

THE OUTLOOK FOR U.S. METEOROLOGICAL RESEARCH IN A COMMERCIALIZING WORLD

Fair Early, but Clouds Moving in?

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The growing economic value of meteorological science and services can bring not only benefits, but also serious pitfalls that may require early attention to avoid.

F AIR WEATHER. Meteorological research is on a roll. In its relatively short lifetime, it has transformed the way society thinks about weather and climate. At the beginning of the twentieth century, most people assumed that the assimilative capacity of the atmosphere was infinite, climate was relatively constant, and most weather events were unpredictable. Today, thanks in large part to meteorological research, most educated people know that the assimilative capacity of the atmosphere is finite, even on global scales; climate is variable, sometimes abruptly so; and weather is considerably more predictable than previously thought.

Furthermore, the immediate future looks bright. New observing technologies are being developed

and deployed rapidly, providing a wealth of data on traditional and new variables. Today's operational observing systems provide unprecedented global coverage and space and time resolution, supporting daily weather services and a variety of weather, climate, and environmental research. The United States and other nations are poised to integrate and enhance the operational global observing network, to make it even more useful for weather, climate, and environmental studies (Lautenbacher 2003). Research, state and local government, and private sector observing capabilities also continue to expand (NRC 1999a; Laursen et al. 2003; NRC 2003).

Information technology is keeping pace. Use of the rapidly growing datasets is supported by high-speed communication links, which facilitate both the real-time acquisition of data for use in predictions and longer-term research access. Rapid advances in computational capabilities are continually improving numerical weather and climate prediction systems, by enabling increased model resolution and more sophisticated numerics, physics, and parameterizations (NRC 1998, 1999a). These same advances have transformed meteorological research—investigations that were painstakingly slow (or impossible) several decades ago can now be performed rapidly

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using complex numerical models, sophisticated data analysis and visualization techniques, and a desktop computer.

As a result, understanding of meteorological processes is accumulating rapidly. Knowledge about related topics—including atmospheric chemistry, radiative transfer, the hydrologic cycle, and sea and land surface interactions with the atmosphere—is also flowering, allowing meteorology to contribute to new multidisciplinary areas. Building off this growth, applications of meteorology and related sciences are expanding in traditional areas, such as weather prediction, and in new areas, such as air quality, space weather, and climate and ecosystem services. Moreover, no end to this growth is in sight; a host of new ideas and applications await exploration and testing (e.g., NRC 1998).

Societal awareness of this progress and its potential socioeconomic benefits has generated significant support for its continuation in both the public and private sectors. The budget of the U.S. National Science Foundation (NSF), which provides much of the funding for academic meteorological research, was, until recently, projected to double over the next five years (Jones 2002; Schultz 2002).¹ Companies in weather-sensitive economic sectors, such as energy, agriculture, and transportation, are bidding for the services of meteorologists, through both in-house hires and contracts with consultants. As a result, private sector meteorological services are growing rapidly (AMS 1998, 1999; White 2001; Pielke et al. 2003). For example, in 1996, 28% of American Meteorological Society (AMS) members were employed in the private sector (AMS 1998); by 2010, this figure is projected to be 50% (AMS 1999).

CLOUDS MOVING IN. However, any realistic forecast for the future of meteorological research cannot be confined to “fair and warmer.” Clouds are moving in, occasioned by the very same advances in science and technology cataloged above. Within the United States, the increasing economic value of weather and climate services is straining the public-private partnership that has successfully provided U.S. weather and climate services for the past half-

century or longer (NRC 2003). On the international horizon, these same increases in economic value have caused international data exchange—fundamental to our field—to grow contentious (Zillman 1997; Saarikivi et al. 2000; Landis 2001).

Until recently, the commercial value of meteorology has been limited. Observations and computer modeling were sufficiently expensive, and research was sufficiently far removed from commercial application, that all three were considered the province of federal governments. Today, private companies collect many of their own observations and are beginning to run numerical weather prediction models (White 2001; NRC 2003)—a reflection of recent growth in the private sector and a sign of the future. This expansion of commercial meteorology can bring many benefits for meteorological research and for society. As the dollar stakes associated with weather and climate services continue to grow, however, it will be tempting to fight harder for a share of the revenues. The current national and international debate over what part of weather and climate knowledge and services should be considered a public good and what part a private good, along with who pays and who benefits, will only grow more pointed (Zillman 1997; Pielke 2001, 2003).

Until recently, most university and government meteorology researchers have been able to remain isolated from such concerns. As meteorological research increasingly has not only intellectual but monetary value, however, these issues will become more and more difficult to ignore. The potential for financial conflicts of interest will increase, along with temptations to generate commercially valuable research results. Conflicts over ownership of intellectual property and knowledge will grow sharper, thrusting some researchers and institutions into interpersonal and legal tangles. Researchers who formerly shared their findings and ideas openly with colleagues and students may now be tempted (or even required) to keep them secret; this not only threatens the collegiality of our field, but also constrains opportunities for future research. Moreover, the increasing privatization of data, tools, and knowledge that have so far been primarily a public good threatens to slow the future pace of innovation, with potentially disastrous consequences for society as it seeks sustainable development in the face of weather and climate vulnerability.

