JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D12, 4347, doi:10.1029/2002JD003287, 2003

Reply to comment by M. Lanfredi et al. to "Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999" by L. Zhou et al.

R. K. Kaufmann,[1] L. Zhou,[2] C. J. Tucker,[3] D. Slayback,[4] N. V. Shabanov,[1] and R. B. Myneni[1]

Received 4 December 2002; revised 12 February 2003; accepted 28 March 2003; published 17 June 2003.

INDEX TERMS: 1640 Global Change: Remote sensing; 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* NDVI, temperature, growing season, climate change

Citation: Kaufmann, R. K., L. Zhou, C. J. Tucker, D. Slayback, N. V. Shabanov, and R. B. Myneni, Reply to comment by M. Lanfredi et al. to ''Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999'' by L. Zhou et al., *J. Geophys. Res.*, *108*(D12), 4347, doi:10.1029/2002JD003287, 2003.

1. Introduction

[1] In their paper, *Lanfredi et al.* [2003] raise several issues about our analysis of normalized difference vegetation index (NDVI) data for areas north of 30°N between 1981 and 1999. As we describe below, their comments represent a basic misunderstanding of the data, a misrepresentation of our work, or an anticipation of our recently published results. Here we address these issues in order in which they are given by Lanfredi et al.

2. Areas Around Water Bodies Characterized by a Large Negative Trend

[2] In section 2.1 of *Lanfredi et al.* [2003] the authors confuse boundaries with NDVI values. This issue cannot be easily detected in the printed figures and does not affect our results. Of the 13,349 grids (0.25 × 0.25 degrees) shown in Plates 1 and 2 of *Zhou et al.* [2001] between 25°N and 75°N, only 10 show 25% decline in NDVI. This confusion partially results from the way that the two figures were plotted as contour maps. However, it can be visually exaggerated if they are displayed for a small region on a slow computer as *Lanfredi et al.* [2003] have done.

[3] Figure 1 shows NDVI trends for the Great Lakes region in North America, where there are many inland seas, water bodies, and lakes. This is one region where *Lanfredi et al.* [2003] argue that the −25% trend is spurious and most significant. We show two versions of these data: Figure 1a is taken from Plate lb of *Zhou et al.* [2001], which Lanfredi et al. cite in many of their arguments, and Figure 1b shows the same data but with the border removed and without smoothing, filtering, or interpolation. Clearly, few pixels show a negative NDVI trend. There are some blue lines around water body and coastal lines in Figure 1a, which are contour lines drawn by the software between pixels with values (vegetated pixels) and those without (nonvegetated pixels). This is the artifact described by Lanfredi et al. Two lines are present along coastlines, one generated by the software from its high-resolution water-land border mask file and the other generated by the coarse resolution of our analysis (0.25 × 0.25 degrees). These lines could generate artifacts around an isolated vegetated pixel, but such a case is extremely rare because the strict criteria for "vegetated pixels" given by *Zhou et al.* [2001] mean that most vegetated pixels are grouped as extended patches.

[4] Perhaps we could have plotted our results more clearly. Nonetheless, we wish to make it very clear that our analyses and results are based on only the NDVI values for vegetated pixels, not those "water or border" pixels. In other words, the minor artifact does not affect our results. If the authors wish to explore this issue further, we will be happy to send the files, from which the maps are made, without the border files.

3. No Differentiation Between Stable Areas With 0-Class Pixels and Nonvegetated Pixels

[5] In their section 2.2, *Lanfredi et al.* [2003] suggest that it would be better to differentiate stable areas with 0-class pixels and nonvegetated pixels. This is a good suggestion. Nonetheless, this does not affect our results because our analysis focuses on large NDVI increase (e.g., classes 1–6).

4. Lack of Randomness in the Spatial and Temporal Patterns of NDVI

[6] In their section 2.3, *Lanfredi et al.* [2003] criticize our work because spatial and temporal changes in NDVI are not random. The lack of randomness in the spatial and temporal patterns of NDVI is exactly what we would expect to see if climate is a significant determinant of spatial and temporal patterns in NDVI. Because spatial and

[1]Department of Geography, Boston University, Boston, Massachusetts, USA.
[2]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.
[3]Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[4]Science Systems & Applications Inc., Greenbelt, Maryland, USA.

