Hurricane driven changes in land cover create biogeophysical climate feedbacks

Robinson I. Negrón Juárez,[1] Jeffrey Q. Chambers,[1] Hongcheng Zeng,[1] and David B. Baker[1]

Received 12 August 2008; revised 10 October 2008; accepted 22 October 2008; published 2 December 2008.

[1] Hurricanes can devastate thousands of hectares of forested area producing changes beyond simply vegetation damage and biomass loss. This study reports changes in regional climate associated with Hurricane Rita which made landfall on the Gulf Coastal Plain on September 24th, 2005. Results demonstrate that over severely disturbed forested areas, biogeophysical effects produced by Rita created anomalous precipitation patterns, with a decrease in precipitation the following winter, and an increase during the subsequent summer season. The dominant biogeophysical effect was a change in albedo caused by ~14,000 km^2 of disturbed forested area (downed and dead, snapped and structurally damaged trees) from Rita, equivalent to a committed carbon release of 32 to 43% of the net annual U.S. sink in forest trees. As recent studies project a likely increase in hurricane intensity during the 21st century, understanding the potential impact of forest damage from hurricanes on regional climate is important. **Citation:** Juárez, R. I. N., J. Q. Chambers, H. Zeng, and D. B. Baker (2008), Hurricane driven changes in land cover create biogeophysical climate feedbacks, *Geophys. Res. Lett.*, *35*, L23401, doi:10.1029/2008GL035683.

1. Introduction

[2] Anthropogenic land surface changes of albedo and surface roughness can alter precipitation and therefore the climate patterns [*Zeng and Neelin*, 1999; *Berbet and Costa*, 2003; *Foley et al.*, 2003] at local and global scales [*Betts et al.*, 2007; *Pielke*, 2005; *Foley et al.*, 2005]. These alterations can be as large as or larger than those resulting from the anthropogenic increase of well-mixed greenhouse gases [*Pielke*, 2005]. However, natural events can also produce dramatic land surface changes and often occur more rapidly than those produced by humans. For instance, Hurricane Katrina caused forest disturbance (downed and dead, snapped and structurally damaged trees) to 320 million trees over an area of 84,000 km^2 [*Chambers et al.*, 2007].

[3] After making landfall, tropical cyclones (i.e., tropical storms, hurricanes, and typhoons) can dramatically modify the landscape through wind damage (abrasion, swaying, twisting, rocking, and breaking), rainfall (flooding, leading to anoxia and subsequent tree mortality), and storm surge (salinity changes, bending or breaking, blowouts, or displacement). Hurricanes (wind speeds exceeding 33 ms^{-1}) have been one of the major natural disturbance factors affecting Atlantic and Gulf Coast landscapes as they reconfigure shorelines, inflict substantial property damage and create extensive tree mortality and damage in forested areas [*Boose et al.*, 1994]. Recent studies have reported an increase in hurricane intensity over the past 30 years [*Emanuel*, 2005; *Webster et al.*, 2005; *Wu and Wang*, 2008] with the 2005 Atlantic hurricane season recognized as the most active season on record (National Clime Data Center (NCDC), 2006, The climate of 2005, http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html, accessed July 2008). The 2005 season had twenty-seven named tropical storms formed, thirteen storms became hurricanes, seven of these hurricanes became Major (> Category 3) hurricanes with four of them (Emily, Katrina, Rita and Wilma) reaching the Category 5 strength on the Saffir-Simpson hurricane scale (NCDC, 2006).

[4] While this increase in hurricane intensity has been well documented, the influence of forest damage by hurricanes on regional climate has yet to be explored. On land, damage produced by hurricanes can affect surface properties such as albedo and roughness that in turn can strongly affect atmospheric thermodynamics and circulation patterns, thereby modifying local climate [*Foley et al.*, 2003]. Understanding how natural events change the landscape becomes more relevant as a number of disturbance processes are expected to increase as the Earth warms, including a likely increase in hurricane intensity for the 21st century [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007].

[5] The main objective of this project was to study changes in vegetation cover produced by Hurricane Rita and the associated biogeophysical climate feedbacks. We used remote sensing data to evaluate disturbance intensity on forested areas (surface cover changes), and climate data to understand how that disturbance affected regional precipitation patterns. The forest carbon impact produced by this disturbance was also estimated.