This evolution of our field is embedded in—and related to—a larger trend: the commercialization of academia and of scientific research. In the United States, these worlds are commercializing in response

¹ Since the first writing of this manuscript, this NSF budget growth has been derailed, at least temporarily, by increasing federal deficits and expenditures associated with homeland security and the Iraq war. However, historical trends for federal funding of science (and more specifically, meteorology and related topics) remain positive.

to numerous pressures, including the increasingly global and information-based economy; the evolving social contract for science; increased competition for federal research support; and decisions by public policy makers to stimulate industry use of federally funded research, in order to enhance science and technology's contributions to U.S. economic competitiveness. Commercialization of meteorology also has many potential benefits, including economic growth and job creation; increased resources for meteorological research; development of new meteorological products and applications; and, more generally, creation of a healthier relationship between meteorological research and societal applications—a relationship that facilitates the transfer of meteorological knowledge and technology to end users. Given these pressures and benefits, the topic addressed here is not whether U.S. meteorological research will or should be influenced by commercialization, but how it will be influenced—and what the potential pitfalls are that we might wish to avoid.²

BIOTECHNOLOGY'S CAUTIONARY TALE.

Such questions have been (and continue to be) faced by a number of scientific and technological fields. But nowhere are the impacts of commercialization—positive and negative—more evident than in biotechnology and related disciplines (including biomedical, pharmaceutical, genetics, and agricultural research and development, hereafter referred to collectively as biotechnology³).

Biotechnology's difficulties are, in large part, the result of its success. Transfer of biotechnology knowledge and tools from government and academia to industry has facilitated the development of numerous commercial products, benefiting society significantly through improvements in health care, food production, and other sectors. This technology transfer has also spawned many private companies and boosted the fortunes of countless others, gener-

ating economic growth and considerable financial benefits (and increased prestige) for a few researchers and universities. However, the commercialization of biotechnology also has downsides—for research and for society—that are growing increasingly apparent.

A brief history of biotechnology. It has been only 50 years since Watson and Crick described the double-helix structure of DNA. Important related discoveries, such as gene splicing and recombinant DNA techniques, followed rapidly—all largely products of academic molecular biology research. These discoveries led to further advances, including (most recently) genetically modified foods, a map of the human genome, and cloned animals. As these advances accumulated, opportunities for commercially valuable applications of biotechnology, in industries such as agriculture and health care, expanded dramatically.

Concurrently, changes in U.S. government technology transfer policy transformed the relationship between government-funded research and private sector applications.⁴ A major factor in this transformation was the Bayh–Dole Act, enacted in 1980 amid concerns about U.S. economic competitiveness. To increase incentives and mechanisms for commercial development of federally funded research, the Bayh–Dole Act allows universities to claim intellectual property rights from federally funded research and requires that universities share any resulting revenue with university inventors. (Bayh–Dole also provides the U.S. government with residual rights to employ publicly funded inventions for its own use and march-in rights to terminate exclusive licenses under certain circumstances.) Although U.S. universities and university investigators participated in technology transfer prior to Bayh–Dole, academic patenting and licensing activities increased dramatically afterward.⁵ By the mid-1980s, similar incentives for technology transfer were extended to U.S. government laboratories and their researchers. During this

² Commercialization will also affect other countries' meteorological communities and the international community; however, because academic, government, and private sector roles and interactions vary among countries, here we have chosen to focus on the United States.

³ Although different biotechnology-related fields have experienced commercialization somewhat differently, here we refer to them collectively in order to condense the paper's primary arguments.

⁴ For a more detailed description of these and related public policy developments, see, for example, Slaughter and Rhoades (1996, 2004), Blumenthal and Campbell (2000), Katz and Merz (2000), and Blumenthal (2003).

⁵ Before 1980, fewer than 250 patents were issued to U.S. universities each year; by 1996, that number had grown to more than 2000 per year, and in 1999–2002, it exceeded 3500 per year. The number of licenses executed by U.S. universities grew more than threefold during the 1990s (AUTM 2000, 2002). Royalties to universities from licensing also grew rapidly in the 1990s, implying that the commercial products developed using these licenses generated significant sales (Blumenthal 2003).

same period, U.S. patent rights also strengthened through decisions such as the Supreme Court's 1980 *Diamond v. Chakrabarty* ruling that genetically engineered organisms could be patented.

Together, these scientific advances, policy developments, and accompanying financial incentives have stimulated extensive relationships between biotechnology-related U.S. academic research and the private sector (e.g., Angell 2000). Private sector funding of U.S. academic biotechnology research is now common; in biomedicine, for example, the share of research and development funded by industry grew from 32% in 1980 to 62% in 2000 [despite large budget increases for the U.S. National Institutes of Health (NIH)], and in the 1990s approximately one-quarter of U.S. academic researchers reported receiving research funding from industry (Bekelman et al. 2003). At a number of prominent institutions, biotechnology companies directly fund major portions of academic departments and institutes (e.g., Macilwain 1998; Rosenzweig 1999; Martin and Kasper 2000). Independent of formal grants or contracts, many academic biotechnology researchers receive research-related "gifts" from industry, including research materials and equipment, support for students, trips to meetings, and discretionary funds—often with restrictions attached (Campbell et al. 1998). Some academics also have personal financial relationships with industry, through consultancies, paid speaking arrangements, advisory board positions, and ownership of company equity—sometimes with the same companies that fund their research (Boyd and Bero 2000). These growing ties between the academic research sector and industry are referred to as the commercialization of biotechnology research.

Consequences of commercialization for biotechnology research. Commercialization of biotechnology has substantially benefited society in many ways, for example, by enabling the development and market availability of products to increase crop yields, enhance the food productivity of animals, and diagnose, treat, and prevent disease. Moreover, commercialization has benefited biotechnology-related research by providing additional sources of funding, improved facilities, and new training opportunities for students; commercialization also helps industry gain access to scientific talent and the latest research developments, and gives academic and government researchers new mechanisms to develop their science and technology into useful market products. However, several negative consequences and risks are also evident and are discussed next.

