Ice Fog

By Carl S. Benson

A Caltech alumnus—and a fugitive from Los Angeles smog—finds a unique type of air pollution in Alaska.

Most people think of Alaska as a big place with a few people and clear air, and in general this concept is correct. However, there are exceptions. Much of Alaska's sparse population lives in crowded though isolated communities, some of which are small copies of urban areas in the United States to the south. Their similarities include, unfortunately, the most extreme cases of water and air pollution.

One of these communities is the Fairbanks-Ft. Wainwright area of interior Alaska, which has an interesting form of air pollution known as ice fog. Ice fog is produced when the water vapor output from urban environments meets an air mass which is too cold to dissolve it and cold enough to crystallize the condensed vapor into tiny (5 to 10 microns) ice crystals. The condition becomes increasingly serious as air temperatures go below −35 degrees C. The ice fog layer has a vertical thickness of about 10 meters and rarely exceeds 30 meters, but its thickness and density increase during extended periods when temperatures remain below −40 degrees. Then street level visibility becomes an acute problem, often being reduced to less than 10 meters, or "measured in arm lengths" in the popular vernacular.

Although reduction in visibility is serious in itself, it is only one of the more obvious manifestations of the problem. The stable air condition (little or no wind) during cold spells in Fairbanks produces concentrations of atmospheric pollutants which are as bad as any on earth.

My study of ice fog began as a purely glaciological one, but it soon blossomed into a study of air pollution—perhaps the first time these particular fields of study have blended.

Ice fog is low-temperature air pollution. It is unique and sufficiently well known to be classified as one of the four major types of air pollution: 1) coal smoke and gases—the major contributor in the industrial world; 2) specific toxicants—usually related to the effluent from a specific industrial source; 3) Los Angeles-type smog—identified by Caltech's A. J. Haagen-Smit to be the result of complex photochemical reactions involving unburned hydrocarbons, primarily from auto exhaust [*E&S*—May 1952], and occurring with varying intensity in metropolitan areas all over the world; 4) ice fog—sometimes called the Fairbanks-type air pollution.

Inversions form the essential ingredient in setting the stage for air pollution. Air temperature usually decreases with increasing altitude; when it *increases* with altitude, a temperature inversion exists. The air within an inversion layer tends to be stable because the colder, denser air lies at the bottom, and the possibility for vertical motion and mixing of the air is reduced. As the temperature gradient (the rate of change of temperature with altitude) within the inversion increases, so does the stability. The magnitude of the temperature gradient is often referred to as the "steepness" or the "strength" of the inversion.

There are two main types of inversion. One is a temperature inversion that forms in the boundary layer between two air masses. For example, in the Los Angeles area where cool air lying on the Pacific Ocean is overlain by warmer air, the temperature slowly decreases from ground level up to 400 or 500 meters; then it increases sharply as the overlying warm layer is encountered. The other type of inversion occurs at ground level when there is a net loss of heat from the earth's surface by outgoing longwave radiation. These radiation inversions become especially well developed at night over snow surfaces and are common both night and day in parts of the Arctic and Antarctic. They are also very common in Fairbanks.

Ice fog in the atmosphere makes visibility difficult in downtown Fairbanks even in the light of midday.

If we compare the air structure over Los Angeles and Fairbanks (right), we find that in the summer in Los Angeles there is a 400- to 500-meter average air thickness beneath the inversion. In the winter in both L.A. and Fairbanks the air is colder, and the inversion begins at ground level; thus there is scarcely any air available to disperse and carry away pollutants beneath the inversion layer.

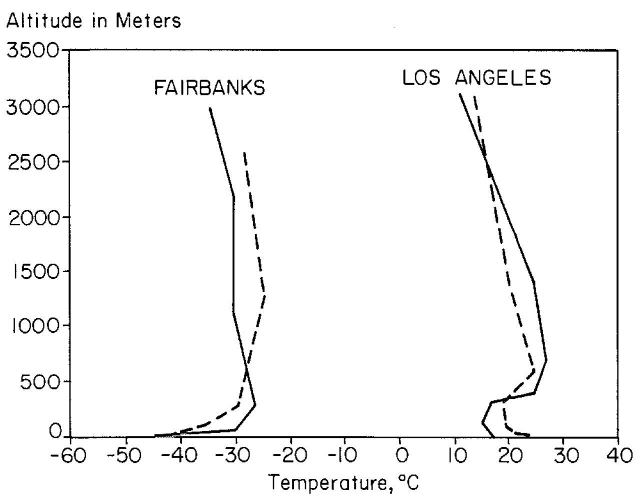
The Fairbanks inversions are also stronger and longer lasting. Maximum gradients in the Los Angeles inversion are about 10 degrees C per 100 meters; those in Fairbanks nearly always exceed this and range up to 30 degrees per 100 meters. The Fairbanks inversions are not only among the steepest in the world, but they sometimes last for weeks at a time. During midwinter the sun is above the horizon for less than four hours per day at a maximum angle of less than 2 degrees. This nearly continuous nighttime environment is partly responsible for the strength and persistence of the surface inversions in the winter.