2. Data and Methods

2.1. Study Area and Data

[6] On the 24th of September, 2005, at ~2:40 AM LT, Hurricane Rita made landfall on the Gulf Coastal Plain between Sabine Pass, Texas and Johnson's Bayou, Louisiana. At landfall, the central pressure of Hurricane Rita was 937 mb with maximum winds of about 185 km/hr (Category 3). The storm surge (maximum height of 3.6 m) devastated coastal communities in southern Louisiana and Texas, with wind, rain, and tornadoes causing fatalities (R. D. Knabb et al., 2005, http://www.nhc.noaa.gov/pdf/TCR-AL182005_Rita.pdf, accessed 11 December 2007;

[1]Ecology and Evolutionary Biology, Tulane University, New Orleans, Louisiana, USA.

0094-8276/08/2008GL035683

NASA, Hurricane season 2005: Rita, http://www.nasa.gov/vision/earth/lookingatearth/h2005_rita.html, accessed 11 December 2007; NOAA, 2005, Hurricane Rita, www.srh.noaa.gov, accessed 11 December 2007) and damages estimated at more than US$ 10 billion (NCDC, 2006). Our study encompasses forested areas (29°N–33°N, 91°W–96°W) between Texas and Louisiana affected by surface wind fields with speeds higher than 18 ms^{-1}. *Marks and Harcombe* [1981] reported the main characteristics of this region including relief, vegetation, climate and soil. This region has little relief and vegetation varies from dry oak woodlands to wet floodplain forest and swamps. The average annual temperature is 19.5°C with minimum in January (10.6°C) and maximum in August (27.6°C). The average annual precipitation is 1320 mm, well distributed throughout the year, with a 50 mm difference between the wettest (April) and driest (March) months. The soil type is predominately ultisols but alfisols and entisols are also important.

[7] To estimate forest disturbance in this study, 500 m 8-day surface reflectance data (MOD09A1 at http://edcdaac.usgs.gov/main.asp) [*Vermote and Kotchenova*, 2008] from the Moderate Resolution Imaging Spectroradiometer (MODIS) were used. To cover our study area, four MOD09A1 scenes (h09v05, h10v05, h09v06 and h10v06) were mosaicked and resampled to a Geographic Lat/Lon (WGS 84) projection using the MODIS Reprojection Tool (MRT) available at http://lpdaac.usgs.gov/landdaac/tools/modis/. MOD09A1 images were processed for times of maximum (May) and minimum (January–February) greenness in 2005 (pre-hurricane) and 2006 (post-hurricane).

[8] Monthly climate data from 1998 to 2007 from the Tropical Rainfall Measuring Mission (TRMM 3B43, http://trmm.gsfc.nasa.gov) [*Huffman et al.*, 2007] and the North American Regional Reanalysis (NARR, http://nomads.ncdc.noaa.gov) [*Mesinger et al.*, 2006] we utilized. TRMM 3B43 provides rainfall data (0.25° of horizontal resolution) which merges TRMM and other satellite data with rain gauge estimates. NARR is a long term, high resolution atmospheric and land surface hydrology dataset (32-km of horizontal resolution and 29 vertical levels from 1000 to 100 mb) for all of North America. Precipitation analysis focused on the winter (December 2005 to February 2006) and summer (June 2006 to August 2006) seasons in 2006 for six contiguous $1° \times 1°$-boxes where different intensities of forest disturbance were observed in the MODIS analysis results. To simultaneously compare precipitation changes over these boxes, we removed the influences of seasonality and location using the standardized precipitation anomaly (z): $z = (x - X)/sx$, where X is the mean value of the raw data, x, and sx the standard deviation of this data [*Wilks*, 2006].

[9] Hurricane Rita wind surface data was downloaded from the Hurricane Research Division of the National Oceanic and Atmospheric Administration (http://www.aoml.noaa.gov/hrd/). This data is based on the H*wind model [*Powell et al.*, 1998] and uses wind measurements from a variety of observation platforms to develop an objective analysis of the extent and strength of wind field speeds from a hurricane.

