EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS

VOLUME 75 NUMBER 31

AUGUST 2, 1994

PAGES 353-368

Developing Service Promises Accurate Space Weather Forecasts in the Future

PAGES 353, 365, 366

G. Siscoe, E. Hildner, T. L. Killeen, L. J. Lanzerotti, and W. Lotko

Space storms—for our purposes, meaning all particle, electromagnetic, and ionospheric disturbances resulting from solar storms, coronal mass ejections, fast solar wind streams, and ionospheric instabilities—pose several costly hazards. They can impair hardware in space and disrupt power and communication grids on Earth and communications with satellites.

U.S. space weather services, as their operators acknowledge, fall short of providing the accurate, reliable forecasts their customers desire. The technological, scientific, and infrastructural resources exist, however, to significantly improve these services before the next solar maximum, expected around 2001.

A famous recent example of a disruption occurred in 1989 when a space storm brought down the Hydro-Quebec power system for 9 hours costing around $500 million, counting only losses from unserved demand. In January, a prolonged energetic-electron storm knocked out one Canadian communication satellite and forced another to resort to a backup system. Full service was restored after 6 months, but the lost revenue and the rescue operation cost the company about $200 million. During and after these events many other failures and degradations caused by space storms added to the total loss.

Annual losses attributable to space storms probably approach $100 million, and future costs could be greater. As power systems interlink and grow more complex to meet increased demand, their vulnerability to shutdowns by space storms increases. *Barnes and Van Dyke* [1990] estimate that if a space-storm-induced power outage were to occur in the northeast United States, it would cost $3–6 billion.

Communications and other service satellites—which now amount to around $50 billion in hardware in geosynchronous orbit (geosats)—also grow more vulnerable to space storms by the sheer explosion of their number. Low-altitude, polar-orbiting satellite constellations are scheduled for launch, while commercial geosats multiply to meet the growing Pacific market. Civilian and government use of the remarkable positioning capability of the Global Positioning Satellite (GPS) is becoming pervasive, and single-frequency users of GPS are susceptible to errors from ionospheric scintillations.

Accurate, specific space weather forecasts would allow customers to take cost- or service-saving evasive actions to reduce

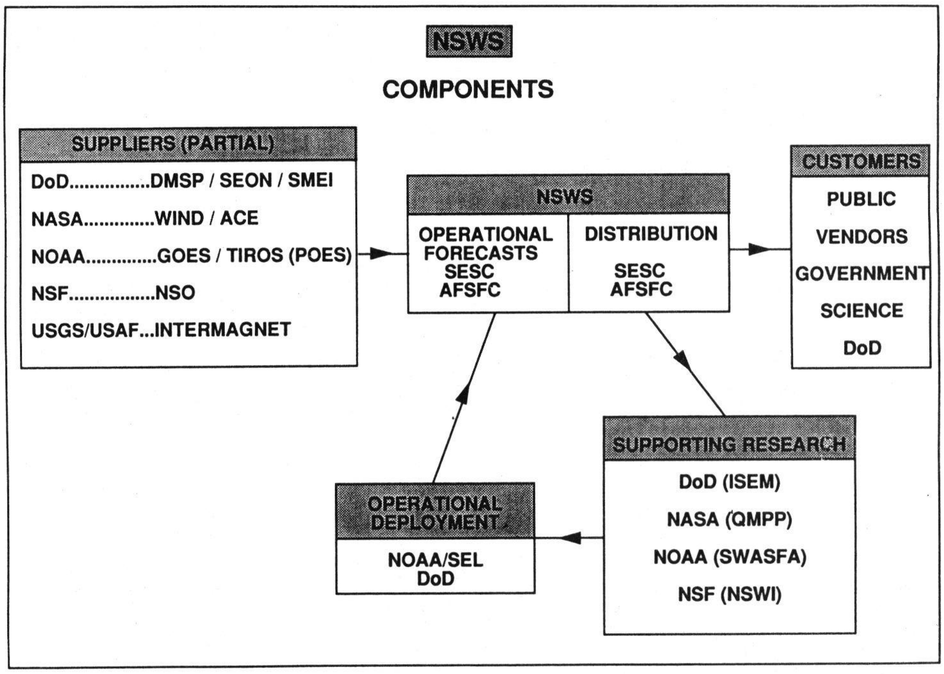

Fig. 1. The interagency components of a National Space Weather Service. The central group forms the NSWS operations office comprising the joint NOAA and USAF forecast offices that make and distribute space weather products. The other groups support the operations office. One group supplies real-time data, another enables research and advanced development, and another supports the operational deployment that produces operating forecast algorithms. To the right is a box listing five general types of customers. Some acronyms: DMSP, Defense Meteorological Satellite Program; SEON, Solar Electro-Optical Observing Network; SMEI, Solar Mass Ejection Imager; Wind, a solar-wind measuring spacecraft; ACE, Advanced Composition Explorer; GOES, Geostationary Operational Environmental Satellite; TIROS, Television and Infrared Observing Satellite; POES, Polar Orbiting Environmental Satellite; NSO, National Solar Observatory; Intermagnet, a global network of surface magnetometers.