Topography is also important. Fairbanks is surrounded by hills on three sides, somewhat like the Los Angeles Basin. This provides wind protection, which enhances the formation of strong surface inversions and permits the air to stagnate in the city. The lowest air layer becomes virtually decoupled from the air aloft.

Most cities evolve enough heat to prevent low-level inversions from forming—indeed, it is rare to find inversions in the lowest 100 meters over cities, and the city influence is sometimes still evident as high as 200 to 300 meters above the surface. In Fairbanks, the city warms the air so that it is about 6 degrees warmer than that of the surrounding areas. This is a significant heat island in the Tanana Valley, but it does not destroy the strong surface inversions because they always involve temperature increases of more than 6 degrees C in the first 50 to 100 meters.

Exceptionally strong inversions, present when surface temperatures drop below −30 degrees and formed by radiative cooling from the surface, restrict turbulence in the lowest levels. Therefore the surface air layers have very low winds, almost always less than 2 meters per second. This is especially true for the bottom 200 meters of air contained by the hills around Fairbanks.

The existing air flow consists of katabatic (gravity drainage) winds which move down the Tanana Valley. This has led to a widespread misconception that the katabatic flow drains cold air from the hills onto the flats, and especially into the lowest pockets. This would be a happy circumstance, if it occurred, because such drainage would tend to flush the air pollutants out of the city. However, the air in the flats is so much colder, and therefore denser, than that moving down from the hills, that it cannot penetrate. It moves across the cold low-lying pool of air as if it were a lake. Thus, the only flushing mechanism for Fairbanks air during cold spells is turned off, and the dense surface layers are effectively decoupled from the air above. Unfortunately, it is precisely during these cold spells, when the air is most able to



A comparison of air temperatures measured at various altitudes in Fairbanks and in Los Angeles shows the colder air in Fairbanks producing inversions at ground level. (Although Fairbanks is 135 miles above sea level and L.A. 38 miles, they have been plotted at a common altitude to compare their inversions and their altitudes.)

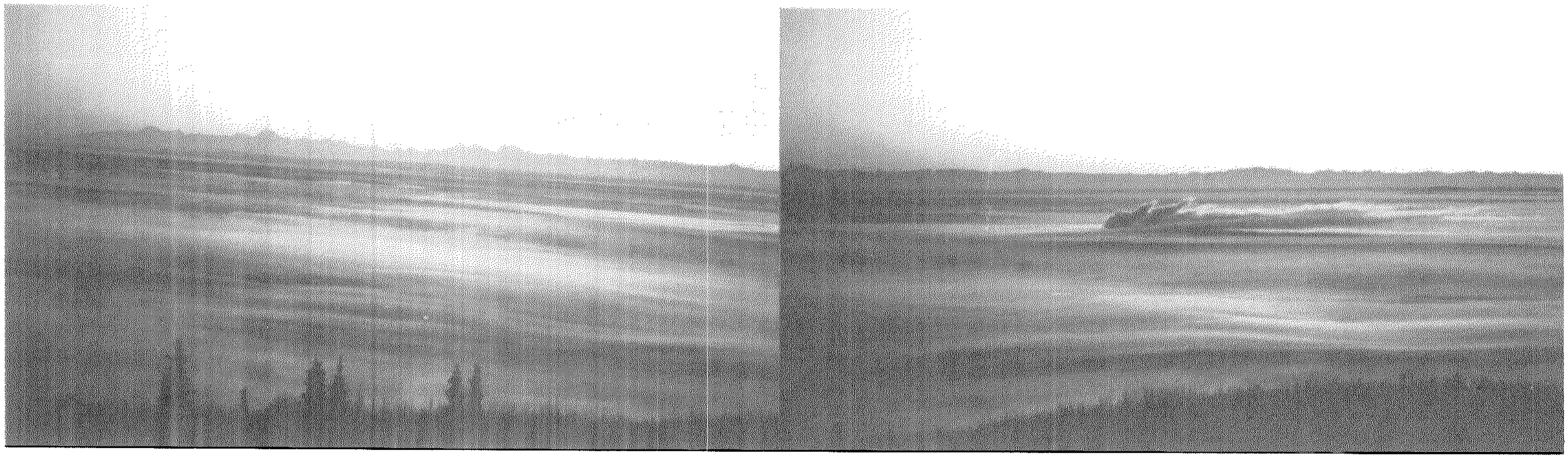
stagnate, that the rate of polluting the atmosphere increases because of increased demands for heat and power. Invariably, natural and man-made factors reinforce one another in ways which lead to intensification of the air pollution.