2.2. Spectral Mixture Analyses, Tree Damage and Biomass Loss

[10] Spectral mixture analysis (SMA) [*Chambers et al.*, 2007] was used on MODIS data to quantify the intensity of forest disturbance produced by Hurricane Rita. SMA quantifies a per-pixel fraction of composite endmembers which sum to match the full pixel spectrum of the image [*Adams et al.*, 1995]. Scene-derived endmembers of green vegetation (GV), non-photosynthetic vegetation (NPV), soil, and shade were obtained using a pixel purity index (PPI) algorithm [*Boardman et al.*, 1995] applied on scenes from January, February, and May 2005 and 2006. PPI and SMA tools from the Environment for Visualizing Images (ENVI, ITT industries, Inc, Boulder CO, USA) software were utilized. Changes in ΔNPV were calculated by subtracting May 2005 NPV from May 2006 NPV, providing a quantitative measure of the changes in dead vegetation and woody biomass associated with disturbance [*Chambers et al.*, 2007].

[11] To estimate biomass loss, we used the approach introduced by *Chambers et al.* [2007] and briefly described here. A scatter plot of minimum green vegetation (GV_{min}, in February) and maximum green vegetation (GV_{max}, in May) was used to show the ternary spread of data, with corners representing pure deciduous, pure evergreen (primarily pine), and pure urban/non-vegetated areas. The absolute perpendicular distance (d) of any pixel to the line connecting pure deciduous and pure evergreen behavior was calculated as a measure of the proximity to forest. If the pixel was classified as forest ($d < 0.20$) then a probability function determined if this pixel was deciduous or coniferous, and stem density was calculated based on a stem density distribution using inventory data from the USDA Forest Service (Forest Inventory and Analysis National Program, FIA). The number of dead and damaged trees per hectare was calculated by multiplying stem density by the damage rate. The damage rate was estimated using a linear function between ΔNPV and damaged trees [*Chambers et al.*, 2007]. For each dead tree, an amount of biomass was generated based on biomass distributions (using FIA data) which were empirically determined to be a logarithmic normal distribution. For simplification, biomass loss from snapped trees was calculated as 50% of dead tree biomass loss. A Monte Carlo model was developed to stochastically estimate stem density and biomass distribution, as well as mortality and damage rates from ΔNPV.

3. Results and Discussion

[12] Overall, this study estimated that the disturbance produced by Hurricane Rita and the associated surface wind field affected ~14,000 km^2 of forested area corresponding to the mesoscale domain (10^2–10^5 km^2). The scale domain of the disturbance is important for our analyses since precipitation processes are dependent on the horizontal scale [*D'Almeida et al.*, 2007] as well as the latitudinal location [*Bala et al.*, 2007]. Figure 1 shows changes in NPV (ΔNPV) produced by Hurricane Rita over forested areas. The average ΔNPV values for boxes A1 through A6 were 0.12, 0.14, 0.15, 0.18, 0.25, and 0.14, respectively. A4 and A5 presented the highest ΔNPV (greatest forest disturbance), a notable increase in surface albedo (verified with the albedo MCD43B3 MODIS product), and strong shifts in surface roughness (aerial photography available at http://

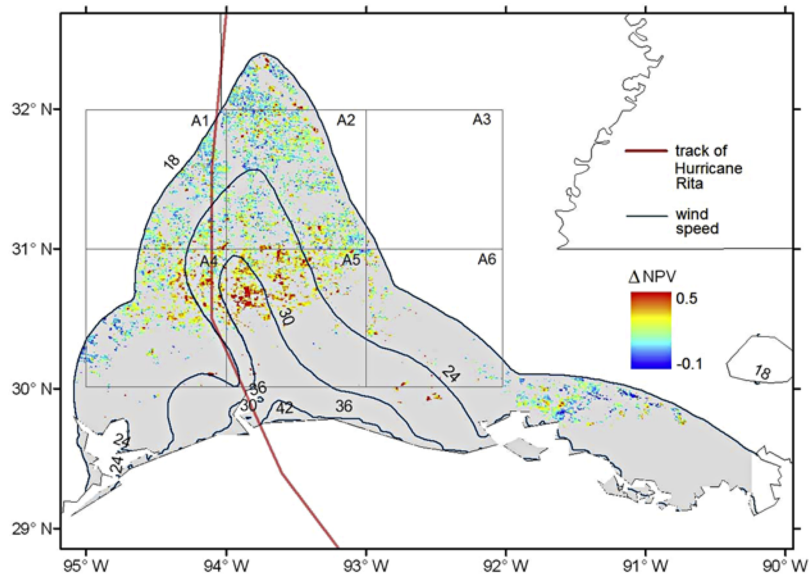

Figure 1. Changes in Non-Photosynthetic Vegetation (NPV) over forested areas produced by Hurricane Rita. Six boxes (A1 to A6) of 1° × 1° are also shown. The figure shows the footprint of Hurricane Rita for wind values $\geq$18 ms^{-1}. Non-forested areas in gray.