0148-0227/03/2002JD003287$09.00

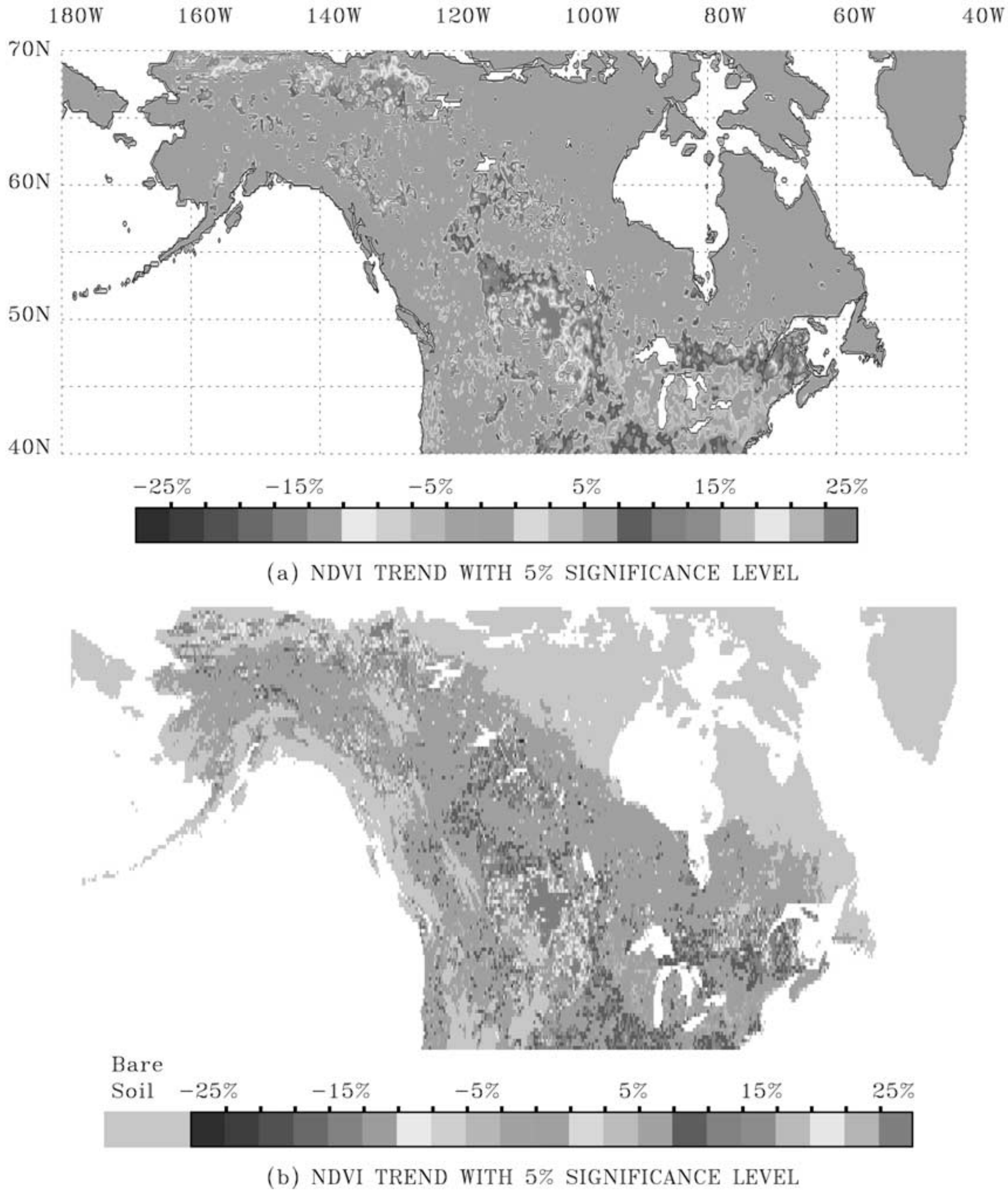

Figure 1. NDVI trends at 5% significance level for the Great Lakes region in North America: (a) a contour map taken from Panel lb of *Zhou et al.* [2001] and (b) same as (a) but plotted as an image, without smoothing, filtering, or interpolation. See color version of this figure at back of this issue.

temporal patterns in temperature and precipitation are not random, neither should the spatial and temporal patterns in NDVI. Indeed, the correlation between these patterns is the basis for our conclusion that changes in NDVI are correlated with changes in temperature.

