatic process in the first term. The latent heat release at condensation or its consumption at evaporation processes is included in the second term, where C_c stands for condensation or evaporation of cloud droplets, and C_h for processes, connected with hydrometeor drops. Water vapour conservation equation includes the effects of the environmental humidity, and the condensation and/or evaporation processes again:

Conservation equation for water vapour

$$\frac{\partial}{\partial s}(qv^2 r^2) = -wr^2 \frac{\partial q_e}{\partial z} - C_c - C_h \quad (5)$$

This equation takes into account the environmental humidity in the first term, as well as the condensation of vapour (or evaporation): C_c and C_h.

Conservation equation for cloud water

$$\frac{\partial}{\partial s}(q_c v^2 r^2) = -C_c - A_{ch} - B_{ch} \quad (6)$$

Here condensation and/or evaporation processes are included. The autoconversion of droplets A_{ch}, which causes the formation of new hydrometeor drops, and the coallescence B_{ch} of cloud droplets with hydrometeor drops act as mechanism of conversion of water from the class of cloud water into the class of hydrometeor water. Both these processes are parameterised.

The last is conservation equation for hydrometeor water

$$\frac{\partial}{\partial s}(q_h v^2 r^2) = -\frac{\partial}{\partial z}(q_h < v_T > r^2) + C_h - A_{ch} - B_{ch} \quad (7)$$

It is taken into account that drops with terminal velocity $\langle v_T \rangle$, being higher than the updraft velocity in the cloud, are falling out from the cloud. The amount of water falling from the cloud depends on the shape of the spectrum of hydrometeor drops, which therefore acts as a parameter of this problem. Condensation or evaporation is considered as well (C_h), and the already mentioned processes of autoconversion and of coallescence are parameterised.

Modelling of other processes

There are some other processes, which are treated with the help of numerical modelling: At the first place, the effect of the tower and the cloud on insolation. The datails of the model are described in the accompanying paper (Petkovšek, 1987), so here we are going to mention only some of its basic concepts, regarding the determination of the cloud border. Namely, it is known (e.g. Thorp and Orgill, 1984) that the shapes of clouds are not so sharp, to diminish considerably the solar radiation at the very border of clouds.

Following the results of Aumf Kampe (1950) on regression between light scattering cross-section s_c and the visibility V:

$$s_c = a/V \qquad (8)$$

and the results of Zabrodski (1963, cit. in Feigel'son, 1966) on the regression between the total water content in a cloud q_{tot} and the visibility V:

$$q_{tot} = b\ V^c, \qquad (9)$$

it is possible to compute the water content, which diminshes the solar radiation to a certain extent. Namely, the optical path through the cloud is namely determined with the shape of the cloud. (its diameter is known as a function of distance and height), and the Beer's law is used for the computation of extinction. So the borders of the cloud are supposed to be, where at least 5 % of solar radiation would be scattered, if passing through the center of the cloud, in a direction normal to the axis. The geometrical treatment of the problem is described, as already mentioned, in the accompanying paper (Petkovšek, 1987).

The problem of precipitation reaching the ground, does not depend only on the quantity of water falling out of the cloud, but also on the spectrum of hydrometeor drops, as well as the wind and humidity in the layer below the cloud. Namely, the drops are evaporating if this layer is not saturated and the evaporation depends on the size of each individual drop. So the spectrum is changing during the fall. The fall velocity also depends on size and so the drops of different sizes are carried by the wind to different distances. The problem can be solved even analitically if the shape of the spectrum is not a too complicated function. So the computation of precipitation distribution at the appropriate distances of the tower can be carried out.

There is an almost negligible amount of dry matter released from the tower with natural ventilation. It depends on chemical treatment of the cooling water, for which minimal standards are prescribed. While drop eliminators are very effective in most cases, emission of dry matter occurs with droplets and only evaporative substances can leave the tower. It is supposed that these substances act as condensation nuclei.

If the fraction of these substances is known, it is possible to treat them as being a part of the cloud. So they can fall out of the cloud with precipitations, or stay in a warm thermal even when the cloud evaporates. There are three ways for these substances to reach the ground:
- with precipitations, where the concentration of these substances in drops grows while the drops are partly evaporating,
- with turbulent diffusion of the part of substances corresponding to drops, falling out of the cloud, but evaporating before reaching the ground, and
- with turbulent diffusion of the rest of substances, which remain in the air after the evaporation of the cloud.

There are two maxima in the distribution of solid deposition at the ground, because the transport to the ground is to smaller distances with precipitation, and to greater distances with turbulent diffusion.

The tower data

For the tower it is assumed to have the characteristisc as the tower of the IBE company, Ljubljana:

- flow of circulating water 33.0 m^3s^{-1}
- cooling power 1930 MW
- water temperature decrease 14.0 K
- radius at the top 44.4 m
- height 162.0 m

The emission of droplets is only 17 kg s^{-1}, while the emission of vapour depends on environmental conditions, as shown on Table 1. These values are fitted as initial conditions with analytical polynomial funcitons for the use in numerical model of the cloud.

Meteorological data

Two types of meteorological data are used for the estimation of possible influence of the tower on the environment. Surface data from neighbouring stations serve for the estimation of climatic situation at the site and for non-numerical evaluation of possible changes.

Table 1: Emission characteristics of the tower
Tabela 1: Emisijske karakteristike stolpa

air temperature temperatura zraka	(°C)	-10		10		30	
rel.humidity rel vlažnost	(%)	60	80	60	80	60	80
water temp. temp. vode	(°C)	25.6	25.8	36.4	37.0	47.6	49.0
emission temp. izstopna temp.	(°C)	15.2	15.4	27.3	28.4	39.4	40.7
vapour flow tok pare	(kg s^{-1})	427	423	588	580	703	692
air flow tok zraka	(10^{3} kg s^{-1})	39.1	39.2	30.4	30.8	22.5	23.2
vert. velocity[1] vert. hitrost	(m s^{-1})	5.2	5.2	4.3	4.3	3.4	3.5

[1] the influence of wind and entrainment of the air into the tower from above are not considered
vpliv vetra in vstopanje zraka odzgoraj v stolp nista upoštevana

Radiosonde data are applicable for the estimation of the situation at upper levels, where the cloud above the tower can occur. The radiosonde data of Zagreb for eight years are used. From these the frequencies of the wind from a certain direction (16 directions of the wind and therefore 16 sectors of the influence of the tower) are computed. The average vertical profiles of wind velocity, pressure, temperature and dew point are computed for every 250 m from the ground, for each month separately. These data serve as environmental (boundary) conditions for the model of cloud.

There are two main important questions how to use the radisonde data. The first is connected with the choice of the height at which the classification is made according to wind direction. In the first place, it is worth considering that close to the ground there is a strong local influence on the measured values. As the radiosonde data are not available at the location, but several ten kilometers away (without considerable orographic obstacles between the locations), the surface values are not used for this purpose. Next factor for the choice is the fact that clouds above the tower occur mainly between 700 and 1000 m above the ground, so that the wind above 1000 m is not very important. At last, it is important to consider the fact that at the location the maximum of recorded precipitations occur when surface wind blows from northeastern quadrant (Ćurković et al., 1986). It is obvious that here, like elsewhere in Mediterranean, the governing factor for this phenomenon is the movement of a cyclon over the area. When southwestern winds at upper levels still advect moist and warm air masses to the area, causing intense precipitations, at the ground, after a cold outbreak, eastern component is prevailing in a not very deep air layer. The wind in this layer is therefore important for the distribution of influences of the tower around it. So the average wind in such a layer, computed from the values at 250 and 500 m above the ground, is used for the classification of the data according to wind directions (and as a consequence, according to the sectors of the eventual influence of the tower).

The second important question is whether average sounding profiles can be used for simulation with numerical model. Namely, it is known that clouds above towers occur in moist weather situations which are in general cloudy and even with precipitations. So it is possible that averaging can wipe out these typical situations. The alternative could be to use a great sample of individual data and then to compute the average influence of the tower from individually simulated cases. This approach is not acceptable where a long series of data would be necessary and therefore an enormous number of individual numerical simulations. There is an indication that grouping according to the above mentioned method would not be too bad (as it is shown just from the close connection between the surface wind and the precipitation amount). The grouping according to months can support this opinion as there are moister and drier seasons as well. Still, we also make tens of individual simulations at extremely moist and extremely dry situations in winter and in summer months to illustrate the extreme possible cloud appearances, caused by the cooling tower.

SOME RESULTS

Detailed results of possible effects of the cooling tower on the environment according to different directions, as well as for separate months and for the whole year can be found in a report of the study (Rakovec et al., 1987). For the illustration of the usefulness of the chosen method of estimation, only some are given here.

First, it is interesting to know which are the simulated frequencies and average cloud shapes. In general, frequencies can reach 50 %. But, if looking into separate sectors around the tower, frequencies of appearance can also be zero in some directions, while the greatest frequencies do not exceed 20 % in any direction or in any month of the year. Clouds are of courseless frequent in summer months. Most frequent is the appearance of clouds to the SW direction, where the probability of cloud appearance is more than 10 % also in summer months (but in these summer cases clouds generally do not extend more than 100 m from the tower). This is in accordance with the measured natural precipitations, which are most frequent when surface winds blow from NE.

In general, clouds have the extension of several hundred meters in horizontal direction, while prevailing vertical dimensions are from 600 to 1400 m in winter, but in summer some can reach the height of over 2000 m. Also very long clouds are simulated according to average conditions: in winter and in early spring they can be more than 2500 m long in particular sectors; their frequencies of appearance are small: 3 to 7 % of the time, and this frequency can reach 10 % only close to the tower.

The computed frequencies and dimensions are in accordance with the values of other investigators (e.g. RWE AG, 1981, Schatzmann and Policastro, 1984).

