METEOROLOGICAL CONSIDERATIONS IN NORTH DAKOTA COAL DEVELOPMENT

J. M. Ramirez

Figure 11. An example of a fanning plume.

Although the total quantity of air around and above us seems to be limitless, it's not exactly true. The earth is so large that you may compare the thin envelope of air around it to a coat of varnish over a classroom globe. And so, our air does not have an unlimited disposal capability for gaseous and small particle sewage of a world-wide technical civilization.

Introduction

Air is naturally dirty, and the level of dirtiness in its natural state is really a blessing we should be thankful for. Absolutely clean air would be catastrophic, for that would mean no clouds, no rain, no snow. Indeed, that would upset the global hydrological balance, and who knows, maybe that would mean no life.

But then, we don't want really dirty air either. Not only would that be physiologically harmful to both animals and plants and man, dirty air upsets the natural atmospheric processes that make up our environment.

The Sun-Earth-Atmosphere System

The instant a foreign material, whether liquid, vapor or solid, enters the atmosphere, it becomes its property. Its further dispersion downwind, upward into the upper layers, or fall-out to the ground surface, is dictated by the physical laws that govern the motions of the atmosphere, that culminate to weather and integrate to climate. Almost symbiotically, while the atmosphere determines the pollutants' fate, in return, pollutants alter, in various levels of significance, the atmosphere's behavior. For this reason, any discussion of atmospheric pollution can not be meaningful without some understanding of the intricate interaction between the sun - our ultimate energy source, the earth - our respondent abode, and the atmosphere - the weather factory.

The sun radiates energy into space. At 93 million miles away, our plant Earth intercepts a small fraction of that energy. Because the earth's mass, diameter, and distance from the sun are as they are, gravitational pull exceeds the escape velocity of gaseous molecules over the earth's surface, creating the ocean of air around us - the atmosphere. It is this normally invisible and usually odorless something that we breathe that serves to screen the energy we get from the sun - very selectively, mostly according to how "dirty" the atmosphere is.

As it is, the air appears to be in layers, both in composition and in thermal structure. Among its constituents, water vapor, ozone and carbon dioxide primarily determine the quantity and quality of solar energy that it allows to penetrate. In addition, a totally foreign but constant visitor, dust, currently plays a similarly important role.

After all the processes in the earth-atmosphere system such as the selective absorption, reflection and scattering of radiant energy by the atmosphere's constituents and by the earth surface itself, about one-third of the energy available from the sun is lost back to space, with a little less than half absorbed by the ground surface. But the energy budget in the earth-atmosphere continuum does not remain balanced, especially across the great breadth of the global surface. It is this imbalance that creates the energy of motion needed in weather-making. It is this imbalance that results in the major winds of the world. These general winds are modified by facial irregularities of the globe to create distinct air masses which primarily determine weather and climate over a region.

Meteorological Concepts Significant in Air Pollution Problems

Temperature Inversion

An **inversion** is a vertical thermal structure in which temperature increases with altitude. In

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Dr. Ramirez is associate professor, Department of Soils.

the layers of the atmosphere closest to the ground, temperature normally decreases with height. But inversions usually occur in relatively stagnant air at night, when the loss of heat by the earth's surface cools the air layers nearest it, then the layers just above, and then the next just above it. These conditions are further induced when skies are clear letting the heat escape out into the upper air layers and when winds are calm.

Inversions are common in the Northern Great Plains, especially those which are due to diurnal variations in the solar and terrestrial energy balance. The march of air masses of varying temperature and humidity properties over an area could also create longer-term inversions, especially when that particular weather system becomes stagnant over the area. An inversion condition is a major deterrent to vertical motion and thus to dilution of contaminants in the lower atmosphere.

Atmospheric Stability

The rate at which air temperature changes with height is the **lapse rate** (δ) of temperature. The temperature distribution of the air in the vertical is usually measured by balloon-carried instruments known as **radiosondes.** Because air changes in pressure and density with height, unsaturated air when initially forced upwards will change its temperature at a constant rate. This is called **dry adiabatic lapse rate** (δ d).

