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# A Culture of Improving Forecasts: Lessons From Meteorology

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Space weather forecasting, like all forecasting, is challenging. Nevertheless, it has the advantage that as a young field it can look to the older field of terrestrial weather forecasting for guidance. Terrestrial weather forecasting enjoys enviable success from the perspective of space weather forecasters, who can learn from the experience of terrestrial weather forecasters as far as circumstances allow.

There is, however, a lesson from forecast meteorology that could have a bigger impact on space weather forecasting if learned not by practicing forecasters but by the general space weather research community: A significant benefit to both research and practice can result when the research community in general is familiar with the problems and the methods of the forecast community. This is a comment about the culture of the community in which space weather research and space weather operations are embedded.

## Comparisons Between the Culture of Terrestrial and Space Weather Forecasting

The orientation of the terrestrial meteorological community, including its research community, is by and large in the direction of improving forecasts. Most researchers in meteorology might not consciously recognize this, but program managers and agency heads apparently do, as evidenced by research programs that they define and support. Moreover, it imbues research meteorology as a community trait, like a shared language. Meteorologists acquire the trait from their undergraduate and graduate courses and from the example of professional icons such as Carl-Gustaf Rossby, Jacob Bjerknes, John von Neumann, Edward Lorenz, and Jule Charney. The result is coherent, discipline-wide progress, discernable against the separate advances of intradiscipline specialties, that moves the full front of operational forecasting forward. Orientation toward improved forecasts, be it of storms, global warming, or the ozone hole, constitutes a binding and supportive matrix within which the whole discipline is consciously or unconsciously embedded.

By contrast, space weather forecasting exists largely in isolation, both institutionally and culturally, from most of the space weather research community. This situation is changing at the institutional level, for example, with the advent in 1995 in the United States of the multiagency National Space Weather Program (http://www.nswp.gov) and in 2000 with NASA's Living With a Star program (http://lws.gsfc.nasa.gov). Internationally, the European Space Agency has held yearly space weather workshops since 2000 (http://www.esa-spaceweather.net).

Despite these strides toward discipline coordination, space weather forecasting is still largely isolated at the cultural level. One reason is that space physicists hail mostly from physics programs, which do not teach space weather forecasting. The field's heroes include Sydney Chapman, Hannes AlfvÃ©n, James van Allen, Eugene Parker, Jim Dungey, and Sir Ian Axfordâ€“all great physicists but not active contributors to developing tools for forecasting. An exception is Syun-Ichi Akasofu, who has pioneered space weather forecasting at the University of Alaska. But this exception proves the rule since Akasofu was trained as a meteorologist.

The difference in cultural attitudes toward forecasting in the terrestrial weather and space weather fields is in large measure historically based. The field of meteorology began to receive institutional funding in the mid-1800s when it became possible actually to forecast storms (however imperfectly). Thus the field advanced with the mindset that improving forecasting meant improving funding. By contrast, the field of space physics began to receive funding in response to the launch of Sputnik (the first artificial satellite) in 1957 and Yuri Gagarin (the first human in space) in 1961. The role of space physics at this time was not to forecast space storms; it was to complement the Apollo program in countering the perception on the part of unaligned nations that the USSR had the lead in space technology [e.g., *McDougall*, 1985].

Now that the Cold War is over, the national need that fostered space physics no longer exists as acutely as before. Meanwhile, however, "space meteorology" (a phrase used here to signify the discipline that studies space weather and develops responses to it) has emerged also to meet a national need and now supplements space physics as a reason to research the space environment. Thinking that the disciplines of space physics and space meteorology might function better as a united field and so emulate the success of terrestrial meteorology, researchers should ask, How does the union work so well in the case of terrestrial meteorology? An answer lies in part in its history.

## Lessons From the History of Forecast Meteorology

One can recognize 10 cumulative stages through which terrestrial forecast meteorology has evolved [*Siscoe,* 2006]. Stage 1â€“the "impacts" stageâ€“emerged in prehistory when farmers and mariners realized they could benefit from storm warnings. This gave rise to stage 2, the "sky signs" period, when early humans used meteorological observables such as solar haloes to predict approaching storms associated with warm fronts (although not understood as such) and towering cumulus clouds to see the approach of thunderstorms. These worked with regularity but could only forecast up to about 12 hours ahead.

Millennia passed before stage 3â€“the "instrument-based forecasts" stageâ€“began in the seventeenth century with the inventions of the barometer, thermometer, hygrometer, and anemometer. In isolation, such forecasts added little to weather prediction, but taken simultaneously at widely separated sites as became possible early in the nineteenth century and displayed retrospectively on a map, they ushered in stage 4â€“the era of synoptic studies of storm systems. Such studies revealed that midlatitude storms were big and moved in general from west to east, which meant that in principle they could be predicted days in advance were it possible to send information ahead of the storm. However, since storms typically travel faster than horses, such predictions needed the electric telegraph and an extensive telegraphic network feeding data to a central bureau, a condition realized in various countries in the 1850s and 1860s (stage 5). This stage marks when meteorology became publicly funded and the business of forecasting grew serious.

