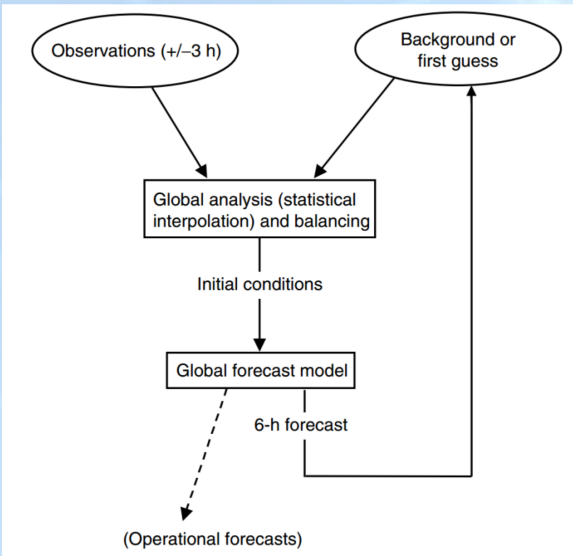
196

TEACHING DATA ASSIMILATION TO UNDERGRADUATES AT THE UNIVERSITY OF GEORGIA

John A. Knox (johnknox@uga.edu)
Department of Geography, University of Georgia, Athens, GA

1. WHAT IS DATA ASSIMILATION?

Data assimilation (DA) is the process by which observational data are optimally incorporated into forecasts of time-evolving phenomena. The subject was pioneered in weather forecasting, and now extends to oceanography, space weather and ecology, to name but a few applications. According to Harvard dynamicist and data assimilation expert Allan Robinson (NPS website), "*The purpose of data assimilation is to provide better estimates than can be obtained by only the data or the model.*" A graphical flowchart of this process (from Kalnay 2003, Fig. 5.1.2) is shown at right. This **melding of data and model** requires an understanding of model physics and dynamics, plus calculus and statistics.

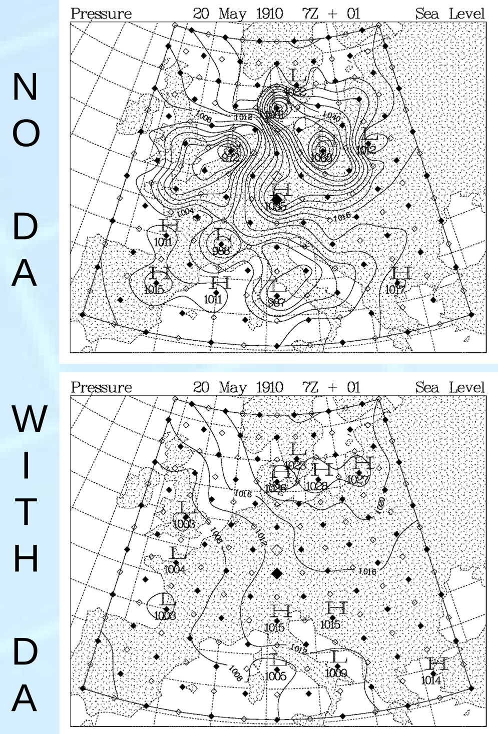


2. WHY SHOULD I CARE?

The first numerical weather forecast (Richardson 1922; LFR) failed miserably because of the lack of data assimilation (unknown in 1922), specifically the insertion of unbalanced wind and mass data into LFR's equations. The imbalance of wind and pressure led to spurious gravity waves that spoiled the solution (top graphic). Lynch (2006) proved that with balancing via initialization (the middle boxed step in Kalnay's graphic at left), LFR's forecast would have been accurate to within 1 hPa (bottom graphic).

