ATMOSPHERIC SCIENCES AT THE SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

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ABSTRACT

The Institute of Atmospheric Sciences (IAS) was established at the South Dakota School of Mines and Technology (SDSMT) in 1959. It started a program in weather modification research slowly as a part-time effort involving existing SDSMT and South Dakota State University faculty, but began to grow rapidly in 1964 with the hiring of its first full-time director, Richard Schleusener. Strong support from federal research agencies, particularly the U. S. Bureau of Reclamation, led to development of a large internationally-recognized research program at SDSMT employing more than 50 staff in the late 1960s. Support for weather modification research began to diminish in the 1970s. Staff numbers declined. The IAS diversified its research portfolio to include a broader meteorological and environmental perspective. A core research effort in storm phenomena relevant to weather modification was maintained. In the 1990s a very successful program in satellite remote-sensing developed, but in 1997 that group moved to a different institution to continue its efforts. In the 2000s a new focus on earth system science developed. Again, the development faltered with the departure of key researchers and shrinking of staff numbers. Through all of these changes an active research program has survived. We survey the scientific achievements of IAS researchers and their continuing successes in the area of atmospheric physics and dynamics, atmospheric chemistry and air quality, remote sensing, land surface-atmosphere interaction, and earth system science and biogeochemical cycles.

INTRODUCTION

Great interest in weather modification developed during the 1950's, particularly in the arid regions of the western United States. An Advisory Committee on Weather Control was formed in 1953 to evaluate the potential of cloud seeding to beneficially modify precipitation. U.S. Senator Francis Case of South Dakota played a key role in the establishment of the Advisory Committee; A.M. Eberle, then Dean of Agriculture at South Dakota State University (SDSU) was named vice-chairman. In 1958 the committee reported favorably regarding the use of cloud seeding for beneficial weather modification. Congress then took action to establish a federally-funded research program.

The early years of atmospheric sciences in South Dakota. The Institute of Atmospheric Sciences (IAS) was established at the South Dakota School of Mines and Technology (SDSMT) in 1959 by Special Resolution No. 30-1959 of the Regents of Education of South Dakota "... to provide for and to conduct a program of basic and applied research in the several atmospheric sciences, which research shall be calculated to expand the knowledge in the atmospheric sciences and to discover methods or procedures for the utilization of old and newly acquired knowledge in the art of weather modification; ..." This resolution took note that the U.S. Congress had implemented support of basic research in the atmospheric sciences and that it was reasonable and proper that South Dakota talent be mobilized to advance that research with this federal support.

In 1961 Congress charged the Bureau of Reclamation within the Department of Interior to develop and manage a program "to conduct research on increasing rainfall by cloud seeding throughout the western states." The legislation included commitments for the establishment of new atmospheric science research programs in many of these so-called Reclamation states. This broad distribution of potential funding brought many members of Congress on board as co-sponsors. U.S. Senator Karl Mundt and Representative E. Y. Berry from South Dakota were enthusiastic supporters who made sure that their state would get its share of the newly available funds. The program that Reclamation started was named Project Skywater. It was managed by Reclamation's Engineering and Research Center in Denver under the direction of Archie Kahan.

A National Science Foundation (NSF)-sponsored conference on atmospheric science research was held in Rapid City in February 1962. Recommendations were made that provided an overall road map for development of the South Dakota research and educational program which followed. The participants included Vincent Schaefer, a member of the research team at the General Electric Company Research and Development Center that discovered the scientific basis for modern cloud seeding and recognized the natural cloud laboratory that the Black Hills provided. Decisions were made to concentrate on studying the possibility of increasing rain and decreasing hail damage from convective clouds.

Pursuant to those recommendations, limited field programs were carried out in the summers of 1963 and 1964. These field experiments in weather modification proceeded under the leadership of Professor Joseph Cope at SDSMT with collaboration by Professor Emily M. Frisby of SDSU. An introductory course in meteorology was listed in the SDSMT catalog under the Physics Department in the early 1960s.