www.lacoast.gov/maps/2005rita/index.htm). Changes in albedo and surface roughness can modify the climate as reported in a number of studies [e.g., *Zeng and Neelin*, 1999; *Foley et al.*, 2003; *Pielke*, 2005; *Foley et al.*, 2005]. Albedo modifies the radiative balance, affecting energy available at the surface for evaporation, heating, and photosynthesis. Surface roughness affects the turbulent transfer of water vapor, sensible heat, and momentum in the atmosphere. Thus, changes in precipitation associated with Rita are more likely to occur over the heavily damaged A4 and A5 regions. Supporting this hypothesis, Figure 2 shows that A4 and A5 presented the strongest negative and positive precipitation anomalies during the winter and summer 2006 seasons, respectively. To explore relationships between ΔNPV and precipitation, ΔNPV was aggregated to the spatial resolution of precipitation data and using those pixels dominated (>70%) by forest. In total 8 pixels were used over A4 and A5. ΔNPV explained 60% (R^2 = 0.60, p = 0.04) of precipitation changes in winter and about 15% (p = 0.2) of changes in the summer. This suggests that the effects of land cover change on precipitation were more evident in the winter than in the summer season, in agreement with results from *Bounuoa et al.* [2002].

[13] During the winter season the observed decrease in precipitation over A4 and A5 (Figure 2a) coincides with precipitation decreases at the mesoscale domain reported in numerical studies over mid-latitude North America [*Govindasaym et al.*, 2001; *Bounuoa et al.*, 2002]. These studies point out that land cover disturbance results in a decrease in precipitation due to physiological effects (e.g., decrease in transpiration) and from the increase in surface albedo which reduces the absorption of incoming short-wave radiation, and decreases net solar surface radiation. Contrary to numerical studies that show lower temperatures over disturbed areas in the winter season, data from both MODIS (terra and aqua) and the Atmospheric InfraRed Sounder (AIRS) (http://www-airs.jpl.nasa.gov) revealed that surface temperatures were higher over A4 and A5 in the 2006 winter with respect to the 2005 winter (not shown). This can be explained by the fact that over the states of Texas (TX) and Louisiana (LA) the 2006 winter temperature was higher with respect to the same season in 2005 (NCDC, 2006, 2007, The climate of 2006, http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html, accessed July 2008). Furthermore, the 2006 winter was far above normal with record warmth in January (NCDC, 2007).

[14] During the summer 2006 season, A4 and A5 showed higher precipitation with respect to the other boxes (Figure 2b). At the mesoscale domain, a landscape discontinuity tends to produce more precipitation [*Avissar and Liu*, 1996; *Boyles et al.*, 2007], and the induced thermal circulation may be as intense as a sea-breeze circulation [*Segal et al.*, 1988] that can enhance precipitation. Comparatively, this increase in precipitation is similar to that reported by *Negri et al.* [2004] over the southern Brazilian Amazon, in Rondonia, Brazil, where native forested areas have been replaced by pastures. These authors found that increased surface heating over deforested areas created a direct thermal circulation, which increased the occurrence of shallow cumulus clouds, deep convective cloudiness, and rainfall. Enhanced precipitation also explains why A4 and A5 had lower temperatures (not shown) even though 2006 summer temperatures were the 2nd warmest in the last 112 years over the contiguous US (NCDC, 2007).