DECREASED EXCHANGE OF SCIENTIFIC INFORMATION AND TOOLS. Scientific information, ideas, and products are both the results of research and the tools for future research. Consequently, the exchange of scientific information and tools is the lifeblood of any scientific community. Yet a growing body of evidence suggests that, over the last several decades, such exchange has decreased in some biotechnology research communities—due in large part to the financial incentives accompanying commercialization (e.g., Boonin 1989; NIH 1998; Florida 1999; Press and Washburn 2000; Bok 2003).

Although researchers have always had incentives for secrecy, such as scientific competition, the dramatic increase in the monetary value of biotechnology products has dramatically raised the stakes of the competition. One commercialization-related incentive for secrecy is the possibility that a scientific idea or result can be transformed into a commercially valuable product. A less apparent—but arguably more disruptive—incentive is the possibility that an idea or result may enable research that, while not commercially valuable on its own, will later help generate something of commercial value. Because any idea or result can facilitate numerous future research paths, many of which are initially unknown, this potential for "downstream" commercial value can motivate individuals and institutions to restrict the exchange of even basic information and tools (Heller and Eisenberg 1998; NIH 1998).

Exchange can be restricted by making information and tools available but limiting their use, for example, through patents and licensing agreements, or by limiting dissemination, for example, by keeping information, tools, and (positive, neutral, or negative) results secret. Both mechanisms are now common in some areas of biotechnology. As noted above, biotechnology patents are increasingly prevalent, and agreements for using patented tools frequently restrict who can use them, how they can be used, and the dissemination and use of any research results they enable. Such restrictive licenses are instituted not only by companies holding patents, but also by universities (NIH 1998; NRC 1999b). Secrecy is often imposed by companies funding academic biotechnology research by forcing publication delays, editing publications, prohibiting conference talks, and/or limiting communication with colleagues (e.g., Blumenthal et al. 1996; Press and Washburn 2000; Bok 2003). Secrecy may be justifiable when companies fund research; however, some university–industry research centers with government funding impose similar restrictions (Cohen et al. 1994), and some academic–industrial

agreements give companies the right to use—and thus to keep secret—*any* research performed in an academic department or center, whatever its funding source (Rosenzweig 1999; Cook-Deegan 2000).

Decreased exchange among biotechnology researchers is partly imposed externally, by companies and research institutions. Perhaps more disturbing, however, are the exchange restrictions self-imposed by some researchers. Withholding of research data and results is now common in some biotechnology-related fields and is more prevalent among researchers involved in commercial activities (Campbell et al. 2002). More generally, academic biotechnology researchers may hesitate to comment on results, discuss ideas with colleagues, or even ask questions at seminars because they are worried that someone will develop a patent from their idea before they do and profit from it or restrict its use (Boonin 1989). According to Derek Bok, the former president of Harvard University, some faculty members have even banned researchers and students from laboratories in their own departments (Bok 2003).

THREATS TO SCIENTIFIC PROGRESS AND CULTURE. Decreased exchange of information and tools threatens scientific progress in several ways. First, it can diminish the quality of research by reducing feedback and criticism on ideas, methods, and results from other researchers. Second, it prevents researchers from accessing the full body of available knowledge, decreasing their capacity to build off this knowledge to generate further advances and increasing the likelihood that they will duplicate existing research or pursue research paths already known to be unproductive (Cohen et al. 1998; Schenk 1999; Bok 2003). Third, it can lead to a research “anticommons.” An anticommons arises when sufficient information and tools are patented such that researchers cannot pursue a topic, because it is either too time consuming or expensive to collect all of the rights required (Heller and Eisenberg 1998). Researchers must then attempt to work around the patents or, if the patented information or tools cannot be substituted, simply avoid the topic.

Moreover, the “objectivity” that is so valued in scientific culture is largely achieved collectively, through review and replication of results by peers, evaluation of others’ ideas, and debate—all of which are based on open exchange of ideas and information (Schachman 2002). When scientists are rewarded for generating commercially valuable products and tools, they also have less incentive to question and seek alternative approaches in their own research, threatening the “organized skepticism” on which sci-

ence is based (Slaughter and Rhoades 2004, p. 103). Furthermore, some have raised concerns that the next generation of researchers is being trained in commercialization-driven science, endangering the scientific culture of the future (Press and Washburn 2000; Harris 2003).

CONFLICT OF INTEREST, BIAS, AND OTHER THREATS TO THE CREDIBILITY OF SCIENTIFIC RESEARCH. Several commercialization-related developments now threaten the credibility of biotechnology research. The first is the now-prevalent potential for conflict of interest. Potential for conflict of interest arises when researchers (or their institutions) have some non-scientific (e.g., financial) interest in their research that might bias their professional judgment. As a field commercializes, opportunities for financial conflicts of interest grow dramatically; examples include researchers (and institutions) who accept gifts from, receive consulting fees from, or own equity in a company with a stake in the outcome of their research. As noted above, such entanglements are now common in some biotechnology fields—so common that, in one study of articles in major medical journals in 1992, 34% of lead authors had relevant personal financial interests in the research (virtually none of which were disclosed; Krimsky et al. 1996). The *New England Journal of Medicine* recently relaxed its long-standing policy prohibiting review articles written by authors with financial conflicts because its editors were having such difficulty finding qualified authors without such ties (a difficulty shared with other prominent biomedical journals; Drazen and Curfman 2002; Holden 2000; Press and Washburn 2000). Concerns about institutional conflicts of interest are also growing (e.g., GAO 2001; Korn 2002; Johns et al. 2003).

