MISCELLANEA GEOGRAPHICA
WARSZAWA 1988

Witold Lenart, Danuta Danielak

DEFORMATION OF HEAT AND MOISTURE CIRCULATION AROUND A LARGE INDUSTRIAL PLANT (THE EXAMPLE OF PŁOCK PETROCHEMICAL COMPLEX)

A growing number of climatologists and hydrologists point out that heat and water balance of the Earth is to an increasing degree affected by heat and water coming from artificial sources or produced by the anthropogenic deformation of natural energy and moisture circulation. The deformation processes are particularly strong in big urban/industrial conurbations. Since urban/industrial centres are usually complex and unique in the geographical sense, it seems purposeful to study hydroclimatic changes in those zones which are affected by the relatively uniform big complexes, such as large industrial plants or huge housing estates. An excellent opportunity for such studies was created by locating the Mazovian Geographical Observatory of Geography and Regional Studies Department of Warsaw University at Murzynowo near Płock. For several years now the observatory has conducted research on the influence of the huge Płock Refining and Petrochemical Plant (MZRiP) on environment. The complex, with the annual processing capacity of some 11 million tons of crude oil, covers around 1,000 hectares of land and is situated North-West of Płock on a watershed or the forestless Płock highland which was formed during Środkowopolskie glaciation.

DEFORMATION OF HEAT CIRCULATION CAUSED BY THE MZRiP

To begin with, it is neccessary to stress an important difference between natural solar energy, i.e. the only source of heat on the Earth, and artificial energies. The sun sends its energy towards the Earth by means of rays (short-wave radiation) and its distribution takes place also in the atmosphere (absorption, selective reflection). Artificial heat emmission takes different forms of which the most frequent are turbulent and convective heating of the air and intensified energy-consuming processes (mainly evaporation). Thus, artificial heat is more quickly absorbed by the environment.

The Płock complex generates heat in a similar way. Taking into consideration its entire area, we can calculate that the approximate daily heat generation during one year equals 180 Ly per day ($Ly = cal/cm^2$). In comparison with solar energy (total radiation), this constitutes around three fourths of the sun's annual total.

In winter, artificial heat is three times higher than natural heat (in January 150/50 Ly/day). If we reduce the area of reference, we will certainly arrive at much higher results. A considerable portion of this heat is consumed in the process of evaporation, which is more intensive there than in the adjacent area. Much energy is also used by intensified convective processes and the remaining heat causes increases in the temperature of soil, surface waters and low air layers. It should be added at this point that without technological heat, i.e. in the situation where