[15] Figures 2c and 2d show the divergence anomalies (shaded) at 850 mb and the vertical velocity anomalies (contour lines) at 500 mb for the winter and summer 2006. Because the strongest vegetation disturbance occurred over A4 and A5, the specific humidity was lowest over these areas and as a consequence, precipitation was highly dependent on humidity advection from remote regions. In the winter, the low-level convergence (negative divergence) over A4 and A5 (Figure 2c) was small (probably not enough to produce precipitation). Note that the center of maximum low-level convergence was far from this area in the winter. There was a center of upward motion over these areas but it lacked

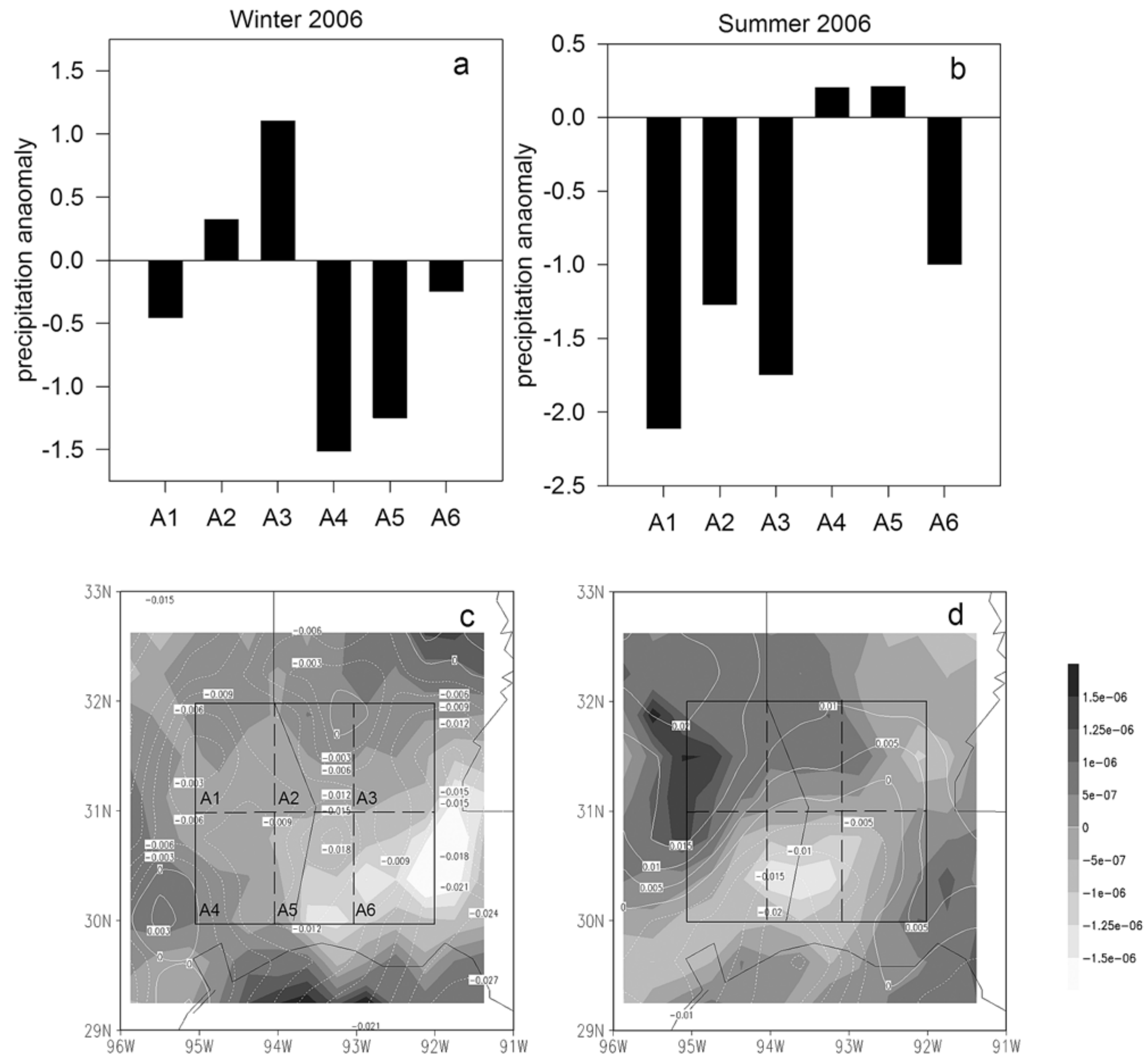

Figure 2. Precipitation Anomaly (base period 1998–2007) over 6 selected areas in our domain for (a) winter (DJF) and (b) summer (JJA) seasons in 2006. (c) and (d) The anomalies (base period 1998–2007) of divergence at 850 mb (shade) and vertical velocity (contour lines) for winter and summer seasons in 2006, respectively.

sufficient specific humidity convergence, and therefore yielded less rain. In the summer, the center of maximum low-level convergence was directly over A4 and A5 (Figure 2d), which was a consequence of the heat island effect, and the precipitation anomaly was positive. In addition, higher specific humidity was expected in this season since increased temperature leads to increased water vapor saturation pressure. Thus, the summer showed a more dynamically favorable environment for precipitation over A4 and A5.

