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Important literature on the use of adjoint, variational methods and the Kalman filter in meteorology

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ABSTRACT

The use of adjoint equations is proving to be invaluable in many areas of meteorological research. Unlike a forecast model which describes the evolution of meteorological fields forward in time, the adjoint equations describe the evolution of sensitivity (to initial, boundary and parametric conditions) backward in time. Essentially, by utilizing this sensitivity information, many types of problems can be solved more efficiently than in the past, including variational data assimilation, parameter fitting, optimal instability and sensitivity analysis in general. For this reason, the adjoints of various models and their applications have been appearing more and more frequently in meteorological research. This paper is a bibliography in chronological order of published works in meteorology dealing with adjoints which have appeared prior to this issue of Tellus. Also included are meteorological works regarding variational methods (even without adjoints) and Kalman filtering in data assimilation, plus some references outside meteorology. These additional works are included here because the main thrust for adjoint application within meteorology is currently concentrated in the development of next-generation data assimilation systems.

1. Introduction

Adjoint equations were widely used in nuclear research as early as the 1950's, but were not seen in meteorology until the 1970's in some works by G. I. Marchuk and colleagues in the former Soviet Union. In the early 1980s, Cacucci and colleagues addressed several issues, including nonlinearity and sensitivity.

Unlike the direct equations which describe the evolution of meteorological fields forward in time, the adjoint equations describe the evolution of sensitivity (to initial, boundary and parameter conditions) backward in time. They are the adjoint of the tangent linear equations which are obtained from the direct equation by linearisation along a trajectory and which describe to first order the evolution of perturbations. After temporal and spatial discretisation the direct model and its tangent-linear and adjoint versions are the tools available for practical use.

The idea of applying variational methods in meteorology can be attributed to Y. Sasaki. In the 1960s and 1970s, he popularised the ideas and demonstrated simple applications of variational techniques. Practical application of these methods was hampered by the difficulty of solving the associated Euler–Lagrange equations.

The use of adjoint equations to iteratively solve variational meteorological problems, using the model as an exact constraint, was introduced by V. V. Penenko from Marchuk ideas, F. X. LeDimet, and

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O. Talagrand in the early 1980s. In the mid-1980s, the variational approach was applied successfully to data assimilation problems using simple 2- and 3-dimensional nonlinear dynamics (Talagrand and Courtier in Europe and Lewis and Derber in the USA). Since the mid-1980s, the application of variational techniques to data assimilation has driven much of the work resulting in the development of the adjoints of more complex models. These models now include full primitive equation dynamics, including some physical parametrizations.

In the 1960s, Kalman, Bucy and others introduced a framework for state estimation (data assimilation) in the engineering literature, from which the modern discipline of systems theory has grown. The linear Kalman filter, which is one of the central algorithms of state estimation, as well as its nonlinear generalizations may require the use of the adjoint of the forecast model for efficiency reasons, even if the tangent linear version availability is enough to allow a practical implementation. Kalman filtering ideas were introduced to meteorology by Z. Jones and D. P. Petersen in the 1960s to early 1970s and, independently at about the same time by E. S. Epstein, R. Fleming and E. Pitcher. Attempts to understand various aspects of the data assimilation problem by use of systems theory have been undertaken by S. E. Cohn, R. Daley, D. P. Dee and M. Ghil beginning in the 1980s and continuing until today.

The use of adjoint equations for determining what are now usually called "optimal perturbations" were introduced into meteorology by E. N. Lorenz and reintroduced later by Farrell and (independently) J.-F. Lacarra and O. Talagrand following B. Urban, 1985. When short time periods are considered, these perturbations often grow faster than the more usually determined exponentially-growing modes, measured using the ratio of final and initial values of some quadratic norm of the perturbation. These modes are now being applied to optimize the selection of perturbation for Monte Carlo forecasting.

Model parameter estimation, introduced by D. G. Cacucci, has not yet been widely used in meteorology. With the availability of the adjoint of NWP models, it is likely to receive more attention in the coming years.