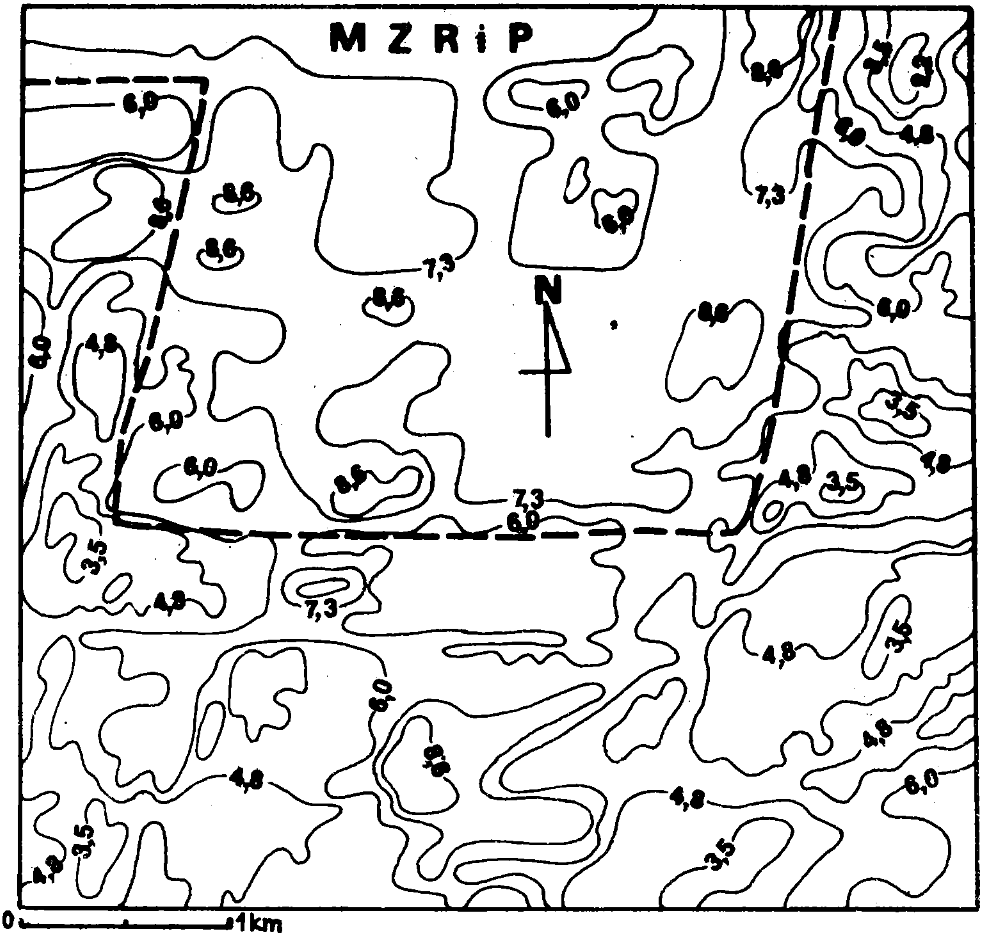

Fig. 1. Distribution of radiative temperature in the southern part of the petrochemical complex in Płock based on the infrared aircraft picture

the plant is put to standstill, the total radiation data would be lower because of high albedo.

Thermal effects of disturbances in natural heat distribution were most thoroughly examined. The infrared picture of MZRiP's protective zone, taken in June 1982, revealed considerable differences of radiative temperature in the Southern part of the complex (Figure 1). Temperatures there were higher by 2—3°C and their distribution corresponded to the position of the particular installations. The picture was taken during cloudless radiative weather at 9.20 p.m. It should be remembered that in the centre of the plant the temperature was much higher.

The Płock complex appears as a very distinct and time-unaffected island of heat whose temperature exceeds that of the surrounding area in a degree similar to that characteristic of big conurbations. Differences in the average highest and lowest temperatures between the complex and its surroundings depend on the kind of weather and therefore differ from one year to another. We can already present the average pattern of these differences for the years 1978—86.

Table 1

Temperature differences	Months												Annual
	01	02	03	04	05	06	07	08	09	10	11	12	
average	0.7	0.9	0.8	0.8	0.9	1.1	1.0	0.8	0.8	0.7	0.4	0.4	0.8
maximum	0.2	0.2	0.2	0.1	0.2	0.4	0.2	0.2	0.2	0.2	0.3	0.2	0.2
minimum	1.0	1.4	0.9	1.3	1.4	1.8	1.6	1.6	1.5	0.8	0.7	1.2	1.2

Table 1 shows that differences of about 1 °C take place throughout a year. Since measurements were taken 1.5 km from the centre of the complex, the actual difference is higher by 0.8°C. The biggest differences were recorded with regard to the minimum temperatures, which can be attributed to physical properties of building materials and installations which accumulate heat at day and generate it slowly at night, while in open areas the temperature at night drops very quickly. Therefore the temperature falls at a slower rate than in open areas; in summer the average lowest temperature is higher by around 1.5°C and on cloudless days the difference can even exceed 3°C. In winter, it is artificial heat emmission that causes higher minimum temperatures. On very cold days ($t_{\min} < -10$°C) the differences in the lowest temperatures between the complex and its surroundings may reach above 5°C.

No significant differences were recorded with regard to the maximum temperatures; they remain at about +0,2°C.

The differences are more distinct in spring than in the autumn. This can be explained by autumn's greater air humidity which has a toning down effect on temperature differences. The influence of the complex on thermal conditions is very well illustrated by differences recorded in the number of the so-called characteristic days. High levels of differences on light frost days ($t_{min} < 0°C$) — 22 days, and on summer days ($t_{av} > 15°C$) — 12 days, are particularly symptomatic. When the correction connected with the observatory's location is taken into account, the differences are actually two times higher and their level is greater than that recorded in big cities such as Warsaw.

Differences were also recorded with regard to other data concerning heat circulation. The dates of extremes and changes of temeperature from hour to hour are different than elsewhere, the threshold value is rarely exceeded, etc.

Higher soil temperatures have a positive effect on the elevation of pollutants (the higher vertical gradient of temperature, the stronger vertical movements). Higher temperature also has an intensifying effect on evaporation which prevents the forming of fogs. Thermal conditions on other altitudes remain to be studied more thoroughly however, and should it prove that the tendency to form a warmer layer takes place there, the eventual effects would be negative.