Richard A. Schleusener was hired to head the IAS as its first full-time director near the end of 1964. He had previously been a consultant to the Bureau of Reclamation while a professor at Colorado State University (CSU) and was quite familiar with the South Dakota plans, having participated in the 1962 Rapid City conference. Senator Mundt's verbal commitment that Reclamation's support for the IAS program would be on-going helped persuade Schleusener to leave CSU and take the reins of the IAS. See Figure 1 for a photograph of the principal participants in the formation of the IAS.

Figure 1. Senator K. Mundt, President F. Partlo, Director R. Schleusener, and Congressman E. Y. Berry during meeting on SDSMT campus in 1965.

In 1965 major research and educational thrusts in cloud modification began. Under Schleusener's leadership, the IAS began to grow. Arnett Dennis joined as associate director. Harry Orville (whose father, Howard, had chaired the Advisory Committee on Weather Control mentioned above) came to found numerical cloud modeling efforts. Paul Smith took charge of engineering and radar operations. Briant Davis established a cloud physics laboratory to study the nucleating characteristics of various cloud seeding agents.

In December of 1965 the Board of Regents approved a Master of Science degree program in meteorology at SDSMT. Schleusener was named head of the department as well as director of the IAS. The M.S. curriculum was developed by Orville and Dennis. The standard offerings at the beginning were courses in general and synoptic meteorology, physical and dynamic meteorology and specialty courses in radar, fundamentals of nucleation, physics and dynamics of clouds, precipitation physics, and weather modification.

With support from Reclamation's Project Skywater, the NSF, and other federal and state sponsors, IAS researchers undertook several important field programs in weather modification, cloud physics and radar meteorology. The field work conducted in South Dakota, North Dakota, and Nebraska involved cloud seeding by aircraft, radar surveillance of the seeded clouds, and a series of rain gauge and hailpad networks on the ground to monitor precipitation. The IAS operated several of the aircraft, including an instrumented Piper Apache and military surplus T-6 trainers, and contracted for use of others. At one time, nineteen IAS radar systems were in operation at five sites in the three states.

Numerical cloud modeling and laboratory experimentation also expanded. The numerical modeling work involved many weekend trips to the National Center for Atmospheric Research (NCAR) computer laboratory in Boulder, Colorado, to use the large computers there. This was the era of entering programs and data into computers using decks of punched cards, and getting output in the form of stacks of fan-folded printer paper, and later, microfilm. Remote access to large computers was a decade or more in the future.

The cloud physics laboratory work involved cloud-chamber studies of the activity of nucleating agents for cloud seeding. Little was known at the time about how these agents worked and the field was wide open for new discoveries.

In the summer of 1966 a field experiment called Project Hailswath was hosted in Rapid City. Personnel from seventeen organizations from around the country and abroad converged on the Black Hills and carried out hailstorm studies. See

Goyer et al. (1966) for a description of the project. At the same time, and in the Black Hills region, the Rapid Project was being conducted to study effects of silver iodide seeding on convective rain showers. The Rapid Project continued through 1968, to be followed by Project Cloud Catcher which ran from 1969-72 (Dennis et al. 1975). Related projects such as the North Dakota Pilot Project and the Grand River Project were initiated in neighboring areas. In 1969, the IAS operated four field sites simultaneously at Alliance, Nebraska; Watford City, North Dakota; and Lemmon and Rapid City, South Dakota. A relatively large workforce was required during this era of numerous field projects and extensive laboratory and computer-based research. Total employment in the IAS exceeded 50 in this era with annual budgets exceeding $1M.

IAS research helped establish the extent to which summertime convective clouds in the northern Great Plains can be modified to increase rainfall (Dennis et al. 1975) and reduce hail damage (Schleusener 1968). Partly as a result of this research, the South Dakota Legislature funded an operational cloud seeding program in parts of the state from 1972 until 1976.