All of the above applications of the adjoint depend on its efficiency for computing the gradient of a scalar functional with respect to the model state vector or any boundary condition and parameters. Examination of this gradient by itself reveals such information about model solutions: it is a quantitative estimate of how possible perturbations of initial fields, boundary conditions or model parameters would affect subsequent solution.

2. Compilation

We have compiled a list of papers addressing applications of adjoint equations to meteorological problems in the following areas:

Variational data assimilation excluding adjoints or Kalman filters	(V)
Variational data assimilation using adjoints	(A)
Kalman filter	(K)
Sensitivity analysis	(S)
Instability	(I)
Parameter estimation	(P)
General	(G)

The letter key will be used in the list of references to indicate the general category of the work. We have limited the references to meteorology, with a few exceptions, although it should be noted that considerable related work has also been done in oceanography. While we have attempted to include all relevant material from the open literature, it is likely that we have missed some work. For some papers, if its subject appeared well described by its title, no annotation was given. The authors would like to apologise for any unintentional omission.

Sasaki, Y. 1955 (V). A fundamental study of the numerical prediction based on the variational principle. *J. Meteor. Soc. Japan* **33**, 262–275.
– Applies Hamilton principle to the derivation of the equation of motion.

Sasaki, Y. 1958 (V). An objective analysis based on the variational method. *J. Meteor. Soc. Japan* **36**, 77–88.
– Applies variational methods to find balanced fields.

Sasaki, Y. 1960 (V). An objective analysis for determining initial conditions for the primitive equations. Tech. Rep. 208. Department of Oceanography and Meteorology, A & M College of Texas.

Washington, W. M. and R. T. Duquet, 1963 (V). An objective analysis of stratospheric data by Sasaki's method. Department of Meteorology, Penn. State Univ., 23 pp.

Jones, R. H. 1965 (K). Optimal estimation of initial conditions for numerical prediction. *J. Atmos. Sci.* **22**, 658–663.
– Introduces the idea of Kalman filtering in meteorology.

Lorenz, E. N. 1965 (I). A study of the predictability of a 28-variable atmosphere model. *Tellus* **17**, 321–333.

Stephens, J. J. 1965 (V). A variational approach to numerical weather prediction. Rep. No. 3, Atmos. Sci. Group. The University of Texas, Austin, USA, 243 pp.
– Stephen's PhD dissertation, in which Sasaki's ideas were applied.

Gruber, A. and J. J. O'Brien, 1968 (V). An objective analysis of wind data for energy budget studies. *J. Appl. Meteor.* **7**, 333–338.
– This paper discusses how to find a non divergent analysis using Lagrange multipliers. The authors were probably not aware of Sasaki's work at this time.

Petersen, D. P. 1968 (K). On the concept and implementation of sequential analysis for linear random fields. *Tellus* **20**, 673–686.
– Proposes an implementation of Kalman filter relying upon Green's functions.

Epstein, E. S. 1969 (K). Stochastic dynamic prediction. *Tellus* **21**, 739–759.
– Implements what could be considered as a Kalman filter. The author was apparently unaware of Kalman's work.

Sasaki, Y. 1969 (V). Proposed inclusion of time variation terms, observational and theoretical, in numerical variational objective analysis. *J. Meteor. Soc. Japan* **47**, 115–124.
– Uses linear advection and diffusion as a constraint.

Thompson, P. D. 1969 (V). Reduction of analysis error through constraints of dynamical consistency. *J. Appl. Meteor.* **8**, 738–742.
– Fits analyses to dynamics using a linearized vorticity equation. Theoretical paper. Expresses the need for appropriate numerical methods for more realistic models.

Jazwinski, A. H. 1970 (K). *Stochastic processes and filtering theory.* Academic press, New York, 376 pp.
– Basic book on Kalman filtering. Demonstrate the (already known) equivalence Kalman filtering/4D-Var: A linear regression is equivalent to a least-square fit.