Common experience suggests that if a parcel of air brought into an environment where its density is less than that of its surroundings (or its temperature greater) at the same pressure, it will experience a positive (upward) acceleration and have a tendency to rise through the environmental air. Under such conditions, the layer where this happens is said to be **unstable.** Conversely, with a higher relative density and lower relative temperature, the air parcel will tend to descend under influence of a negative acceleration, and that layer is said to be **stable.**

Atmospheric stability then becomes dependent upon the relationship between the temperature structure of the environment (δ) and the dry adiabatic lapse rate (δ d):

Unstable, or thermal instability when	$\delta > \delta d$
Neutral, or thermal neutrality when	$\delta = \delta d$
Stable, or thermal stability when	$\delta > \delta d$

Mixing Depth or Mixing Layer Heights

The concept of mixing layer heights appears often in discussions on the ability of the atmosphere to diffuse or disperse pollutants. Basically, the **mixing layer height** is defined as the thickness of that layer above the surface within which vertical mixing is enhanced relative to higher layers. Deep mixing heights indicate a large volume of air through which pollutants can readily disperse. Shallower depths, with less available mixing volume, create conditions that do not readily dilute air contaminants. The intersections of the dry adiabatic lines and the environmental temperature profile define the **mixing depth.** Over most continental areas as in North Dakota, mixing depths are greater during the summer when the atmosphere is more unstable. In North Dakota, mixing depth values are about 600 to 1000 meters in the winter and about 2000-3200 meters during the summer (Holzworth, 1962).

The "Greenhouse" Effect

The atmosphere, like most gases, has a different band transmissivity for solar (shortwave) radiation than for terrestial (long wave) radiation. In general, the atmosphere has better short wave transmissivity than long-wave. Water vapor and CO_2 in the atmosphere are two of the primary contributors to this "Greenhouse Effect." They are better media for transmitting short wave solar energy than of long wave energy emitted by the earth. Some scientists insist that comparing the atmosphere to a horticultural greenhouse in this regard is misleading, since in a glass greenhouse much of the trapped heat results from restriction of free wind movement (advection).

Anti-Cyclones

It is not mere coincidence that the major deserts of the world linger around 30° north or south of the global equator. These latitudinal bands are areas of high pressure characterized by normally calm winds and divergence of windflow at the surface, which by the law of continuity of mass must be accompanied by subsidence from aloft. These conditions are least conducive to cloud formation and thus precipitation. This subsidence, associated with high pressure areas or anticyclones, produces a suppression of positive or upward vertical ventilation. Clear skies due to absence of cloud build-up increases the likelihood of radiation inversions formed usually at night. If surface air stays cooler than the subsiding air, inversions lasting for many hours can develop. Such conditions are not foreign to North Dakota, especially during the winter.

The combination of both radiation and subsidence inversions, when the latter is produced by a slow-moving high that persists over an area for several days, produces the greatest incidence of pollution potential.

Atmospheric Diffusion

Experience tells us that wind near the earth's surface does not blow steadily and smoothly from