All precipitation amounts simulated in our study according to average conditions are less than 0.2 mm per month. This value is found only close to the tower in certain sectors, in winter months. Already at a distance of 500 m from the tower the value of 0.1 mm per month is never and nowhere exceeded. As an example the distributions for January and for July are shown in Fig. 2. Also solid deposition is distributed similarly.

But it is also interesting to look closer at some individual simulations. It is possible that absolute extremes are not simulated, while only January and July cases are chosen. From these the extreme quantity of precipitation amount which is simulated occurs in January, but the value of 0.016 mm per hour is limited to a very small area of 200 m x 400 m close to the tower. This is due to extremely moist atmosphere and very light wind, causing nearly vertical cloud and no precipitation drift (Fig. 3). Some situations in winter with broader areas of precipitations can be found as well but with small amount of precipitation.

In July there is no individual case, in eight years' period, of precipitations only close to the tower. An example is given in Fig. 4, showing precipitations with intensity greater than 0.01 mm per hour between 1700 and 3700 m from the tower. They are caused by saturated layer between 860 and 700 mbar level: all extra moisture of any agregate state entering into this layer is removed from it. Precipitations evaporate only partly, and are driven by the wind also far from the tower.

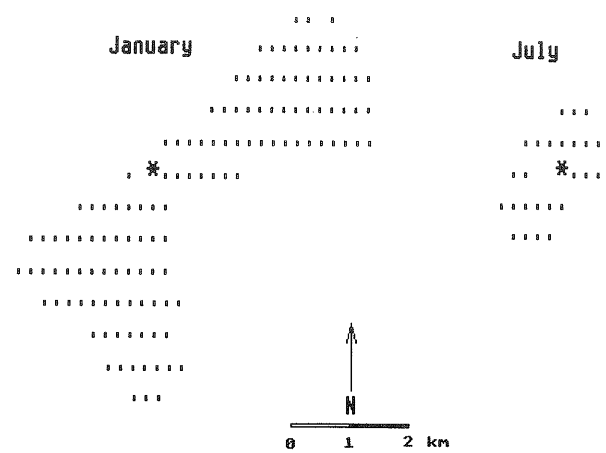

Figure 2: Distribution of precipitations near the cooling tower for January and for July

Slika 2: Razporeditvi padavin v okolici hladilnega stolpa v januarju in v juliju

The effects on insolation are presented in a separate, accompanying paper (Petkovšek, 1987). Here we are going to mention only the fact that there is a broad area of influence in morning and evening hours, but as at that time the amount of energy is not great, these broader areas are affected mainly as regards sunshine duration. The shapes of the affected areas resemble a heart in summer and a kidney in winter months. Both, the quantity of effects and the shapes are in accordance with the observed ones at other locations (RWE AG, 1981).

CONCLUSIONS

The described methods of simulation of possible influences of the cooling tower with natural ventilation are proved to be appropriate for the estimation of these influences in advance, in the phase of planning of the thermo plant with the tower. This is prooved by comparisons with the observed influences (EKM, 1981; RWE AG, 1981; Abwaermekommission, 1981; Schatzmann and Policastro, 1984). The simulated values agree with the observed ones as regards the area of possible influence and as regards the quantitative values of these influences.

From the obtained results for the planned great tower with cooling power of 1930 MW in the investigated area it is possible to summarize:

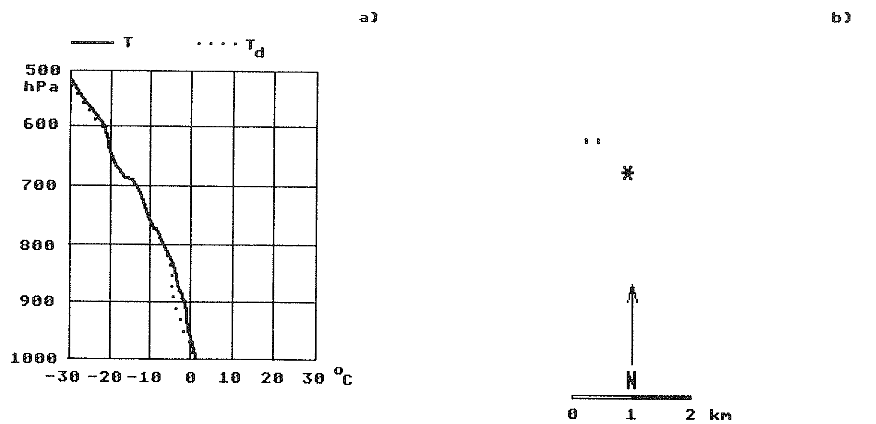

Figure 3: An example of distribution of precipitations near the cooling tower for the selected case in January: a) vertical distribution of temperature and dew temperature and b distribution of precipitation

Slika 3: Primer razporeditve padavin v okolici hladilnega stolpa za izbrani primer v januarju: a) potek temperature zraka in rosišča z višino, b) razporeditev padavin

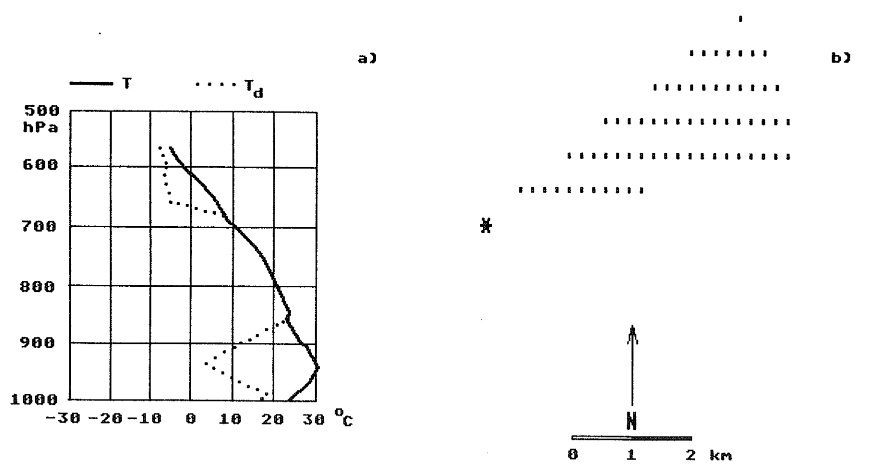

Figure 4: As Fig. 3, but for a case in July

Slika 4: Kakor slika 3, toda za izbrani primer v juliju

Cloudiness

The appearance of the cloud has an allover frequency of 50 %, but for individual directions this frequency is generally less than 5 % and never greater than 20 %. In summer the distribution is more uniform, while in winter some directions have greater frequencies. Long clouds, as well as high ones, are rare: only a few cases are found with average radiosonde data. Most clouds are several hundred meters high, sometimes up to 1500 m, and they extend several hundred meters from the tower, sometimes even thousand meters.

Precipitations

The duration of precipitations is slightly increased over the natural duration, mainly in colder parts of the year. The quantity can be slightly greater too, but this increase (for about 1 %) is below accuracy of measurements and cannot be verified. Amount of drizzle is estimated to be increased from stratus cloud and fog, for several mm per year. The number of precipitation days can be greater for a few days per year due to the drizzle, while the number of the days with precipitation from Nimbostratus and Cummulonimbus clouds is not increased.

Insolation

Sunshine duration can be diminished for 40 % close to the tower and for more than 10 % of the present duration as far as 4 km from the tower in winter, and 2 km in summer. The area of influence on insolation energy is smaller. The decrease for 50 % is close to the tower, while the decrease in energy for more than 10 % does not extend more than 1 km from the tower. In winter mainly northern places are affected, but in summer the ones lying souhteast and southwest from the tower.

Temperature and humidity

Neither air nor soil temperature can be modified to such an extent that this could be verified with measurements. The same is valid for humidity.

Hydrometeors

Due to only very small changes in temperature and humidity, the changes in dew and frost are not to be expected. Frequency of fog cannot be changed, only density of fog or Stratus can be increased, which is the reason of a possible slightly increased hoar. Glaze can be slightly more frequent, but more important can be slippery roads due to light snow from Stratus clouds or deep fog.

Visibility

Visibility at the ground is not affected by the cooling tower, but is changed only in clouds; these are not of a great extent.

Human activities

In winter there can be more slippery roads due to glazed snow. This effect can be expected not more than 2 km from the tower. There is a lack of precipitations in the area in summer months, but the quantity of precipitation in general is not great enough to be important for agriculture. So also effects on plant deseases are negligible. Only in certain situations some precipitations, which could affect the agriculture are possible.

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REDUCTION OF INSOLATION DUE TO THE CLOUD FROM A COOLING TOWER

ZMANJŠANJE OSONČENJA ZARADI OBLAKA IZ HLADILNEGA STOLPA

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ABSTRACT

A model of the reduction of sunshine duration and solar energy due to the cloud from a cooling tower of a thermoplant is presented shortly, including some examples. Calculations are based on the known cloud characteristics and on determination of shadow-loaded area-elements around the tower in typical clear days of separate months. Diminishing of the influence of tower cloud due to natural cloudiness in real days is obtained afterwards by the introduction of weighting factors calculated from radiosonde and climatic data of the region.

POVZETEK

Emisija vode iz hladilnega stolpa večjega termoenergetskega objekta je nekaj ton vode na sekundo. Del te vode se v atmosferi kondenzira in tvori oblak nad stolpom, ki meče na tla svojo senco in vpliva tudi na osončenje v okolici stolpa. Določitev zmanjšanja trajanja osončenja in energije obsevanja v okolici stolpa je odvisno od mnogih faktorjev, prikazan pa je en način pristopa.