NO DA

WITH DA



Advances in the use of variational methods of data assimilation in the past two decades have allowed satellite data to be incorporated into model forecasts. Satellite data now compose more than 99% of the data ingested in the numerical weather forecast process. The use of satellite data has enabled weather forecasts in the once-data-sparse Southern Hemisphere to "catch up" and become nearly as accurate as Northern Hemisphere forecasts. The superior performance of the ECMWF model versus U.S. models is often attributed in part to the sophisticated data assimilation techniques employed at ECMWF (Ackerman and Knox 2015). In short, **data assimilation is the engine behind better numerical weather prediction.**

3. TO WHOM DO WE TEACH DATA ASSIMILATION?

Undergraduate programs in meteorology in the U.S. are near historic highs in enrollment and degree recipients (Knox 2008), and most of these undergraduates are interested in weather forecasting. Despite the close connections between data assimilation and weather forecasting, however, **data assimilation education during the past decade has been targeted at the graduate students, and/or outside of meteorology altogether**.

For example, Fritsch and Carbone (2004, p. 959) noted "a serious deficiency in human resources working on data assimilation." They called for the U.S. Weather Research Program to "promptly consider focused actions to stimulate education and training in data assimilation" that "could include the entrainment of young scholars from applied mathematics and other fields of science"—but not from within meteorology itself! Vukicevic et al. (2004) called for a national data assimilation education program, noting that graduate-level courses at a few institutions were not enough, because they "do not reach out to the wider pool of future professionals at the B.S., M.S., and Ph.D. levels…" Rienecker (2008 AMS Annual Meeting) discussed the shortfall in human resources in practical terms: "understanding DA requires a level of mathematical sophistication that most students simply do not have… students are averse to this."

But *are* students unprepared for/averse to data assimilation? Undergraduates in meteorology are expected to have the training in math, statistics, and atmospheric science necessary to understand data assimilation. Furthermore, in a tight (and tightening) job market in weather forecasting, could students be enticed to "stretch" in order to master the latest advances in a subject they love? To explore these possibilities, **beginning in 2003 I embarked on a decade-long project to develop an undergraduate-focused data assimilation course at the University of Georgia (UGA).**

4. DATA ASSIMILATION AT UGA: SPRING 2003

Course Title: GEOG/ENGR 4113/6113+L Introduction to Geophysical Fluid Dynamics With Applications
Students: **10** (including 2 graduate students)
Texts: Holton (1992), chapter 13
Topics Covered: **One-week module on data assimilation, including analogies between physical and social systems.** Geostrophic adjustment and Rossby radius of deformation; the initialization problem; nonlinear normal mode initialization; variational data assimilation.
Evaluations: **anonymous pre- and post-module assessments were conducted:**

Question	Pre-Module	Post-Module
Do you know what DA is?	0.5/10 (5%)	9/9 (100%)
How interested are you in DA?	Very: 10% Somewhat: 50% A Little: 30% Not at All: 0% Don't Know: 30%	Very: 22% Somewhat: 56% A Little: 22% Not at All: 0% Don't Know: 0%
How important is DA to NWP?	Very: 50% Somewhat: 20% A Little: 0% Not at All: 0% Don't Know: 30%	Very: 100% Somewhat: 0% A Little: 0% Not at All: 0% Don't Know: 0%
How effective were the analogies?	N/A	Very: 78% Somewhat: 22%
Would you recommend a UGA DA course?	N/A	**Yes: 100% No: 0%**
What level should the DA course be at?	N/A	Undergrad/Grad: 88% Grad only: 12%

5. DATA ASSIMILATION AT UGA: FALL 2004 and FALL 2007

Course Title: GEOG/ENGR 4180/6180 Special Topics in Atmospheric Sciences: Introduction to Data Assimilation
Funding: "The Assimilation Process in the Earth, Space and Social Sciences" (PI), Georgia Space Grant
Students: **Fall 2004: 5** (including 1 graduate student); **Fall 2007: 7** (including 1 graduate student)
Texts: Daley (1991); Kalnay (2003) required for graduate students, recommended for undergrads
Topics Covered: **Semester-long course**, including history of data assimilation, the "rejection problem," adjustment to balance, balance constraints, nonlinear normal mode initialization, and variational data assimilation.
Special Features: **biweekly Assimilation Movie Nights linking physical and social assimilation concepts: *Star Trek: The Next Generation* "Best of Both Worlds"; *Apollo 13*; Challenger disaster and *Groupthink*; *Carrie*; *Tuskegee Airmen*; *Avalon*.**

Evaluations:
- Undergraduate teaching evaluations (1-5, 1=best): Fall 2004: 1.33; Fall 2007: 1.00.
- ABET learning outcomes: 4.0-4.5 out of possible 5
- Student grades: Fall 2004: 88-92%; Fall 2007: 75%-94%.