The Rapid City flood that occurred in June of 1972 led to cessation of cloud seeding activity in the immediate Black Hills area. Hygroscopic (powdered salt) seeding operations had been carried out by IAS researchers on the plains east of the Black Hills earlier in the day of the Rapid City flood. The flood occurred late in the evening as a large slow-moving thunderstorm sat over the upper Rapid Creek catchment in the central Black Hills. IAS and independent review scientists concluded that the seeding experiments had not contributed to the flood (St. Amand et al. 1972), and persons raising that possibility never proposed any physical mechanism through which the IAS experiments over the plains could have influenced developments in clouds that reached the central Black Hills a few hours later. Nevertheless, an association between the seeding and the flood remained in the minds of some of the residents of the area.

Elsewhere in the state, operational seeding continued, but not without opposition. The main source of concern in these areas was that cloud seeding could be suppressing rather than enhancing rainfall in the counties participating in the program. Typical stories circulated at protest meetings concerned promising clouds that failed to produce rain after an airplane, assumed to be part of the seeding program, flew over or under them. The opposition grew with time, eventually leading to the cessation of the state cloud seeding program in South Dakota after 1976.

The graduate program in meteorology at SDSMT started out much smaller than the nationally supported IAS research program. The first two M.S. degrees were awarded in 1968, to John Yu-Ming Liu and Martin Schock. While students, they were employed as research assistants on the IAS research projects. Since that time over 200 degrees have been awarded. Most graduate students have been supported during their studies by graduate research assistantships funded under IAS research projects. Results from roughly half of their masters theses have led to publications in national and international scientific journals.

The T-28 storm penetrating aircraft (Figure 2) was acquired and outfitted for research in 1969 with funding from the NSF. Paul MacCready, a renowned

soaring pilot and aeronautical engineer as well as meteorological researcher, had championed the idea of armoring an aircraft for storm studies during Project Hailswath. He partnered with Schleusener to bring the idea to fruition at SDSMT. After extensive modifications including 700 pounds of armor plating on all leading edges, a few test flights were conducted in 1970 during the Northeast Colorado Hail Experiment (NECHE). Wayne Sand was hired to pilot the T-28 in 1971, but engine problems prevented participation during the subsequent 1971 NECHE summer field season in Colorado. After a new larger engine was installed, the first series of research flights were conducted during the National Hail Research Experiment (NHRE) beginning in 1972 in northeastern Colorado and continuing through 1976 (Sand and Schleusener 1974). The unique capabilities of the T-28 made it central to the research conducted during NHRE, and it became a fixture in a wide variety of successful convective storm field programs for more than three decades.

Figure 2. Armored T-28 flying by Mt. Rushmore in 2003.

Major Reclamation research support committed to the IAS for cloud seeding experiments ended in 1973, during a period of general cutbacks in federal research expenditures. The era of running regional weather modification field research programs ended at SDSMT. With reduced funding, staff numbers were dramatically reduced; some IAS staff left SDSMT while others moved to different positions. Schleusener moved up to become Vice President and Dean of Engineering of SDSMT (and within two years its president) and Dennis became director of the Institute. Orville was appointed head of the Department of Meteorology.

After the weather modification field programs. An era of research diversification began in the IAS in the mid-1970's and new courses were introduced in the department. Air pollution became part of the curriculum in 1974, and many of the staff researched air quality and the relationship between regional air quality

and the energy developments in Wyoming and Montana. This involved both field work and computational studies (Davis et al. 1976; Orville et al. 1981). Much of the field work was accomplished using a specially-equipped motorhome obtained with funding from the Department of Energy in 1976. This effort involved a variety of air-quality-related measurements conducted repeatedly over a circuit involving the five states of South Dakota, Nebraska, Wyoming, Montana, and North Dakota. The air quality group went on to perform studies related to the fugitive dust problem in the Rapid City area in the late 1980s and early 1990s (e.g. Davis et al. 1981), providing the basis for improving air quality in the metropolitan area.