Fairbanks is ideal as an air pollution laboratory. The city is isolated—its nearest neighbor is Anchorage, a full day's drive to the south—and its sources of supply are limited almost exclusively to the Alaska Railroad, which is easy to monitor. Thus Fairbanks, at the end of the line, not only has a simple, two-layer atmosphere which serves to concentrate pollutants, but the sources of all its pollutants may be accurately measured as well. This ideal simplification is virtually impossible to duplicate.

One of the most interesting things about the Fairbanks air pollution is that atmospheric water itself is a pollutant, even in amounts that would be considered negligible at higher temperatures. It is surprising how much water vapor is put into the atmosphere by the activities of man. For example, the automobile creates water and carbon dioxide when gasoline is burned in the engine. The actual mass of water ejected as vapor from the exhaust is 1.3 times greater than the mass of gasoline burned. The amount of carbon dioxide produced is 3.1 times the amount of gasoline burned.

In the Fairbanks area more than 30,000 gallons of gasoline are burned every day. This alone results in a daily input into the atmosphere of 120 tons of water vapor and 295 tons of carbon dioxide. Similar relationships exist for fuel and coal. (The coal used in Fairbanks is slightly more complex than the liquid fuels because it contains some gravel, 10 percent ash, and 20 percent water.) The total input from all combustion products is 1,300 tons from water and 4,100 tons from carbon dioxide. This figure represents only 32 percent of the daily input of water from all sources.

The largest man-made source of water vapor in the Fairbanks-Ft. Wainwright area is the evaporative loss from power plant cooling waters. There are five power plants in the area, each using a large amount of cooling water. The designs for discharging this cooling water are crude, especially considering how greatly the discharge contributes to the ice fog. For example, one power plant discharges about 110 gallons of water per second at a temperature of 15 degrees C into a stagnant slough. The water remains, for 3 kilometers, as a stretch of open water which does not freeze even in the coldest weather. The resulting



This mosaic of four pictures, taken in December at sunset from Birch Hill, north of Fairbanks and Ft. Wainwright, shows (left) the eastern edge of the ice fog over Ft. Wainwright to the southeast; (above) the exhaust plume from

evaporative loss to the atmosphere is nearly 900 tons of water per day. The five power plants contribute a total of 23,400 gallons per minute. The evaporative loss from this source exceeds 2,500 tons of water per day and constitutes 64 percent of the total man-made input into the Fairbanks atmosphere.

The Los Angeles area puts far more water into the air by combustion than Fairbanks does. But air in L.A. at 20 degrees C can hold 255 times more water in solution, without condensing and forming fog, than air at —45 degrees C in Fairbanks. It is striking how little moisture is required to generate a dense fog when the saturative value for the air is less than 0.1 grams of water per cubic meter.

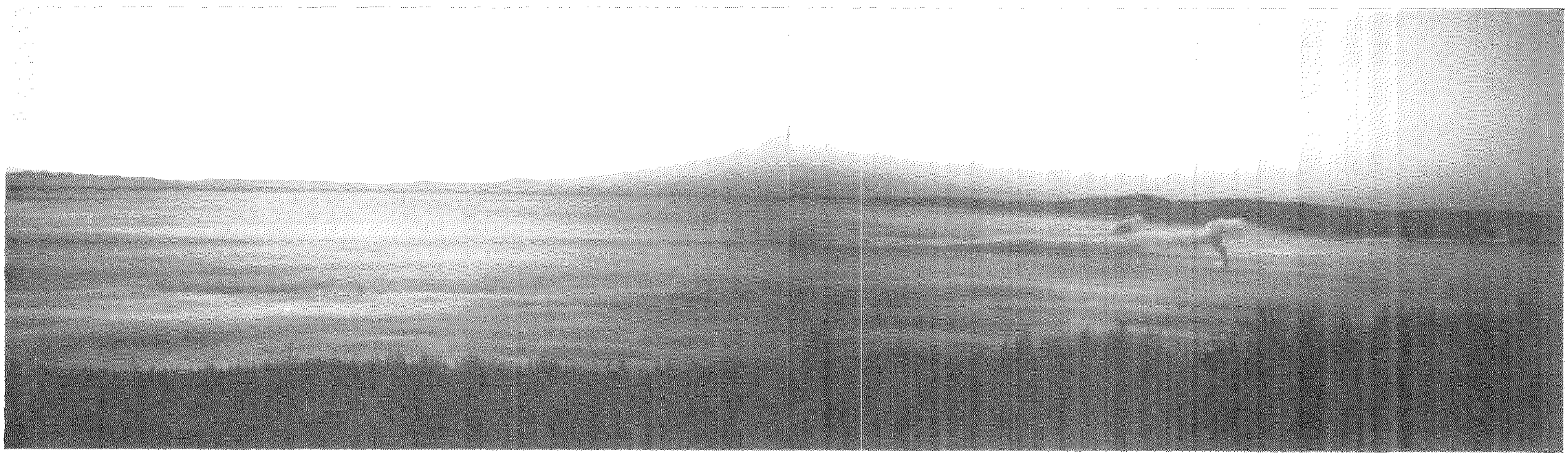
Under these conditions all sources of water vapor produce small (about 5-micron in diameter) spherical or columnar ice crystals which have an average specific surface area in excess of one square meter per gram (about 9 square feet) and terminal falling velocities of less than one centimeter per second. The large surface area allows the crystals to adsorb pollutants in the air, to the extent that 0.5 percent of their mass consists of foreign matter; the slow terminal velocity keeps them suspended in the slowly moving air.

