INDIA RISING

India excels in rocketry and nuclear science but has produced few breakthroughs in other fields. Now, free of sanctions and swimming in cash, the world's largest democracy is gunning for status as a scientific powerhouse

BANGALORE, INDIA—When A. P. J. Abdul Kalam, the father of India's missile program, inaugurated a center of excellence in aerodynamics here last November, he emphasized how the new facility would boost the nation's defenses. Indo-Russian missilemaker BrahMos Aerospace helped bankroll the center at the Indian Institute of Science (IISc) Bangalore as a testing ground for its next-generation BrahMos-II missiles and hypersonic space vehicles. Indeed, after the ceremony, Kalam, the octogenarian former president of India, urged BrahMos to think grander and pioneer a reusable hypersonic cruise missile that would return after dropping a payload—a feat that could rival technology under development in the United States.

In a hangar here on the IISc Bangalore campus, BrahMos projects and other sensitive ventures are hidden behind black curtains. The military R&D is the center of excellence's raison d'être and a jewel in the crown of India's vaunted defense R&D establishment. But what's out in the open in the cavernous laboratory is far more revealing about the rapid development and entrepreneurial spirit of Indian science.

"I want to show you our latest invention," says aerospace engineer K. P. J. Reddy, head of IISc's Laboratory for Hypersonic and Shock Wave Research. He walks past a 16-meter-long steel shock tunnel, stops at a lab bench, and picks up what looks like an ordinary medical syringe. It's outfitted with a "Reddy tube": a shock tunnel writ small that's capable of generating shock waves traveling at twice the speed of sound. Applications abound. One Reddy tube called "Super Bull" boosts the success of livestock artificial insemination by slinging sperm deep into the uterus. A micro–Reddy tube delivers DNA through a nuclear membrane for cell transformation. Another is a juicer: Aim it at an apple, and shock waves disintegrate pulp while leaving the skin intact. "Juice doesn't get any fresher," Reddy says.

Such bench-top derring-do may seem incongruent with India's reputation as a champion of Big Science. After the nation's first atomic bomb test in 1974, the United States and other countries slapped sanctions on India that squeezed its supply of high-tech equipment and materials. Over the next 3 decades, India grew an indigenous civilian nuclear power industry and a space program on par with those of leading nations. In 2008, a landmark civilian nuclear pact between India and the United States beckoned Indian scientists in strategic sectors to come in from the cold; access to imported precision instruments is allowing India to make up ground in areas such as nanotechnology and supercomputing.

Now the government intends to lift all disciplines on a rising tide. At the Indian Science Congress in Bhubaneswar last month, Prime Minister Manmohan Singh pledged to hike R&D expenditures during the 5-year plan that begins this spring, from around \$3 billion last year to \$8 billion in 2017. In an exclusive interview with *Science* (see p. 907), Singh explained how his government plans to "increase gradually the proportion of money that is spent on R&D and at the same time create a system of incentives which will induce the private sector to increase their spending on science and technology."

The windfall is meant to turbocharge initiatives under way to create elite research institutions, bring expatriate Indian scientists home, enrich science education, and equip smart new laboratories. Included in this push

Online
sciencemag.org
Podcast interview (http://scim.ag/pod_6071) with co-author Pallava Bagla.