[16] The seasonal changes observed in precipitation in 2006 were not observed in 2007. The above average precipitation over TX and LA during the 2007 winter and summer seasons (NCDC/Feb07, NCDC/Aug07) due to large scale weather patterns may have overwhelmed any lingering hurricane-related effects. It is also possible that rapid forest recovery observed over the damaged areas may also have contributed to mute this signal. Although a detailed study would include the interaction among soil, land cover, land surface fluxes and atmosphere through modeling approaches, these were beyond the scope of this study, and the analyses presented here nevertheless provide some insights for future work.

[17] The disturbance produced by Hurricane Rita affected 106 million trees including both dead and snapped but still living trees with a total biomass loss of 48 Tg C, an amount equivalent to 32 to 43% of the net annual U.S. carbon sink in forest trees [*Pacala et al.*, 2001]. Although our study focused on the mesoscale domain, mesoscale circulation can affect atmospheric circulation on both the local [*Zhong and Doran*, 1998] and global [*Copeland et al.*, 1996; *Pielke et al.*, 1998] scales. Our results indicate that hurricanes can modify regional climate and carbon balance. Predicted increases in hurricane intensity [*IPCC*, 2007] will only

serve to heighten the future importance of these hurricane-related climatic effects.

[18] **Acknowledgments.** We would like to thank comments from 2 anonymous reviewers. This study was supported by a grant from the National Institute for Climatic Change Research (NICCR) Coastal Center, which is sponsored by DOE's Office of Biological and Environmental Research.

References

Adams, J. B., D. Sabol, V. Kapos, R. Almeida, D. Roberts, M. Smith, and A. Gillespie (1995), Classification of multispectral images based on fractions of endmembers: Application to land-cover change in the Brazilian Amazon, *Remote Sens. Environ.*, *52*, 137–154.

Avissar, R., and Y. Liu (1996), Three-dimensional numerical study of shallow convective clouds and precipitation induced by land surface forcings, *J. Geophys. Res.*, *101*, 7499–7518.

Bala, G., K. Caldeira, M. Wickett, T. Phillips, D. Lobell, C. Delire, and A. Mirin (2007), Combined climate and carbon-cycle effect of large-scale deforestation, *Proc. Natl. Acad. Sci. U.S.A.*, *104*, 6550–6555, doi:10.1073/pnas.0608998104.

Berbet, M. L., and M. H. Costa (2003), Climate change after tropical deforestation: Seasonal variability of surface albedo and its effects on precipitation change, *J. Clim.*, *16*, 2099–2104.

Betts, R. A., P. D. Fallon, K. K. Goldewijk, and N. Ramankutty (2007), Biogeophysical effects on land use on climate: Model simulations of radiative forcing and large-scale temperature change, *Agric. For. Meteorol.*, *142*, 216–233.

Boardman, J. W., F. A. Kruse, and R. O. Green (1995), Mapping target signatures via partial unmixing of AVIRIS data, *JPL Publ.*, *95-1*, 23–26.

Boose, E. R., D. R. Foster, and M. Fluet (1994), Hurricane impacts to tropical and temperate forest landscapes, *Ecol. Monogr.*, *64*, 369–400.

Bounuoa, L., R. Defries, G. Collatz, P. Sellers, and H. Khan (2002), Effects of land cover conversion on surface climate, *Clim. Change*, *52*, 29–64.

Boyles, R., S. Raman, and A. Sims (2007), Sensitivity of mesoscale surface dynamics to surface soil and vegetation contrasts over the carolina sandhills, *Pure Appl. Geophys.*, *164*, 1547–1576.

Chambers, J. Q., J. Fisher, H. Zeng, E. Chapman, D. Baker, and G. Hurtt (2007), Hurricane Katrina's footprint on Gulf Coast Forest, *Science*, *318*, 1107, doi:10.1126/science.1148913.

