for example, sink into a grid-size plateau only 1000 meters high. Even topography must be averaged over a grid space, one of which takes in the entire French Alps. But the real winds slamming into the Alps must go over or around the highest barrier, which could be the highest mountains, passes, or even valleys filled with stagnant air.

The European Center's researchers have alleviated most of their shrunken mountain problem with their own version of a technique called envelope orography. In their revision of the model, rough mountain chains are made higher and valleys are filled in when air stagnates within them. The changes, which European forecasters are now inserting into their operational model, have extended experimental forecasts at least 6 to 12 hours on average, according to Wallace. Under some circumstances, they added 2 to 3 days.

The forecasts finally produced by these models come in a variety of forms. The standard for comparison is the forecast of atmospheric pressure distribution, the highs and lows that generally correspond to fair weather and foul. Such forecasts by the European Center are useful out to about 6 days, according to standard statistical tests. No one's temperature forecasts extend quite so far, though they are improving, and precipitation forecasts, the most difficult to make, fall apart after about 3 days. Meteorologists believe that they have more skill than that in forecasting the major weather events of special interest to the public, but they have yet to develop valid statistical tests for such events.

The race for the lead in medium-range forecasting may close to neck-and-neck later this year as NMC brings on its Control Data CYBER 205, at about 80 million instructions per second the computational equal of the Cray-1. Most NMC personnel expect to achieve equivalency with the European Center within about a year of taking delivery of the CYBER this April. The Americans will also be competing with the United Kingdom, which is already operating a CYBER 205 of its own.

The Americans may have little time to savor their newly won equality. According to Bengtsson, the European Center is eyeing Cray's X-MP for acquisition in early 1984. The X-MP is a multiprocessor having three to five times the computing power of the Cray-1. The most obvious step to take with such a machine, says Woods, would be to increase the model's resolution.

How long this race may run is not certain, but the end cannot be too far off. Computer power may have no immediately obvious bounds, but the predictability of the atmosphere must have inherent limits. Edward Lorenz of the Massachusetts Institute of Technology has estimated this upper limit of predictability by comparing a number of the European Center forecasts made for a particular day and the actual conditions of that day. His best estimate is that forecasts as skillful as the Center's present 7-day forecast can be extended to perhaps 10 or 12 days. The barrier to detailed, long-range forecasts, he says, is the tendency of the inevitable errors in describing the smallest-scale structure of the atmosphere to cascade into large-scale weather patterns. There is a limit, it appears, to what even a supercomputer can do about the weather.

—RICHARD A. KERR

Plants' Resistance to Herbicide Pinpointed

The change of a single nucleotide in a chloroplast gene can make plants resistant to the widely used herbicide atrazine

A group of investigators at Michigan State University (MSU) recently found that a single change in a chloroplast gene can account for the development of resistance to the herbicide atrazine in certain weeds. According to Charles Arntzen of MSU, who presented the results at the Miami Winter Symposium,* the discovery could lead to the introduction of similar herbicide resistance into important crop plants. Since this endeavor requires the transfer of just one gene, it may achieve success more readily than many other potential projects for the genetic engineering of plants.

One likely target for genetic manipulation is the soybean, which is currently very susceptible to atrazine. Soybeans are often planted in rotation with corn, a crop which is tolerant to the herbicide. If atrazine residues remain in the field from the previous season, soybean yields may be markedly reduced.

*Held in Miami on 17 to 21 January under the auspices of the Department of Biochemistry of the University of Miami and the Papanicolaou Cancer Research Institute.

Around 1970 farmers first noticed that weeds were becoming resistant to atrazine, principally in areas where it had been applied repeatedly without switching periodically to other herbicides. Now more than two dozen different weed species in Europe, southern Canada, and several states in this country are resistant.

Corn is tolerant because it naturally contains enzymes that detoxify atrazine. Investigators originally assumed that weeds became resistant because they acquired the ability either to detoxify atrazine or to prevent its uptake by plant cells. But that turned out not to be the case. "There was no difference in anything until we looked at the site of atrazine action," Arntzen says.

Research in his and other laboratories has shown that atrazine blocks electron transport in chloroplasts, killing weeds by depriving them of the energy and reducing power needed for photosynthesis. "Atrazine displaces a quinone from a specific protein involved in electron transport in the chloroplast and shuts off electron flow," Arntzen explains.

Attempts to isolate and characterize the protein, which is tightly bound to chloroplast membranes, proved futile. To detect the protein in a preparation of chloroplast membranes, Arntzen and Gary Gardner, who is now at Shell Development Company in Modesto, California, labeled it with a radioactive atrazine derivative. Atrazine itself does not covalently bind to its target, but the derivative becomes covalently attached to the binding site when illuminated with ultraviolet light. The investigators found that chloroplasts from susceptible plants contain a 32- to 34-kilodalton protein that is labeled by the atrazine derivative. The protein is present in resistant plants but does not become labeled.

Because atrazine and the quinone compete for the same binding site, it was possible to conclude that this protein is the photosynthetic quinone-binding protein. The mutation that confers atrazine resistance apparently prevents binding of the herbicide but not of the quinone; resistant plants have no defect in electron transport. Arntzen remarks, "It is a very subtle change that reduces the binding of one chemical but not of a related one."

Meanwhile, other investigators had shown that the gene for atrazine resistance was maternally inherited. This suggests that the gene is located not in the nucleus but in a cytoplasmic organelle, the chloroplast or mitochondrion, both of which carry their own genomes.