Flattery, T. W. 1970 (V). Spectral analysis and forecasting. Numerical Weather prediction activities, National Meteorological Center, Second half 1969, 51 pp.
– Uses Hough modes for objective analysis. Ancestor of NMC's SSI and Meteo-France and ECMWF's 3D-Var.

O'Brien, J. J. 1970 (V). Alternative solutions to the classical vertical velocity problem. *J. Appl. Meteor.* **9**, 197–203.
– Applies Sasaki's formalism for solving the omega equation.

Sasaki, Y. 1970 (V). Some basic formalisms in numerical variational analysis. *Mon. Wea. Rev.* **98**, 875–883.

– Basic paper which introduces the variational approach with the weak and strong constraints concepts. Ahead of its time in that the numerical tools were lacking.

Sasaki, Y. 1970 (V). Numerical variational analysis formulated under the constraints as determined by longwave equations and a low pass filter. *Mon. Wea. Rev.* **98**, 884–898.
– Applies variational formalism to filter high frequency oscillations in a shallow-water model.

Sasaki, Y. 1970 (V). Numerical variational analysis with weak constraint and application to surface analysis of severe storm gust. *Mon. Wea. Rev.* **98**, 899–910.
– Uses two-dimensional linear advection as a weak constraint.

Sasaki, Y. and J. Lewis, 1970 (V). Numerical variational objective analysis of the planetary boundary layer in conjunction with squall line formation. *J. Meteor. Soc. Japan* **48**, 381–398.
– Practical application of Sasaki's formalism.

Stephens, J. J. 1970 (V). Variational initialization with the balance equation. *J. Appl. Meteor.* **9**, 732–739.
– Applies Sasaki's formulation to a 2-D initialization problem.

Lions, J. L. 1971 (G). *Optimal control of systems governed by partial differential equations* (English translation). Springer-Verlag, Berlin.
– General introduction to the application of functional analysis to optimal control.

Sasaki, Y. 1971 (V). A theoretical interpretation of anisotropically weighted smoothing on the basis of numerical variational analysis. *Mon. Wea. Rev.* **99**, 698–708.
– Uses Green's function to justify some enhancements of Cressman iterative analysis scheme.

Wagner, K. 1971 (V). Variational analysis using observational and low pass filtering constraints. M.S. thesis. Univ. of Oklahoma, Norman, 39 pp.

Lewis, J. M. 1972 (V). An operational upper air analysis. *Tellus* **24**, 514–530.
– Uses Sasaki's formalism to obtain an analysis which projects on the slowly evolving solutions of a model.

Lewis, J. M. and T. H. Grayson, 1972 (V). The adjustment of surface wind and pressure by Sasaki's variational matching technique. *J. Appl. Meteor.* **11**, 586–597.
– Find slowly varying (balanced) fields using a 2-D model.

Petersen, D. P. 1973 (K). Transient suppression in optimal sequential analysis. *J. Applied Meteor.* **12**, 437–440.
– Proves that Kalman filter preserves geostrophy. Remarks that any assimilation scheme will have to be adaptive.

Petersen, D. P. 1973 (K). A comparison of the performance of quasi-optimal and conventional objective analysis schemes. *J. Applied Meteor.* **12**, 1093–1101.
– Attempts at a proper comparison of operational and statistical analysis optimal schemes.

Sheets, R. C. 1973 (V). Analysis of hurricane data using the variational optimization approach with a dynamic constraint. *J. Appl. Meteor.* **9**, 732–739.

Marchuk, G. I. 1974 (G((Russian version 1967). *Numerical methods in weather prediction.* Academic Press, New-York, 277 pp.
– Chapter 5 is dedicated to the use of the adjoint formalism to derive integral conserving numerical schemes.