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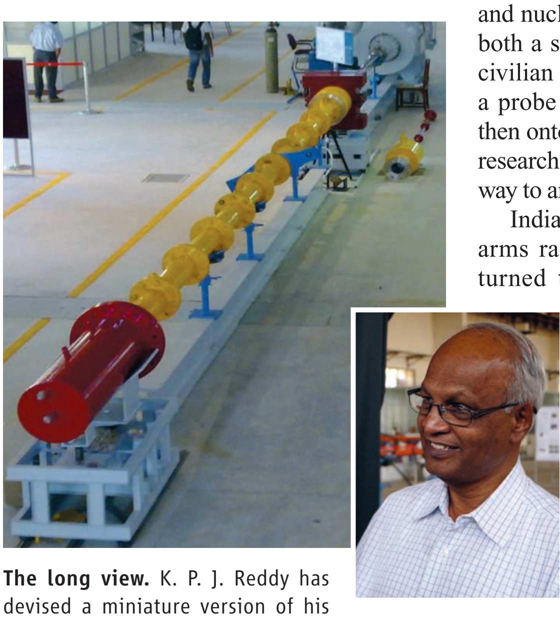
is South Asia's first biosafety level–4 lab for handling the most dangerous pathogens, slated to be up and running at the National Institute of Virology in Pune this spring. "Funding is no longer a constraint. What we once had to do abroad we can now do here," says Govindaraju Thimmaiah, a chemist at the Jawaharlal Nehru Centre for Advanced Scientific Research here. Over the next 5 years, an estimated $1.2 billion in public funds will be funneled to a new National Science and Engineering Research Board. Modeled after the U.S. National Science Foundation, the board is just now getting off the ground and is expected to fund its first competitive grants this year. "It's critical to our future, because it's run by scientists for scientists," says Raghunath "Ramesh" Mashelkar, former director general of the Council of Scientific and Industrial Research (CSIR), a national network of 37 laboratories.

Researchers will have to clear some daunting hurdles, though. India's legendary bureaucracy can snarl grant proposals and expenditures in red tape for months. The anticipated R&D budget boost "will be useless if structural reform is not undertaken," warns vaccine specialist Maharaj Kishan Bhan, secretary of the Department of Biotechnology, the central government's main conduit for supporting applied biology in India. Another woe is that scores of universities are deteriorating or riddled with corruption. They nurture few stars and are overburdened with dead wood. "On a day-to-day basis, people are discouraged from doing breakthrough research," says Raghavendra Gadagkar, a sociobiologist at IISc Bangalore. "Our system creates followers, not leaders. That's our biggest problem."

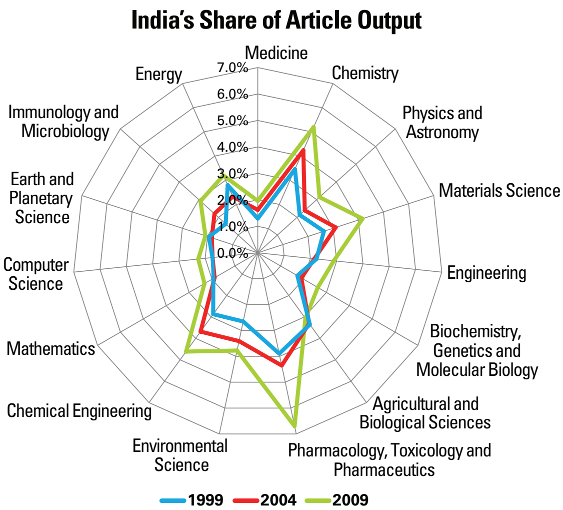
Still, the scientific outlook is brightening rapidly. From 2000 to 2010, India's peer-reviewed publications more than doubled to 40,000 a year, its world share rose from 2.2% to 3.4%, and citation impact improved from 40% to nearly 60% of the world average, according to the Thomson Reuters Web of Knowledge database. Moreover, Indian scientists are keenly aware of the need for research that raises living standards in the world's largest democracy, home to 1.2 billion people. "We are promoting what we call 'inclusive innovation,'" says Mashelkar, who like other top scientists here believes that a new day is dawning for Indian science.