Potential conflicts of interest are primarily a potential problem—unless they affect research. Unfortunately, there is ample evidence that some do. Several studies have found that industry-sponsored research is more likely than nonindustry-sponsored research to 1) report results favorable to industry and 2) use methods that favor positive results⁶ (Bekelman et al. 2003). This may not indicate conscious ma-

⁶ For example, industry-sponsored medical studies are more likely to evaluate a treatment’s effectiveness by comparing it to an inactive control (e.g., placebo or no therapy) rather than a leading alternate treatment, increasing the likelihood of favorable results (Bekelman et al. 2003 and references therein).

nipulation of results. Instead, industry-funded studies may publish positive results more frequently than negative results; tend to emphasize certain types of conclusions; or simply prefer topics, research questions, or methods that favor certain outcomes (Bero and Rennie 1996). A similar proindustry bias by industry-associated authors has also been found in review articles (Barnes and Bero 1998). Moreover, even when researchers maintain their integrity and do not allow potential conflicts to affect their judgment, financial entanglements can still erode the credibility of research through the appearance of bias or impropriety.

The credibility of biotechnology research is also threatened by industry attempts to influence academic research results. One technique for influencing results, sometimes used by pharmaceutical companies, is to retain control over studies' designs, datasets, and analysis techniques—before, during, and after a study, and over the dissemination of results (Bodenheimer 2000; Schulman et al. 2002; Baird 2003; Bok 2003). This control can limit academic research paths but helps companies ensure that academic research generates favorable conclusions. Of course, sometimes commercially neutral or unfavorable results turn up anyway, and researchers wish to publish them. In some such situations, companies have resorted to more direct interference, including, in several high-profile cases, trying to block dissemination of unfavorable results through threats, lawsuits, campaigns to discredit researchers, and even outright harassment (e.g., Deyo et al. 1997; Shenk 1999; Hailey 2000; Oliveri 2003). Because most cases of company interference in research probably never become public, the prevalence of such overt interference is unknown. An additional concern, however, is that in several such cases, the researcher's institution has sided with the company, against its own researcher.

A third threat to credibility is ghostwriting of peer-reviewed journal articles. In ghostwriting, a company pays someone to write an article for an academic "author," who often has not seen or analyzed the raw data and may be unfamiliar with the details of the study. In return for providing the company's favorable results with the credibility of academic research, the academic enhances his or her resume and reputation for minimal effort; he or she may also receive speaking engagements and monetary compensation (Larkin 1999; Boseley 2002). In several biotechnology-related fields, ghostwriting and guest authorship are now said to be widespread (Bodenheimer 2000; Boseley 2002; Healy 2003), appearing,

according to one study, in over 20% of biomedical journal articles (Flanagan et al. 1998).

Potential conflict of interest, company influence on research, and ghostwriting have so threatened the credibility of biomedical research that in 2001, 12 leading medical journals adopted strict policies in response (Davidoff et al. 2001; Baird 2003). For these journals, it is no longer sufficient for authors to disclose potential conflicts of interest and study sponsorship. Authors submitting manuscripts must now also describe their own and the sponsors' roles in the study, including who designed the study; who collected, analyzed, and interpreted the data; who wrote the manuscript; and who controlled the decision to publish. In some cases, "editors may ask authors to sign a statement such as, 'I had full access to all of the data in this study and I take complete responsibility for the integrity of the data and the accuracy of the data analysis.'" (Davidoff et al. 2001, p. 827). In other words, authors must now formally assert that the research they publish is their own. In meteorology, such integrity of authorship is taken for granted, but in some biotechnology-related fields, it no longer can be.

REDIRECTION OF ACADEMIC RESEARCH AND THE PUBLIC INTEREST. Commercialization can redirect academic research in several ways. As noted above, the prevalence of patenting may lead to research anticommons, effectively blocking off certain areas of research (Heller and Eisenberg 1998). Researchers and their institutions may also avoid certain topics for fear of threatening industry sponsors (Burtman 2002).

In addition, the lure of research funding and financial gain accompanying commercialization provides strong incentives for academic researchers and institutions to shift toward more commercially applicable research. Providing such incentives was a major goal of the Bayh-Dole Act and related U.S. public policy developments, and the resulting shift can significantly benefit society through improved commercial products. Its flip side, however, can be a shift away from research that is important for the public good but that has less commercial potential (Press and Washburn 2000; Baird 2003; Harris 2003). For example, U.S. health care research and development obtains significant funding from the pharmaceutical industry, which seeks to maximize profits by targeting potentially lucrative markets. This affects the health research and development system, which has a tendency to emphasize issues affecting affluent countries—and affluent populations within those countries—and patentable, pharmaceutical remedies

to diseases instead of less commercially profitable (but perhaps more societally cost effective) strategies, such as behavior modification (Reich 2000; Willett 2002; Willison and MacLeod 2002). According to Krimsky (2003), the situation is similar in weed science, where the vast majority of research now focuses on chemical treatments rather than strategies such as biocontrol or crop rotation. As these examples illustrate, commercialization can tend to direct research and development toward what is most profitable in the market, which is not necessarily what is best for the public. Research that is unlikely to produce patentable, commercializable, and sufficiently profitable results may then be less frequently pursued.