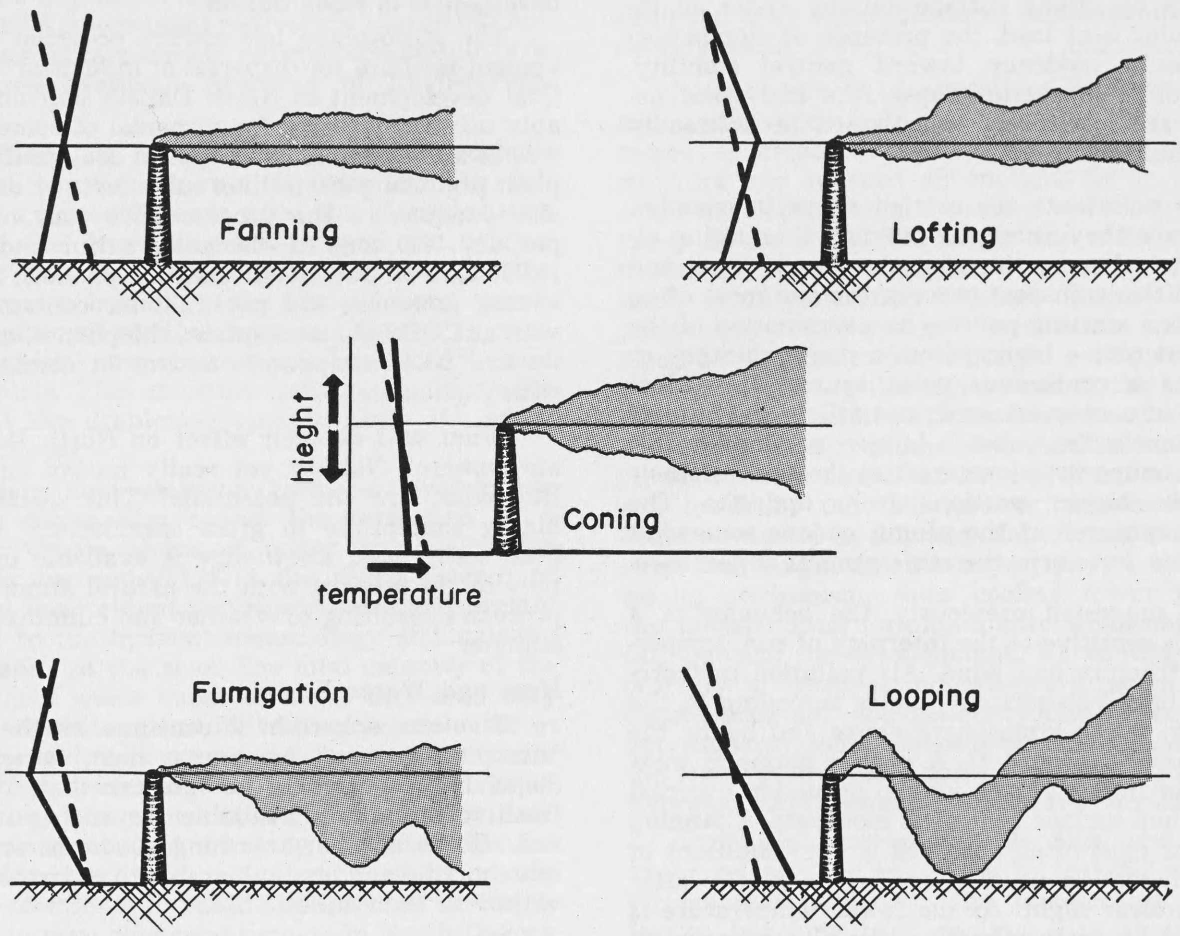

Figure 1. Plume Behaviors Related to Vertical Temperature Distribution in the Lower Layers of the Atmosphere. Dotted Line is Dry Adiabatic Lapse Rate (δ d); Solid Line Indicates Observed Temperature Profile.

the same direction at the same speed. Wind gusts on face and body, rippling flags, and the erratic flight of paper scraps or dust particles make this fluctuation visible. This uneven flow is referred to as **turbulence.** We often find it convenient to think of the motion as being made up of a basic smooth flow with constant speed and direction, upon which are superimposed the random contributions of swirls or "eddies" in a wide range of sizes.

The eddies of turbulent motion are of two basic types, caused by two different processes. Air forced to move past an object protruding into the windstream will tumble and turn on itself, producing eddies having sizes and speeds related to the average wind speed and to the shape and size of the object. This result is called **mechanical turbulence.**

The other type of turbulent motion results from parcels of superheated air rising from the surface, and the descending motion of other parcels taking the place of the rising air. This results in **thermal turbulence.** In most cases, air turbulence is a mixture of the two types, but under very special circumstances air may move with essentially no turbulence at all in **laminar flow.** Such motion produces nearly a straight line in its wind-record trace.