V prikazanem modelu je najprej določena navidezna pot sonca po nebu v času, ko je sonce več kot 9° nad obzorjem. Nato je določena lega sence za vsako uro ob predpostavljeno jasnem dnevu in je določen vpliv naravne oblačnosti,

končno pa so izračunane obremenitve posameznih površinskih elementov tal v okolici stolpa.

Model omogoča izračun sence za vsako uro tipičnega dne vsakega meseca in za vsako od 16 smeri orientacije oblaka oz. vetra nad stolpom. Velikosti oblaka v prostoru ob posameznih smereh vetrov so bile izračunane po posebnem modelu (Rakovec - te Razprave). Obremenitev s senco se računa za površinske elemente v okolici stolpa velikosti 200m x 200m. Seštetje vseh urnih obremenitev posameznih površinskih elementov za vse ure in značilnosti oblaka, nam da obremenitve tal ob jasnem vremenu. Vpliv naravne oblačnosti pa je treba izločiti.

Izčrpna obdelava oblačnosti ter višinskih podatkov o vetru in vlažnosti zraka da kriterije in podatke o naravni oblačnosti pri posameznih smereh vetrov in mesecih oz. jasnini v njih. Le ob jasnini se namreč pojavlja vpliv oblaka iz hladilnega stolpa. Ustrezni utežni faktorji nam omogočajo izračun obremenitve s senco vsakega površinskega elementa okrog stolpa za tipičen dan vsakega meseca, iz teh pa dobimo tudi letne vrednosti.

Iz zmanjšanja trajanja osončenja dobimo lahko tudi zmanjšanje energije sončnega obsevanja za vsak element površine tal okrog stolpa. Pri tem potrebujemo relacijo med trajanjem in energijo, ki jo dobimo iz drugih obdelav (Hočevar in sod.1982). Primeri kažejo, da je obseg zmanjšanja energije okrog stolpa ožji, toda jakost zmanjšanja je ob stolpu relativno večja. Rezultati modela se ujemajo z rezultati po modelu RWE AG(1981) in kažejo na pravilnost in uporabnost našega modela.

INTRODUCTION

The lack of cooling water and thermal pollution of rivers, especially at low water, demand the use of cooling towers at large thermoenergetic plants. They lead away the waste heat in amount usually greater than the useful part.

Although latent heat of water evaporation is considerable and the drop collectors are installed in the cooling tower, the water vapour and droplets emission from the tower can be some metric tons per second. At least a part of this water is condensed in the air above and/or around the tower, forming a cloud, which casts a shadow over the surface, diminishing the duration and energy of insolation and so changing the microclimate in the surroundings of the tower. However, determination of cloud influence on insolation is not simply obtained.

Momental size of the cloud, its height, direction of its spreading from the tower, as well as its influence on insolation, depend on the momental weather conditions. Its general climatic influence on the surroundings, however, depends on the climatic conditions at the location of the tower or thermoenergetic plant. These influences are roughly and generally known. They are studied more exactly and established in different ways, which are more or less exactly presented with different skill and probability (e.g. Hanna 1982, Thorp and Orgill 1984, Ćurković et al.1985). None of them are presented completely enough to be used directly. It is also true, that the problem is rather complicated, and a complete presentation of all necessary details and computer program would be far beyond any technical article.

Therefore we are presenting only main propositions and methods of work and a model for the determination of reduction of insolation on the ground surface will be presented together with some results as examples. Final consequences of reduction of insolation may be found on growth and augmantation of the local vegetation, but this is already another problem.

MAIN FEATURES OF THE MODEL

For determination of the reduction of insolation round the cooling tower due to its cloud in a day, the shadow and its daily travel round the tower should be determined. First we put the system of equations, supposing clear sky for the whole day and afterwards the influence of natural cloudiness is introduced. The duration of shadow of the tower cloud on separate parts of the ground depends on the geographic position and on:

a) apparent way of the sun over the sky, and
b) dimensions and direction of the cloud from the tower.

The first group of dependent variables depends on astronomic conditions: zenith angle of the sun (z), its azimut (α) or from the time in a day and in a year. These variables are determined with the known equations for the position of the sun:

$$\cos(z) = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(H)$$

$$\sin(\alpha) = \frac{\cos(\delta)\sin(H)}{\sin(z)} \qquad (1)$$

where φ is latitude, δ declination and H stellar time. Knowing the dimensions and the position of cloud in a space, the position of cloud shadow on the surface can be determnined, although not quite simply, however.

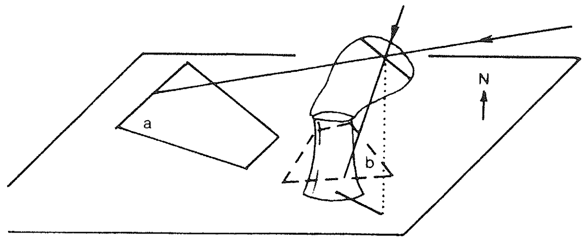

Fig. 1: Schematic presentation of cooling tower with the cloud and two of possible shadows

Slika 1: Shematičen prikaz hladilnega stolpa z oblakom in dveh od možnih senc

In our model the shadows are calculated for every hour of the typical day of every month and for each of the 16 directions of cloud orientation; it means in a direction rose with the steps of 22.5 angular degrees.

The dimensions of tower cloud and its spreading direction in space at separate wind directions were calculated with the help of a special model, given in the accompanying paper (Rakovec et al. 1987). The borders of the cloud were assumed to be where more than 5% of sunshine is dissipated.

Wind data are taken from the top of the tower and radiosonde station in the neighbourhood for the layer up to some hundred meters above the tower. By some wind directions the advection of more humid air can be greater and the tower cloud more extensive, but probably in the same time the sky is highly naturally clouded, and the influence of the large tower cloud on insolation can be smaller than by the lower air humidity and smaller tower cloud. The relative frequency of chosen or separate wind direction is of course very important, as well.

Using a cylindric coordinate system, cloud and sun position for every hour of daytime and the shadow in characteristic points at the surface are determined. As the sun apparently travels along the arc (mainly) south of the tower, the shadow is travelling in the opposite direction and has generally of the form of unsymmetric trapezoid (Fig. 1), which can be also overturned by high sun position and toward the sun oriented cloud (b in Fig.1), what demands additional care in programming. So, e.g., also the radius of the shadow on the

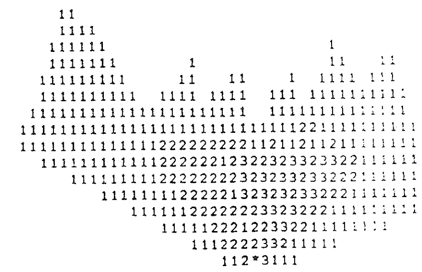

Fig. 2: An example of the shadow, cast by the tower cloud at one wind direction in a clear day

Slika 2: Primer sence, ki jo da oblak iz stolpa pri eni smeri vetra tekom celega jasnega dne

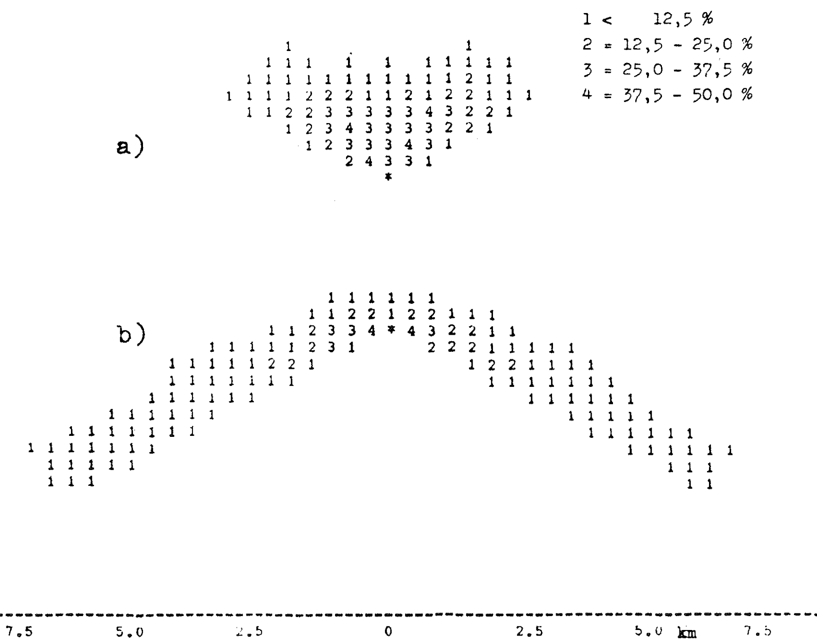

Fig. 3: Distribution of daily reduction of sunshine duration due to tower cloud shadow in a chosen month - a) wintertime, b) summertime

Slika 3: Razporeditev dnevnega zmanjšanja trajanja sončnega obsevanja zaradi sence iz stolpa v izbranem mesecu - a) pozimi, b) poleti surface (R^{*}) depends on real radius of the cloud (R^{o}) and on the connected position of the sun direction and cloud axes, given by the expression

$$R^{*} = R^{o}(1 + |(\sin(\beta - \alpha)[\sin(h) - 1]|) \qquad (2)$$

where β is the angle determining azimuth of cloud axis, α azimuth and h the elevation angle of the sun.

Apart from the projection of the cloud shadow axes on the surface, also border lines of the cloud shadow should be determined, and then transferred in a grid point system of elementary areas of e.g. 200m x 200m. By low sun (in the morning or evening) the shadow can be very long, but none of the shadow points is allowed to fall out of the treated or calculated area. Therefore, the extreme dimensions of the cloud have to be limited, as well as the smallest elevation angle of the sun above the horizon which in this case was 9°. On the other side, the treated area must be large enough, e.g. 32km x 32 km, which includes 161 x 161 grid points for the basic calculations. Their number can be diminished in final distribution presentations, as will be shown in examples.