Marchuk, G. I. 1974 (SG((Russian version 1967). *The numerical solution of problems of atmospheric and oceanic dynamics*, 387 pp., Gidrometeoizdat, Leningrad, USSR. (English translation, Rainbow Systems, Alexandria, va.).
– Presents some application in meteorology of the adjoint formalism.

Achtemeier, G. C. 1975 (V). On the initialization problem: a variational adjustment method. *Mon. Wea. Rev.* **103**, 1089–1103.
– Applies Sasaki's formalism to the initialization problem.

Marchuk, G. I. 1975 (VG). *Methods of numerical mathematics.* Springer-Verlag, 313 pp.
– Chapter 5 applies adjoint technique to inverse problems.

Marchuk, G. I. and Y. K. Skriba, 1976 (S). Numerical calculation of the conjugate problem for a model of the thermal interaction of the atmosphere with the oceans and continents. *Izvestiya Atm. and Ocean Phys.* **12**, 5, 459–469.
– Use adjoint equations to compute sensitivity of climate anomalies to surface temperature.

Penenko, V. V. and N. N. Obratsov, 1976 (A). A variational initialization method for the fields of the meteorological elements (English translation). *Soviet Meteorology and Hydrology* **11**, 1–11.
– Apply 4D-Var assimilation to a linear primitive equation model minimizing a cost function. The gradient is computed using a discretized form of the continuous adjoint equations. Uses analyses as "observations".

Sasaki, Y. 1976 (G). Variational design of finite difference schemes for initial value problems with an integral invariant. *J. Comp. Phys.* **21**, 270–278.
– Similar idea as Marchuk (1974) although it uses the Euler–Lagrange equations.

Gordin, V. A. 1977 (V). Variational adjustment of meteorological fields. *Soviet Meteorology and Hydrology* **12**, 95–96.
– Uses variational framework for imposing geostrophy. Mentions application to time dependent problems.

McFarland, M. S. and Y. K. Sasaki, 1977 (V). Variational analysis of temperature and moisture advection in a severe storm environment. *J. Met. Japan* **55**, 421–430.

Marchuk, G. I. and G. P. Kurbatkin, 1977 (S). Physical and mathematical aspects of weather analysis and forecasting. *Soviet Meteorology and Hydrology* **11**, 25–33.
– Explains how the adjoint can be used for sensitivity experiments. Presents results for climate.

Penenko, V. V. 1977 (PG). A numerical model of the thermal regime of the atmosphere. *Izvestiya Atm. and Ocean Phys.* **13**, 6, 401–407.
– Proposes to use the adjoint in order to compute gradients of a functional for a parameter estimation.

Penenko, V. V. 1977 (G). Energy balanced discrete models of atmospheric process dynamics. (English translation) *Soviet Meteorology and Hydrology* **10**, 3–20.
– Uses adjoint formalism to derive energy conserving finite difference schemes.

Sadokov, V. D. and D. B. Steinbok, 1977 (S). Application of conjugate functions in analysis and forecasting of the temperature anomaly. (English translation) *Soviet Meteorology and Hydrology* **10**, 16–21.
– Computes sensitivity of 30-day average tropospheric temperature anomaly to the ocean surface temperature using the adjoint of a simple model.

Seaman, R. S., R. Falconer and J. Brown, 1977 (V). Application of a variational blending technique to numerical analysis in the Australian region. *Austr. Meteor. Mag.* 3–22.

Daley, R. 1978 (V). Variational non-linear normal mode initialization. *Tellus* **30**, 201–218.
– Variational assimilation with a Machenhauer balance constraint (tendencies of gravity waves approximately set to zero).

Lewis, J. M. and S. C. Bloom, 1978 (V). Incorporation of time continuity into subsynoptic analysis by using dynamical constraints. *Tellus* **30**, 496–516.
– Surface wind and pressure analyses are coupled in time using a simple horizontal momentum equation model.

Stephens, J. J. and K. W. Johnson, 1978 (V). Middle-large-scale variational adjustment of atmospheric fields in mesoscale diagnostic numerical variational analysis models. Final report, Department of Meteorology, Florida State Univ., 1–38.