DEFORMATION OF MOISTURE CIRCULATION AROUND THE COMPLEX

The main reasons for changes in water circulation which occurred near Płock after the complex was built can be summarized in four points.

1. Big increase in water demand. The annual water consumption by the complex totals 50 million cubic metres. This demand by far exceeds the supply of surface and underground waters in the plant's direct surroundings, which means that water has to be transported from a more distant reservoir (the Vistula river). Thus, on a relatively small area, large quantities of water are concentrated in various types of collectors and a closed water cycle. In this situation water balance of the area, which lost its natural protection, changes greatly and transforms into an industrial water balance. The supply of water is supplemented by water transported from outside the local reservoir, i.e. from the Vistula's surface waters and by apotamic waters artificially included in the complex's water system.

2. Sewage disposal. Due to high water consumption, the plant has to dispose of sewage which must be properly treated beforehand. For this purpose a big area is needed for sewage collection and treatment. The annual disposal of industrial and other sewage to the Vistula totals 35—40 million ton.

3. Industrial buildings of different designations cause an increase in impermeable areas and upset natural stratification of land, thus producing changes in the hydrological cycle.

4. The process of production causes increases in the amount of water vapour, gases and dust and generates plenty of heat.

From the nature's point of view it is the definition of the plant's influence on evaporation and precipitation which is particularly important. In case of plants availing themselves of surface waters, changes in water run-off are of lesser importance. The water inlet on the Vistula is situated only several hundred metres from sewage outlet so no major differences occur in the river's flow. But, as it will be seen later on, changes in evaporation matter greatly.

From the point of view of natural moisture circulation the 1986 data was not much different from the 1978—86 average. The 1986 production cycle was also a typical one. It was rather easy to establish the level of precipitation since data obtained from the complex's meteorological station were satisfactory. It was more difficult to measure the level of evaporation which differs from one part of the complex to another. It was expected that evaporation would be particularly intensive in those areas where large quantities of dispersed water and water vapour are let out to the atmosphere in a technological process. The installations (cooling beds, warm water collectors) cover rather small areas and evaporation there by far exceeds natural evaporation.

The natural process of evaporation is upset inside the complex. Impermeability of the soil (buildings, installations, roads) and quick disposal of precipitation waters by means of artificial drainage reduce the evaporation. In those areas where plants are cultivated, the level of evaporation is similar to natural. Greater evaporation, in turn, is caused by industrial units where heated, frequently dispersed water, has direct contact with the air. These units include:

Heat and power generating plant which produces steam for the whole complex. During steam production and in emergency situations (putting new boilers into operations) large quantities of water vapour are generated into the atmosphere.

Ventillated cooling beds cool down the water to be reintroduced to production. The cooling of water is done by means of evaporation and generation of heat into cooler air around. The cooling effect is stronger when the area on which water meets with the air is greater (this is achieved by means of dispersing the water into drops with the help of a special device called a "sprinkler") and when the quantity and velocity of air around the water increases (with the help of artificial air movement caused by ventillators). (The character of evaporation in cooling beds is very different from natural). The movement of water particles corresponds to the direction and force of air passing through the ventillator and to the work of the sprinkler, while in natural conditions it is caused by molecular forces. Cooling beds send drops of water into the air, which does not occur in natural conditions. Certain construction solutions guarantee continuous character of evaporation which is impossible in nature. In addition, continuous air movement in cooling beds facilitates evaporation, while in natural conditions the velocity of wind changes, which also affects evaporation.

Heated-water reservoirs, pre-cooling bed canals, and water collectors in the area of the sewage treatment plant (the water is heated instantly, up to 35°C; increased evaporation is seen throughout the year, especially in winter when temperature differentials between water and air are the greatest). In the unheated water reservoirs the character of evaporation is similar to that of evaporation from near-by natural water bodies.

And finally, large quantities of water vapour come to the atmosphere through leaked installations. Especially intense evaporation from these surfaces is seen in the winter.

In addition to water vapour emissions, the changes in natural circulation of moisture are also influenced by increased heat given off by installations heated up in the process of production, and by emissions of hot waste products (gas, dust). The impact of dust and gaseous emissions upon air pollution above the complex is substantial, and they also influence the cloud cover and the possibility of increased precipitation-generating processes. To reflect the diversified character of evaporation from different areas the complex was divided into semi-uniform sectors in which the level of evaporation was measured independently.