Big bang theory

For many Indian researchers, a long night preceded the dawn. When Mashelkar, a chemist, returned to India in 1976 after a postdoc stint in the United States, he says it was a struggle to keep pace with his field. Scientific journals took 4 months to arrive by mail. "We were out of competition before we started," he says. Everything was difficult and slow. Mashelkar waited 6 years for installation of a phone line because he refused to pay an exorbitant fee for



The long view. K. P. J. Reddy has devised a miniature version of his lab's shock tunnel (*above*) for applications as diverse as artificial insemination and cell transformation. Over the past 20 years, Indian scientists have expanded their reach in the literature.



faster service. C. N. R. Rao, Singh's science adviser and a chemist at the Jawaharlal Nehru Centre for Advanced Scientific Research here, recalls that as a young professor decades ago he would receive the equivalent of about $60 per year for research. "I got my first spectrometer 17 years into my career and first electron microscope 30 years into my career," he says. Rao—éminence grise and India's most-cited scientist—was exceptionally productive. In the sprawling field of biology, "I don't think there were any breakthroughs in India" for decades, says L. S. Shashidhara, a geneticist at the Indian Institute of Science Education and Research (IISER) in Pune.

While basic research and living standards languished, India was pouring massive resources into two strategic areas: rocketry and nuclear science. The former gave rise to both a sophisticated missile program and a civilian space program that intends to send a probe to Mars and astronauts into space then onto the moon (see p. 906). India's early research on nuclear power, meanwhile, led the way to an atomic arsenal.

India's first atomic test ignited a nuclear arms race with China and Pakistan—and turned the nation into a nuclear pariah: Western countries banned most high-tech exports to India. Self-reliance promoted technological ingenuity, as India's nuclear and space programs have demonstrated on numerous occasions. India's research on using thorium as fuel for nuclear power reactors is nonpareil, and this year it will bring online a homemade prototype fast breeder plutonium reactor. Denied access to radiation-hardened computer chips and lightweight silica tiles for satellites, Indian space researchers developed their own.

The demise in 1991 of the Soviet Union, then India's main ally, was a turning point. India narrowly averted a financial meltdown. "CSIR had a tough time even to pay its electricity bills," recalls biophysicist Samir Brahmachari, CSIR's director general. Singh, as finance minister in the early '90s, engineered radical reforms that steered India from socialism to a free market economy. A few years later, the country's information technology industry took off—and "started taking away all the bright students," says chemical biologist Krishna Ganesh, director of IISER Pune.

Another signature Singh accomplishment was the Indo-U.S. nuclear agreement, which paved the way for the export of high-tech instruments and sensitive materials to India. Institutes across the country have since gone on a spending spree.

Muscling up

In a corner of IISc Bangalore down the road from the aerospace hangar, workers are putting the finishing touches on a

CREDITS (TOP TO BOTTOM): COURTESY OF K. P. J. REDDY; R. STONE/*SCIENCE*; ELSEVIER SCOPUS

$30 million, 1300-square-meter clean lab for nanotechnology. It's instrumented to the hilt. "Money is not much of a problem," says materials scientist Srinivasan Raghavan, one of four IISc Bangalore researchers who are helping midwife the new lab. All is not flawless: Raghavan and his colleagues suffer "supply-chain" delays due to Indian import regulations, he says, and a sanctions hangover. It took several months, for instance, to import a 2-centimeter-square piece of ultrathin zirconia foil for experiments with nanoporous zirconium. That foil is used in the nuclear industry, and despite the easing of restrictions, some countries still hesitate to export high-tech equipment and materials to India, says IISc Bangalore's S. A. Shivashankar, who got the ball rolling on the nanotech lab a decade ago. It will be fully operational next month and is expected to churn out 50 Ph.D. scientists a year.

State-of-the-art facilities are popping up far and wide. Ensuring their smooth operation is a challenge, however. "We readily can purchase expensive equipment," Shashidhara says. But he and others are frustrated over Indian regulations that limit spending on reagents and other research materials. "The government tells us to cut down consumables. It's considered waste."