G. Siscoe, Phillips Laboratory, 29 Randolph Rd., Hanscom AFB, MA 01731-3010; E. Hildner, NOAA Space Environment Laboratory, 325 Broadway, Boulder, CO 80303; T. L. Killeen, University of Michigan, Space Physics Research Laboratory, 2455 Hayward St., Ann Arbor, MI 48109; L. J. Lanzerotti, AT&T Bell Laboratory, 600 Mountain Ave., Murray Hill, NJ 07974; and W. Lotko, Dartmouth College, Thayer School of Engineering, Hanover, NH 03755

these hazards, disruptions, losses, and errors. For example, during January's eastern cold wave, the power industry proved that it can avoid outages by implementing a load-reducing routing procedure—good also for avoiding a space storm blackout. However, to do so, it must know in advance when and where to invoke such a procedure.

Similarly, satellite system operators can be on station alert to counter phantom commands and to reroute video transponders if they know in advance when and on which satellites to expect trouble. Currently, the nation's ability to forecast space weather lacks the accuracy and specificity to justify operators taking costly evasive actions. Too often, false positives would add to the losses, while false negatives would miss the savings. Many administrators in the agencies involved with space weather service and scientists in the space physics and aeronomy (SPA) community believe that accurate predictions can become a reality. The nation has the resources needed to evolve the present national space weather service into a full-service, state-of-the-science National Space Weather Service (NSWS) that can forecast with accuracy and specificity to permit cost-effective evasive actions.

The interagency infrastructure needed to create and support a NSWS includes the Department of Defense, NASA, the National Oceanic and Atmospheric Administration, and the National Science Foundation. At a meeting in March called by Robert Corell, assistant director for NSF's Directorate for Geosciences, we discussed the growing need for, possible structure of, and the scientific and technical capabilities necessary for a NSWS with leaders from four agencies and representatives from several affected industries. Corell volunteered to head an interagency executive committee to consider how to evolve from the present national space weather services toward a NSWS in the sense described above, and its first meeting took place in June. Its recommendation will be based in part on a report prepared, in cooperation with many SPA community members, by an interagency committee that will formulate an implementation plan.

Infrastructure for a National Space Weather Service

NOAA's National Weather Service (NWS), though larger than that envisioned for a NSWS, is a useful analog. The NWS delivers accurate tropospheric weather forecasts directly to weather-sensitive commercial sectors and, through the media, to the public. It also supplies weather data and related products to vendors of weather services.

The infrastructure underlying the success of the NWS has six elements. A central agency—the NWS—coordinates the gathering, analysis, and dissemination of weather data and products. A global network of observing stations supplies essential, real-time data and computers assimilate the data into an array of specification and prediction algorithms to generate numerical weather products. Forecasters integrate these products with other information from the NWS, like satellite imagery, to prepare regional, local, and tailored forecasts for distribution to customers, and a research community advances the state-of-the-art in data gathering, new data instruments and products, assimilation techniques, algorithm development, and interpretations. Finally, the NWS customer base is distributed over the society so that, while no single sector within the society could pay for the service, the total value of the service exceeds its cost.

Counterparts to these six infrastructural elements exist in the space weather field. Its civilian coordinating agency is NOAA's Space Environment Services Center (SESC), which forecasts and monitors geomagnetic storms, radiation hazards, and geomagnetic conditions, including intervals of geomagnetic calms. The Air Force Space Forecast Center (AFSFC) performs these tasks for the DoD, and the SESC and AFSFC share data sources and products. Together they could constitute a foundation on which to build an operational office of a NSWS.

The second element in the NSWS infrastructure is continuous, real-time receipt of essential data. SESC and AFSFC now receive energetic particle, solar X ray, magnetometer, trapped particle, and precipitating particle data from the Geostationary Operational Environmental Satellite, Television and Infrared Observing Satellite, and the Defense Meteorological Satellite Program. From ground observatories they obtain near-real-time solar optical, solar radio, neutron monitor, geomagnetic, riometer, and ionosonde data.