So the shadow of the tower cloud can be presented in the separate month for every hour of the day at chosen direction and withappropriate characteristics of the cloud. Summation of shadow frequencies in separate area elements for all hours of daytime and all directions of the cloud, gives burdening of areas with the tower cloud's shadow in a typical day of the chosen month, supposing that the sky was clear all the time. An example is presented in Fig. 2. On the other side, however, if by one direction of wind (and opposite direction of cloud) the sky in climatic data was always overcast, there was no shadow of the tower cloud at all, and for this direction in this month no reduction of insolation due to the tower cloud exists. The majority of the cases lies between these two extremes. The appropriate weighting factors, depending on climatic characteristics of the region, should therefore bedetermined very carefully.

WEIGHTING FACTORS AND DURATION

From the data of the nearest radiosonde station the frequency of winds in the layers of the tower cloud can be calculated for all directions together with the relative air humidity in the layers. Cirrus clouds are neglected, but the middle and lower stratiform clouds and convective clouds being formed in the levels between 300 and 6000 m are effective. Computer treatment of upper level data of wind, relative humidity and cloudiness in the region, showed that the relative humidity of 85% is the most appropriate border value for determination of the natural cloudiness.

As in the upper levels there are no calms, the sum of all wind direction frequencies is 100%. However, the sum of cases with relative humidity above 85% in upper levels is mainly lower, than the difference between climatic cloudiness in % and 100%, because in upper levels the clouds can also be formed at the relative humidity under 85%. Therefore the frequency of natural "clearness" at the separate wind directions has to be corrected with the factor, the sum of cloudiness and clearness being just 100%. So the clearness (J) in the separate month and chosen wind direction is given by the equation:

$$J = P - U\,(\overline{N}/\overline{U}) \qquad (3)$$

where P is frequency of the wind direction, U relative humidity, $\overline{U}$ its mean value and $\overline{N}$ mean cloudiness in the chosen month on the location of the tower or on the nearest meteorological station with similar conditions.

Only at the time of "clearness", the tower cloud casts a shadow and reduces insolation in the surroundings. Therefore, to every shadow field or element of the field an appropriate weighting factor of clearness is applied, presenting partial reduction of insolation in that element. This method is used for all the 16 wind directions and 12 months in which 192 whole-day calculations have to be done using the same number of weighting factors. Summation of shadow loadiness in separate area elements for all hours and directions gives proper relative reduction of sunshine duration in separate area elements round the tower for a typical day of a month. From these the annual mean values can be obtained finally.

So the real climatic distribution of total reduction of sunshine duration round the tower in separate months and the annual average is obtained - examples are presented in Fig. 3. Every second value is printed here with the integers presenting the classes with 10% range - it means in relative values. The absolute values of reduction in hours are of course interesting as well. These can be obtained retrogradely from relative values by considering the duration of daytime or the number of hours in previous integration. This was done for the hours with the sun more than 9° above the horizon. Such a day is - in our latitudes - only 7 hours long in December and January, but 15 hours in June and July.

So e.g. the value 5 represents the reduction of sunshine duration in the range from 41 to 50 % which is in January (by its total clearness of 1.6 hour) only 0.8 hour but, about 3 hours in June. It is belived, however, that the distributions presented in relative values are more evident and more convenient for comparisons among the months with different day lengths.

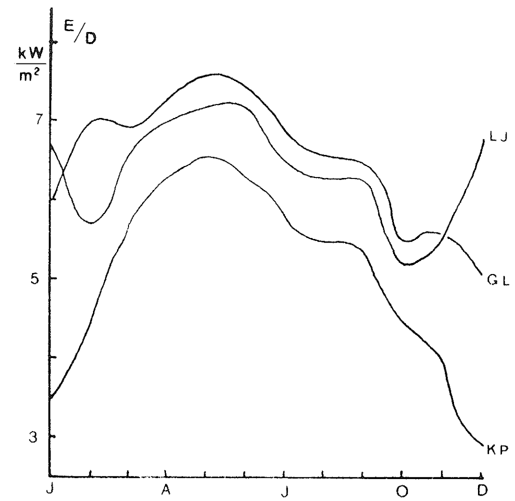

Fig. 4: Annual course of relation between duration and energy of insolation for three locations in Slovenia

Slika 4: Letni potek razmerja med trajanjem in energijo sončnega obsevanja za tri kraje Slovenije

REDUCTION OF SOLAR ENERGY

A good estimation of solar energy reduction on the surface round the tower due to the shadow of the cloud, can be obtained from the sunshine reduction. The method needs a correct determination of relation between duration and energy of insolation in the given conditions.

Relation between duration and energy of global radiation is known for 30 places in Slovenia (Hočevar et al. 1982). This relation depends on relief and climatic characteristics as well, and is rather different for different places - for three of them the annual distributions are presented in Fig. 4. Choosing - to the location of cooling tower - the most appropriate station and smoothing its annual distribution, the weighting factors for every month can be obtained. These enable us to calculate the amplitude of the insolation energy reduction in separate months due to the cooling tower cloud.

Like daily distribution of insolation energy also its reduction distribution is typical. This can be presented well with the "lifted" sinus curve. Here the

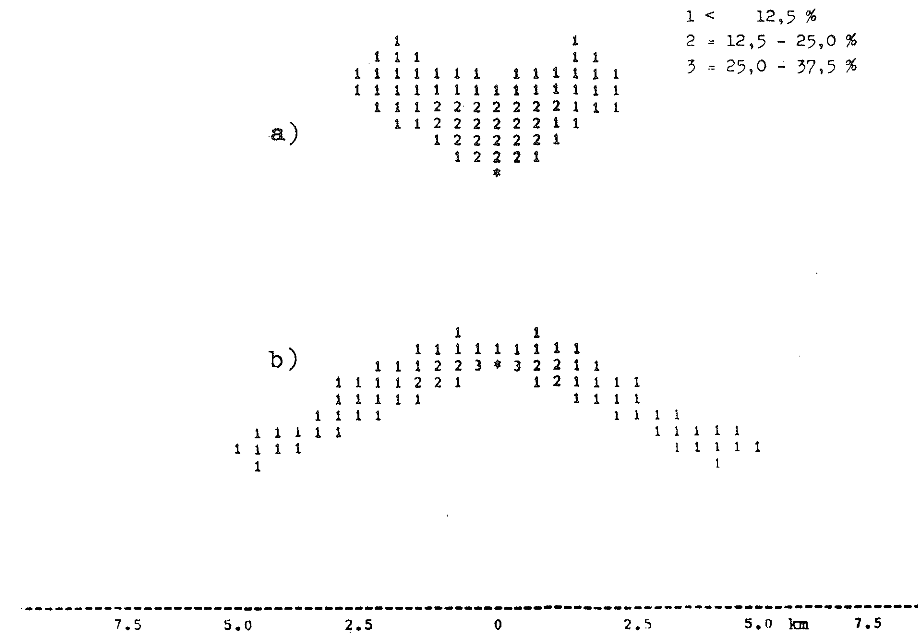

Fig. 5: Distribution of daily reduction of solar energy due to the cloud from a cooling tower in a chosen month - a) wintertime, b) summertime

Slika 5: Razporeditev dnevnega zmanjšanja sončne energije zaradi oblaka iz hladilnega stolpa v izbranem mesecu - a) pozimi, b) poleti

relative values are more appropriate than the absolute, as well - the examples are presented in Fig. 5. In comparison with the distribution of sunshine duration reduction (Fig. 3), the energy reduction is diminished on smaller area, but relative energy reduction near the tower is vigorous. This is the consequence of greater flux density of solar energy at noon, when the influence of the shadow is therefore the greatest.

In wintertime, as the sun travels apparently along the lower and shorter arc over the sky, the distributions of insolation reduction show the typical form of a heart; in the summertime, however, the shape of the shadow is like a thin kidney and has the opposite curvature. The results agree with those obtained by RWE AG (1981).

CONCLUSION

Considerations and test calculations show that the model is appropriate and useful. Although some simplifications were introduced, the calculations need a lot of computer' space and time due to many equations with trigonometric functions and different transformations.

Obviously the presented model can be used for similar applications with relatively little additional work. Most of that would take the determination of cloud characteristics and weighting factors, which includes the treatment of long set of radiosonde and climatic data for the tower's or analogous location.

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SIMULACIJA DVODIMENZIONALNEGA TOKA ZRAKA PO POBOČJU

SIMULATION OF A TWO DIMENSIONAL AIR FLOW ALONG A SLOPE

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POVZETEK

Predstavljen je poiskus numeričnega obravnavanja dvodimenzionalnega toka zraka po pobočju. Po pobočju z zmernim nagibom teče zrak s sprva stalno vertikalno temperaturno in hitrostno razporeditvijo, kasneje pa se na vrhu pobočja pojavi hladnejši zrak. Za simulacijo toka ob pobočju je bil narejen numerični model, katerega lastnosti so popisane v prvem delu tega članka, v drugem delu pa so predstavljeni rezultati simulacije toka pri pojavu hladnešega zraka pod toplim.

SUMMARY

A numerical simulation of a two dimensional air flow along a mountain slope is presented. Along the mountain slope with moderate incline flows the air with a constant lateral boundary conditions. After steady state is achived, colder air invades on the top of the mountain and cold air descends and accelerates along the slope. In the first part of this article a nonhidrostatical anelastic numerical model for the simulation of the flow is presented, in the second part some results of the simulation are discused.

TEORETIČNE OSNOVE

Tok zraka prek in okoli vzpetin, dogajanja v zraku ob njegovem spuščanju in dviganju ob pobočju je eden od bolj proučevanih problemov s področja mezometeorologije. Mnogokateri avtorji npr. (Pielke 1984, Mahrer in Pielke 1976, Klemp in Lilly 1978, Smith 1985) so na različne načine poiskušali z numeričnimi modeli pojasniti vzroke za dogajanje v toku.

