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Collapse of the Maya: Could deforestation have contributed?

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[1] The collapse of the Maya civilization during the ninth century A.D. is a major conundrum in the history of mankind. This civilization reached a spectacular peak but then almost completely collapsed in the space of a few decades. While numerous explanations have been put forth to explain this collapse, in recent years, drought has gained favor. This is because water resources were a key for the Maya, especially to ensure their survival during the lengthy dry season that occurs where they lived. Natural drought is a known, recurring feature of this region, as evidenced by observational data, reconstructions of past times, and global climate model output. Results from simulations with a regional climate model demonstrate that deforestation by the Maya also likely induced warmer, drier, drought-like conditions. It is therefore hypothesized that the drought conditions devastating the Maya resulted from a combination of natural variability and human activities. Neither the natural drought or the human-induced effects alone were sufficient to cause the collapse, but the combination created a situation the Maya could not recover from. These results may have sobering implications for the present and future state of climate and water resources in Mesoamerica as ongoing massive deforestation is again occurring.

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1. Introduction: The Maya and Their Collapse

[2] The Peten region of northern Guatemala is where the Maya civilization began, flourished, and then for unknown reasons abruptly disappeared during the ninth century A.D. Nomadic hunting and gathering bands entered into the area around 1500 B.C. and subsequently organized into large village groups and shifted to food production. By 600 B.C. these pioneer farmers had severely modified most of the landscape and much of the forest was cut down [*Adams*, 1996]. The soil runoff from the environmental destruction transformed the large karst depressions, known as bajos, (which make up 40%–60% of the land surface) from perennial wetlands and lakes into seasonal swamps between 400 B.C. and A.D. 250. Pollen records indicate that by the ninth century A.D. most of the forest had been cut down, and *Adams* [1996] speculates that by 750 A.D. "nearly every square meter of land had been modified."

[3] Maya civilization reached its spectacular peak during its Late Classic Period (A.D. 600–850). This peak was followed almost immediately by a devastating collapse in which population declined by more than 80% in little more than a century [*Culbert*, 1988]. At the time of their collapse, the Maya had attained one of the highest population densities in human history with 6700 people per square kilometer in the center and 1300–3400 per square kilometer in the more rural areas [*Rice*, 1991]. This population density is rivaled today only by China and Java [*Culbert*, 1993]. The only Maya cities where humans survived the collapse were located near long-term stable sources of drinking water. The Maya did not survive in the vast majority of cities that depended on surface reservoirs for their water supply [*Gill*, 2000].

[4] Numerous explanations for the Mayan collapse have been proposed, including climatic change, exhaustion and/or erosion of soil, epidemic disease, earthquakes, warfare, overpopulation, external invasion, peasant revolt, hurricanes, malnutrition, and national decadence [*Gill*, 2000; *Webster*, 2002]. Most scholars agree that it was brought on by a combination of ecological, political, and social factors. *Culbert* [1993] and *Fagan* [1999] argue that the magnitude of the population collapse was such that social malfunction alone cannot account for it.

[5] Recent data indicate that a major drought at this time may have been a key factor in the collapse. Research along

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the Holmul River, which runs through several bajos and connects 10 major Maya cities, indicates that between A.D. 750 and 850 the river either dried up or became swampy, perhaps as a result of a long period of drought [*Sever and Irwin*, 2003; T. P. Culbert, personal communication, 2002]. These data correlate with that of other researchers who have found evidence of a major drought at 750 A.D. in lake core sediments, one of the driest, if not the driest, in a 7000 year period [*Hodell et al.*, 2001], as well as intense multiyear droughts centered at A.D. 810, 860, and 910 [*Haug et al.*, 2003]. *Gill* [2000] speculated that drought conditions between A.D. 800–900 were related to the local manifestation of Northern Hemisphere weather patterns, especially involving the so-called "North Atlantic Oscillation" (NAO). More recent studies, although not focused on the Maya, suggest that the Atlantic Multidecadal Oscillation (AMO) may play a key role in the droughts that recur in this region on multidecadal time scales [*Feng et al.*, 2008]. *Hunt and Elliott* [2005] found that, in a long 10,000 year simulation with a low-resolution GCM through natural variability (as simulated by the model), long periods of drought occurred in the Yucatan peninsula and, in their words, attributed these to "the geographic location coinciding with the interface of the trade winds and the ITCZ." Tree ring evidence, on the other hand, suggests that major Yucatan droughts are part of an overall pattern of North American drought [*Cook et al.*, 1999]. Lastly, *Hodell et al.* [2001] attribute drought in this region to a 206 year solar cycle.