Models of storms emerged in the last half of the nineteenth century, taking forms of eastward migrating low-pressure areas sectioned into compartments where particular weather types prevailed (stage 6). Predictions based on such models were subjectiveâ€“given the same data and the same model, two forecasters often predicted different weather scenarios. Subjective forecasts improved radically in the 1920s after Jacob Bjerknes introduced the polar front theory of extratropical cyclones (stage 7). With their choreographed waltz of cold and warm fronts pivoting around an eastward gliding low-pressure center, Bjerknes showed that storms evolved predictably as they moved. Stage 7, though improved over stage 6, was similarly subjective, which in reaction brought "objective" forecasting (stage 8). Objective forecasts (statistical forecasts) typically used correlation formulas obtained by multiple regression analysis, giving, for example, the probability of rain versus barometric trends. In this, they divorced the forecast from the forecaster.

The 1950s brought a dramatic revolution in forecast meteorology when electronic computers became powerful enough to integrate the dynamic equations that govern atmospheric motion, thus issuing in the present era of numerical weather predictions (stage 9) [*Cressman,* 1996]. Stage 10 comprises real-time storm tracking by satellite and radar imagery.

The improvement that numerical predictions eventually made to forecast range and accuracy cannot be overstated [*Fishman and Kalish,* 1994; *Nebeker,* 1995]. Figure 1 makes the point graphically. It shows that the skill in the 36-hour forecast of the height of the 500-mbar surface (which divides the atmosphere about in half in terms of the amount of mass above it and below it) over the United States has increased from about 33% in 1955, when numerical prediction was inaugurated at the U.S. Weather Bureau, to 98% by the 1990s. The entire increase in skill can be attributed to numerical forecasting and associated increased power of computers.

The graph teaches two lessons of paramount importance to space weather: (1) Once a field reaches the stage of numerical predictions based on integrating the operative dynamical equations, it is guaranteed to move up the slope of increasing skill over time; and (2) increases in skill will be incremental, not discontinuous.

Lesson 1 follows from the fact that in numerically simulating the laws of nature itself, forecast failure simply means imperfect simulation. Failures tell how better to implement numerical integration algorithms (e.g., better parameterization of sub-grid-scale processes, better data assimilation, etc.). Lesson 2 has the immensely important corollary that the sooner one begins numerical forecasting, the sooner one starts moving up the skill curve. Meteorologists stress that one cannot start at the top of this curveâ€“one must climb there. If one wants to start at the top, one will never start. This has the major operational implication that you cannot just design such a forecast code and then leave it in the hands of the forecasters. Instead, a continual process of forecaster feedbacks guiding code-maker upgrades is needed.

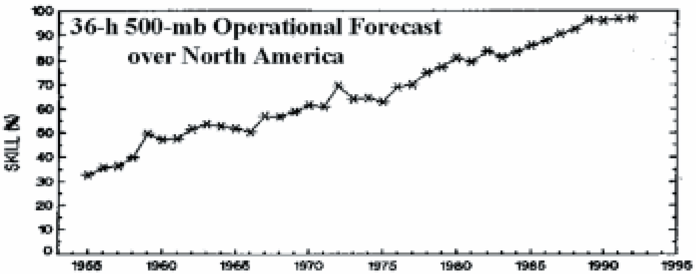

**Figure 1.** Forecast skill from 1955 to 1992 in the 36-hour predicted height of the 500-mbar surface over the United States, showing the escalator effect on skill that occurs once forecasting bases predictions on numerical integrations of the equations of motion (stage 9) [*McPherson,* 1994].

## Lessons Applied to Space Weather Forecasting

To see how these lessons apply, consider the stages through which space weather forecasting has progressed. Analogs exist to all cumulative stages of forecast meteorology. The space weather impacts stage (stage 1) began in the middle of the nineteenth century when magnetic storms disrupted electric telegraph communications. Radio, electric power transmission, commercial and military satellites, and other electrically enabled technologies have since been affected. Stage 2, forecasting by sky signs, developed between about 1850 and 1950 as auroras, sunspots, and solar flares were found to correlate with disturbances of these technologies.