Redirection of research priorities is particularly evident and worrisome in areas where the majority of academic research and development funding comes from industry, such as weed science (Krimsky 2003) and pharmaceutical trials (Bodenheimer 2000). This trend might be partially balanced, therefore, by sustained public funding for research. In the current research climate, however, continued public funding is unlikely to be sufficient: universities are increasingly encouraging and rewarding commercial activity and entrepreneurship among their faculty, and public policy makers and federal agencies continue to focus on funding scientific research as an engine for near-term technology transfer and economic growth (Slaughter and Rhoades 1996). As noted above, for example, health care research and development often emphasizes commercially profitable strategies despite significant increases in NIH funding. By focusing on intellectual property rights as the incentive for transferring federally sponsored research into useful applications and economic growth, the biotechnology research and development system—in the public and private sector—has, according to some, tilted toward targeting potentially lucrative markets (generating large profits for the owner of the intellectual property), at the expense of some people in need (e.g., Katz and Merz 2000; Willison and MacLeod 2002; Krimsky 2003; Slaughter and Rhoades 2004). Market needs and overall economic growth are related to societal needs, but they are not always equivalent. The resulting shift in priorities affects all aspects of the research-and-development enterprise.

Broader consequences of commercialization: Academia, public trust, and the public good. On a broader level, closer ties between academia and the biotechnology industry have likely spurred innovation, benefiting society through a range of improved techniques and products for food production, health care,

and other applications—at least in the short term. Commercialization has also increased resources for biotechnology research and development, which at first glance suggests that this pace of innovation is likely to continue. As noted above, however, increased secrecy, shifts in the academic incentive/reward structure, and other commercialization-related developments may be threatening long-term scientific progress, and thus long-term innovation and societal benefit. Moreover, concerns have been raised about the decreased freedom in designing studies and interpreting results that sometimes accompanies industry-funded or commercially motivated research, which may be driving academic researchers and their students toward more routine forms of analysis—at the expense of the creative, fundamental research that has (until now) been the foundation of academic research and training (Baird 2003; Harris 2003). Without the continued fundamental advances on which future applications can be built, longer-term societal benefit from scientific research is threatened, with potentially severe consequences for the public good.

In addition, by privatizing their knowledge, universities are jeopardizing the culture that has made them such powerful contributors to the national benefit. Industry now funds more than \$2.3 billion in university research each year—an increase of nearly 50% over the last decade (accounting for inflation; NSF 2003)—and this amount does not include the major corporate contributions to universities for buildings, equipment, endowed chairs, and activities such as athletics. As universities chase commercial resources, the strings attached are leading them to act more and more like institutions with profit, rather than knowledge and education, as their primary mission (e.g., Slaughter and Leslie 1997; Brown 2000; Press and Washburn 2000; Bok 2003; Oliveri 2003). The gains are proving to be short term at best and illusory at worst; patent-related litigation and staffing expenses are increasing rapidly, and only a few elite universities have realized the hoped-for commercialization-related profits (AUTM 2002; Mowery 2002; Bok 2003). Professors heavily involved in commercialization have more demands on their time, which can limit their focus on other professional responsibilities, such as teaching, service, and education of graduate students.

Commercialization also threatens the integrity of science and academia, and the public trust they have enjoyed for decades. Prominent academics have raised concerns about universities allowing commercial interest to affect decisions about hiring, promotion, and research directions (e.g., Rosenzweig 1999; Bok 2003).

Major lapses in the management of academic research conflicts of interest in clinical trials have made national news, generated lawsuits against researchers and institutions, and damaged public confidence (e.g., Nelson and Weiss 2000; Shalala 2000; Gillis 2002; Willman 2003). As universities and academic science grow more intertwined with corporations, and as the public sees this evolution, universities and scientists may cease to be the independent source of expert knowledge and opinion that society depends on to help solve its increasingly complex technical problems (Bok 2003; Krimsky 2003).

The slippery slope. As biotechnology's experience illustrates, commercialization is a slippery slope: once a field starts down the path, it can be difficult to stop. As academic researchers grow more dependent on industry funding, the threat of withholding funding, or fear of not obtaining future funding, proliferates in its influence on academic research. As academic entanglements with industry grow more prevalent, potential for conflict of interest becomes the rule, rather than the exception, and standards governing conflicts of interest must be relaxed, reducing barriers to more dangerous types of conflicts. As academic institutions grow captivated by their potential income from commercialization, they sometimes begin to encourage their researchers to surrender traditional academic commitments and public responsibility to industry interests, and may even aid in the attacks of companies dissatisfied with research results. Soon, further slides down the slope appear unavoidable. For example, in defending Berkeley's controversial arrangement with the biotechnology company Novartis, one dean argued that the arrangement was necessary, since without it faculty and students would lack the modern laboratory facilities and access to proprietary databases required to continue their research (Press and Washburn 2000). At Harvard Medical School, a panel of senior faculty recently recommended relaxing conflict-of-interest guidelines, amid concerns that Harvard's guidelines, which are stricter than those at many other leading institutions, were inhibiting faculty recruitment and retention (Abel 2000; Nadis 2000).

The temptations of commercialization are progressive; once an individual, institution, or research community takes the first step, subsequent steps seem easier, then natural, then inevitable. Moreover, individuals and institutions are competitive and often lead by example, so once a few succumb to the negative consequences of commercialization, others are likely to follow. The biggest danger is that, eventually,

a research community (and society) may come to consider secrecy, serious financial conflicts of interest, and proindustry bias in academic and governmental research as normal, inevitable—or even necessary. The battle is then lost.

