JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D2, 4054, doi:10.1029/2002JD002410, 2003

# Tangent linear analysis of the Mosaic land surface model

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Received 3 April 2002; revised 8 August 2002; accepted 16 October 2002; published 24 January 2003.

[1] In this study, a tangent linear eigenanalysis is applied to the Mosaic land surface model (LSM) [*Koster and Suarez*, 1992] to examine the impacts of the model internal dynamics and physics on the land surface state variability. The tangent linear model (TLM) of the Mosaic LSM is derived numerically for two sets of basic states and two tile types of land condition, grass and bare soil. An additional TLM, for the soil moisture subsystem of this LSM, is derived analytically for the same cases to obtain explicit expressions for the eigenvalues. An eigenvalue of the TLM determines a characteristic timescale, and the corresponding eigenvector, or mode, describes a particular coupling among the perturbed states. The results show that (1) errors in initial conditions tend to decay with e-folding times given by the characteristic timescales; (2) the LSM exhibits a wide range of internal variability, modes mainly representing surface temperature and surface moisture perturbations exhibit short timescales, whereas modes mainly representing deep soil temperature perturbations and moisture transfer throughout the entire soil column exhibit much longer timescales; (3) the modes of soil moisture tend to be weakly coupled with other perturbed variables, and the mode representing the deep soil temperature perturbation has a consistent e-folding time across the experiments; (4) the key parameters include soil moisture, soil layer depth, and soil hydraulic parameters. The results agree qualitatively with previous findings. However, tangent linear eigenanalysis provides a new approach to the quantitative substantiation of those findings. Also, it reveals the evolution and the coupling of the perturbed land states that are useful for the development of land surface data assimilation schemes. One must be careful when generalizing the quantitative results since they are obtained with respect to two specific basic states and two simple land conditions. Also, the methodology employed here does not apply directly to an actual time-varying basic state. *INDEX TERMS:* 1704 History of Geophysics: Atmospheric sciences; 3210 Mathematical Geophysics: Modeling; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; *KEYWORDS:* tangent linear analysis, land surface state variability, soil moisture dynamics

**Citation:** Yang, R., S. E. Cohn, A. da Silva, J. Joiner, and P. R. Houser, Tangent linear analysis of the Mosaic land surface model, *J. Geophys. Res.*, *108*(D2), 4054, doi:10.1029/2002JD002410, 2003.

## 1. Introduction

[2] A land surface model (LSM) or soil-vegetation-atmosphere-transfer (SVAT) scheme exhibits variability on a wide range of timescales from hours to months, and even years through atmospheric interactions [e.g., *Delworth and Manabe*, 1988, 1993; *Entekhabi*, 1995; *Robock et al.*, 1998]. These timescales are strongly influenced by external forcing, especially precipitation and downward short-wave and long-wave radiation at the surface. They are also modulated by the internal dynamics and physics of land surface systems, in particular by soil moisture dynamics. There are numerous studies on the variability of land surface models. Approaches to date include: (1) performing numerical simulations, (2) performing numerical sensitivity tests, and (3) building relatively simple land surface models that can be solved analytically.

[3] In the first approach, either a general circulation model (GCM) which includes an LSM or a stand-alone LSM is integrated over long time periods [e.g., *Dickinson*, 1984; *Sato et al.*, 1989; *Koster and Suarez*, 1994]. These studies have demonstrated the main variability of the land surface system, as modeled, and the pronounced effect of the land surface on atmospheric variability. In the second approach, using either an LSM coupled to a GCM or a stand-alone LSM, sensitivity experiments are usually performed with a change in one particular parameter or parameterization scheme [e.g., *Henderson-Sellers et al.*, 1995; *Xue et al.*, 1996a, 1996b]. The results are then compared with a control integration to reveal the impact of the change. This type of sensitivity experiment identifies important parameters or parameterizations in land surface models. The third approach, solving equations of a simple

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0148-0227/03/2002JD002410$09.00

LSM analytically, estimates characteristic timescales of land surface variables in simplified cases [e.g., *Delworth and Manabe*, 1988; *Brubaker and Entekhabi*, 1995; *Yang et al.*, 1995]. This approach simplifies complex land surface processes. For example, one can represent the evaporation and runoff process as a bucket model or treat the soil moisture system as a first-order Markov process.