5. Inability to Discriminate Spatial Coherence and Fragmentation From Artifacts

[7] In section 3 of *Lanfredi et al.* [2003] the authors argue that we are not able to discriminate spatial coherence and fragmentation from artifacts. This is a misunderstanding. Our calculation is based on only the NDVI values for vegetated pixels, not those “water or border” pixels in the figures, and not smoothed or filtered values.

6. Systematic Errors Responsible for Spatial Patterns in NDVI

[8] In their section 3, *Lanfredi et al.* [2003] argue that systematic errors in the AVHRR data could be responsible for the spatial pattern in the NDVI data. We are not sure

what *Lanfredi et al.* [2003] mean by "systematic errors." As we state in our paper, nonvegetation effects may influence our results. These effects, which may include satellite drift/changeover, navigation uncertainties, atmospheric effects, variations in the viewing and illumination geometry, and variations in the soil background, can cause errors in measured values for NDVI, both in space and time. These effects probably are small relative to those of climate, as indicated by the correlation between NDVI and land surface air temperature, which are compiled from thousands of meteorological stations. Indeed, this correlation suggests that the changes in NDVI described in our paper reflect changes in vegetation because temperature is an important determinant of plant growth in northern high latitudes.

[9] Problems in the Advanced Very High Resolution Radiometer (AVHRR) data have been investigated by many [e.g., *Gutman*, 1999]. The major problems are errors associated with satellite drift/changeover. It has been a challenge to develop a "clean" correction without simultaneous correction for bidirectional effects because the satellite-target-Sun geometry is changing and sometimes it is difficult to find a compatible geometry to exclude this effect in different points of time in the time series.

[10] The effects of satellite drift/changeover have been investigated using first principles and statistical analyses [*Kaufmann et al.*, 2000]. Equations for radiative transfer indicate that the NDVI of a vegetated surface is minimally sensitive to changes in solar zenith angle (SZA) and that this sensitivity decreases as leaf area increases. This result is confirmed by a cointegration analysis of the NDVI data set, which indicates that NDVI is not related to SZA in a statistically meaningful manner except for biomes with relatively low leaf areas. These results imply that orbital drift and satellite changeover have little effect on NDVI measurements. Additional assessments of the AVHRR data quality are given by *Tucker et al.* [2001], *Zhou et al.* [2001, 2003], and *Slayback et al.* [2003]. Recent analysis of four AVHRR NDVI data sets with different atmospheric corrections and calibrations suggests a widespread increase in NDVI for northern high latitudes [*Slayback et al.*, 2003].

[11] To quantify the effects of satellite drift/changeover and variations in stratospheric aerosol optical depth on NDVI, *Zhou et al.* [2003] include solar zenith angle (SZA) and stratospheric aerosol optical depth (AOD) in their analysis of the relation between NDVI and climate (land surface temperature and precipitation). The effects of spatial heterogeneity and unobserved variables are estimated with specifications and statistical techniques that allow the regression coefficients to vary among boxes. Of the variables examined, changes in temperature account for the largest fraction of the change in NDVI between the early 1980s and the late 1990s. Changes in AOD and precipitation have a smaller effect, while artifacts associated with variations in SZA are negligible. These results indicate that temperature changes between the early 1980s and the late 1990s are responsible for much of the observed increase in satellite measures of northern forest greenness. This result is reproduced by a biogeochemical model that is simulated with observed climate data [*Lucht et al.*, 2002]. Finally, this temperature-induced greening is consistent with a wide array of environmental indicators, such as earlier snowmelt [*Dye*, 2003], earlier soil thaw [*Zhuang et al.*, 2003], and changes in plant phenology (e.g., trees bud and flowers bloom earlier) and animal behavior (birds lay their eggs earlier and birds and butterflies migrate farther north) [*Penuelas and Filella*, 2001; *Walther et al.*, 2002].