Many of commercialization's benefits are concrete, clearly visible, and realized relatively rapidly, over months or years. Commercialization's major costs, on the other hand, tend to be diffuse, more subtle, and realized more slowly, over decades or longer (Krimsky 2003). The costs are also often indirect, accruing from the cumulative effects of many activities and decisions. This suggests that to experience the benefits of commercialization while minimizing the pitfalls, active, conscious management is needed. Calls for such management in biotechnology have been growing, from public interest groups, public policy makers, research institutions, and researchers themselves.

FORECASTING BY ANALOGY: BIOTECHNOLOGY AND METEOROLOGY.

In meteorology, such difficulties are just emerging. This suggests "forecasting by analogy," that is, using biotechnology's experience to foresee the risks that commercialization may bring to our field (and the Earth sciences). In support of this approach, we note that biotechnology is not alone; similar commercialization-related issues now exist or are appearing in a number of other fields, including information technology, chemistry, and engineering. Responding to this broad trend, both *Science* (since 1992) and *Nature* (since 2001) now request that all authors declare competing financial interests (Koshland 1992; Campbell 2001). If meteorology never faces these dilemmas, we would therefore be a rare exception among scientific and technological fields. Consequently, although the analogy between biotechnology and meteorology is imperfect, it is still instructive.

How are biotechnology and meteorology similar? First, both fields have extended histories as fields largely of intellectual interest, but motivated by practical concerns (e.g., human health and food scarcity, societal vulnerability to weather and climate). Capabilities in both fields are burgeoning rapidly, and both have significant and growing implications for society. In addition, in both fields, one person's end product can be a necessary tool for another's research. Some of these products/tools are patentable, and all can be kept secret, and, if access is restricted, whole lines of future research and development can be cut off to all but a few.

What about the differences? First, the meteorology community is significantly smaller than the primary

biotechnology research communities. This could be advantageous for meteorology, facilitating cooperation and protection of our community's culture, or disadvantageous, accelerating the fall down the slippery slope. Second, in medical biotechnology, the stakes are high not only financially, but also because the technology can directly affect the length and quality of human life, and because research bias can lead to deaths in clinical trials. Here, one might suppose that the analogy breaks down. However, application of meteorological research results can also directly affect human life, for example, by protecting people from a flood or alleviating the negative impacts of a drought, and meteorological experiments and clinical trials have a number of parallels that can lead to similar biases (Gabriel 2000). Moreover, biotechnology fields such as crop research, which affect human life less directly than medicine, have experienced similar commercialization-related difficulties. On a broader level, both meteorology and biotechnology are intimately connected with the human capacity to live sustainably, enjoy prosperity, and experience a high quality of life. Societies, corporations, and individuals will pay for knowledge that holds promise to help cope with these challenges.

Another difference arises from the different types and roles of intellectual property in biotechnology and meteorology. In biotechnology, intellectual property often takes the form of chemicals, organisms, and genetic sequences, which, once patented, cannot be generated by other means and may not be substitutable. Patent protection for genetic sequences is particularly controversial—and valuable—because genetic sequences can be key parts of biological processes. Such patents can therefore be used, on their own, to block others from using a biological process in research or in generating valuable intermediaries or products. This type of intellectual property has no precise analog in meteorology, although the patenting of meteorological numerical models or algorithms may play a similar role.

In meteorology, the building block of much research and product development is meteorological (and related) data. Meteorological data that is collected at a specific place and time cannot later be reproduced by another means, nor can they generally be substituted for in research or in generating forecast products. Although one can protect data by keeping them secret, another person can circumvent this protection, at least in theory, by taking duplicate measurements. In practice, however, this may be prohibitively expensive, or, in the case of in situ or ground-based measurements in foreign countries or

on private property, impossible. In addition, unlike some forms of biotechnology intellectual property, meteorological data generally have market value only when aggregated to generate a product, such as a weather forecast. This provides a strong incentive for developing data-sharing schemes; however, as mentioned earlier, the current international data-sharing scheme has developed serious cracks. Data sharing is also growing more complex as more private sector and nonfederal government entities get involved in data collection.

Biotechnology and meteorology may also differ in the financial dimensions—the level of investment resources, the role of venture capital, and so on. Such differences may largely disappear, however, as the commercial value of meteorology grows. The financial environment and intellectual property law in this area are also evolving, so their effects on the commercialization of meteorology are unclear. For now, the analogy between biotechnology and meteorology appears sufficiently good that biotechnology's current dilemmas serve as an illustrative example of meteorology's possible future. The details of the analogy, particularly how intellectual property may play out in the commercialization of meteorology, is one of several areas that might merit further research.

SIGNS OF EARLY CUMULUS DEVELOPMENT.

Already we are seeing academic ventures into commercialization in meteorology. Through the University Corporation for Atmospheric Research (UCAR) Foundation, UCAR recently established Peak Weather Resources, Inc., to facilitate transfer of UCAR-developed technology to the private sector (Gordon and Henson 2003). At several universities, professors and researchers are founding major for-profit enterprises adjacent to, but institutionally distinct from, the not-for-profit institution where the underlying research was performed (e.g., Droege-meier 2001). Academic meteorology research is also beginning to obtain major industry funding, as indicated by the recent 5-year, \$10.6 million agreement between Williams Energy and the University of Oklahoma (Henson 2001).