Marchuk, G. I. and V. V. Penenko, 1979 (S). A study of the sensitivity of discrete models of atmospheric and oceanic dynamics. *Izvestiya Atm. and Ocean Phys.* **15**, 11, 785–789.

– Presents how the adjoint can be used for sensitivity application. Discusses the importance of having the adjoint of the discrete model.

Ghil, M., S. Cohn, J. Tvantzis, K. Bube and E. Isaacson, 1980 (K). Application of estimation theory to numerical weather prediction. 1980 ECMWF seminar on "Data assimilation methods," pp. 249–334. Also in Dynamic Meteorology, *Data assimilation methods.* (L. Bengtsson, M. Ghil, E. Källen, editors), Springer-Verlag, 1981.
– Popularises Kalman filtering in Meteorology. Theory and applications to linear shallow-water models.

Lewis, J. M. 1980 (V). Dynamical adjustment of 500 mb vorticity using P. D. Thompson's scheme: a case study. *Tellus* **32**, 511–524.
– Uses a linearised vorticity equation to fit analyses.

Wahba, G. and J. Wendelberger, 1980 (V). Some new mathematical methods for variational analysis using splines and cross-validation. *Mon. Wea. Rev.* **108**, 1122–1143.
– Integrates variational formalism and statistical formulation. Authors stress that the raw data should be used directly with no prior gridding and that the radiances should be used directly with no prior inversion. The importance of the paper has been underestimated in the 1980s, mainly because General Cross Validation is more appropriate for case studies than for operational problems where statistics are available from the past.

Cacucci, D. G. 1981 (S). Sensitivity theory for nonlinear systems. I. Nonlinear functional analysis approach. *J. Math. Phys.* **22**, 2794–2802.
– Theoretical introduction to the adjoint formalism applied to sensitivity experiments.

Navon, I. M. 1981 (V). Implementation of "a posteriori" methods for enforcing conservation of potential enstrophy and mass in discretized shallow-water equations models. *Mon. Wea. Rev.* **109**, 946–958.

Phillips, N. A. 1981 (V). Variational analysis and the slow manifold. *Mon. Wea. Rev.* **109**, 2415–2426.

Sasaki, Y. K. and J. McGinley, 1981 (V). Application of the inequality constraints in adjustments of superadiabatic layers. *Mon. Wea. Rev.* **110**, 1635–1644.

Cohn, S. E. 1982 (K). Methods of sequential estimation for determining initial data in numerical weather prediction. PhD Thesis. Published as report CI-6-82, Courant Institute, New York University, 183 pp.

Ghil, M., S. E. Cohn and A. Dalcher, 1982 (K). Sequential estimation, data assimilation and initialization. In: The Interaction Between Objective Analysis and Initialization (ed., D. Williamson), *Publ. Meteorol.* **127**, (Proc. 14th Stanstead Seminar), McGill Univ., Montreal, 83–97.

Hall, M. C. G., D. G. Cacucci and M. E. Schlesinger, 1982 (S). Sensitivity Analysis of a Radiative-Convective Model by the Adjoint Method. *J. Atmos. Sci.* **39**, 2038–2050.
– Use the 2 layer Oregon State University model physics. Integrates a radiative-convective model until equilibrium. Compute the sensitivity of asymptotic temperature to 312 parameters (including basic physical constants).

Hoffman, R. N. 1982 (V). SASS wind ambiguity removal by direct minimization. *Mon. Wea. Rev.* **110**, 434–445.

Le Dimet, F.-X. 1982 (G). *A general formalism of variational analysis.* CIMMS report 22, Cooperative Institute for Mesoscale Meteorological studies, 815 Jenkins Street, Norman, Ok., 73019, 34 pp.
– Proposes several algorithms for solving variational problems including the use of adjoint.