Broadly speaking, mechanical turbulence associated with neutral thermal stability [$\gamma e = \gamma d$] is neither suppressed nor enhanced by the thermal structure of the air, because the fluctuations are produced mechanically by rough elements in the windstream. By the same kind of reasoning, thermal turbulence is associated with thermal instability ($\gamma e > \gamma d$) because any fluctuations are immediately damped out. Clearly then, wind behavior and temperature structure are closely related.

Because pure thermal turbulence and laminar flow occur only with light winds, wind behavior most of the time has a generous contribution of mechanical turbulence in the mixture. In fact, the greater the wind speed, the more the temperature profile approaches the condition of neutral stability — the dry adiabatic lapse rate. Furthermore, since pure thermal turbulence is produced most of the time by strong surface heating under an intense solar heat load, the presence of clouds also produces a tendency toward neutral stability. Thus sun, temperature lapse rate and wind behavior are all closely intertwined in a broadly predictable manner.

Air pollutants are carried about in complex ways once they enter the moving, fluctuating atmosphere. Among the several ways to view and analyze this transport process, the one most often taken as a starting point is an examination of the pollutant plume issuing from a single chimney or stack as a **continuous point source.** Individual parcels of contaminants do not follow the path of the plume's "snapshot." Lower portions result from a temporary downdraft at the time of their emission; higher portions from updrafts. The "time exposure" of the plume widens somewhat with time, but keeps the same general appearance.

As suggested previously, the behavior of a plume is sensitive to the interplay of sun, temperature structure and wind. Air pollution meteorologists have categorized plumes according to the stability of the atmosphere above and below the stack height (Figure 1). A **coning plume** is most probable under strong winds, or under overcast skies when surface heating is moderate. A **fanning** plume is most often observed under conditions of strong inversion, usually just before sunrise after a calm, clear night. As the lower temperature is modified by surface heating, the plume begins to **fumigate.** If the sun is bright and winds light, the plume will then tend to become a **looping type.**

Not all pollutants come from continuous point sources. In the language of air pollution meteorologists, an explosion is an example of an **instantaneous point source,** while the plume from the pass of a crop-duster aircraft over a field is an example of an **instantaneous line source.** A freeway choked with traffic is an example of a **continuous line source.** All of these source configurations are modeled by similar mathematical methods. **Area sources,** such as that in an extensive refinery complex with multiple sources of the same pollutants, or the center of a major city as a source of the same pollutants, or the center of a major city as a source of dust and smoke, require different approaches to analysis and prediction. When space and time dimensions of an analysis increase well beyond the microscale, still other methods are required.

Based on the above basic principles, the fate of an air pollutant from a given source may be described mathematically. **Air pollution potentials** during a given period over a given area are based on the sun, temperature lapse rate, wind behavior, nature of pollutant and source type relationships.

Meteorological Implications of Coal Development in North Dakota

The atmosphere has always provided a convenient medium for dispersal of industrial wastes. Coal development in North Dakota will unavoidably use this medium for dispersal of some of its wastes and by-products. A typical coal gasification plant producing 250 million cubic feet per day will also produce in the process 2,000 tons of char per day, 450 tons of elemental sulfur and some 14,000 tons of CO_2, not to mention phenols, thiocyanates, ammonia and potential air contaminants such as COS, CS_2, mercaptans, thiophenes, aromatics and NOx compounds, and/or in combination with particulates.

What will be their effect on North Dakota's atmosphere? Nobody yet really knows for sure. But what are the potentials? This question is highly susceptible to gross speculations, but at least some basic knowledge is available on how they might interact with the natural atmospheric processes resulting to weather and culminating to climate.

Heat and Water Vapor

The atmosphere will continue as the main "dumping ground" for excess heat, because its dispersive capacity is far greater than that of fresh water bodies available for such purposes, and also because air-breathing life forms are both more mobile and less vulnerable to environmental variations than aquatic life.

Unlike most of the other pollutants from power-generating facilities, heat and water vapor are not only natural properties of the atmosphere but they are exceedingly variable properties as well. This variability, coupled with man's ability to tolerate a wide range of climatic conditions, makes the establishment of standards for heat and moisture a very different problem from that encountered in dealing with alien chemical compounds, where one need only accept a given concentration level as having significant effects.