Evaporation from natural areas was computed with the help of the Miezentsev method, linking the level of evaporation with temperature, the shortfall vapour pressure in the air and soil humidity. Evaporation from unheated water reservoirs was measured according to the Sermet method, linking evaporation with the shortfall of air humidity. Water loss due to evaporation at the cooling bed was determined with the help of a simplified method of heat balance, linking the amount of evaporated water with the season of the year and the so-called cooling depth, or the temperature difference between the heated water reaching the cooling bed and the cooled water. Water losses at the cooling bed caused in effect of larger drops being taken away by wind were estimated according to the MZRiP's balances, and their breakdown into individual months was determined by the pattern of monthly losses due to cooling bed evaporation. Evaporation from heated water reservoirs was calculated on the basis of the Shulakovski formula, recommended for approximating evaporation from heated water. This method links the level of evaporation to the temperature of water surface, the temperature of the air over the evaporating surface, the pressure of water vapour (actual and in the temperature of the evaporating surface), and to the wind velocity. Atmospheric emissions of water vapour from installations leakage and from power plant chimneys were estimated according to the MZRiP's balance sheets. The results of the computations are presented in Table 2.

Evaporation from the MZRiP area is very high. In 1986, it reached 1,536 mm, or four times the level of evaporation in natural conditions.

Table 2

Evaporation in the MZRiP area in 1986 (in per cent)

	Natural surfaces	Unheated water reservoirs	Heated water reservoirs	Buildings	Roads	Water blocks	Heat and power generating plant	Total
	58.70	0.10	0.40	33.60	6.80	0.40	0.00	100.00
I	0.34	0.00	0.15	0.16	0.02	4.39	0.69	5.75
II	0.26	0.00	0.14	0.15	0.01	3.95	0.69	5.20
III	1.03	0.00	0.16	0.11	0.02	5.35	0.68	7.35
IV	2.00	0.01	0.13	0.13	0.02	6.20	0.68	9.17
V	2.76	0.01	0.13	0.14	0.02	5.72	0.68	9.46
VI	2.39	0.01	0.09	0.08	0.01	7.33	0.68	10.59
VII	2.26	0.01	0.09	0.16	0.02	7.39	0.68	10.61
VIII	1.97	0.01	0.12	0.18	0.02	8.89	0.68	11.87
IX	1.17	0.01	0.13	0.12	0.02	6.06	0.68	8.19
X	1.19	0.01	0.12	0.10	0.01	6.06	0.68	8.17
XI	0.52	0.00	0.15	0.13	0.02	5.54	0.68	7.04
XII	0.41	0.00	0.16	0.14	0.02	5.18	0.69	6.60
Annually	16.30	0.07	1.57	1.60	0.21	72.06	8.19	100.00

The lowest evaporation was found in winter months and the highest in the summer. The bulk (72%) was accounted for by evaporation from ventillation cooling beds which, it may be noted, cover a relatively small area (0.4% of the total area of the complex). A large proportion (11.3%) was also contributed by evaporation caused by wind action. Another major source of water vapour were natural areas (16.3% of overall evaporation), totalling 58.7% of the overall area of the complex.

Let us have a look at evaporation process in the course of a year, and at changes in the weight of its components. In summer months, the importance of natural evaporation (from natural areas and unheated water reservoirs) increases, while the share of technological evaporation drops below the average. The reverse is true of winter months when natural evaporation falls to its lowest levels while the weight of technological evaporation is on the rise.

The intensification of evaporation from the area of the complex has accelerated the small-scale moisture circulation. Increased overcast and slightly increased precipitation have been observed over the complex. The MZRiP can influence elements of moisture circulation on a large territory. The range of this influence may reach several kilometres to the leeward. The complex may deform the fields of cloud cover, fog and precipitation in an area four times larger than its own territory. The area of the complex's influence upon the intensity of evaporation was estimated at 28 sq. km. The extents of influences differ according to direction and they coincide with the frequency of air-mass transfers into areas in question. On a plane, this is represented by a mirror reflection of the frequency of wind rose, showing atmospheric conditions over the complex. In the case of the MZRiP, the figures on wind at the 200-m altitude were used. The area of influence (28 sq.km) approximately coincides with an area which in 1982 was embraced by a snow cover caused by anthropogenic precipitation. The latter reached some 30 sq.km and it can be assumed that its extent was in accordance with the direction of air-mass transfers in February 1982, and perhaps even in the preceding year. Presumably, this percipitation came as a result of the condensation of the water vapour carried away from the water bodies of the complex. The vapour was condensed and then returned to the complex in the form of precipitation. No other instances of such precipitation have so far been recorded.