A crucial input for magnetospheric and ionospheric forecasting is missing, however, and that is upstream measurements of solar wind parameters including the interplanetary magnetic field (IMF). In the interest of space weather forecasting, NOAA, NASA, and DoD have reached an interagency agreement to secure the capability of receiving quasi-continuous, real-time solar wind and IMF data from NASA's Wind and Advanced Composition Explorer (ACE) spacecraft. Wind is scheduled for launch late in 1994; ACE, in 1997. These spacecraft will provide a suite of solar wind and IMF data to a NSWS through the next maximum of the solar activity cycle, which is expected to peak in 2001.

The third infrastructural element is numerical forecasting. AFSFC is putting into operational deployment over the next several years 10 numerical specification and forecast algorithms that cover the solar wind, the magnetosphere, the ionosphere, the thermosphere, and the integration of the outputs of these algorithms. The first of these algorithms, the magnetospheric specification model, will go into operation later this year. SESC will receive numerical specification products from the AFSFC algorithms on a per request basis.

The fourth element underlying a NSWS concerns forecasting personnel. SESC and AFSFC now employ forecasters to interpret the data and serve their customers. Nonetheless, the current infrastructure probably could not support the increase in data flow, space weather products, research management, and customer traffic that a full NSWS would. The number of agency forecasters may need to be increased. Part of the increased demands on operational personnel might be met by a latent industry of commercial, value-added vendors of space weather products.

The fifth element is an involved scientific community. For 3 decades a large expenditure of national resources has supported research in space physics and aeronomy. Professionals in these fields now possess a mature science ready to interpret space weather phenomena, develop specification and forecast algorithms, and establish new data sources. The creation of a comprehensive, state-of-the-science NSWS would give the nation a significant return on its investment in space physics and aeronomy.

The sixth essential element is the customer base. SESC serves 25 types of customers, such as power companies, communications satellites, and long-line telephone systems. The list continually grows. AFSFC also has many DoD customers. As SESC and AFSFC services improve during the upgrade to a NSWS, their customer bases would expand further. Customer reliance on these services would also increase as they become more accurate and specific.

There is a realistic potential to reduce the total losses from space storms by amounts significantly over the full cost of a NSWS operation, including its infrastructure. A quality-of-life benefit to society would be NSWS forecasts that reduce disruptions in services from industries sensitive to space weather. Avoiding a major power grid outage has considerable strategic value.

Another possible NSWS function would reside in an office for developing and marketing the applied aspects of solar-terrestrial "climate." This office would make longer-term forecasts, like solar rotation, seasonal, and solar activity cycle forecasts, and a NSWS space climate office would foster the application of Sun-climate research as this field matures. Here too, applications to determine changes in the upper atmosphere resulting from anthropogenic influences might develop.

Vision of a National Space Weather Service

Unlike the NWS, whose infrastructure remains largely within one agency, a NSWS would probably start out as a multiagency entity. Figure 1 shows a possible grouping of agencies that could make up its infrastructure.

In this scenario, the "Suppliers" supply real- and near-real-time data to SESC and AFSFC. Research leading to algorithm development and deployment makes a loop that circulates from "Supporting-Research" to "Operational-Deployment" to "Operational-Forecasts" back to "Supporting-Research." Closing the loop this way provides feedback that tells the research community what improvements to build into the next generation of algorithms and what algorithms to add. It also provides a valuable check on the validity of the science underlying the prediction algorithms. This check is the payoff for SPA science. In the "Customers" box, "Public" includes the commercial sectors of communication satellite systems, the power industry, and surface telecommunication networks. Other potential customers are insurance companies needing to compute actuarial tables on the risks of space storm losses. A new industry of vendors would emerge to supply value added, tailored space weather products to these space-sensitive businesses. This vendor industry would in turn be a customer of the NSWS, just as commercial vendors of weather products are customers of the NWS.

Relation to SPA

There is a considerable gap between today's forecasting ability and that which a NWS-quality NSWS would provide. The gap will shrink as AFSFC's "in press" library of numerical forecast algorithms sequences into operation. Power companies, satellite operators, and other customers want warnings based on quantitative spatially and temporally specific information. Even AFSFC's library of numerical forecast algorithms is not intended to meet the needs of the commercial sector. Also, being the first generation of such models, they do not incorporate the full capability of SPA science.