Lewis, J. M. 1982 (V). Adaptation of Thompson's scheme to the constraint of potential vorticity conservation. *Mon. Wea. Rev.* **110**, 1618–1634.
– Fits 2-layer quasigeostrophic baroclinic model to analyses.

Marchuk, G. I. 1982 (S). Mathematical issues of industrial effluent optimization. *J. Meteor. Soc. Japan* **60**, 481–485.

Navon, I. M. 1982 (V). A posteriori numerical techniques for enforcing simultaneous conservation of integral invariants upon finite-difference shallow-water equations models. *Notes on Numerical fluid dynamics*, vol. 5. (Henri-Viviand Vieweg ed.) 230–240.

Tribbia, J. J. 1982 (V). On variational normal mode initialization. *Mon. Wea. Rev.* **110**, 455–470.
– A detailed analysis of Daley's approach and some extensions, with applications to a shallow water model.

Williamson, D. 1982 (VK). The interaction between objective analysis and initialization. *Publ. Meteorol.* **127** (Proc. 14th Stanstead seminar), Mc Gill Univ., Montreal.
– Several papers on variational initialization and on Kalman filter.

Balgovind, R., A. Dalcher, M. Ghil and E. Kalnay, 1983 (K). A stochastic-dynamic model for the spatial structure of forecast error statistics. *Mon. Wea. Rev.* **111**, 701–722.

Bloom, S. C. 1983 (V). The use of dynamical constraints in the analysis of mesoscale rawind sonde data. *Tellus* **35A**, 363–378.
– Finds an analysed state which approximately satisfies a 2-D evolution equation.

Hall, M. C. G. and D. G. Cacucci, 1983 (S). Physical interpretation of the adjoint functions for sensitivity analysis of atmospheric models. *J. Atmos. Sci.* **40**, 2537–2546.
– Shows that the adjoint solution can be used as a whole for sensitivity experiments.

Lewis, J. M. and L. Panetta, 1983 (V). The extension of P. D. Thompson's scheme to multiple time levels. *J. Clim. Appl. Meteorol.* **22**, 1649–1653.
– Generalize their previous work to several time levels.

Navon, I. M. and R. de Villiers, 1983 (GO). Combined penalty multiplier optimization methods to enforce integral invariants conservation. *Mon. Wea. Rev.* **111**, 1228–1243.

Puri, K. 1983 (V). Some experiments in variational normal mode initialization in data assimilation. *Mon. Wea. Rev.* **111**, 1208–1218.

Cacucci, D. G. and M. C. G. Hall, 1984 (S). Efficient estimation of feedback effects with application to climate models. *J. Atmos. Sci.* **41**, 2063–2068.
– Proposes the use of the adjoint formalism for the estimation of sensitivity to feedback loops.

Courtier, P. 1984 (A). Présentation d'une méthode variationnelle quadridimensionelle d'assimilation de données distribuées dans l'espace et dans le temps. Note de travail de l'EERM no. 101. Available from Météo-France, Paris.
– Results obtained with the barotropic vorticity equation and real wind and height radiosondes observations. Far better described in Courtier and Talagrand (1987).

Hoffman, R. N. 1984 (V). SASS wind ambiguity removal by direct minimization. Part II: use of smoothness and dynamical constraints. *Mon. Wea. Rev.* **112**, 1829–1852.

Temperton, C. 1984 (V). Variational normal mode initialization for a multilevel model. *Mon. Wea. Rev.* **112**, 2303–2316.

Courtier, P. 1985 (A). Experiments in data assimilation using the adjoint model technique. *Workshop on High-resolution analysis*, ECMWF, UK, June 1985, 20 pp.
– In addition to the vorticity equation results, this paper demonstrates how to control gravity waves in 4D-Variational Assimilation. Better described in Courtier and Talagrand (1990).

Derber, J. C. 1985 (A). The variational four-dimensional assimilation of analyses using filtered models as constraints. PhD Thesis, University of Wisconsin–Madison, 142 pp.