7. Representation of Lagged Effects

[12] In section 4 of *Lanfredi et al.* [2003] the authors argue that statistical correlations between NDVI and climate should specify lagged effects. The lagged effects of climate are represented by *Zhou et al.* [2003]. That paper estimates statistically meaningful relations between NDVI and climate during spring, summer, and autumn for forests between 40°N and 70°N in North America and Eurasia. The statistical equations specify lagged values for climate variables in a way that is consistent with the notion of physiological optimum.

8. Short-Term Versus Long-Term Responses

[13] In their section 4, *Lanfredi et al.* [2003] argue that short-term responses cannot be considered representative of links between long-time vegetation changes and climatic variations, such as global warming. We agree and make no such claims. At no place in the paper by *Zhou et al.* [2001] do we ascribe the spatial and temporal changes in temperature and precipitation between 1981 and 1999 to long-run changes in climate such as global climate change.

References

Dye, D., Interannual variability and trends in the Northern Hemisphere annual snow-free period, 1971–1994, *Hydrol. Processes*, in press, 2003.

Gutman, G., On the use of long-term global data of land reflectances and vegetation indices derived from the advanced very high resolution radiometer, *J. Geophys. Res.*, *104*, 6241–6255, 1999.

Kaufmann, R. K., L. Zhou, Y. Knyazikhin, N. V. Shabanov, R. B. Myneni, and C. J. Tucker, Effects of orbital drift and sensor changes on the time series of AVHRR vegetation index data, *IEEE Trans. Geosci. Remote Sens.*, *38*(6), 2584–2597, 2000.

Lanfredi, M., T. Simoniello, and M. Macchiato, Comment on "Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999" by L. Zhou et al., *J. Geophys. Res.*, *108*, doi:10.1029/2002JD003046, in press, 2003.

Lucht, W., L. C. Prentice, R. B. Myneni, S. Sitch, P. Friedlingstein, W. Cramer, P. Bousquet, W. Buermann, and B. Smith, Climatic control of the high-latitude vegetation greening trend and Pinatubo effect, *Science*, *296*, 1687–1689, 2002.

Penuelas, J., and L. Filella, Response to a warming world, *Science*, *294*, 793–795, 2001.

Slayback, D., J. Pinzon, S. Los, and C. Tucker, Northern Hemisphere photosynthetic trends 1982–1999, *Global Change Biol.*, in press, 2003.

Tucker, C. J., D. A. Slayback, J. E. Pinzon, S. O. Los, R. B. Myneni, and M. G. Taylor, Higher northern latitude NDVI and growing season trends from 1982 to 1999, *Int. J. Biometeorol.*, *45*, 184–190, 2001.

Walther, G., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. C. Beebee, J. Fromentin, O. Hoegh-Guldberg, and F. Bairlein, Ecological responses to recent climate change, *Nature*, *416*, 389–395, 2002.

Zhou, L., C. J. Tucker, R. K. Kaufmann, D. Slayback, N. V. Shabanov, and R. B. Myneni, Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999, *J. Geophys. Res.*, *106*, 20,069–20,083, 2001.

Zhou, L., R. K. Kaufmann, Y. Tian, R. B. Myneni, and C. J. Tucker, Relation between interannual variations in satellite measures of vegetation greenness and climate between 1982 and 1999, *J. Geophys. Res.*, *108*(D1), 4004, doi:10.1029/2002JD002510, 2003.

Zhuang, Q., et al., Carbon cycling in extratropical ecosystems of the Northern Hemisphere during the 20th century: A modeling analysis of the influences of soil thermal dynamics, *Tellus, Ser. B*, in press, 2003.