[4] These three approaches mainly reveal the impact of external forcing [*Entekhabi*, 1995; *Delworth and Manabe*, 1988, 1993] on the land surface variability, because the forcing terms exert the dominant control on the variability of land surface models. In the data assimilation context, we need to understand the impact of internal dynamics and physics on the variability of a land surface model. For this purpose we employ tangent linear analysis to an LSM in this study.

## 6. Conclusions

[60] This study explores the application of a tangent linear analysis to a land surface model using a reasonable basic state and a simple land surface condition at the HAPEX site in summertime. Several simplifications are made in this application, including the assumption of a constant tangent linear matrix and the exclusion of interception storage. The eigenanalysis readily yields the characteristic timescales and the structure of the perturbed states of the Mosaic LSM. It effectively synthesizes the impact of different basic state and vegetation conditions on the linear evolution of initial errors. It also quantifies the intrinsic variability of the Mosaic LSM. An understanding of these features is important for developing a land-surface data assimilation scheme and for improving the physical parameterizations of an LSM.

[61] The main results are summarized as follows:

1. The Mosaic LSM exhibits a wide range of internal variability. The e-folding times of the different modes range from a few minutes to several months. Modes representing the evolution of perturbations in surface temperature and surface moisture exhibit short timescales. The modes representing the evolution of deep soil temperature perturbations and soil moisture perturbations coupled within the whole soil column exhibit longer timescales. The mode representing the deep soil temperature ($T_d$) perturbation is weakly coupled to the other land-surface variables and has a consistent e-folding time across the experiments.

2. The e-folding timescales depend clearly upon soil layer depth, soil parameters, and basic state conditions. In particular, the modes representing the behavior of soil moisture perturbations have significantly longer timescales for the deep soil layer. The influence of the difference in basic states studied here is small because they are rather similar to each other. However, warmer surface temperature and higher surface-air moisture tend to shorten the e folding times.

3. For the simplified soil moisture dynamics subsystem, the terms representing soil moisture fluxes are the most important factors for determining the timescales. The effect of evaporation and evapotranspiration is much less significant, simply because we have chosen a fairly moist basic state soil moisture. The key parameters determining the e folding timescales include the mean depth between soil layers, the soil hydraulic conductivity and potential, the soil parameter $\beta$, and the basic state soil moisture. Deeper and wetter soils have longer timescales, and larger soil parameter $\beta$ and higher soil hydraulic conductivity and potential tend to shorten timescales.

4. In stand alone mode, the Mosaic LSM is stable for the basic states considered. Any initial perturbation, or initial error, will decay with time. The formulation of the Mosaic LSM appears to prevent instabilities.

[62] The results agree qualitatively with previous studies. In particular, the importance of accurate soil moisture and the longer timescale of soil moisture have been pointed out by previous studies [e.g., *Robock et al.*, 1998; *Schlosser et al.*, 1997; *Vinnikov et al.*, 1996; *Yang et al.*, 1995, 1994]. For example, *Robock et al.* [1998] gave a comprehensive evaluation of soil moisture simulated by the models of the Atmospheric Model Intercomparison Project (AMIP) based on soil moisture observations. They pointed out a long term (1–4 months) scale in soil moisture variation and that the key parameter of soil field capacity is the maximum soil moisture held in a column. Soil layer structure is related to this parameter. Our study provides a new perspective to view these timescales and key parameters.

[63] One must be careful when generalizing the results of this study. First, the results were obtained with respect to two types of land conditions, and the basic state was held constant in time. For different atmospheric and vegetation conditions, eigenvalues and eigenvectors will be different. The methodology employed here does not apply directly to an actual time-varying basic state. In particular, in case the LSM state changes with time through coupling to an atmosphere model, a more general type of tangent linear analysis would be required to study fully the stability properties of the coupled system. Second, the tangent linear approach itself applies, in principle, to small perturbations only. The linear approximation does not always hold. A thorough discussion regarding this issue is given by *Errico* [1997]. Finally, the precise interpretation of the eigenmodes we have obtained depends on our choice of scaling magnitudes. These were derived empirically based on standard deviations from the control runs. They would be different for different land surface regimes.