The main impediment, scientists often say, is the bureaucracy. "Even the best of intentions can disappear without a trace in the quicksands of officialdom," IISc Bangalore Director Padmanabhan Balaram penned in an editorial last month in India's premier journal, *Current Science*. There's a lack of transparency. And bureaucrats sometimes demand that researchers give a regular accounting of progress on their grants. According to IISc Bangalore's Gadagkar, who studies social behavior of wasps, "I will be evaluated as if I was building a road. They want a report every 3 kilometers."

On the bright side, Indian researchers will have more opportunities to explain how they are spending their money. Major directions in the next 5-year plan include a $350 million Neutrino Observatory in Theni—India's single largest investment to date in basic

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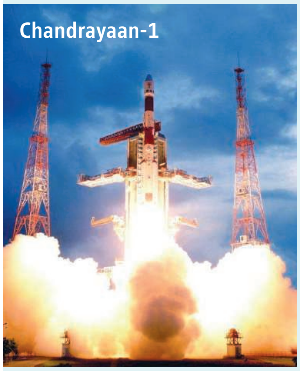
Dreaming small. IISc Bangalore's Srinivasan Raghavan and S. A. Shivashankar will roll out their nanotechnology clean lab next month.

CREDITS (*TOP TO BOTTOM*): ISRO; R. STONE/*SCIENCE*

Ad Astra, With a 'Uniquely Indian Flavor'

BANGALORE, INDIA—India's space program has a bold agenda this year: It aims to launch five rockets and four satellites, all built at home. The Indian Space Research Organisation (ISRO) already has 11 remote-sensing satellites in orbit—the largest constellation of civilian eyes in the sky. This record puts India securely in the global space club.

Part of India's achievement is to have joined at a modest cost. ISRO's $1.5 billion annual budget is almost 10 times smaller than NASA's. But its dreams are not modest. In the coming years, ISRO plans planetary exploration missions, a reusable launch vehicle, and a program to send astronauts into space. "In a very tough economic environment, India remains one of the few countries in the world which maintains and even reinforces its space program," says Jean-Yves Le Gall, chair and CEO of Arianespace in Paris. "This is absolutely remarkable."



Chandrayaan-1

In its 5-year plan submitted last month, ISRO sets some concrete goals. One is to see that its big rocket—the Geosynchronous Satellite Launch Vehicle (GSLV)—becomes "a reliable vehicle." The GSLV can put a 2-ton communications satellite in orbit; a new version is designed to launch 4-ton satellites. But GSLV's record is spotty. Only two of seven launches have been fully successful. One of the liquid cryogenic upper stages—designed in India—packed up within seconds after ignition in an April 2010 launch. Retooling it is a top priority.

On the scientific front, last October, India launched Megha-Tropiques, an Indo-French satellite to collect data on water and energy balance over the tropics. This mission marked the 19th consecutive successful launch of India's smaller rocket, the Polar Satellite Launch Vehicle. After lengthy delays, ISRO plans to use that rocket in 2013 to orbit its first dedicated astronomy satellite, Astrosat, which will be equipped with a suite of telescopes to view the sky in optical, infrared, ultraviolet, and gamma wavelengths.

ISRO's greatest claim to fame is the scintillating finding of water on the moon. Instruments aboard the 2008–09 Chandrayaan-1 probe, a bargain at about $100 million, uncovered water molecules on the lunar surface. The finding demonstrates that "the moon can support long-term human presence, a discovery of vital significance to man's future in space," says Paul D. Spudis, a lunar scientist at the Lunar and Planetary Institute in Houston, Texas, who ran a radar experiment aboard Chandrayaan-1 that detected traces of water. India is planning a return trip to the moon with a lander and rover in 2014. Also in the works is a solar mission in 2014 called Aditya and, in the next 5 years, an asteroid flyby. And while NASA earlier this month revealed that it has canceled a pair of upcoming Mars missions, ISRO is sketching out a robotic mission to Mars within a decade.