Meritve v toku zraka ob gorski pregradi navzdol (Smith 1982, Pettre 1986, Frost et al. 1986) so pokazale, da je zračna masa ob spuščanju v višjih plasteh večinoma nevtralno stratificirana, v spodnih plasteh pa posebno pri burji (Smith 1982, Urbančič 1983) lahko opazimo temperaturno inverzijo. Spuščajoči se zrak je ponavadi močno turbulenten, sunkovitost - nagle spremembe horizontalne hitrosti - lahko v spuščajočih se vetrovih opazujemo predvsem ob njihovem pričetku (Petkovšek 1984). Zrak, ki se spušča ob pregradi, ima včasih že ko priteče do vrha hriba dokajšno horizontalno hitrost (Smith 1982), približno polovica pospešitve se zgodi pred prihodom do grebena. V višjih plasteh atmosfere je hitrost vetra dokaj različna: pri burji je v višjih plasteh veter često šibak ali pa celo po smeri nasproten (Jurčec 1981), v nekaterih drugih lokalno okrepljenih padajočih pobočnih ali dolinskih vetrovih - francoski mistral, plitvi fen na severni strani Alp, Boulder windstorm - pa je opažena (Klemp, Lilly 1978) tudi v višjih plasteh ozračja hitrost vetra v isti smeri kot pri tleh. Mehanizem pospešitve toka ob pobočju navzdol je bil v preteklosti deležen velike pozornosti meteorološke javnosti. Dejstvo, da so maksimalne hitrosti opazene v sorazmerno tanki plasti in da je ta plast tudi v horizontalni smeri omejena na področje tik ob vznožju hriba, je bilo razlagano na več načinov. Scorer in Klieforth (1959) in Aanenson (1965) so nastanek velikih hitrosti razlagali z ujetimi gravitacijskimi valovi, Kuettner (1959), Arakawa (1969) in drugi so razlagali velike hitrosti kot odraz hidravličnega padca zraka po pobočju, Klemp in Lilly (1975) pa sta razložila močne vetrove pri tleh z linearno teorijo, ki trdi, da pospešitev nastane zaradi delnega odboja valovne energije navzgor razširjujočih se valov ob diskontinuitetah vertikalne stabilnosti atmosfere. Ugotovitve v okviru ALPEXa, kot jih je predstavil Smith (1986), glede na šibke ali obrnjene vetrove v višjih plasteh, zaradi katerih so dogajanja v spodnjih in zgornjih plasteh atmosfere razklopljena (nepovezana), potrjujejo, da je bolj verjetna teorija o hidravlični pospešitvi toka, vsaj kar se tiče mehanizma pospešitve burje.

OPIS MODELA

Za obravnavo toka zraka po pobočju navzdol smo izdelali dvodimenzionalni numerični model s prvotnimi enačbami.

Poenostavljeno stanje v suhi atmosferi popisujemo z vektorjem hitrosti, pritiskom, gostoto in temperaturo. Če vpeljemo potencialno temperaturo iz enačbe stanja lahko izrazimo gostoto zraka:

$$\rho = \frac{p}{R\theta(\frac{p}{p_{00}})^{R/C_p}} \qquad (1)$$

kjer je $p_{00} = 10^5$ Pa, R = 287 J/K, c_p = 1008 J/K. Potencialna temperatura θ se zapiše:

$$\theta = T(\frac{p_{00}}{p})^{R/C_p}$$

Potencialno temperaturo in pritisk zapišemo kot vsoto hidrostatično uravnoteženega in nehidrostatičnega dela:

$$p = p_0 + p_1$$

$$\theta = \theta_0 + \theta_1$$

Kontinuitetno enačbo zapišemo z omejitvijo na nestisljivo, anelastično tekočino. Hkrati smo predpostavili, da v atmosferi ni globoke konvekcije, tako da se kontinuitetna enačba zapiše kot:

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \qquad (2)$$

Masa lahko doteka ali odteka v modelski prostor ob straneh in na zgornji meji, tla pa so seveda za masni tok zraka neprepustna.

Predpostavili smo, da v atmosferi ni vode in tako tudi faznih sprememb, da ni diabatnih vplivov (segrevanja od tal, sevanja na zgornjem in spodnjem robu atmosfere, itd.) in da se turbulentni transport zaznavne toplote lahko popiše s K teorijo. Glede na tla je torej atmosfera izolirana, skozi stranske robove pa je možen transport toplote z advekcijo.

Energijsko enačbo tako zapišemo kot prognostično enačbo za potencialno temperaturo:

$$\frac{\partial \theta}{\partial t} = -u\frac{\partial \theta}{\partial x} - w\frac{\partial \theta}{\partial z} - K\frac{\partial^2 \theta}{\partial z^2} \qquad (3)$$

Ker je model le dvodimenzionalen, gibanje popisujeta le enačbi za u in w. Enačba za u je zapisana ob predpostavki o veljavnosti K teorije za turbulenco oz. linearnega zakona trenja pri tleh. Progostična enačba za u ima tako obliko:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial \tilde{x}} - w\frac{\partial u}{\partial \tilde{z}} - K\frac{\partial^2 u}{\partial \tilde{z}^2} - \frac{1}{\rho_0}\frac{\partial p}{\partial \tilde{x}} \qquad (4)$$

Vertikalna gibalna enačba se v mezometeoroloških modelih lahko upošteva na dva načina, glede na to, če je upoštevana hidrostatična aproksimacija ali ne. V primeru, ki ga želimo obdelati (tok zraka po pobočju, tok hladnejšega zraka pod toplejšim) je atmosfera nehidrostatična. Zaradi vertikalne neusklajenosti p in θ pride do vertikalnih pospeškov in sprememb hitrosti (neuravnoteženi vzgon). Enačbe za w pa ne zapišemo v prognostični obliki, pač pa z daljšo izpeljavo (Pielke 1984) dosežemo, da namesto tega iz polju u in potencialne temperature izračunamo hidrostatično neuravnoteženi del pritiska, ki potem vpliva na vertikalna in horizontalna gibanja. Vertikalno hitrost potem izračunamo diagnostično iz kontinuitetne enačbe. Enačbo za odstopanje pritiska zapišemo:

$$\frac{\partial^2 p_1}{\partial x^2} + \frac{\partial^2 p_1}{\partial z^2} = -\frac{\partial^2(\rho u w)}{\partial x \partial z} - \frac{\partial^2 p_0}{\partial x^2} + g\frac{\partial}{\partial z}(\frac{\rho\theta_1}{\theta_0}). \qquad (5)$$

Hidrostatični del pritiska izračunamo iz preostalega dela vertikalne gibalne enačbe.

$$\frac{\partial p_0}{\partial z} = -\rho_0 g \qquad (6)$$

Velikost območja modela

Z modelom želimo obravnavati tok zraka po pobočjih z zmernim naklonom, torej z nagibi med 10° in 30°. Za tipično višinsko razliko med vrhom in vznožjem pobočja smo si izbrali 1500m, tako da je vrh hriba na nadmorski višini okoli 1600m, vznožje pa pri 100m. Na spodnji meji je torej modelsko območje omejeno z nagnjeno ploskvijo (nagib je v smeri X spremenljiv), na zgornji meji pa je model zaprt na nadmorski višini 4000m. Horizontalne razsežnosti modelskega prostora so omejene z zmogljivostmi računalnika: ker želimo imeti v horizontalni smeri korak x dolg največ 500m, smo morali omejiti skupno dolžino modela na 7500m. Pri dimenzijah modela 4000 X 7500 m je nedvomno povsem ustrezna zanemaritev Coriolisovih členov v gibalni enačbi.

Koordinatni sistem

V našem modelu smo uporabili koordinatni sistem, katerega koordinatne ploskve slede reliefu. Vertikalna koordinata se v t.i. zeta koordinatnem sistemu tako zapiše:

$$\zeta = z_t\frac{z - z_s}{z_t - z_s} \qquad (7)$$

kjer je z_s višina reliefa, z_t pa višina zgornjega robu.

Zaradi transformacije (7) moramo primerno transformirati tudi sistem enačb (1) - (6). Pri tej transformaciji smo si izbrali kovariantno vektorsko bazo, tako da komponenta u vektorja hitrosti kaže v smeri pobočja, komponeta w pa v nasprotni smeri vektorja gravitacijskega pospeška. Zaradi te transformacije se bistveno spremeni predvsem enačba (4), saj se v njej pojavi člen z gravitacijskim pospeškom, ki se v največji meri kompenzira z gradientom pritiska po zeta ploskvi.

Prognostično enačbo za u tako zapišemo:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial \bar{x}} - w\frac{\partial u}{\partial \bar{z}} - K\frac{\partial^2 u}{\partial \bar{z}^2} - \frac{1}{\rho_0}\frac{\partial p}{\partial \bar{x}} + g\frac{\zeta_{z_t}}{z_t}\frac{\partial z_s}{\partial \bar{x}} \qquad (8)$$

kjer je x koordinata v smeri koordinatne osi .

Tudi ostale enačbe sistema (2), (3), (5) in (6) ustrezno transformiramo v kontravariantno formulacijo koordinatnega sistema, katerega ploskve sledijo reliefu.