R. K. Kaufmann, R. B. Myneni, and N. V. Shabanov, Department of Geography, Boston University, 675 Commonwealth Avenue, Boston, MA 02215, USA. (kaufmann@crsa.bu.edu; rmyneni@crsa.bu.edu; shabanov@crsa.bu.edu)

D. Slayback and C. J. Tucker, Biospheric Sciences Branch, Code 923, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (dan@manyu.gsfc.nasa.gov; compton@kratmos.gsfc.nasa.gov)

L. Zhou, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 221 Bobby Dodd Way, Atlanta, GA 30332, USA. (lmzhou@eas.gatech.edu)

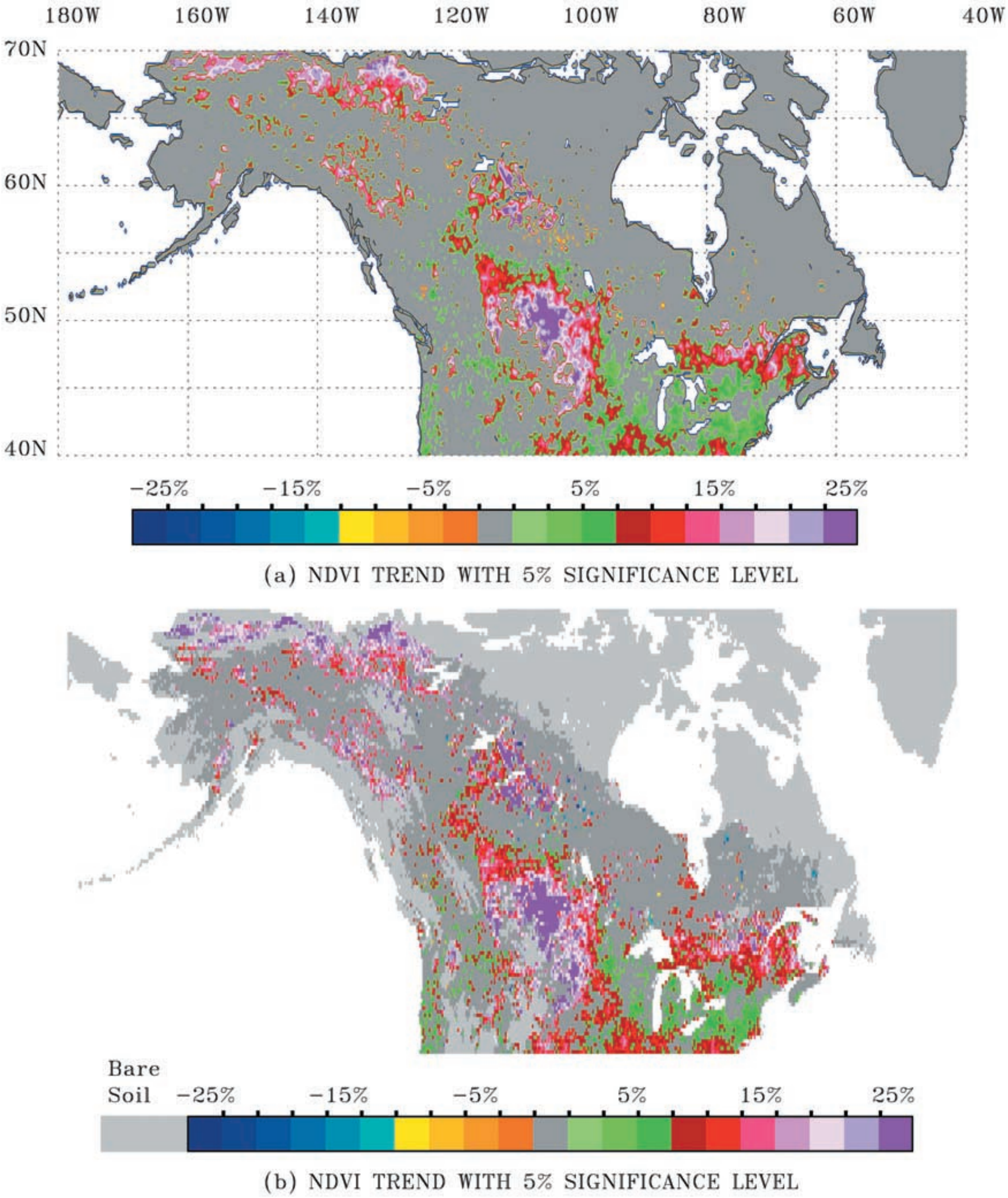

Figure 1. NDVI trends at 5% significance level for the Great Lakes region in North America: (a) a contour map taken from Panel lb of *Zhou et al.* [2001] and (b) same as (a) but plotted as an image, without smoothing, filtering, or interpolation.