Currently, our mean global energy production is 0.01 watts/m^2, and it is unlikely that the increase will be greater than the factor of 5 by the year 2000. Man's contributions total much less than 0.1 per cent of the natural heat, and it seems very doubtful that such a small change would seriously alter the global balance. In terms of sensible heat, the mean value of absorbed solar energy at the earth's surface is 350 MW/km^2, and the 1,500-2,500 MW of waste heat from a 1,000 MW (electrical) power plant is, therefore, equivalent to the sun's influence over an area 2.5 km on a side. Translated in terms of water vapor, as is largely the case with an evaporative tower, the rate of moisture release is approximately equivalent to the natural evaporation from the soil and vegetation over an area 4.25 km on a side on a typical summer's day in the central United States. Thus, a 1,000-MW power plant represents a large but not enormous abberation of natural conditions in a local area (National Academy of Engineering, 1972).

Emission of waste heat to the atmosphere produces buoyant plumes of warm air. The volume of a plume depends upon the characteristics of both the generating facility and the cooling system. With an evaporation tower, much of the waste heat is initially in the form of water vapor, but additional sensible heat is released as soon as the water vapor begins to condense into a cloud of droplets. This moisture returns to the vapor form as the droplets evaporate along the edges of the plume.

Waste heat emission from an evaporative cooling tower also causes the formation of a usually visible plume of water droplets. These droplets are embedded in the rising column of air, and their extent and significance are directly related to the incident meteorology and existing topography of the area. The total capacity of the air to hold water vapor as a gas decreases very rapidly with temperature. As an example, air at 0°F can maintain only 3 per cent of the water vapor that it is capable of holding at 85°F. Thus, at freezing temperatures, a visible cloud will almost always persist for long distances. To the general public, the most obvious effect of the tower release will be the creation of a visible plume in very cold conditions as in North Dakota, or humid conditions which may create an aesthetic problem.

These plumes do not usually touch the ground in flat or gently rolling terrain of central North Dakota. They will cause small changes in the mean ambient temperature and humidity over a broad area, but these would normally become significant only in conjunction with numerous other sources.

Serious environmental problems may be created, however, if the terrain is rugged or man-made structures rise to great heights. The intersection of such a plume with obstacles may produce local fog and noticeably alter local temperature and humidity. When the ambient temperature is below freezing, such a cloud can produce icing on the incident vegetation, roads and structures.

Very light precipitation may also fall directly from the cooling tower plumes, usually a drizzle or fine snowflakes. There have been reports of large water droplets falling from cooling tower plumes, but these seem to have been associated with earlier tower designs in which the device known as a "drift eliminator" was not used. The drift eliminator is essentially a baffle designed to prevent the transport of large droplets directly from the tower structure, and all modern units are equipped with them (National Academy of Engineering, 1972).

Indirect effects of alterations in atmospheric and water vapor may also alter the natural processes of cloud formation. Natural sources of moisture and upward air motions favor certain cloud developments, and cooling towers may certainly do the same. The larger and more concentrated the heat and moisture release, the more likely cloud generation becomes. Essentially, the plume may act as a trigger mechanism, initiating cloud development where it might not occur otherwise or increasing the dimensions of the existing clouds. Instances have already been noted wherein a cooling tower plume has created cumulus clouds in otherwise clear air, and there is no reason to doubt that showers or thundershowers could be started in this way. One should not, however, over-emphasize the importance of this triggering mechanism, since cooling tower plumes can initiate cloud formation only when nature itself permits the development. No cooling tower is likely to create thunderstorms in areas where nature does not, and generally clear regions are not suddenly going to become cloudy. At most, the tower plume could influence only slightly the frequency and location of natural phenomena.