Early in 1978 the IAS was awarded the contract for the design and evaluation of the High Plains Experiment (HIPLEX). This was a national study of summertime rain enhancement capabilities in the US High Plains region funded by Reclamation. Exploratory phases of this project had started a few years earlier with sites in three states (Montana, Kansas, and Texas). Many of the IAS staff were involved in this effort in either field work or computational studies. The HIPLEX project summer field experiments continued through 1980 when they were suspended so the large multi-agency-supported Cooperative Convective Precipitation Experiment (CCOPE) could be hosted at the Miles City, Montana, HIPLEX research site in the summer of 1981. Because of subsequent cuts in federal funding, HIPLEX never got back into the field in subsequent years. Results based on a smaller dataset than originally planned suggested limited capability to increase precipitation in the High Plains region from summertime clouds by cloud seeding (Mielke et al. 1984). The early 1980s saw the end of significant involvement of Reclamation in weather modification research.

The research portfolio of the IAS continued to diversify in the 1980s. Andre Doneaud joined the IAS in the late 1970s after fleeing repressive conditions in Romania. He developed a program of research on mesoscale precipitation systems, developing the area-time-integral method for estimating precipitation from radar observations. See, e.g. Doneaud et al. 1981, 1987.

Ronald Welch joined the lAS in 1982 and created a research program in remote sensing, satellite meteorology, and global environmental change. Welch was the recipient in 1992 of the largest contract ever awarded up to that time to a SDSMT faculty member: $15,000,000 to support research as part of several National Aeronautics and Space Administration (NASA) Earth Observing System programs which were expected to continue through the year 2002. With this funding, Welch assembled a remote sensing group consisting of a dozen or more researchers at any one time. In 1997 Welch and most of his remote sensing group left SDSMT to continue their work at the University of Alabama-Huntsville and Marshall Space Flight Center. This was a loss of roughly one third of the IAS staff at that time.

The T-28 participated in its first field project abroad with a trip to Switzerland in 1982 to participate in the Grossversuch IV project, a study of the use of cloud seeding to reduce hail damage. The aircraft stayed for a second season in 1983, and T-28 observations inside the thunderstorms revealed that the conceptual model upon which the seeding approach to hail suppression was based was not

applicable to Swiss storms (Waldvogel et al. 1986). In 1985 the T-28 went to Alberta, Canada, to participate in a similar hail suppression project. In 1987, the T-28 entered into a formal NSF facility mode of operation with the NSF providing base support to maintain the aircraft, and covering deployment costs for NSF-funded projects requiring its services. A part-time facility staff of six was associated with this mainly summertime operation. The aircraft was operated in this way through 2003, and was retired in 2004. During this period as a facility it supported almost two dozen national research projects in various regions of the US.

The 1990's saw the end of air quality laboratory work at the IAS, and Davis became dean of graduate education and research at SDSMT. The South Dakota Space Grant Consortium came into being in the early 1990's. Local Space Grant activities were managed by the IAS for the first few years before being transferred to the graduate dean in 1995. Also in 1995 the local National Weather Service (NWS) forecast office moved from the Rapid City Regional Airport to a site adjacent to the SDSMT campus, as part of the national move to co-locate National Weather Service offices with universities. At the same time a NWS WSR-88D Doppler weather radar was sited near New Underwood, about 20 miles east of Rapid City. The office co-location and availability of sophisticated radar observations in the region opened the door for increasing collaboration between IAS researchers and NWS forecasters on research related to regional weather. Examples include Klimowski et al. (2004) and Bunkers et al. (2006).

The later years. The mid to late 1990s were years of major changes for the IAS and the department. Orville stepped down as academic Department Head in 1994, and Smith retired as IAS director in 1996. Patrick Zimmerman became the Director of IAS in 1997, and, as noted earlier, the Remote Sensing Group relocated to Alabama.

Zimmerman sought to broaden the IAS and academic departmental focus to an Earth systems perspective with new emphases on atmosphere-biosphere interactions, global change, and linkages between atmosphere, ocean, land, and subsurface processes. He brought on board several energetic and capable young faculty and researchers.