The importance of developing a full-service, state-of-the-science numerical space weather forecast capability cannot be overstressed. Numerical weather prediction was institutionalized within the U.S. Weather Bureau (later the NWS) nearly 40 years ago. Today, numerical weather prediction forms the foundation of modern weather forecasting, with over 95% of the centralized NWS forecasting being done by automated numerical codes. The NWS uses several versions of forecast codes based on different approaches to formulating the physics or the mathematics of the problem. The NWS still works to improve its codes, for example, by extending their applicability to longer-range forecasting and to smaller-scale forecasting.

In a NSWS setting, the first-generation space numerical weather prediction codes being transitioned to operational deployment at the AFSFC are analogous to early tropospheric numerical weather prediction codes. Supplementing and augmenting these codes and creating alternative versions of them for implementation within a NSWS, like the multiple, yet nonredundant, codes within the NWS, represent opportunities for continued application of SPA science. Such applications entail implementing supporting research programs aimed at improving the understanding of the physics that underlies space weather phenomena.

At the same time, a NSWS needs support from SPA science in the form of new empirical approaches to space environment specification and forecasting. Allied to this, the supporting-research programs need specific, relevant data for guidance and testing. Both needs call for observing components to the supporting-research programs. Space physicists and aeronomers should be trained to be familiar with space weather phenomenology, space weather impacts on society, and space weather forecasting procedures and codes.

If achieved, a full-service NSWS will benefit the nation through providing cost-saving and quality-of-life-enhancing forecasts, and it will benefit the SPA community by providing a customer for its science (a NSWS) with national strategic importance.

Acknowledgments

Many people have contributed to the development of a National Weather Service. They include Richard Behnke, Robert Carovillano, Timothy Eastman, John Freeman, Michael Heinemann, John Kappenman, Nelson Maynard, Rita Sagalyn, and Thomas Tascione. We also thank Santimay and Sunanda Basu, Odile de la Beaujardiere, Robert Robinson, and David Sime for suggestions for improving this article.

References

Barnes, P. R., and J. W. Van Dyke, Potential economic costs from geomagnetic storms, *IEEE Spectrum*, March 1990.

An Appreciation of Paul A. Siple

PAGES 355, 361

Robert F. Benson

A major inspiration for writing this long overdue appreciation of Paul A. Siple was a wind chill temperature in Washington D.C. of -39°F.

Other inspirations have come over the years from colleagues who either know about Paul Siple or Siple Station but not both. In 1957 I had the unique fortune to spend a year with Paul Siple as a scientific member of the first wintering-over party at the U.S. Amundsen-Scott South Pole Station at 90°S. He was the leader of the station during the first winter of the International Geophysical Year (IGY) 1956–1957.

So, what does all this have to do with wind-chill during a record-breaking cold January day in Washington? This "wind chill temperature," a common term used in daily weather reporting on cold winter days, has its origin in the "Wind Chill Index" specifically designed for Antarctic conditions, which was introduced in Siple's 1939 Ph.D. dissertation. It was developed to simplify the complicated formulas for expressing the relative comfort scales of different weather conditions. The motivation for this goal came from experience gained by Paul Siple during the first two Byrd Antarctic expeditions. As stated by Siple and C. F. Passel in 1945: "Perhaps there is no place on Earth where one is so acutely aware of the need for a suitable scale to express sensible temperatures as the polar regions. Here there is striking contrast between relatively tolerable days of calm, subzero weather, and windy days that are warmer although sensibly much more unpleasant."

Code 692, Goddard Space Flight Center, Greenbelt, MD 20771

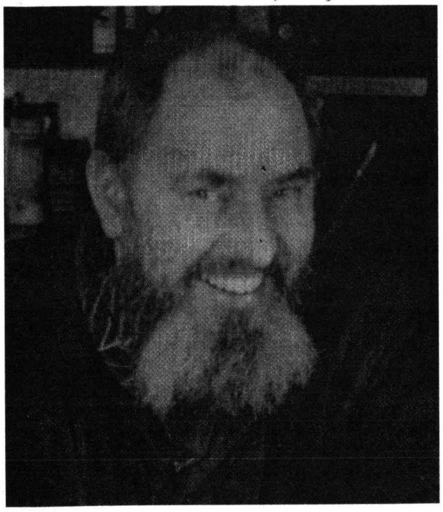

Fig. 1. Paul A. Siple in the Amundsen-Scott South Pole Station library in 1957 [courtesy of Robert F. Benson].

The wind chill index was refined based on research carried out during Siple's third expedition to Antarctica from 1939 to 1941. During this expedition, he was geographer