Lewis, J. M. and J. C. Derber, 1985 (A). The use of adjoint equations to solve a variational adjustment problem with advective constraints. *Tellus* **37A**, 309–322.
– First, test the method on the 1D advection equation, then real data test using the quasi-geostrophic potential vorticity equation and analyses which were produced using Barnes scheme applied to RAOBS and VAS data.

Marchuk, G. I., Y. K. Skriba and I. G. Protsenko, 1985 (K). Method of calculating the evolution of random hydrodynamic fields on the basis of adjoint equations. *Izvestya Atm. and Ocean Phys.* **21**, 2, 87–92.
- Propose to use the fact that the adjoint equations lead to local influence to simplify the transport in time of the covariance matrix of forecast errors.

Marchuk, G. I., Y. K. Skriba and I. G. Protsenko, 1985 (K). Application of adjoint equations to problem of estimating the state of random hydrodynamic fields. *Izvestya Atm. and Ocean Phys.* **21**, 3, 175–184.
- Implement a Kalman filter based on their simplification of the transport in time of the covariance matrix of forecast errors.

Parrish, D. F. and S. F. Cohn, 1985 (K). *A Kalman filter for a two-dimensional shallow-water model: formulation and preliminary experiments.* NMC office note no. 304.

Talagrand, O. and P. Courtier, 1985 (GPA). *Formalisation de la méthode du modèle adjoint. Applications météorologiques.* Note de Travail No. 117. EERM, Paris, France. 10 pp.
- Theoretical introduction to adjoint model. Describes adjoint with respect both to initial conditions and to parameters.

Urban, B. 1985 (I). *Maximal error amplification in simple meteorological models* (in French). Working note, Ecole Nationale de la Météorologie, Toulouse, France.
- Finds most unstable modes in the energetic sense of vorticity equation model and 2-layer Q.G. model.

Budgell, N. P. 1986 (K). Nonlinear data assimilation for shallow-water equations in branched channels. *J. Geophys. Res.* **91**, 10633–10644.

Courtier, P. 1986 (G). *Détermination pratique de l'adjoint d'un modèle de prévision.* Note de Travail No. 159. EERM, Paris, France.
- Describes the way the author derived the adjoint of a vorticity equation model and a shallow-water equation model (not to be followed any longer). Presents two ways of validating the adjoint code which should be systematically followed. (Green identity and Taylor formula).

Courtier, P. 1986 (SP). *Le modèle adjoint, outil pour des expériences de sensibilité.* Note de Travail No. 166. EERM, Paris, France. 36 pp.
- Use of primitive equations for a 2D fluid on a sphere (shallow-water equation). Looks at the sensitivity to initial conditions, to the initialization process and to orography. Uses it to diagnose tidal waves. Example of misuse: find the orography that minimizes the forecast error.

Hoffman, R. N. 1986 (V). A four-dimensional analysis exactly satisfying equations of motion. *Mon. Wea. Rev.* **114**, 388–397.
- An example of 4D-variational assimilation without the use of adjoint equations.

Le Dimet, F. X. and O. Talagrand, 1986 (G). Variational algorithms for analysis and assimilation of meteorological observations: theoretical aspects. *Tellus* **38A**, 97–100.
- Describes several variational algorithms introducing the "augmented Lagrangian" and the adjoint method for data assimilation.

Lorenc, A. C. 1986 (V). Analysis methods for numerical weather prediction. *Q. J. R. Meteorol. Soc.* **112**, 1177–1194.

Sasaki, Y. K. 1986 (VAG). Variational methods in geosciences. *Proceedings of the International Symposium on Variational methods in geosciences*, University of Oklahoma. Norman, OK., 15–17 October 1985. Elsevier, 309 pp.
- In addition to papers published later in open literature, we should mention a good review paper by I. M. Navon on variational and optimization methods in meteorology and an introduction to the application of optimal control to meteorological problems by O. Talagrand.