The first major institute-wide project under Zimmerman was the Upper Missouri River Basin Pilot Project (UMRBPP), which was undertaken to better establish and understand the water budget for the region. This collaborative research project, involving various universities and federal agencies, was funded by NASA as part of the Global Energy and Water-cycle Experiment (GEWEX) and Continental-scale International Project (GCIP). South Dakota Senator Larry Pressler was a strong proponent of water budget studies within the Upper Missouri River Basin, and was influential in seeing that funding was provided. Early preparatory work for this project was supported by the NSF-EPSCoR program. An intensive observing period for UMRBPP was centered over the Black Hills region in spring 1999. A comprehensive data set was obtained, but funding to analyze the data and publish results was limited.

In the early 2000s, the Earth systems emphasis adopted a much stronger focus on the carbon cycle and carbon sequestration. Zimmerman was able to convince Governor William Janklow of the need for additional state-supported positions within IAS. Two additional positions were instituted through the governor's office: a State Carbon Scientist and a State Wildfire Meteorologist. Both positions involved teaching, research and service. These staff members competed for additional research funding from state and federal agencies, supported graduate research assistants, served the state as members of various committees and commissions, and in the case of the wildfire meteorologist, served as incident forecaster during wildfire events.

In the mid-2000s, key Earth systems researchers left for tenure-track appointments at other institutions. Zimmerman left the IAS in 2007 to concentrate on carbon sequestration efforts in private industry based on a patent he obtained for a procedure to certify carbon sequestration during agricultural operations he named C-Lock (Zimmerman et al. 2005). These researchers were not replaced. Leadership of the IAS fell to John Helsdon until in 2012, campus management eliminated the IAS from the campus organizational chart and made the Atmospheric Sciences Department into a tenure-track academic unit. During this period major research efforts included lightning and storm electrification, assessment of weather forecast accuracy and reliability, stream and wetland ecology, and severe storm dynamics.

In 2013 the Department of Atmospheric Sciences became the Department of Atmospheric and Environmental Sciences (AES) in an effort to make its name better characterize its curricular and research strengths. Then in 2014 during a period of austerity on campus, the department was eliminated. As a predominately graduate department with small classes it was not generating sufficient tuition income compared to other departments, and at the same time research funding was in decline. Faculty were dispersed to other departments with larger undergraduate programs, including Chemistry and Applied Biological Sciences, Civil and Environmental Engineering, Mathematics and Computer Science, and Physics. This organization continues. These AES faculty still teach in support of the AES academic programs in addition to teaching courses in their new departments. They continue their ongoing atmospheric and environmental research projects and are developing new collaborative research with their colleagues in their new departments.

Research portfolio. The following is a survey, rather than a comprehensive summary, of major research activities and accomplishments of IAS and Department of AES researchers since the founding of the IAS in 1959. Examples are given and references cited that represent the main research activities in the different periods in which they existed. A complete summary of all research would require a book-length treatment.

The IAS began as a pioneering research group relating cloud physics to severe storm research, an area of national concern with strong federal funding support. During the 1960s the IAS organized numerous field projects while conducting research on cloud seeding for rainfall enhancement and hail suppression

(see, e.g., Dennis et al. 1970; Biswas and Dennis 1971; Dennis and Koscielski 1972; Dennis et al. 1975; Koscielski and Dennis 1976). In the 1970s and 1980s IAS researchers were involved in several large national and international projects focused on hail damage mitigation, including NECHE, NHRE (Knight et al. 1979), Grossversuch (Waldvogel et al. 1986), and the Alberta Hail Project. Airborne *in situ* observations were crucial in better understanding processes occurring in the cores of hailstorms studied during these projects (Musil et al. 1973, 1986, 1991).