At this point, the research on atrazine resistance converged with research on gene expression in chloroplasts that is being performed in the laboratory of Lawrence Bogorad at Harvard University. The MSU workers continued to be plagued by the difficulty of isolating a membrane-bound protein. "We spent three unsuccessful years on protein chemistry," Arntzen says, "but were not able to isolate and characterize the right 32-kilodalton protein. We needed a new approach and that is where recombinant DNA technology came into play."

While studying expression of the chloroplast genome, Bogorad and his colleagues found that these organelles make a number of proteins in response to light exposure. Among the proteins was one with a molecular weight of 34,500, which is subsequently processed to form a molecule with a molecular weight of 32,000. The gene for this protein was designated photogene 32.

The Arntzen and Bogorad groups showed that the product of photogene 32 and the atrazine-receptor protein are one and the same molecule, a big boost to the research because Lee McIntosh of Bogorad's group had already cloned the gene and it is easier to sequence genes than proteins. McIntosh, who is now at MSU, and Joseph Hirschberg, also of MSU, have determined the nucleotide sequence of the normal photogene 32. They have also cloned and sequenced the mutant gene from herbicide-resistant plants. There is only one change in the mutants, a substitution of an adenine for a guanine. This changes a single amino acid in the protein, but the alteration is enough to produce a product to which atrazine can no longer bind.

With the biochemical basis of atrazine resistance now well in hand—and showing a highly circumscribed change in a single gene—Arntzen thinks it should be possible to apply the knowledge to the development of new herbicide-resistant plant species. In some cases, it may be possible to do this by standard breeding methods. Arntzen cites as an example the production of an atrazine-resistant strain of oilseed rape (*Brassica napus*) by W. Beversdorf and his colleagues at the University of Guelph. The Guelph workers performed a series of repeated backcrosses, starting with a resistant strain of the weed, bird's rape (*B. campestris*), as the maternal parent, to introduce chloroplasts with the atrazine-resistance gene into *B. napus*.

Standard breeding methods work only for species that are sexually compatible, a condition that applies to very few crop plants and weeds. Another approach now being tried in several laboratories is fusion of plant protoplasts, cultured cells from which the rigid walls have been removed. Such fusions between protoplasts of the potato (*Solanum tuberosum* L.) and of black nightshade (*S. nigrum* L.) have been achieved in the laboratories of Jonny Gressel at the Weizmann Institute in Rehovot, Israel, and of Horst Binding at Christian-Albrechts University in Kiel, West Germany. The fusions produced hybrid protoplasts from which whole plants could be regenerated, but the plants more closely resembled the weed than the potato.

The discovery may lead to the development of new herbicide-resistant crop plants.

Because the goal is to introduce a cytoplasmic trait into the crop plant without reducing the yield or quality of the product, the results might be improved, Arntzen suggests, by first irradiating the protoplasts of the weed species to destroy the nuclei. Nevertheless, problems may still arise if there is incompatibility between the nuclei and cytoplasms of the hybrids. Such incompatibility may result in male sterility. Moreover, at present only a few crop plants can be successfully regenerated from protoplasts, so this approach would also be of limited value.

Screening crop plants for the herbicide resistance trait is not likely to pay off in the identification of plants with the mutation, Arntzen says. He estimates that in nature only about one plant in every 10^{10} becomes resistant to atrazine. But under some circumstances the frequency of the mutation may be increased.

He and John Duesing of MSU identified a "plastome mutator" gene in a strain of atrazine-resistant black nightshade. It is a nuclear gene that increases the frequency of mutations in the chloroplast genome by 100- to 1000-fold. The investigators postulate that the plastome mutator gene may have facilitated the development of atrazine-resistant weeds in regions where prolonged application of the herbicide provided the pressure for selection of the trait.

The chances of the resistance mutation occurring in crop plants might also be improved if they, too, carried a plastome mutator. So far the gene has not been identified in crop plants, but if it does not occur naturally then it may be possible to introduce it with a carrier such as the Ti plasmid, which is ready for exploitation as a gene transfer vector for plants (*Science*, 18 February, p. 830).

Arntzen suggests that direct introduction of cloned genes into the chloroplast genome may ultimately prove to be the best approach. "It has the greatest potential in the long run," he asserts, "but we must overcome some difficult obstacles. There is no vector available." (The Ti plasmid puts genes into the nuclear genome.) One approach to overcoming the vector problem is to try to microinject chloroplasts with the cloned atrazine-resistance gene.

Objections have been raised to the development of new herbicide-resistant crop plants because of the possibility that their wide-scale use might accelerate the development of resistant weeds. For example, in the U.S. Corn Belt, the rotation of corn with soybeans automatically precludes the annual use of atrazine. If soybeans were resistant, farmers might use atrazine every year, thus fostering the emergence of resistance.

Arntzen does not think that is an unsurmountable difficulty. Many different kinds of chemicals are available for weed control, and the standard practice is for farmers to use more than one. "We have found," he points out, "that the genetic mutation that causes atrazine resistance increases the sensitivity of the weeds to other chemical classes of herbicides."

In addition, atrazine resistance has generally arisen only in areas where the standard practice was not followed and the herbicide was used exclusively for a number of years. The probability of weeds becoming resistant to two types of herbicides at once, Arntzen calculates to be no better than 1 in 10^{16}. (This is based on a probability of 1 in 10^{10} for the mutation in the chloroplast gene and a maximum probability of 1 in 10^{6} for the second mutation, which, if it occurred in a nuclear gene, would be passed more efficiently to progeny.) "That is just astronomical," he maintains. "By using a combination of herbicides, you limit the probability of selecting a resistant strain to such an extent that it becomes irrelevant."—**Jean L. Marx**