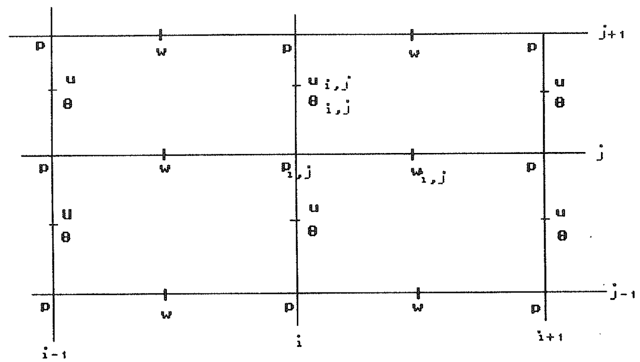
Razporeditev računskih točk

Pri numeričnem reševanju sistema enačb (1) - (6) s končnimi diferencami smo v našem primeru izbrali Arakawino E mrežo (Arakawa 1977). Razpored točk, kjer so definirane posamezne spremenljivke prikazuje slika 1. S premikom za polovico intervala v smeri X in Z med točkami z u, w glede na p dosežemo, da ne pride do šuma dveh korakov mreže, hkrati pa se poenostavijo tudi računanja centralnih razlik pri numeričnem določevanju odvodov.

Numerični postopki

Bodoča stanja polj dobimo s postopno numerično integracijo sistema enačb od (1) do (6), dolžina časovnega koraka te integracije pa je odvisna od stabilnosti časovne integracijske sheme.

V enem koraku časovne integracije si posamezni postopki sledijo takole:



Slika 1: Razporeditev točk, v katerih so definirane posamezne meteorološke spremenljivke. Indeks i šteje odseke v smeri X, indeks j pa v smeri Z.

Fig. 1: The grid structure whith the points where various meteorological variables are defined. Index i is in direction X, index j in the direction Z.

1. časovna integracija prognostičnih enačb za horizontalno hitrost in dejansko potencialno temperaturo
2. diagnostični izračun hidrostatičnega pritiska
3. diagnostična določitev nehidrostatičnega dela potencialne temperature
4. diagnostični izračun vertikalne hitrosti z vertikalno integracijo kontinuitetne enačbe
5. določitev nehidrostatičnega dela pritiska z iterativnim reševanjem enačbe (5)
6. določitev dejanskega pritiska s seštevkom hidrostatičnega in nehidrostatičnega dela pritiska

Časovna integracija horizontalne gibalne enačbe

Enačbo (8) zapišemo s končnimi razlikami v izbrani mreži točk. Advekcijski del enačbe integriramo z Lax-Wendrofovo shemo (Tatsumi 1984), člene s trenjem, z gradientom pritiska in komponento gravitacijskega pospeška na zeta ploskvi, pa integriramo s shemo naprej. Zaradi stabilnosti Lax-Wendrofove sheme mora biti za časovni korak t izpolnjen pogoj

$t < x/U$

oziroma

$t < z/W$

Če ocenimo $U_{max} = W_{max} = 20$m/s, x = 500m, z_{min} = 140m (ko so nivoji najbolj gosti), potem mora biti časovni korak t = 5s, da bo rešitev gotovo stabilna.

Lax-Wendrofova shema je znana po tem, da duši kratke valove, če je le izpolnjen zgornji kriterij za stabilnost.

Z enako shemo intergiramo tudi energijsko enačbo.

Izračun hidrostatičnega dela pritiska

Z vertikalno integracijo enačbe (6) lahko diagnostično določimo hidrostatični del pritiska. Enačbo (6) moramo integrirati od zgornjega roba modela navzdol, saj je pritisk na zgornjem robu podan kot robni pogoj rešitve. Temperatura, ki nastopa v enačbi (6) je definirana sredi med dvema pritiskoma, tako da v vertikalni integraciji nastopa kot poprečna temperatura plasti.

Enačbo za nehidrostatični del pritiska rešujemo iterativno s Seidlovo (konsekutivno) relaksacijo. Ko je dosežena predpisana natančnost rešitve, tako dobljeno polje prištejemo k hidrostatičnemu delu pritiska, seštevek obeh pa v naslednjem časovnem koraku služi za določitev gradienta pritiska.

Diagnostična določitev vertikalne hitrosti

Vertikalno hitrost w določimo diagnostično iz novoizračunanega polja hitrosti na koordinatni ploskvi zeta. Pri tem enačbo (2) numerično integriramo od spodaj navzgor, saj je pri tleh podan robni pogoj w(x,z=0,t)=0.

Parametrizacija trenja in turbulentnih prenosov

V prvi gibalni enačbi (8) in v energijski enačbi (3) sta turbulentna prenosa gibalne količine in zaznavne toplote popisana s K teorijo. Člen s turbulentnim prenosom poenostavljeno zapišemo (Pielke 1984)

$$F_{tr} = K\frac{\partial^2 u}{\partial z^2}$$

Pri tem smo privzeli, da je K v posameznih plasteh konstanten, profil K pa popišemo z enačbo :

$$K(z_j) = \begin{cases} a\, z_j & \text{če } j = 5 \text{ ali } j < 5 \\ b\, K(z_5) & \text{če } j > 5 \end{cases}$$

kjer je a= 0.5 m/s in b= 0.1, tako da približno popišemo profil K kot je podan pri Bodinu (1980).

Na najnižjem nivoju je člen turbulentnega prenosa gibalne količine v (8) nadomeščen z linearnim zunanjim trenjem, v (3) pa je turbulentni prenos zaznavne toplote še vedno upoštevan po K teoriji. Za izvednotenje drugega odvoda θ na spodnjem nivoju smo pod njim ekvidistantno vpeljali pomožni računski nivo, na katerem se θ spreminja tako kot na prvem računskem nivoju.

ROBNI POGOJI IN ZAČETNO STANJE

Spodnji robni pogoji

- Za w velja w(z'=0,x,t)=0 saj je prvi nivo, kjer je definirana w, postavljen na dejanska tla.
- Za u na najnižjem nivoju ni eksplicidnega robnega pogoja, u je namreč definirana na nivoju, ki je za pol vertikalnega intervala dvignjen od tal, trenje je na spodnjem nivoju popisano z linearnim izrazom - ponorom gibalne količine.
- Za θ in θ_1 pri z'=0 ni posebnih pogojev, saj je predpostavljeno, da ni diabatnih vplivov tal.
- Poprečni pritisk p, nehidrostatični pritisk p_1 in hidrostatični pritisk p_0 se integrirajo od zgoraj navzdol, tako da na spodnjem robu ni potreben robni pogoj.

Stranski robni pogoji

V našem modelu smo stranske robne pogoje postavili takole:

a) vhodni robni pogoji pri x = 0
- polja u, w in θ so stalna, vrednosti so določene po dolgotrajni integraciji
- polji θ_1 in p_1 sta stalno postavljeni na 0
- polje p je stalno enako polju p_0, ki ustreza hidrostatično uravnoteženi temperaturi θ_0
- če v modelski prostor vpeljemo hladnejši zrak, potem se ustrezno zmanjšajo θ in θ_1, spremeni pa se tudi p. Polji p_0 in θ_0 ostaneta seveda nespremenjeni.

Taka postavitev vhodnih pogojev je smiselna, če vhodno stanje res dobro poznamo, oziroma če bi želeli ugotoviti, kakšen je odziv modela na spreminjajoče se vhodne podatke.

b) izhodni robni pogoji pri x = x_{max}
- vrednosti vseh meteoroloških spremenljivk v zadnji vertikali modelskega prostora določimo izogradientno tj. vsa polja se zaključijo gladko. Gradient določimo iz dveh robu ($x=X_{max}$) sosednjih točk ($x=x_{max}$ - x in $x=x_{max}$- 2x).

Zgornji robni pogoji

V našem modelu smo bili zaradi tehničnih omejenosti prisiljeni postaviti zgornji rob modela na nadmorsko višino 4000m. Na zgornjem robu smo predpisali stalno razporeditev pritiskov p in p_0 in konstantno vrednost θ_0. U, θ in w se tudi na zgornjem nivoju izračunavajo, s tem, da smo nad zgornjim robom vpeljali še en pomožni ekvidistantni nivo, na katerem se hitrosti in spreminjajo enako kot na robu. S tako brezgradientno postavljenim robom smo predpostavili, da je modelski prostor zgoraj odprt, zrak lahko vanj vstopa, vstopajoči zrak pa ima trenutnemu stanju v modelu enake lastnosti.

Začetno stanje

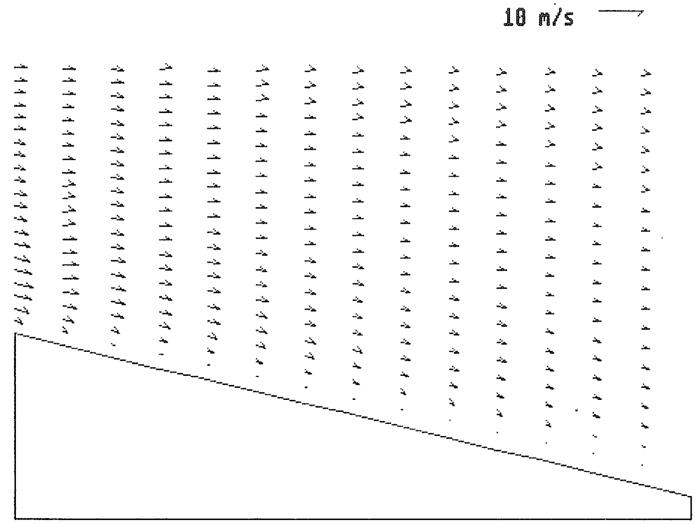
Začetno stanje polja θ in θ_0 smo določili tako, da smo privzeli, da je na nadmorski višini 0 m potencialna temperatura povsod enaka 283 K. Od tod naprej smo predpostavili, da θ narašča z gradientom 0.03 K/m vse do najvišjega računskega nivoja. Začetni polji p in p_0 določimo hidrostatično z integralom enačbe (6), za zgornjo mejo integrala pa vzamemo pritisk na zgornji (horizontalni) modelski meji, kjer smo postavili, da je horizontalni gradient pritiska enak 0. Ker so računski nivoji nagnjeni, se torej vzdolž vsakega nivoja pojavi temperaturni gradient, glede na pritiskove ploskve pa je polje θ paralelno - začetno stanje je torej barotropno.