Although research activities in weather modification declined, some projects continued in the 1980s and 1990s. IAS researchers were in involved in several field projects in Illinois and North Dakota that were focused on better understanding of the cloud seeding process under the NOAA Federal-State Cooperative Program in Weather Modification. In 1988, a year of drought in the region, the IAS also organized a locally-funded trial cloud seeding effort directed at augmenting water resources in the Black Hills. This trial was coordinated with numerical simulations (Farley et al. 1997). During the 2000s a small program of observational and numerical investigations of hail damage mitigation was sponsored by Reclamation (Farley et al. 2004). Statistical analysis of results from operational cloud seeding programs also contributed to better understanding of the effects of cloud seeding (Smith et al. 1997).

Work on weather modification conducted by researchers at the IAS and many other institutions worldwide has generally shown that the promise of cloud seeding for reliable, consistent precipitation enhancement and hail suppression is more difficult to achieve than was expected when activities began in earnest in the early 1950s (Garstang et al. 2005). Operational cloud seeding does continue in parts of the US and elsewhere; more projects are conducted abroad than within the US.

During its weather modification research era, researchers at the IAS spearheaded efforts directed at computer-controlled radar scans and data processing with real-time visual displays of radar data that helped lay the groundwork for modern radar meteorology (Boardman and Smith 1974). Laboratory work contributed to better characterization of the performance of cloud seeding aerosols, some of which are still in use today (e.g. Davis et al. 1975). Observational studies used various airborne instruments custom-developed to probe storms to determine strength of updrafts and downdrafts, concentrations and types of cloud and precipitation particles, and, beginning in the late 1980s, electric fields (Bringi et al. 1997) and cloud chemistry. These contributed to advances in the basic science of convective storms. Since the 1980s there have been important research efforts in *in situ* verification of polarimetric radar hydrometeor classification schemes, a key line of research that can enable more effective use of new radar technology for research and forecasting. The recent NWS WSR-88D radar polarimetric upgrades are based in part on results from IAS research collaborations. More recently there has been significant work on characterizing hydrometeor size distributions for use in understanding radar signatures of rain and snow (Kliche et al. 2008; Johnson et al. 2011, 2014).

Beginning in 2012 researchers at SDSMT became involved in the development of a long-awaited replacement for the T-28 armored storm penetrating aircraft. The project was led by the Center for Interdisciplinary Remotely-Piloted Aircraft Studies at the Naval Postgraduate School in Monterey, California. The aircraft chosen was an A-10 "Warthog" aircraft, which is more versatile than the T-28. The project currently is in-progress. When modifications are complete**,** there will be new observing capabilities for convective storm studies and also for other atmospheric studies as well.

The IAS numerical cloud modeling group addressed a variety of topics over the years. Throughout much of the history of the IAS the effort was directed at the development, refinement and application of various schemes to simulate microphysical processes for studies of basic convective cloud microphysical processes including the growth of hail and the effects of cloud seeding (Orville 1978; Lin et al. 1983; Farley 1987). Cloud mergers, microbursts, marine stratocumulus, cold season orographic clouds, and the effects of waste heat on convection have also been modeled (Hjelmfelt et al. 1978; Hjelmfelt 1992; Wang et al. 2003; French and Parker 2012).

Physics-based storm electrification/lightning modeling was originated and developed by IAS researchers (Chiu 1978; Helsdon and Farley 1987). Capabilities were developed for simulating charge separation in storms, and initiation and propagation of lightning discharges. These improved the understanding of charging mechanisms and microphysical interactions for comparisons with observations and for studying lightning's effects on atmospheric chemistry (Helsdon et al. 2001; Zhang et al. 2003). Better understanding of cloud electrification and lightning is useful in many lines of research and forecasting, including forecasting "dry" lightning for predicting wildfire danger and examining the potential for modification to reduce lightning-caused fires. Lightning is a primary producer of nitrogen oxides. The only *in situ* observations of these gases in storm cores have been made using the T-28 storm-penetrating aircraft. These observations and the cloud electrification simulations challenge some currently held estimates and theories. Beginning in 2011 numerical simulation studies of lightning were further augmented with a field study of lightning including VHF mapping and high-speed video of lightning events that gave new insight into lightning initiation and propagation (Warner et al. 2013).