In stage 3 (instrument-based forecasts), the magnetometer became the space weather forecaster's barometer, whose dispersal in ground-based networks revealed magnetic storms to be globalâ€“the synoptic stage 4. Governments began funding space weather forecast centers during World War II to assist radio communications (stage 5). These centers developed qualitative forecast rules based, at first, on the corotation of solar streams and the preflare dynamics of solar active regions. This represents the subjective stages 6 and 7. As Figure 2 indicates by an absence of an upward slope in the skill, operational space weather forecasting still lies mainly within this stage (using more indicators than here named, however).

Nonetheless, operational objective forecast algorithms (stage 8) are becoming increasingly evident in predicting parameters such as solar wind speed and the magnetic disturbance indices Ap and Kp. Indeed, the field seems to be entering a golden age of objective forecasting with the research community developing empirically based nowcast and forecast algorithms for most space weather elements of interest, such as the storm index (Dst), coronal mass ejections (CMEs), shock arrival times, CME magnetic structure, radiation belt electrons, energetic particle fluxes at synchronous orbit, global ionospheric total electron content (TEC), and more.

This emphasis on objective forecast algorithms reflects a difficulty that space weather forecasting is having in moving to stage 9: numerical predictions. Two academic efforts are under way to achieve this stage, one at the University of Michigan and the other a consortium led by Boston University, but operational implementation of these efforts lies in the indefinite future. Here is where one lesson from forecast meteorologyâ€“start operational numerical predictions as soon as possible and stick with it in a feedback and upgrade process for as long as necessaryâ€“would seem to apply. If implemented, this imperative could move the field onto the rising curve of skill faster than possible with the current course.

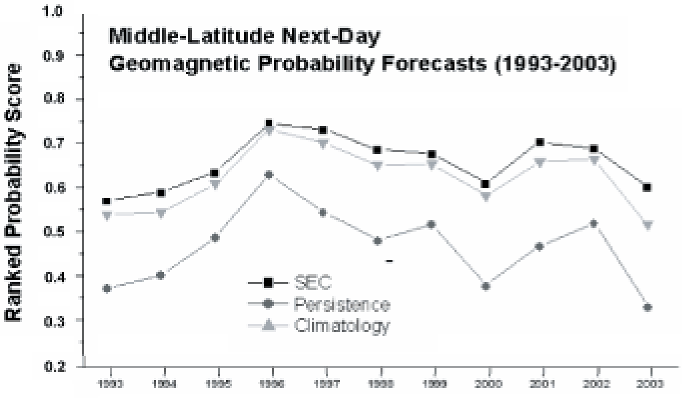

**Figure 2.** Forecast skill from 1993 to 2003 in the 24-hour predicted Ap index (modified from NOAA's Space Environment Center Web site). The Center's current forecast skill using subjective forecast techniques is contrasted with skill based on persistence (tomorrow's

Ap will be the same as today's) and climatology (the statistical average).

## Changing the Culture of Space Weather Science

There is a cultural impediment to automatically moving space weather into the realm of operational numerical modeling (stage 9), which brings the discussion back to the primary lesson from forecast meteorology: Instill a discipline-wide orientation toward improving forecasts. This cultural impediment is simply that the trained physicists who develop physics-based codes aimed at space weather forecasting naturally wish not to release their codes until they are perfect. From the viewpoint of the forecast meteorologist, this is like wanting to start at the top of the skill curve with the perfect code, which they know from experience is impossible without the corrective guidance that operational forecasting provides. But so far in space weather, physics imperative trumps forecast imperative.

How might this be reversed? Maybe two other keys to the success of forecast meteorology hold the answer: teaching forecasting as standard curricula and private sector forecasting.

Meteorology students are taught weather forecasting. They learn what parameters professional forecasters actually predict and the techniques for doing it. They compete weekly with students from other schools to predict the weather for 1 week at some specified location. They get frustrated by the limitations of current forecasting tools. So when they become researchers, they are motivated to improve the tools [*Houghton*, 1996].

Space physics students are not taught forecasting. They do not know what professional space weather forecasters (who mostly are trained in meteorology) are tasked to predict (there is no call for Dst, for instance). They do not become frustrated by trying to predict the daily Ap index 3 days ahead. When they become researchers, they are not motivated to improve forecast tools, since they do not know what they are.

Boston University yearly holds an excellent 2-week summer school on space weather forecasting, and the U.S. National Center for Atmospheric Research last year held a 2-week summer school on space weather that included forecasting. Were these examples multiplied, some in the next generation of space physicists might opt for the forecast imperative over the physics imperative.

Finally, forecast meteorology benefits enormously from the leverage it receives from private sector vendors. The Weather Channel and the USA Today weather page illustrate the point. Customer pull is an incentive that strongly motivates everyone involved in providing forecasts to improve the scope and quality of forecast services. Should space weather develop a strong vendor sector [*Fisher*, 2004], customer pull might make the forecast imperative more interesting even to physicists.

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