Talagrand, O. 1986 (G). Application of optimal control to meteorological problems. In: *Variational methods in geosciences*, vol. 5. (Y. K. Sasaki, ed.) Elsevier, pp. 13–28.
- Mathematical description. Short overview of meteorological applications.

Courtier, P. 1987 (A). *Assimilation variationnelle d'observations météorologiques à l'aide des équations de Saint-Venant directes et adjointes.* Note de Travail No. 175. EERM, Paris, France. 62 pp.
- Presents the control of the gravity waves in variational assimilation of real observations relying on the shallow-water equations. Results also described (more briefly) in Courtier and Talagrand, 1990.

Courtier, P. 1987 (ASPG). *Application du contrôle optimal à la prévision numérique en météorologie.* Thèse de Doctorat, Université Paris, France.
- Gathers all previous publications on this subject. The adjoint of the 3-dimensional primitive equations is derived in continuous form.

Courtier, P. and O. Talagrand, 1987 (A). Variational assimilation of meteorological observations with the adjoint vorticity equation. Part II. Numerical results. *Q. J. R. Meteorol. Soc.* **113**, 1329–1368.
- Uses the vorticity equation and all the data for a 24 hour period. Starts from an atmosphere at rest. Finds that the Aleutian low is reconstructed even though there were no observations there. Reduction of small scale noise by adding a smoothing term in the cost function.

Derber, J. C. 1987 (A). Variational four-dimensional analysis using quasi-geostrophic constraints. *Mon. Wea. Rev.* **115**, 998–1008.
- Extension of the work by Lewis and Derber. Further tests of technique. With regular insertion, best fit is in the center of the data period. Used the same quasi-geostrophic model as in the previous work and either primitive equation simulation or satellite observations for data.

Navon, I. M. and D. M. Legler, 1987 (O). Conjugate-Gradient Methods for Large-Scale Minimization in Meteorology. *Mon. Wea. Rev.* **115**, 1479–1502.
- Review of conjugate gradient methods; applies four methods to two problems.

Panchang, V. G. and J. J. O'Brien, 1987 (P). On the determination of hydraulic model parameters using the adjoint state formulation. In: *Modelling marine systems, vol. 1.* (A. M. Davies, ed.). CRC Press, Inc., Boca Raton, FL., USA, 18 pp.
- Estimates various parameters involved in modelling hydraulic systems, particularly the friction factor of tidal rivers. Uses the Lagrange multipliers form of the adjoint.

Talagrand, O. and P. Courtier, 1987 (GA). Variational assimilation of meteorological observations with the adjoint vorticity equation. Part 1: Theory. *Q. J. R. Meteorol. Soc.* **113**, 1311–1328.
- Develops theory of adjoint assimilation from first principles. Applies to data assimilation for Haurwitz waves. Appendices give description of adjoint formalism in general, time stepping, handling of FFTs.

Farrell, B. 1988 (I). Optimal excitation of neutral Rossby waves. *J. Atmos. Sci.* **45**, 163–172.
- One of the first papers on using adjoints for determination of optimal modes.

Lacara, J.-F. and O. Talagrand, 1988 (VI). Short-range evolution of small perturbations in a barotropic model. *Tellus* **40A**, 81–95.

LeDimet, F. X. 1988. *Determination of the adjoint of a numerical weather prediction model.* Tech. Rep. FSU-SCR1-88-79, Florida State University, Talahassee, Florida, 32306–4052, 22 pp.

Lorenc, A. C. 1988 (V). A Practical Approximation to Optimal Four-Dimensional Objective Analysis. *Mon. Wea. Rev.* **116**, 730–745.
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Fillion, L. and C. Temperton, 1989 (V). Variational implicit normal mode initialization. *Mon. Wea. Rev.* **117**, 2219–2229.
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Thépaut, J.-N. and P. Moll, 1990 (A). Variational inversion of simulated TOVS radiances using the adjoint technique. *Q. J. R. Meteorol. Soc.* **116**, 1425–1448.
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