Numerical weather prediction models have been used by IAS researchers to study the effects of topography and surface characteristics in regional-scale weather systems. These models are used in the Black Hills to study storm development and predict precipitation distribution. Coupled with land surface and hydrologic models, the local-regional scale hydrologic cycle, including snowmelt, runoff and flash floods has been simulated. Feedbacks to storm initiation have been and continue to be studied (Davis et al. 1999). Cloud modeling studies and cooperative research with the Rapid City National Weather Service Forecast Office on severe storms with damaging winds, hail, and flash floods are aiding forecasts of these events. Observations and numerical models are also used to study lake-effect snow storms that impact tens of millions of people and cause hundreds of millions of dollars in damage a year. This long-term collaborative

research is an example of the application to national problems of capabilities developed for studying South Dakota weather issues. A project with the U.S. Department of Defense was completed to assess the role of assimilating abridged atmospheric data into incident meteorology scenarios. Results from efforts to downscale global climate model results to study regional effects in the upper Missouri River basin were published (Wang et al. 2014).

The remote sensing group led by Welch was very productive during the 15 years it was part of the IAS. Its research ranged from basic investigations in radiative transfer (Kuo et al. 1996) to application of the best theoretical knowledge to practical problems in the analysis and interpretation of satellite imagery (Han et al. 1997; Christopher 1998). These IAS researchers formed integral parts of several NASA teams associated with new missions involving satellite observations of Earth's surface, The Mission to Planet Earth.

Atmospheric chemistry and air quality research by IAS researchers contributed both to fundamental observational science (Davis et al. 1994) as well as to addressing local air quality issues related to particulate matter in the air. With the arrival of Zimmerman in 1997, biogeochemical investigations dealt mainly with terrestrial vegetation and the carbon cycle. Examples are Baker et al. (2000) and Vierling et al. (2006). More recently the focus of biogeochemistry research work has been on coupled cycles of carbon, nitrogen, phosphorus and sulfur in aquatic and terrestrial ecosystems, ecosystem dynamics and microbial ecology, ecosystem structure and function, wetland ecology, water quality issues, and the dynamics of coupled natural and human systems. In 2005, P.V. Sundareshwar obtained a major equipment grant through the NSF to establish the Biogeochemistry Core Facility; projects utilizing the analytical equipment in this lab and others led to work on wetland and stream biogeochemistry published in national and international journals (Sunsdareshwar 2009, 2011; Kunza and Hall 2013). As state carbon scientist, Sundareshwar also contributed to studies of the environmental impact of extraction, transportation, and use of coal (Sundareshwar 2011).

Researchers in the IAS have developed models and remote sensing techniques to simulate and monitor local and regional hydrologic processes. They also are developing tools applicable for mitigating sediment from agricultural practices and examining regional water resource issues (Das et al. 2004). Remote sensing is used for determining fire danger and burn severity, the hydrology of the post-fire environment, the vegetation stress, and for modeling of water deficiencies. Current and future emphasis is to establish the Black Hills as a laboratory to study fire weather processes and behavior. The state wildfire meteorologists had previously conducted research on the science of fire weather (Benson et al. 2009; Clabo 2017).

The IAS has been a driving force in high-end computing and visualization at SDSMT. Other departments involved include Electrical and Computer Engineering, Mathematics and Computer Science, and Mechanical Engineering.

With the retirement of the T-28 came the need for an archive of the airborne *in situ* observations obtained during the T-28's history of summer thunderstorm field projects. All digital data from projects occurring within the period 1989-2004 and all reports related to T-28 activity from 1969-2014 are housed in an

on-line archive maintained by the Earth Observing Laboratory at NCAR in Boulder, Colorado (https://www.eol.ucar.edu/field_projects/t-28; Detwiler et al. 2012). Data in this archive have been used to develop an observational climatology of the physical characteristics of storm interiors (Honomichl et al. 2013).