Polji u in w morata biti vskaljeni s polji temperature in pritiska in z zunanjimi silami. Usklajenost teh polj smo poiskusili doseči z dinamično inicializacijo: v model smo vstavili polja p in θ in model pognali. Začetno polju u smo določili tako, da skozi vsak vertikalni presek modela steče enaka količina mase, na zgornji meji zato v začetku ni vstopanja okolišnjega zraka. Po 200 korakih integracije (korak je dolg 5 sekund) smo privzeli, da je stanje usklajeno. Končno stanje - prikazuje ga slika 2. - smo nato zgladili in uporabili kot začetno stanje pri nadaljnih poiskusih.

POSKUS Z VSTOPOM HLADNEJŠEGA ZRAKA

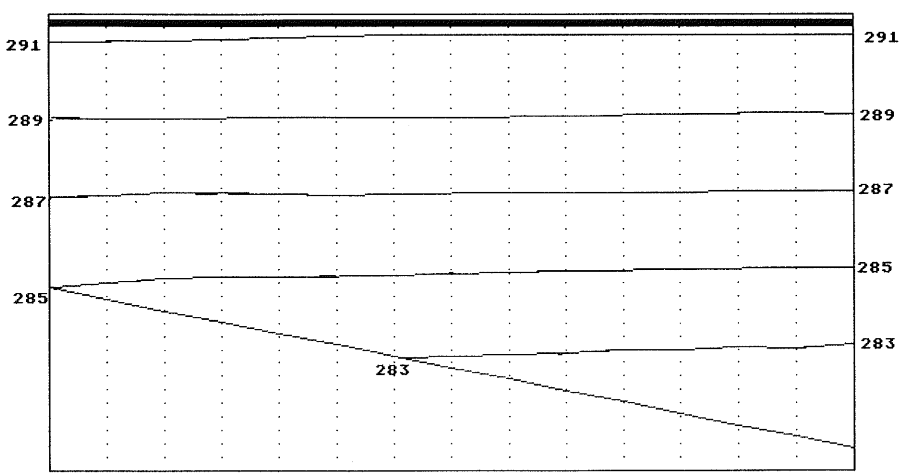
Oblika reliefa in oblika vstopajočega hladnega zraka

Pri poiskusih z dotokom hladnega zraka smo postavili, da je relief preprost. Privzeli smo, da je vrh pobočja pri nadmorski višini 1600m, iztek pa pri 100m. Vmes pobočje enakomerno pada in sicer 100m višine na 500m horizontalne razdalje. Zgoraj omenjano začetno stanje smo izdelali za takšno reliefno obliko, zatem pa smo dodati hladen zrak.



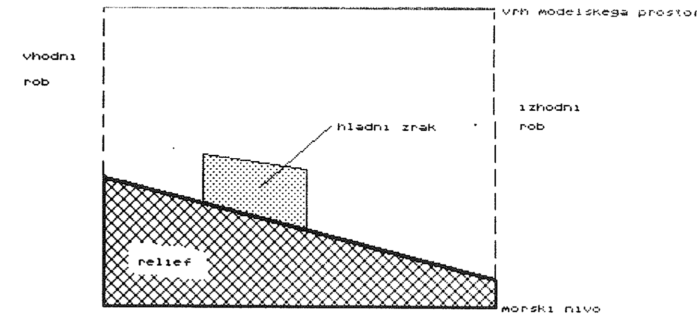
Slika 2a. Začetno stanje hitrostnega polja, kot smo ga dobili po dolgotrajni integraciji (60 časovnih korakov po 5 s) s konstantnimi robnimi pogoji.

Fig. 2a. Initial state of wind velocity field as result of models integration (60 time steps of 5 s) with constant boudary conditions



Slika 2b. Začetno stanje polja potencialne temperature pri enakih pogojih kot pri slika 2a.

Fig. 2b. Initial state of potential temperature field with the same conditions as fig. 2a.



Slika 3. Shematična predstavitev začetne oblike gmote hladnega zraka na pobočju. Obris gmote ustreza diskontinuiteti 4k v polju potencialne temperature

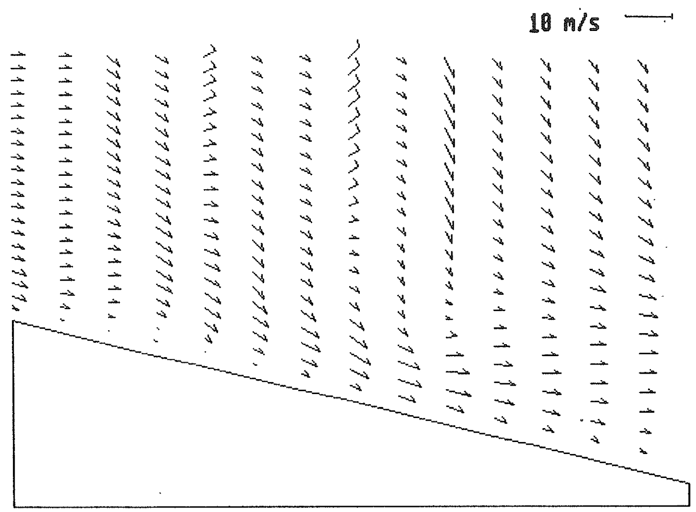
Fig. 3. A schematic representation of initial state with a mass of cold air on the slope. The conture of the cold air corresponds to 4K discontinuity in potential temperature field.

Hladni zrak se v modelu pojavi hipoma in sicer smo na petih odsekih sredi pobočja in na prvih petih nivojih modelskega prostora temperaturo θ zmanjšali za nekaj K. Obliko gmote hladnega zraka prikazuje slika 3. Vidimo lahko, da je gmota - klada - hladnega zraka na prednjem robu debelejša kot na zadnjem, spredni rob pa je vertikalen. Takšna oblika temperaturnega polja: izentrope so na sprednjem delu klade hladnega zraka povsem pravokotne na izobare je seveda izjemno baroklina in tako nestabilna. Pričakovati je torej, da se bo ta oblika hitro transformirala v bolj stabilno, pritiskov gradient, povzročen z velikim temperaturnim gradientom v horizontalni smeri, mora namreč pognati tok, s tem pa se masa in notranja energija prerazporedita.

Na zgornji meji klade je močna temperaturna inverzija, saj se temperatura θ med dvema nivojema (razdalja okoli 150m) spremeni za 4K.

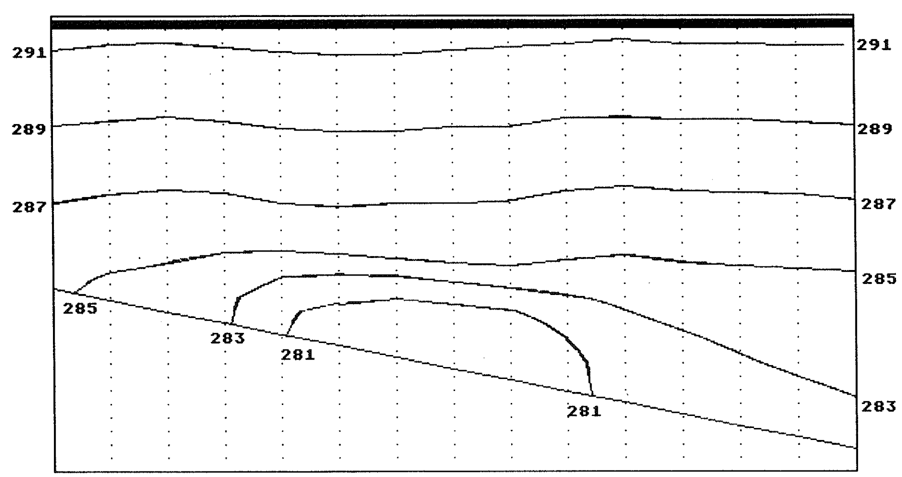
Poskus z 4K hladnejšim zrakom

V modelsko področje z vsklajeno hitrostno in temperaturno razporeditvijo (slika 2.) postavili za 4K hladnejši zrak. Sledeče slike od 4. do 6. prikazujejo razvoj in prilagajanje hitrostnega in temperaturnega polja s takšnim začetnim stanjem. Časovni interval med dvema slikama je 100 sekund (20 časovnih korakov modela), na poljih θ so izentrope risane v razmiku 2K. Predpostavili smo, da je razporeditev parametra turbolentne difuzivnosti ves čas integracije enaka in sicer doseže največjo vrednost na petem računskem nivoju (10 m/s), k tlem linerno pada, nad petim nivojem pa ima konstantno vrednost, desetino vrednosti na petem nivoju. Linerno trenje pri tleh je stalno in znaša 0.004 s^{-1}.



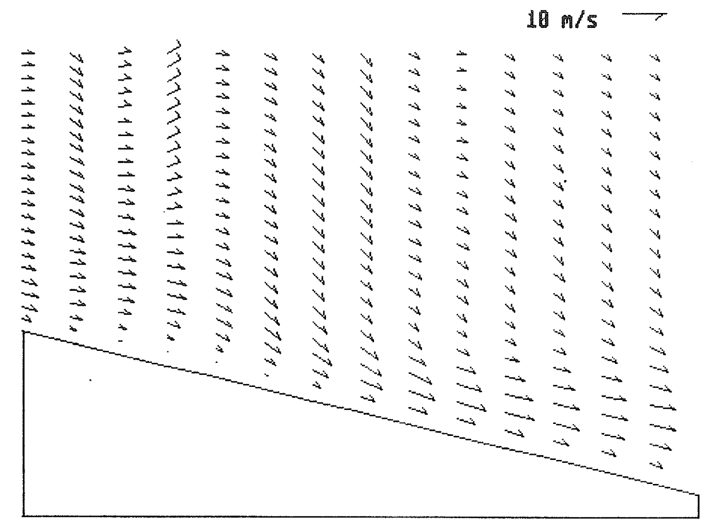
Slika 4a. Hitrostno polje 100 s po vstopu hladnega zraka.

