

# The Adjoint Workshop Series

(Excerpted from the proposal to NSF for workshop support)

## Introduction

Model adjoints are powerful, but still under-utilized tools for efficiently estimating sensitivities of aspects of model forecasts with respect to possible small, but significant, perturbations of model input. Their potential applications include all problems for which estimates of sensitivity would be useful. In dynamic meteorology, these applications include data assimilation, dynamic stability analysis, ensemble forecasting, observation targeting, synoptic studies, and parameter estimation. Some climate study applications have also been proposed.

The Adjoint Workshops are intended to expedite the exchange of ideas regarding the many applications of adjoint models and to correct misconceptions or errors that have been identified. For these reasons, the workshops are designed to maximize scientific dialog. Substantial time is reserved for discussion, not just questioning, after each presentation. Unlike at most other venues, presentation time limits are therefore strictly enforced, but the subsequent discussion periods remains open-ended. Participants attend not simply to witness presentations but rather to hear what others have to say in response to them.

Each session begins with a review or tutorial. Additional evening presentations are offered on more speculative or review topics. All presenters are explicitly encouraged to “teach the audience about a few things you have learned from your work rather than advertise the many things you have done.” For this reason, the quality of presentations is very high, with enough detail offered so that the audience can contribute critical comments and assessments. All participants depart claiming that they have learned much and have been stimulated by the extended, highly focused discussions.

There have been 7 Adjoint Workshops (as they are more commonly called) thus far: 1992 in Pacific Grove, CA; 1995 in Visegrad, Hungary; 1998 in Lennoxville, Quebec; 2000 in Moliets-et-Maa, France, 2002 in Mount Bethel, PA, 2004 in Aquafredda di Maratea, Italy, and 2006 in Obergurgl Austria. Except for the 7<sup>th</sup> workshop, their locations have alternated between North America and Europe. Four workshops have been described in Errico et al. (1993 *BAMS*), Prager et al. (1995 *BAMS*), Errico (2003 *BAMS*), Errico and Ehrendorfer (2007 *BAMS*) and Ehrendorfer and Errico (2007 *Meteorol. Z.*). Issues of *Tellus* (October 1993) and *Meteorologische Zeitschrift* (December 2007) have been devoted to the workshop presentations.

The specification of “dynamic meteorology” in the workshop’s title was originally introduced to limit its attractiveness so that its size would be reasonable. From the first, however, it has attracted presenters with other expertise. This includes oceanographers, atmospheric chemists, and engineers who are utilizing adjoints as well as meteorologists using alternative techniques in applications that otherwise would use an adjoint model.

Examples of the latter include the Kalman filter and ensemble techniques for data assimilation. Attendance has been fairly steady, with at least 70 participants and 60 presenters. Generally, about half of the attendees are from Europe and half from North America. Almost all participants attend every session, including the last.

The workshop venues are also chosen to maximize opportunities for interactions. Our selection criteria are: (1) a self-contained site, providing accommodations, meeting rooms and all meal services; (2) a location in a pleasant environment that, however, is not near major attractions that would serve as distractions; (3) a location within 90 minutes from an international airport easily accessible from both Europe and North America; (4) a good conference room accommodating a large screen visible to all; (5) a lounge serving beer and wine for evening gatherings so that the group remains together; (6) a relatively inexpensive total cost per person. Under these conditions students and senior personnel have many opportunities to discuss issues at length. By keeping participant costs low, organizations or schools can afford to send multiple persons. Past workshops have been extraordinarily inexpensive at \$200-\$500 per person for the full five days total cost, excluding transportation.

These workshops have been open to all who wish to attend, although in the past our ability to advertise has been limited. For the 8th workshop, however, the AMS Bulletin will list it with upcoming meetings. One likely change in the format will be to include an extended lecture on adjoint model fundamentals geared to students.

Financial support for the 8<sup>th</sup> Adjoint Workshop will be provided by the U.S. National Science Foundation (NSF) and the Global Modeling and Assimilation Office (GMAO) at NASA's Goddard Space Flight Center. Those funds will be administered by the Joint Office for Scientific Support (JOSS) at UCAR and the Goddard Earth Sciences and Technology Center (GEST) at UMBC, respectively, as directed by the workshop organizing committee.

Ronald Errico (UMBC) is the chief organizer for the 8<sup>th</sup> workshop, as he has been for 5 of the previous 7. Other members of the 8<sup>th</sup> workshop's organizing committee include Martin Ehrendorfer (formerly U. Reading and U. Innsbruck), Jeff Kepert (BMRC), Liang Xu (NRL), Saroja Polavaparu (AEC), Jan Barkmeijer (KNMI), Susan Ballard (UKMO), Gerald Desroziers (Meteo-France), Carla Cardinali (ECMWF), and Runhua Yang (SSAI).

## **Expected Impact**

The past workshops have served not only to acquaint researchers with the latest works being performed but also have provided a public evaluation of those works. They have provided expert elucidations of outstanding issues and historical reviews to help place both current and planned works in an informed perspective. They have suggested new avenues of work and have corrected errors in present works. Novices who sometimes have found themselves in environments where adjoint techniques were foreign have been

encouraged. The workshops have also encouraged conduction of corroborative experiments and system inter-comparisons, demonstrating the robustness of past results. Examples of all these past impacts can be provided. Partly as a consequence of the Adjoint Workshops, dynamic meteorology is now generally considered the scientific and technical field with the most advanced adjoint model applications. The next planned workshop will be held 3 years after the previous one, and is being designed to sustain and extend the past proven successes.

The advantage of an adjoint-based 4DVAR system for data assimilation has been amply demonstrated. While, based on heuristic arguments, many investigators had regarded tropopause potential vorticity as supremely important for weather forecasting, adjoint models have shown the much more critical dependence on temperature just above the planetary boundary layer. As profoundly, adjoints have also shown the importance of moisture on barotropic vorticity forecasts in precipitating regions and of temperature on predicting precipitation. Severely undesirable consequences of using nudging techniques for mesoscale data assimilation also have been revealed. That growth rates of forecast errors can be much more rapid locally than previously thought has been demonstrated, requiring consideration of non-modal error structures. Unexpected sensitivities of forecasts with respect to observation errors have been revealed and explained. Since adjoint models are based on and consistent with numerical models at the pinnacle of meteorological research, all these results have been confirmed in the most sophisticated modeling contexts. Although most of these results actually concern fundamental properties of atmospheric dynamics and modeling, they had been unknown until revealed using adjoint techniques. References supporting all of these claims can be provided upon request or in a formal proposal.

Although the impact of adjoint modeling on meteorology has not yet been universally recognized, it has already been truly profound. Yet, much more development and application remains, with potential for further, equally profound impacts. Such are expected because adjoints explicitly and efficiently provide quantitative answers to many of our fundamental questions concerning forecast sensitivity.