A recent NSF project entitled *He Sapa Bloketu Woecun* paired science with Native American culture through the exploration of special places in the Black Hills and surrounding area. Groups of Native American middle and high school students, along with a family member, participated in week-long summer camps in 2007 and 2008. Project scientists worked with several of the camp participants in preparing entries for the High Plains Regional Science Fair the following spring.

Other current research efforts include weather and climate-related impacts on infrastructure resilience; the dynamical interactions between neighboring convective storms and storm systems, meteorological education, and nutrient cycles in several rivers and streams in South Dakota and neighboring states.

Graduate research assistants. The IAS graduate research assistant population has been quite diverse. Nearly 40% of the over 200 graduates of the program are from foreign countries. Taiwan has provided the greatest share of these (32), being a major source of foreign students up to 1990. The People's Republic of China has provided the second largest contingent of foreign students (23); most of these have been post 1990. These are followed by India (10), Morocco (6), Romania and Thailand (3 each), Korea (2), Nepal (2) and one each from Bangladesh, Belize, Germany, Jordan, Russia, Ukraine, Vietnam, and Zimbabwe. The U.S. Agency for International Development foreign assistance program funded most of the students from Morocco and Thailand. Foreign student numbers dropped dramatically following restrictions put in place as a result of security concerns in the wake of the events of 9/11/2001.

Most states are represented by our American graduates. The largest contingent of these are from South Dakota, with strong representation from neighboring states and the upper Midwest. New York and Pennsylvania have provided the majority of students from eastern states. Several of our graduates came into our programs as a result of being stationed at Ellsworth Air Force Base; most of these were during the 1970s.

The majority of graduates from the M.S. program found employment as forecasters with the National Weather Service or commercial forecast providers, computer programmers in federal and state research laboratories, in air quality work either for consulting firms or government regulatory agencies, and a variety of other areas of the economy. Roughly one in four went on to earn Ph.D. degrees elsewhere, although in the last two decades several earned their Ph.D. through interdisciplinary Ph.D. programs at SDSMT. These graduates have gone mainly into academia and government research laboratories, although several have been successful in the commercial sector, some working in areas far removed from atmospheric science.

Summary. The IAS was established at SDSMT in 1959 in response to national and international interest in the science and practical application of cloud seeding to enhance rainfall and mitigate damage from hail. The Black Hills region was a natural laboratory for scientific studies and the western Dakotas are a semi-arid region plagued with high crop losses due to hail, making this region a natural home for such a research enterprise. Initial efforts involved a collaboration with agricultural interests at SDSU but in a short period, with generous federal support, the research effort at SDSMT ramped up and became independent of SDSU. Collaborations between SDSMT and other national and international institutions with strong research efforts in weather modification were established in the 1960s and 1970s. Research opportunities in weather modification began to diminish in the later 1970s. At the same time the research portfolio of the IAS began to broaden into regional energy-related weather and climate issues, air chemistry and air quality, regional-scale storm systems, and the science and application of radar and satellite remote sensing to weather and climate issues. A core effort in convective storm dynamics and physics continued. In the 1990s the local NWS forecast office moved to a site adjacent to campus and increased collaboration developed between the NWS and the IAS. In the late 1990s research efforts began to trend more toward Earth system science, while effort continued in the areas of remote sensing, storm physics, land-atmosphere interactions, and regional climate interactions. Researchers in the IAS were active members of national and international research communities in these fields.

The IAS was dissolved in 2012 and the atmospheric science researchers combined into a traditional academic department structure as its six Ph.D. researchers converted to tenure-track faculty in the Department of Atmospheric and Environmental Sciences. This situation lasted only a short time. In 2014, that department was eliminated. Atmospheric and environmental science faculty were assigned to other existing departments. Currently these faculty continue their ongoing atmospheric and environmental research efforts while beginning new interdisciplinary collaborations with their new departmental colleagues.

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