It is impossible to eliminate all sources of water vapor into a cold atmosphere. Some of these are as basic as breathing itself. There are 30,000 people and about 2,000 dogs in the Fairbanks-Ft. Wainwright area. The air that they exhale is saturated with water vapor at a temperature of 35 degrees. The dogs breathe at an average rate of 5.2 liters per minute even when they are resting; this provides 7.5 cubic meters of air per dog, per day, with a moisture content of 40 grams of water per cubic meter. So the total moisture put into the air by 2,000 *Canis familiaris* is at least 0.6 tons per day. This is a conservative estimate, because all of the dogs don't rest all of the time.

The people must be separated into 20,000 males and 10,000 females. At rest, the lung tidal volumes are .75 liters for males and .34 liters for females. But the respiration rate is 11.7 per minute for both groups. These rates increase with activity. Respiration and tidal volumes for males doing light work are 17.1 per minute and 1.6 liters respectively, and for heavy work 21.2 per minute and 2.0 liters. As an overall average for an order of magnitude calculation, this results in 29 tons of water per day breathed into the air by *Homo sapiens* in the Fairbanks-Ft. Wainwright area.

Contributions to the total man-made input of 4,000 tons of water vapor to the area are:

Source	*Amount in tons per day*	*Percent*
Combustion products		
Gasoline	124	3
Fuel oil	202	5
Coal, domestic	207	5
Coal, power plants	760	19
Cooling water from power plants	2600	64
Miscellaneous sources	170	4
(leaks from steam lines,		



Ft. Wainwright's power plant penetrating the ice fog; (above) Mt. McKinley on the horizon some 160 miles away to the southwest; and (above) to the southwest the exhaust plumes from two power plants in Fairbanks.

houses, laundries, university mine shaft, sewage plant, people and animals breathing)		
Total	4063	100

It would be misleading to assign importance to the sources on a basis of quantity alone because the altitude at which the exhaust is put into the air is a critical factor. In the case of cooling waters, low altitudes and high input rates are combined. However, the 3 percent added by automobile exhaust contributes more frequently to ice fog than does the 19 percent from power plant exhaust stacks. The latter become very important when the thickness of the fog increases sufficiently so that the power plant exhaust plumes blend into it. The automobile is the worst source because it moves about and is concentrated where people concentrate. The altitude of its exhaust outlet is essentially at ground level, and it contains other undesirable products in addition to the water vapor.

A mass balance of the ice fog has been calculated by equating the rate of input from all sources to the rates of precipitation, evaporation, and growth of the fog. The present sources maintain a maximum ice fog volume of about 3 billion cubic meters over a fairly well-defined area of nearly 200 square kilometers. There are some fascinating dynamic problems of the air within this ice fog layer which are now being studied.

There are, of course, products other than water put into the air during the ice fog attacks. Combustion processes also introduce into the Fairbanks air mass:

Compounds	*Amount (kilograms per day)*
Carbon dioxide	4,100,000
Sulphur dioxide	8,600
Lead in salts	60
Bromine in salts	46
Chlorine in salts	20

The last three of these products are from the tetraethyl fluid in gasoline. The concentration of lead in Fairbanks air during extreme conditions probably exceeds the values measured in most urban areas. So far we have measured concentrations of 6 micrograms of lead per cubic meter of air under conditions when a relatively weak inversion was present. This value may be one-half to one-third of the maximum values attained.

Our research on ice fog and the associated low-temperature chemical reactions in the air is just beginning. It is a serious problem and one that will continue to increase with population. One only wishes that the existence of ice fog was limited to that observed many years ago by a traveler to these parts:

"There was not a breath of air stirring . . . there were only a few clearings in the wood, but wherever the animals were you could discover their presence by the clouds of steam that rose from them high above the tops of the trees. Wherever a band of caribou was running, you could see a cloud of steam hovering over their trail and marking it out plainly for a mile behind them."