Copeland, J. H., R. A. Pielke, and T. G. F. Kittel (1996), Potential climatic impacts of vegetation change: A regional modeling study, *J. Geophys. Res.*, *101*, 7409–7418.

D'Almeida, C., C. J. Vorosmarty, G. Hurtt, J. A. Marengo, S. Dingman, and B. Keim (2007), The effects of deforestation on the hydrological cycle in Amazonia: A review on scale and resolution, *Int. J. Climatol.*, *27*, 347–633, doi:10.1002/joc.1475.

Emanuel, K. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686–688.

Foley, J. A., M. H. Costa, C. Delire, N. Ramankutty, and P. Snyder (2003), Green Surprise? How terrestrial ecosystems could affect Earth's climate, *Frontiers Ecol. Environ.*, *1*, 38–44.

Foley, J. A., et al. (2005), Global consequences of land use, *Science*, *309*, 570–574.

Govindasaym, B., P. B. Duffy, and K. Caldeira (2001), Land use changes and Northern Hemisphere cooling, *Geophys. Res. Lett.*, *28*, 291–294.

Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, E. J. Nelkin, K. P. Bowman, Y. Hong, E. F. Stocker, and D. B. Wolff (2007), The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales, *J. Hydrometeorol.*, *8, 38–55.*

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., 996 pp., Cambridge Univ. Press, Cambridge, U. K.

Marks, P. L., and P. A. Harcombe (1981), Forest vegetation of the big thicket southeast Texas, *Ecol. Monogr.*, *51*, 287–305.

Mesinger, F., et al. (2006), North American regional reanalysis, *Bull. Am. Meteorol. Soc.*, *87*, 343–360.

Negri, A., R. Adler, L. Xu, and J. Surrat (2004), The impact of Amazonian deforestation on dry season rainfall, *J. Clim.*, *17*, 1306–1319.

Pacala, S. W., et al. (2001), Consistent land- and atmosphere-based US carbon sink estimates, *Science*, *292*, 2316–2320, doi:10.1126/science.1057320.

Pielke, R. A. (2005), Land use and climate change, *Science*, *310*, 1625–1626.

Pielke, R. A., R. Avissar, M. Raupach, A. J. Dolman, X. Zeng, and A. S. Denning (1998), Interactions between the atmosphere and terrestrial ecosystems: Influence on weather and climate, *Global Change Biol.*, *4*, 461–475.

Powell, M. D., S. H. Houston, L. R. Amat, and N. Morisseau-Leroy (1998), The HRD real-time hurricane wind analysis system, *J. Wind Eng. Ind. Aerodyn.*, *77–78*, 53–64.

Segal, M., R. Avissar, M. C. McCumber, and R. A. Pielke (1988), Evaluation of vegetation effects on the generation and modification of mesoscale circulations, *J. Atmos. Sci.*, *45*, 2268–2292.

Vermote, E. F., and S. Y. Kotchenova (2008), MOD09 (Surface Reflectance) User's Guide, MODIS Land Surf. Reflectance Sci. Comput. Facil., College Park, Md. (Available at http://modis-sr.ltdri.org/MAIN_SURFACE_PRODUCTAND%20USER%20GUIDE/MOD09_UserGuide.pdf)

Webster, P. J., G. J. Holland, J. A. Curry, and H. R. Chang (2005), Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, *309*, 1844–1846.

Wilks, D. S. (2006), *Statistical Methods in the Atmospheric Sciences, Int. Geophys. Ser.*, vol. 91. 2nd ed., Elsevier, New York.

Wu, L., and B. Wang (2008), What has changed the proportion of intense hurricanes in the last 30 years?, *J. Clim.*, *21*, 1432–1439.

Zeng, N., and J. D. Neelin (1999), A land-atmosphere interaction theory for the tropical deforestation problem, *J. Clim.*, *12*, 857–872.

Zhong, S., and J. C. Doran (1998), An evaluation of the importance of surface flux variability on GCM-scale boundary-layer characteristics using realistic meteorological and surface forcing, *J. Clim.*, *11*, 2774–2788.

D. B. Baker, J. Q. Chambers, R. I. N. Juárez, and H. Zeng, Ecology and Evolutionary Biology, Tulane University, New Orleans, LA 70118–5698, USA. (rjuarez@tulane.edu)