These are just glimpses of a complex, rapidly evolving picture; in fact, as an illustration of the rapidly changing environment, Williams, affected by the Enron scandal, recently withdrew much of this support.⁷ These commercialization-related activities have

⁷ This raises another potential challenge associated with commercialization: increased instability in research funding.

many potential advantages; thus, we are not arguing that they are negative, undesirable, or even avoidable. They have also been instituted with safeguards to limit negative influences on academic research (e.g., creation of a separate commercialization-focused entity), and, to our knowledge, they have not produced any of the dramatic negative consequences noted above. However, there are nascent signs of difficulty that risk escalation as commercialization evolves.

The most evident difficulty so far is the controversy generated by such activities, threatening collegiality and cooperation in our field. For example, several of the activities mentioned above generated dissatisfaction, uneasiness, or conflicts among staff at the associated nonprofit institution. In two recent workshops [U.S. Weather Research Program (USWRP) Workshop on the Weather Research Needs of the Private Sector in Palm Springs, California, in 2000; National Weather Service–World Meteorological Organisation (NWS–WMO) workshop at the 2003 AMS Annual Meeting in Long Beach, California], disagreements emerged between private sector providers of meteorological services and academic researchers about university involvement in for-profit activities. Similar conflicts are evident in the recent National Research Council report on academia/government/private sector partnerships in meteorology (NRC 2003). Internationally, differences with respect to privatization and cost recovery of some weather services have begun to drive a wedge between nations and institutions, endangering historical data-sharing agreements (e.g., Zillman 1997; Landis 2001).

Currently, reports of conflict-of-interest-driven bias in meteorology research and publication are anecdotal and relatively rare, and academics and the U.S. government remain committed to conducting meteorological research in the public interest. Based on biotechnology's experience, however, as the commercialization of meteorological tools and knowledge grows more prevalent and more lucrative, the risk of the commercialization-related challenges documented above increases dramatically. The costs of commercialization may not be apparent at first, but may grow as such activities accumulate. The question is: how will our community act so that we—and society—can realize the benefits of commercialization while minimizing the pitfalls?

OPTIONS. The biotechnology community has discussed and tested possible actions for years. However, there is still no consensus on how to deal with these issues, nor is it clear how successful biotechnology's attempts to address them have been (e.g., Cohen

1995; Marshall 1997; Agnew 2000a,b; Monmaney 2000; GAO 2001; Schachman 2002; Bekelman et al. 2003; Ready 2003). Wrestling with these issues will therefore necessarily remain a work in progress; the options suggested here are intended as a starting point for discussion.

In general, biotechnology's experience suggests several approaches.

The path of least resistance. One approach is to ignore the issue and hope that our field will avoid the risks described above. Proponents of this approach might argue that meteorology and biotechnology are sufficiently different that we may be able reap the benefits while avoiding the pitfalls, or that significant commercialization of research is the best (or only) way to translate research results into useful applications. In the short term, taking this path of least resistance may seem attractive, since it requires minimum infringement on current practices. Over the long term, however, it carries significant risk—particularly given the slippery slope described above and the different nature of the costs and benefits.

Proponents of this approach might also argue that because of biotechnology's experience, institutions are learning how to manage such issues and are putting policies in place that may protect us. In reality, however, institutions have been slow to manage academia–industry ties, despite significant external pressure. Although NSF and NIH have had commercialization-related policies for a decade and most research institutions have followed suit, biotechnology's experience has shown that many policies and guidelines remain vague, without basic safeguards, and/or poorly enforced (Cho et al. 2000; van McCrary et al. 2000; GAO 2001). Moreover, even if suitable general policies were widely implemented, meteorologists still have unique needs, for example, for international data sharing, and so policy prescriptions designed for other fields might prove insufficient or even unworkable in ours.

Independent, voluntary efforts. Individual researchers and individual institutions could make a conscious effort to learn from biotechnology's experience, and then independently explore and pursue a range of prevention and mitigation measures. These measures might borrow from biotechnology or might be novel, given our field's unique needs. This approach has a significant advantage: it allows people to experiment with different approaches and learn their strengths and weaknesses from experience. In biotechnology, however, such uncoordinated strategies have met with

limited success; biotechnology's experience is filled with guidelines proposed or implemented by various parties, and still the difficulties escalate. Moreover, once the playing field is no longer level, researchers may be drawn to institutions and dissemination venues offering the fewest constraints, encouraging or even forcing others to relax their guidelines.

Community-wide attention and discussion. The community could initiate a long-term discussion of commercialization-related issues in meteorological research among all parties, with two goals: 1) building awareness of the issues, to help individuals and institutions make more informed choices; and 2) developing a framework for proactively examining the issues and exploring options for dealing with them. Here, a few institutions that represent major portions of the academic meteorology community, for example, UCAR and AMS, might take the lead—not in driving the conclusions, but in facilitating the dialogue—in partnership with universities, the private sector, federal agencies, and other stakeholders. One promising forum for such sustained discussion is the new Commission on the Weather and Climate Enterprise recently established by the AMS in response to the 2003 NRC panel recommendations (AMS 2004). Taking community action as well as independent steps may seem like an unwelcome additional burden to many scientists and managers. However, by developing mechanisms for addressing commercialization-related issues in our field before the risks become realities, we significantly increase the odds of achieving workable outcomes.

The outside world weighs in. Should our field attempt to glide through on the path of least resistance, or should individual or community-wide efforts fail, we might find others, outside our field, making policy for us. Given such a prospect, surely some process of self-examination makes sense.