The complex accelerates the natural pace of water circulation. In natural conditions, the water taken anually by the MZRiP from the Vistula's surface would be evaporating for 15 years and 4 months. In conditions of changed technological evaporation, the time needed for the same amount of water to evaporate shrinks to 4 years and 3 months.

Precipitation spheres emerge more often above the complex than outside it. The effect is a slight rise in precipitation-generating processes, resulting in increased repetition of precipitation days (3.6 more) and probable increase in the duration of precipitation.

The increase in the sum total of annual precipitation stands at 5.3%. While in the warm season this increase represents a mere 0.1%, in the winter it is much bigger (8.6%). This confirms that fact of precipitation in February 1982.

As is known, the influence of evaporation upon precipitation varies with the size of built-up areas. In an area of 100 sq. km, the local water vapour contributes to just 1% of precipitation. The complex occupies less than 0.1% of this area and consequently only 0.001% or 0.4 mm, of annual precipitation can be attributed to it. Even with a high increase in evaporation, the impact upon precipitation in the complex area will be marginal — and even more so outside the complex.

Precipitation can also be influenced by land forms caused by buildings of various sizes. This influence materializes only when the built-up area exceeds 10 sq.km and the MZRiP occupies a smaller territory; yet in our case the whole Płock urban/industrial area may exert such influence.

The complex constitutes a local source of large amounts of impurities. According to our researchers, a too high number of condensation nuclei may actually lead to the reduction of precipitation, as water vapour appears on a higher number of droplets which grow to smaller sizes and have slower precipitation spread. Besides, the emissions of SO_2, CO and NO_x gases, produced by the MZRiP in large quantities, may disactivate the nuclei.

It is not inconceivable that the locally intensified precipitation over the area of the complex may be accompanied by local processes which keep the measured level below the actual one. The following causes can be mentioned here (in addition, of course, to a measurement error):

1. After the condensation process, clouds together with the water vapour in them can be carried outside the complex — as a result of convection, increased turbulence and quicker transfer of higher-altitude air-masses — and the precipitation then takes place at a long distance.

2. The precipitation may be locally intensified, but, in effect of increased heat emissions by installations, its drops may evaporate in the air and not reach the surface.

A slightly more perceptible influence was found after analyzing condensation in, and above, the area of the complex.

Above the area of the complex, increased cloud-generating processes were recorded. In addition to the locally intensified evaporation, this could also be influenced by an increased number of condensation nuclei, local rise in the intensity of upward currents and the complex's location in the sphere of increased convection processes caused by the nearby Vistula embankment.

In the summer, small-size clouds of the Cumulus type develop over the complex. Often, they are the only clouds on the otherwise cloudless sky. These clouds will not reach a precipitation size. Compared to the surrounding areas, the Cu-cloud cover here is 10% higher.

Fog frequency over the complex is clearly increased, especially in the winter. The presence of fog is caused by local condensation of water vapour in lower layers of the atmosphere in favourable conditions (increased evaporation, increased number of condensation nuclei, and low velocity of low-altitude wind). The period of fog occurrence, as a result of poorer ventillation of the area above the complex, may be longer compared to other areas.

Because of substantial water losses — both in the form of water vapour and strongly dispersed water — increased occurrence of precipitates (dew, frost, rime, etc.) can be expected.

A characteristic feature of the winter period is the condensation of water in the form of ice near cooling beds. The cooling bed intakes are covered with ice as a result of condensation caused by wind action and evaporation. In the vicinity of cooling beds "icy overgrowth" can be seen on railings, poles, elements of the installations, trees and bushes. It always continues for a short period after frost recession.

The MZRiP sends water vapour to the cloud layer when it is lacking in the lower troposphere. Presumably, the water vapour from the complex takes part in convection-cloud formation on free-convection days. The number of such days in a year is estimated at thirty.

The expected increase in relative air humidity in the area of the complex in periods of increased technological evaporation was not found to be the case.

Changes in evaporation and precipitation in the area of the MZRiP complex and the specific pattern of water management influence the water balance in this area. The share of non-natural items (water intake) on the balance sheet's generation side exceeds 90%. On the expenditure side, the highest proportion is accounted for by sewage removal (nearly 70%), with evaporation exceeding 20%.