Whereas the United States has given up on shuttles, India now wants to build its own. Recyclable technology would sharply reduce launch costs, ISRO says. A first-generation vehicle would lift off vertically and land in the sea; later models would glide to a runway. A prototype is housed at a secret facility in Kerala, says ISRO Chair K. Radhakrishnan.

The defining moment for India's space program will come when India sends humans into space, Radhakrishnan says. ISRO has proposed a massive $2.5 billion project. Within 7 years of receiving government approval, India could orbit a few astronauts for a week, then later send them to the moon, Radhakrishnan says.

The government has approved about $25 million for preliminary studies "to wet our hands" with technology involved in human space flight, Radhakrishnan says. The big project may run into resistance. Asked whether this is the right thrust for Indian science, C. N. R. Rao, science adviser to Indian Prime Minister Manmohan Singh, said, "I have nothing against man going anywhere, but I am more worried about people on this earth." In an interview with *Science*, Singh declined to endorse the human space flight program (see p. 907).

Radhakrishnan is confident that ISRO's vision will prevail. "India is poised to soar higher in space," he says. "But it will be done with a uniquely Indian flavor." **–P.B.**

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research—a novel open-source drug discovery program (see sidebar below), a $1 billion supercomputing initiative, and an effort to improve forecasts of the summer monsoon (see p. 910). At the science congress last month, Singh also vowed to double public and private R&D spending as a percentage of GDP to 2% by 2017. That will require much higher expenditures from the private sector, which currently contributes a mere 33% of total R&D spending.

Some observers wonder whether India's scientific community can make good use of the windfall. By Western standards, few disciplines or institutes have built up a critical mass. "The entire biology community of India is smaller than that of Boston," Shashidhara says. In genetics and development, he says, "many people are just doing gap-filling work." Researchers in other disciplines voice similar complaints. "In any given area of science or engineering, the number of experts is rather small in India," says Rao, who says that nationwide only five or six researchers are studying graphene—one of the hottest areas of materials science.

To build capacity, the government is wooing overseas talent through fellowship programs. "There's a concerted movement to bring people back," says Savita Ayyar, head of the research development office at the National Centre for Biological Sciences (NCBS) here. And scientists on their own have organized "Young Investigator Meetings" in U.S. cities meant to entice newly minted Ph.D.s and postdocs.

Feeling caged in. The Indian system discourages breakthrough research, says sociobiologist Raghavendra Gadagkar, who studies wasp behavior.

Science for the masses

The flip side of the shortage of well-trained researchers is the inadequacy of labs and institutes. Most of the 350-odd state universities "are terribly run," Ganesh says. Few can brag of world-class research. "They're broken down," says physical chemist Sourav Pal, director of the National Chemical Laboratory in Pune. This is a legacy of the Cold War years. After independence in 1947, India adopted a Soviet-style academic system in which "undergraduate teaching was decoupled from research," Ganesh says. Then a decade ago came a "great awakening," he says: "We realized we needed to merge teaching and research."

One obstacle to reform is India's employment laws. Researchers of any caliber can easily gain tenure. At the same time, scientific stars have limited opportunities to advance in salary or rank. "Administrations must follow the policy of benign neglect with respect to high performers, even while turning a blind eye to the significant dead wood accumulating in our institutions," Balaram noted in his editorial.

As a cure, the government has opted to spawn new institutions. In the past 5 years, Singh has presided over an expansion of

Crowd-Sourcing Drug Discovery

NEW DELHI—Each year, India tallies an astounding 1.7 million cases of tuberculosis (TB). Some 400,000 people succumb to the disease, making it the leading cause of death in India for those in the prime of life, from 15 to 45 years old. Most victims are poor, and pharmaceutical companies have little incentive to develop new drugs against the bug that causes TB, *Mycobacterium tuberculosis*. But the Indian government has a big incentive to reduce the disease burden.