Starting points. What are some more specific options? Biotechnology has tended to focus on financial conflicts of interest as the root of many difficulties (e.g., Blumenthal 2003). Because knowing about a potential conflict of interest is a prerequisite to managing it, disclosure of potential conflicts is generally considered a first step. Disclosure to research institutions is now mandated by NSF and other federal agencies, leaving the institution to decide what to do with the information, that is, which potential conflicts it should manage or prohibit—and institutional policies and procedures vary widely (e.g., Cho et al. 2000;

van McCrary et al. 2000; GAO 2001; Bekelman et al. 2003). Disclosure in publication is another common option (e.g., Davidoff et al. 2001; Koshland 1992; Campbell 2001), although, again, policies vary widely (e.g., on whether disclosure is voluntary or mandatory; whether it applies to articles, reviews, editorial, and/or correspondence; and whether the information is provided to journal editors, reviewers, and/or readers). Instituting disclosure of conflicts of interest would be a good starting point in meteorology; the question is then which conflicts should be disclosed, when, to whom, and how. Biotechnology's experience also suggests that disclosure of conflicts of interests is insufficient, unless disclosure is mandatory, and unless regulations and guidelines for managing disclosed conflicts are clear, proactive, and enforced.

Another set of options could focus on helping academic researchers, institutions, and organizations minimize negative consequences when negotiating academic–industry agreements and participating in commercialization-related activities. A first step would be to raise awareness of potential issues to consider, by disseminating information and promoting discussion. A further step would be to develop and recommend (or establish) community guidelines for academics engaging in commercialization-related activities. Guidelines applicable to meteorology already exist in some U.S. agencies and institutions; in biotechnology, a variety of guidelines have been developed by agencies, professional organizations, task forces, research institutions, and researchers in different countries (e.g., AAMC 2001; AAU 2001; Cech and Leonard 2001; Lewis et al. 2001; Coyle 2002; Walt et al. 2002; Evans and Packham 2003; Marwick 2003). Although such guidelines can be helpful, biotechnology's experience suggests that they are of limited use unless they are clear and are followed.

A number of other options proposed or tested in biotechnology might be implemented in meteorology. Examples include convening expert panels or workshops to discuss issues and recommend guidelines or other actions, engaging stakeholders in the research process, funding ethics-related research programs, developing or requiring research ethics classes for students, and developing professional codes of ethics. A code of ethics or other professional statement could, for example, include the continuing commitment of the academic/government research segment of our community to research integrity and the public interest, where commitment to the public interest is exhibited through contributions to knowledge and applications that are commercially useful, and those

that benefit humanity in other ways. Another option for our field might be to augment the incentives provided by intellectual property and related monetary profits, by developing or strengthening incentives and mechanisms to promote the transfer of knowledge and technology for public sector applications (e.g., to the NWS and other federal, state, and local agencies) and for the public good.

Unfortunately, the analogy with biotechnology suggests that there is no silver bullet for dealing with these problems, especially for managing the longest-term but most dangerous risks. Given that commercialization of meteorology is multifaceted, rapidly evolving, and likely to be an issue for years to come, we do not believe that it is yet time to prescribe specific actions. Rather, by raising awareness of the potential difficulties associated with commercialization and identifying some starting points for options, we hope to create the basis for a sustained discussion of issues and approaches. Because stakeholders in the meteorological research process have different interests and thus are unlikely to fully agree on a preferred course of action, only through discussion can we develop mechanisms that are appropriate for our field, agreeable to most participants, and most beneficial to the public welfare.

Before our community is ready to develop and institute specific options, it may also be necessary to gather further information and conduct more focused research on commercialization in meteorology. Potentially important topics include the current status and potential future role of intellectual property in meteorology, past and present commercialization-related activities in academic and government meteorology and their successes and failures, and the advantages and disadvantages of various options tested in biotechnology and other fields.

CLOSING REMARKS. We close with a few observations. First, even within academia and the public sector, participants and stakeholders in biotechnology research still do not agree on appropriate action, or on how effective various actions have been. Hence, our field cannot simply follow blindly in biotechnology's path. There is a finite, but perhaps catastrophic, risk that inattention now will eventually paralyze further progress in our field. The consequences of failure to successfully navigate commercialization are so severe that we believe our community ought to err on the side of overattention—early study, discussion, and exploration of alternatives—before potentially problematic situations become more prevalent and thus more difficult to address.

Second, we are not suggesting *limiting* academia–industry ties, but rather *managing* them proactively, to reap the benefits for our field and for society with minimum negative consequences. The U.S. government and many universities have decided that the benefits of technology transfer and commercialization of scientific research outweigh the costs, at least for now (Lawry and Anderson 2000). The resulting stronger dialogue between industry and academia might also help our community face a number of challenges, including making our research and knowledge more valuable to end users and educating meteorologists for future private sector or application-oriented jobs that require new combinations of expertise.

Third, our field arguably stands on the threshold of its greatest contributions to humanity. Weather, the oceans, climate, and the hydrologic cycle are threaded throughout human efforts to ensure public health and safety, enhance economic growth, protect the environment and ecosystems, and provide national security. The next two decades will be critical to global efforts toward a more sustainable, more equitable path (Rischar 2002). From society's point of view, we can ill afford a slowing rate of progress or application of atmospheric and related sciences during this period. From the meteorological community's point of view, future work (as well as funding and other resources) will be available in proportion to society's overall success, functionality, and appreciation for meteorology's positive contributions. Meteorologists are therefore most likely to find continuing opportunities to conduct research, develop user applications, and help humankind by remembering that the partnership among academic researchers, government, and the private sector exists primarily to serve society, and by acting accordingly.

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