6. DATA ASSIMILATION AT UGA: QUALITATIVE EVALUATIONS

Fall 2004 student Jarrett Bachman (8 years later):
…As someone now halfway through a PhD program, it is still the most difficult class I've ever taken. However, I really enjoyed the class. It remains one of my favorites as well. Learning how to incorporate action with simulation/observation with forecast was a great experience, especially following the set of core atmo sci as an undergrad. The course certainly assisted my ability to comprehend and perform during my [Hollings Scholarship] undergrad internship with NOAA in Taunton, MA… It is a course I have highly recommended to younger students and is one that comes with great difficulty and personal satisfaction…

Fall 2007 student Jonathan Tarantino (5 years later):
Out of all of my classes I ever took at UGA, both undergrad and graduate levels, Dr. Knox's Data Assimilation class was the most challenging yet rewarding class… I am still able to refer back to [the] class and quote specific pieces of information to explain to my friends why we can use satellite data to make weather forecasts. The most influential effect from this class was it marked the starting point when I started to think deeper in class rather than just taking in the information presented for granted…

7. DATA ASSIMILATION AT UGA: SPRING 2013

Course Title: GEOG 4116/6116+L Introduction to Data Assimilation
Funding: Summer 2012 Innovative Instruction Faculty Grant (PI), UGA
Students: **17** (including 2 graduate students)
Texts: Daley (1991) and Kalnay (2003) both required; Lahoz et al. (2010) recommended for graduate students.
Topics Covered: **Semester-long course** covering history of data assimilation, the "rejection problem," adjustment to balance, balance constraints, nonlinear normal mode initialization, variational data assimilation, Kalman filter methods and applications to different disciplines and data types.
Special Features: **Weekly computer lab using Data Assimilation Research Testbed (DART) and other data assimilation software; biweekly Assimilation Movie Nights.**

8. SUMMARY AND CONCLUSIONS

During the past decade, an Introduction to Data Assimilation course has been developed at the University of Georgia. Student feedback strongly suggests that data assimilation is teachable and rewarding for students at the undergraduate level. I encourage instructors at other institutions to pursue this line of innovative undergraduate teaching.

9. REFERENCES

- Ackerman, S.A., and J.A. Knox, 2015: *Meteorology: Understanding the Atmosphere* (4th ed.). Jones & Bartlett.
- Daley, R., 1991: *Atmospheric Data Analysis*. Cambridge University Press, 457 pp.
- Fritsch, J. Michael, R. E. Carbone, 2004: Improving Quantitative Precipitation Forecasts in the Warm Season: A USWRP Research and Development Strategy. *Bull. Amer. Meteor. Soc.*, **85**, 955–965.
- Holton, J. R., 1992: *An Introduction to Dynamic Meteorology* (3rd ed.). Academic Press, 511 pp.
- Kalnay, E., 2003: *Atmospheric Modeling, Data Assimilation and Predictability*. Cambridge Univ. Press, 341 pp.
- Knox, John A., 2008: Recent and Future Trends in U.S. Undergraduate Meteorology Enrollments, Degree Recipients, and Employment Opportunities. *Bull. Amer. Meteor. Soc.*, **89**, 873–883.
- Lahoz, W., B. Khattatov, and R. Menard, 2010: *Data Assimilation: Making Sense of Observations*. Springer, 732 pp.
- Lynch, P., 2006: *The Emergence of Numerical Weather Prediction: Richardson's Dream*. Cambridge Univ. Press, 279 pp.
- NPS web site: http://www.oc.nps.edu/nom/modeling/data_assimilation.html
- Richardson, L.F., 1922: *Weather Prediction by Numerical Process*. Cambridge Univ. Press, 274 pp.
- Vukicevic, T., E. Kalnay, T. Vonder Haar, 2004: The Need for a National Data Assimilation Education Program. *Bull. Amer. Meteor. Soc.*, **85**, 48–49.