Faced with this conundrum, Samir Brahmachari had a brainstorm a few years ago: crowd-sourcing. "That means looking for experts you don't know exist," he says. "I wanted to do something very different." So in 2008, Brahmachari, a biophysicist and director general of the Council of Scientific and Industrial Research (CSIR), India's largest network of scientific laboratories, launched the Open Source Drug Discovery (OSDD) network. Modeled after the open-source software community, OSDD's army of volunteers is building a kind of Wikipedia on TB. Some 5500 participants in 130 countries respond to "work packages" posted by OSDD: questions on everything from the biology of *M. tuberculosis* to leads on drugs; answers are tagged and credited.

"OSDD is an exciting new approach to drug discovery," says Melvin Spigelman, president of the TB Alliance in New York City. "It provides the opportunity for virtually a limitless number of scientists to contribute to the solution of any given problem." The Indian government gave OSDD $12 million in seed money; CSIR has requested $200 million over the next 5 years as the program ramps up for clinical trials and expands to other neglected diseases such as malaria and leishmaniasis, and possibly even cancer. "Drug discovery," Brahmachari says, "is too serious a business to be left solely in the hands of pharmaceutical companies."

The first challenge that OSDD's cyber-community assigned itself was to glean more information from the *M. tuberculosis* genome. It was sequenced in 1998, but researchers had clues to the functions of only a quarter of its 4000 genes. In December 2009, OSDD set out to reannotate all possible genes. Some 500 volunteers got the job done in a mere 4 months. Now OSDD is trying to exploit these data. "The more people you put to work on the problem, the more chances you will have to identify the set of compounds that will likely make it through compound optimization, animal models, preclinical, and, eventually, clinical trials. If you increase your success chances, then your overall costs decrease," says Marc Marti-Renom of the National Center for Genomic Analysis in Barcelona, Spain.

Open-source guru. CSIR's Samir Brahmachari.

OSDD's iterative approach has identified two drug candidates that it has contracted for testing. Under OSDD rules, data from program-sponsored clinical trials must be open for all to see—"a clear alternative," OSDD states, "to expensive clinical trials conducted in secrecy at high costs." OSDD drugs will be available in the developing world as generics, Brahmachari says. "When it comes to health, we need to have a balanced view between health as a right and health as business," he says. For TB and other neglected diseases, drug companies might embrace that philosophy. For cancer, all bets are off. **–P.B.**

CREDITS (TOP TO BOTTOM): R. STONE/SCIENCE; PALLAVA BAGLA the education and research system not witnessed since the 1940s. Back then, the country's first prime minister, Jawaharlal Nehru, saw research labs as the "temples of modern India" and set in motion the creation of the elite Indian Institutes of Technology.

An impressive new phenomenon is the Indian Institutes of Scientific Education and Research, of which there are now five. The decision to establish them was controversial. "A lot of people were against the IISERs. They thought, 'Why not upgrade existing universities?' " Pal says. Skeptics warned that there wouldn't be enough skilled instructors to go around. The rapid buildup in fact has meant uneven faculties at some institutes. "If you can't get teachers who are qualified, you start compromising," Mashelkar says. Critics also say that the IISERs will skim off talented high school science grads, leaving impoverished universities in worse condition.

"We need to find ways to attract intelligent students into science," Ganesh says. Toward that end, the government's Department of Science and Technology hopes to hook youngsters on science through INSPIRE—Innovation in Science Pursuit for Inspired Research—a 5-year, $500 million program that hands out $125 grants to top science students at every high school in the nation. "We hope to catch them young and build a cadre of top-quality researchers," says T. Ramaswami, secretary of the Department of Science and Technology in New Delhi. He spearheads this ambitious scheme, which aims to have supported 1 million students by the end of next year.

Minding the gap. Krishna Ganesh is melding teaching and research.

Institutes, meanwhile, are striving to close the gap between education and research. IISER Pune, for instance, encourages its undergraduates to join labs and author publications. And CSIR is venturing into the teaching business. Last year, it established an accredited institution that's gunning for 6000 students. "It's a very important break from the Soviet model," Pal says.