Fig. 4a. Wind velocity field 100s after the entraintment of the cold air.



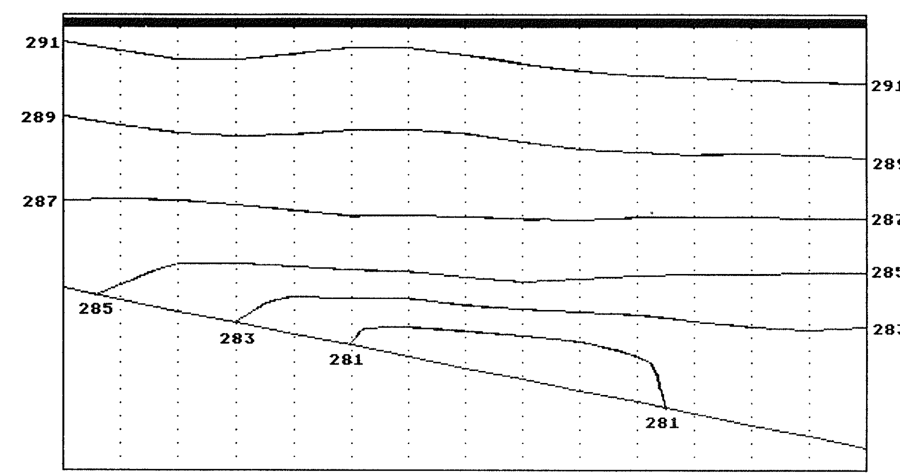
Slika 4b. Polje potencialne temperature 100 s po vstopu hladnejšega zraka.

Fig. 4b. Potential temperature field 100s after the enteraintment of the cold air.



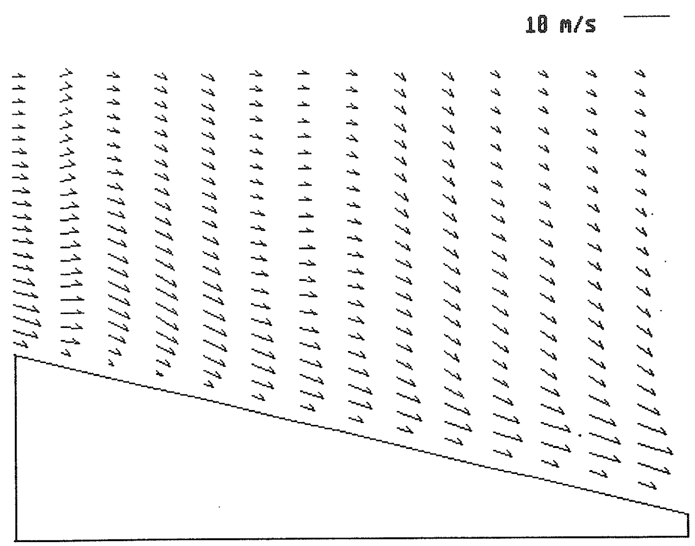
Slika 5a. Isto kot slika 4a, le 200 s po vstopu.

Fig. 5a. Same as fig. 4a., but 200 s after the enteraintment.



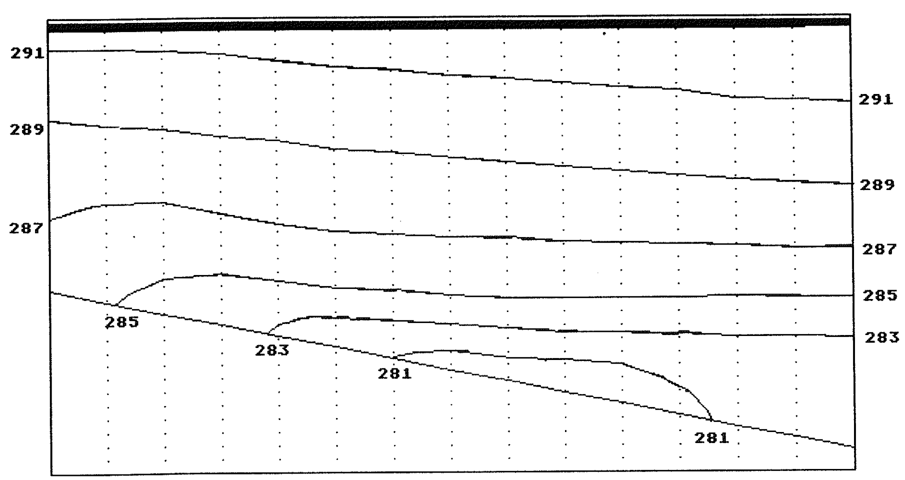
Slika 5b. Isto kot slika 4b, le 200 s po vstopu.

Fig. 5b. Same as fig. 4b., but 200 s after the enteraintment.



Slika 6a. Isto kot slika 4a, le 300 s po vstopu.

Fig. 6a. Same as fig. 4a., but 300 s after the enteraintment.



Slika 6b. Isto kot slika 4a, le 300 s po vstopu.

Fig. 6b. Same as fig. 4b., but 300 s after the enteraintment.

Na zgornjem robu modelskega prostora je predpisan konstanten horizontalni pritiskov gradient 0.2 10^{-3} Pa/m. Na robovih je rešitev delno dušena, v notranjosti pa uporabljamo po vsakem koraku integracije šibak Asselinov filter s konstanto filtriranja F=0.1.

Pojav hladnga zraka povzroči velike vertikalne hitrosti v toplem zraku tik nad klado hladnega zraka. Hladna klada se namreč poiskuša razteči po pobočju navzdol in tako zmanjšati baroklinost. Višina hladne klade se zato zmanjšuje, topli zrak pa se zato nad klado hladnega zraka začne močno spuščati. Na prednjem robu klade se ob močno baroklini coni pojavijo velike horizontalne hitrosti, cona najmočnejših horizontalnih vetrov pri tleh se v 100s med slikama 4a. in 5a. razširi na precejšen del prostora pri tleh pred klado. Hladen zrak se delno razteka tudi na začelju gmote hladnega zraka, vendar to raztekanje hitro poneha, saj se glavnina hladnega zraka razteče po pobočju navzdol, tako da se višina hladnega zraka zniža. Zaradi premika hladnega zraka se začne pospeševati tudi topel zrak, ki se tako umakne hladnejšemu.

Valovanja nad gmoto hladnega zraka se počasi umirijo: na sliki 4a. še zelo vidno valovanje z valovno dolžino dveh korakov mreže se zaduši, za vrhom hriba se postopoma vzpostavi val v hitrostnem polju z valovno dolžino okoli 8 korakov mreže. Pri tleh oziroma na nivojih tik nad tlemi se pojavi precej močan stržen v hitrostnem polju, (slika 6a.) ki poskrbi za veliko iztopanje mase na izhodnem robu modelskega prostora. Zaradi močnega izstopanja pri tleh začne zrak v modelski prostor kompezacijsko vstopati na vrhu modelskega prostora.

Temperaturno polje se s časom močno spremeni. Sprva jasno izražena klada hladnega zraka na sliki 4b. se postopno deformira, tako da hladen zrak postopoma napreduje v dolino. Pri tem prihaja do mešanja hladnega zraka z okolico, tako da najhladnejši zrak postopno izgineva. Baroklinost polj potencialne temperature in pritiska se zmanjšuje, izoterme s časom postajajo vedno bolj horizontalne. Čelo hladnega zraka se v 40 korakih integracije (med slikama 4b. ob času 100s in 6b. ob času 300s) premakne za 4 horizontalne enote mreže (2000m). Vstop gmote hladnega zraka ne vpliva le na lokalno temperaturno in hitrostno polje, pač pa se zaradi take motnje spremenita ti polji v celotnem modelskem prostoru.

ZAKLJUČKI

Pričujoči dvodimenzionalni nehidrostatični model s prvotnimi enačbami smo uporabili za simulacijo toka hladnega zraka po pobočju.

Dovolj daleč stran od stranskih robov se hladni zrak, ki se hipoma pojavi v prej temperaturno - hitrostno vsklajeni atmosferi, obnaša približno tako, kot bi iz fizikalnega premisleka pričakovali: hladni zrak steče po pobočju navzdol, pri tem izriva toplega, oba skupaj pospešujeta, zaradi trenja pri tleh je največja hitrost spuščanja opažena nekaj 100m visoko nad reliefom - pojavi se stržen v hitrostnem polju. V prostor, kjer je bil sprva navzoč hladen zrak, se spusti okolišni toplejši zrak.

Pojav gmote hladnega zraka sredi ali vrh pobočja, posebno če je ta gmota bistveno hladnejša od okolišnjega zraka povzroči velike in hitre spremembe hitrosti. Če je v naravi prisoten mehanizem, ki poskrbi za zaporedno spuščanje gmot hladnega zraka prek grebena kot domneva Petkovšek (1984), potem je verjetno, da je sunkovitost opažena v spuščajočem se toku prav posledica pospeškov, ki se pojavijo na horizontalnih diskontinuitetah potencialne temperature. V tem delu se je pokazalo, da se pri temperaturni razliki 4K in pri spustu zraka za okoli 400m na sprednjem delu gmote hladnega zraka hitrost zraka v strženu glede na stacionarno stanje poveča za 4 do 5 krat in to v pičlih 200 sekundah.

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