Problems associated with heat and water vapor release are not likely to include rude environmental surprises. The meteorological profession has long been dealing with clouds, fog, precipitation and icing; and while the exhaust stack source of heat and moisture is new, the atmospheric problems are not. Obviously, as coal combustion exhaust stacks grow in capacity and number in a growth area the effects will become more obvious and frequent, but nothing meterologially seems likely to develop suddenly.

Visibility

Atmospheric effluents from coal combustion stacks contain large numbers and types of particles. Small-diameter particles contribute to haze and smog formation and lowering visibility. Gaseous emissions (namely, sulfur and nitrogen oxides and hydro-carbon compounds) also contribute to the atmospheric particulate load by indirect means. Both photochemical and thermal reactions occurring in the atmosphere generate large numbers of particles which reduce visibility.

It is estimated that more than half of the aerosols in the lower atmosphere come from chemical reactions involving volatile hydrocarbons, nitrogen oxides, ammonia and sulfur compounds. This man-made contribution is about 6 per cent of the 10 million tons per day emitted from all earthly sources and may cause an 11 per cent increase in aerosol concentration by the year 2000 (Hidy, 1970). Sulfur dioxide concentrations of 0.1 ppm reduce visibility significantly by aerosol formation when atmospheric relative humidity is greater than 50 per cent (NAPCA, 1969). Although it is very difficult to determine the exact consequences of coal combustion plant emissions to visibility reduction, it is clear that coal development can make a significant contribution to the man-made production of visibility-reducing aerosols and particles.

Solar Radiation

Particulates in the atmosphere are effective in diffusing, reflecting and absorbing light. Recent estimates by Bryson and Wendland (1968) indicate that a reduction in the total amount of solar radiation reaching the earth may be occurring due to accumulation of particulate matter in the atmosphere.

Acidification of Rain and Soil

In several parts of the world, increased sulfate and sulfuric acid content of rainwater, lakes and soil in areas near and far from pollution sources has been demonstrated (Gorham and Gordon, 1960). The immediate consequences to the biosphere from current power plant emissions appear slight. However, probable continued deposition from planned coal development sites in western North Dakota requires that more attention be paid to the possibility that soil micro-organisms and plants might be harmed by fallout of pollutants in rain in areas downwind of large generating facilities, especially those that may constitute an impacted area source.

Coal Development in North Dakota: The Climatologist's Point of View

Development of the mineral resources in North Dakota will undoubtedly have an environmental impact upon the area. The extent of such impact unfortunately is still unknown. Yet, gross deductions may be made. Our atmospheric conditions generally are good for safe dispersion of contaminants. Low frequencies of stagnation exist in our area mostly due to fronts moving in from the northwest and air masses from the Gulf of Mexico tending to produce a well-mixed atmosphere. The state's generally flat or rolling terrain, along with higher than national average wind velocities, should help avoid the formation of trapped and impacted plumes as is experienced by other parts of the country.

But we do have calm, cold, snowy, severe winters in North Dakota, resulting in deep radiational inversions which may last for hours. There is no region in the world, given enough pollution, in which the self-cleansing properties of its atmosphere cannot be overwhelmed.

However, industry should use extreme care in choosing their sites for operations. The potential cumulative effect of several power plants in a given locality must be considered. This is difficult to accomplish because of the interplay of so many factors such as emission release rates, stack parameters, terrain, atmospheric conditions and others; but it can be done at least to some useful level. In a study in southwest U.S., NOAA estimates that the effects of average-size power plants to air quality is insignificant if such plants are located at least 100 km apart. However, closer sitings can produce additive effects both on short-term and long-term impacts. How about in the Northern Great Plains? No such study has been made, but one must now be undertaken.

There is almost no question that some development of our coal resources, for power generation or coal gasification, is almost inevitable, and is probably what we should do to help combat the present energy crisis. We must take advantage of the fortunate circumstance that such industrial development in our state waited until the present stage of our technological advancement. Tremendous amounts of scientific and technological knowledge have been gathered to this day, some through unfortunate consequences of environmental degradation from short foresight of industrial planning in other parts of the country. We are indeed fortunate we have all that available to better guide us in planning for coal development in North Dakota.

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