One long-standing problem for science faculties is that many top graduates turn up their noses at academic careers. They flock to information technology, where companies offer large entry-level salaries. Meanwhile, those who stick with science tend to go overseas for postdocs, depriving Indian labs of the creative sparks that are the hallmark of labs in Europe and the United States. Stints in overseas labs are seen as a ticket to a decent position back in India. "People think you need to go abroad to get a job here," says NCBS neuroscientist Sumantra Chattarji.

Hoping to show that's not necessarily the case, the Department of Biotechnology and the U.K.'s Wellcome Trust teamed up in 2008 to create a 5-year, $140 million fellowship program for up to 375 young investigators in India. "Now we're able to create an environment and mechanisms for postdocs to stay here," Ayyar says. "You might think this is a small step. But it's about changing the way people think."

As India's economy roars and Western nations limp along, the trickle of talented expatriates returning home may turn into a flood. "You can be richer in India as an assistant professor than in the United States," says Ganesh, who says that new recruits to IISER Pune receive royal treatment. "We give them whatever they want to start up a lab." His institute may be a new kid on the block. But considering the climate for science in India these days, Ganesh says, "I have no excuse to fail."

–RICHARD STONE

With reporting by Pallava Bagla.

Drawing a Bead on India's Enigmatic Monsoon

NEW DELHI—India's booming economy is still a gamble on the monsoon. In any given year, if rainfall climbs more than 10% above a long-term monsoon average, floods ensue. If it declines more than 10% below average, a drought is declared. Slippage in either direction brings misery. For example, a drought in 2002 shrank India's GDP by an estimated 5.8%. Every meteorologist's dream here is to accurately predict the monsoon's arrival, distribution, and departure. Toward that end, this year the Ministry of Earth Sciences is launching a 5-year, $75 million "monsoon mission" to improve the study of complex ocean-atmosphere interactions.

India receives 105 cm of rainfall on average per year, 80% carried on southwest winds that sweep in from the Indian Ocean from June to September. A winter monsoon also brings moisture from the northeast. Farming is heavily dependent on the exact timing of the rain, especially where it is needed to germinate seed. Since official record-keeping began 137 years ago, the monsoon has never failed to arrive, and it has never delivered less than 75 cm of rain. But the spatial and temporal variations are vast—and this is what befuddles scientists. "Every year, the monsoon is peculiar in its own way," says atmospheric scientist Jayaraman Srinivasan of the Indian Institute of Science in Bangalore.

Extreme misfortune. A farmer in Orissa examines his parched field in 2003.

The India Meteorological Department here issues monsoon forecasts but has not been able to accurately predict when the worst floods and droughts will occur. "Extremes are really difficult to forecast," says Ajit Tyagi, the department's former director general. Everything needs closer study: how clouds form, develop, and die—and, crucially, how global warming will change the monsoon.

India's "current prediction capabilities are inadequate," concedes geologist Shailesh Nayak, secretary for the Earth Sciences Ministry. A big bottleneck, he says, is a shortage of trained scientists. By Nayak's estimate, over the next 5 years India will need about 1200 skilled meteorologists, but today has only about 350. The ministry has just launched a recruitment campaign.

In the new initiative, Indian scientists and overseas colleagues will try to adapt computer models developed by the U.K. Met Office and the U.S. National Centers for Environmental Prediction for long-range forecasting in India. The mission will also make use of data pouring in from Megha-Tropiques, an Indo-French satellite launched in October to monitor water and energy balance over the tropics. The Indian Institute of Tropical Meteorology in Pune will take the lead in seasonal forecasts and prediction of active and break periods of the monsoon. A key aim is to produce a prediction model that uses open-source software such as Linux.

The collaborative effort, Tyagi hopes, may at last "unravel the enigma that surrounds the Indian monsoon."

–P.B.

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