[6] Were these major droughts the result of normal climate variability? Alternatively, could they have been induced by Maya land use practices, especially almost complete deforestation? Modern-day droughts do occur over Mesoamerica in general and the Maya region in particular; the causes of these droughts are still debated, although as noted above some workers have related them to quasi-cyclical changes in either solar output or climatic phenomena such as NAO or AMO. Furthermore, a large body of work has demonstrated the general importance of land cover changes in affecting climate [*NRC*, 2005] and, in particular, the specific effects of tropical deforestation for the Amazon [*Lean and Warrilow*, 1989; *Henderson-Sellers et al.*, 1993], tropical Africa [*Zeng and Eltahir*, 1997; *Clark et al.*, 2001], and tropical Asia [*Suh and Lee*, 2004]. Other works in our study region (northern Costa Rica) demonstrated that cumulus clouds form higher and later in the afternoon over deforested areas, resulting in less rainfall [*Lawton et al.*, 2001; *Nair et al.*, 2003; *Ray et al.*, 2006; *Pielke et al.*, 2007].

[7] To summarize, the key question we address in this paper is: Did the extensive deforestation, land use changes, and environmental degradation of the ancient Mayan empire contribute to climate variability and drought in the past and was this human-induced modification to the landscape a major contributor to the collapse of the Maya? If so, how did it compare with naturally occurring droughts? Our hypothesis is that neither the naturally occurring drought nor the drying due to human-induced deforestation by themselves was sufficient to cause the collapse. However, the conjunction of the two forcings reduced water resources to a point that was devastating for the entire Mayan civilization. In other words, the continuing deforestation over hundreds of years slowly put more and more stress on water availability; however for much of this time, the Maya were able to cope through continuous adaptive strategies, even during occasional periods of drought. Once deforestation became near total and a natural drought of sufficient severity came along, the Maya could no longer adapt, and the resulting water shortages lead quickly to extreme social unrest and political instability that in turn induced almost complete collapse of their civilization. Since the occurrence of natural drought has already been extensively studied, the goal of the current study is to focus on the manner by which deforestation may impact drought and to compare these effects to those that occur due to natural drought.

2. Model Descriptions and Experiment Scheme

2.1. MM5

[8] The Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) Mesoscale Model 5 version 3, known as MM5, is described in the works of *Dudhia* [1993] and *Grell et al.* [1994]. The MM5 allows the choice of several different physical parameterization schemes for radiation, boundary layer, and convective processes. In this study, the model was implemented with the short-wave radiation scheme described by *Grell et al.* [1994], the nonlocal K approach found in the work of *Hong and Pan* [1996] and the Grell scheme for convective precipitation. The model requires lateral forcing provided either from a reanalysis (essentially a General Circulation Model (GCM) constrained by observations) or a "pure" GCM with no data assimilation (as described below, we employ both methods). Land surface-atmosphere interactions are handled via the NOAH land surface scheme, which provides fluxes of moisture, heat, and momentum to the atmosphere. The regional model is a more appropriate tool than the global model when a high-resolution look at climatic effects (e.g., due to local deforestation) is required over Mesoamerica; this is especially important for precipitation.

[9] A nested, two-domain configuration was used for all MM5 runs. The model resolution (that is, the horizontal grid increment) was set to 36 km for the outer domain and 12 km for the inner domain (Figure 1a). The outer domain serves two purposes: (1) it steps the forcing down from the scale of the reanalysis (approximately 250 km) or global model (approximately 140 km) to the fine resolution of the inner domain and (2) it allows for analysis of large-scale effects and forcings influencing Mesoamerican climate. We use one-way downscaling, that is, the changes we impose in the inner domains cannot feedback to the outer domain or global models/reanalyses used to drive MM5. While this lack of feedback may constrain our results somewhat, it is the local effects of deforestation that we are attempting to define in this study. The inner domain (which includes all of Mesoamerica and adjacent oceans) is the one from which we obtain our main results. Figure 1b shows the model topography at the 12 km resolution; the major mountainous features are all readily identifiable.

[10] A series of MM5 control runs was made to document how well the model simulates the climate and especially precipitation over Mesoamerica. These runs also provide a bench mark against which to compare deforestation runs. They included a 5 year run for 1997–2001, with National Centers for Environmental Prediction (NCEP)/NCAR reanalyses

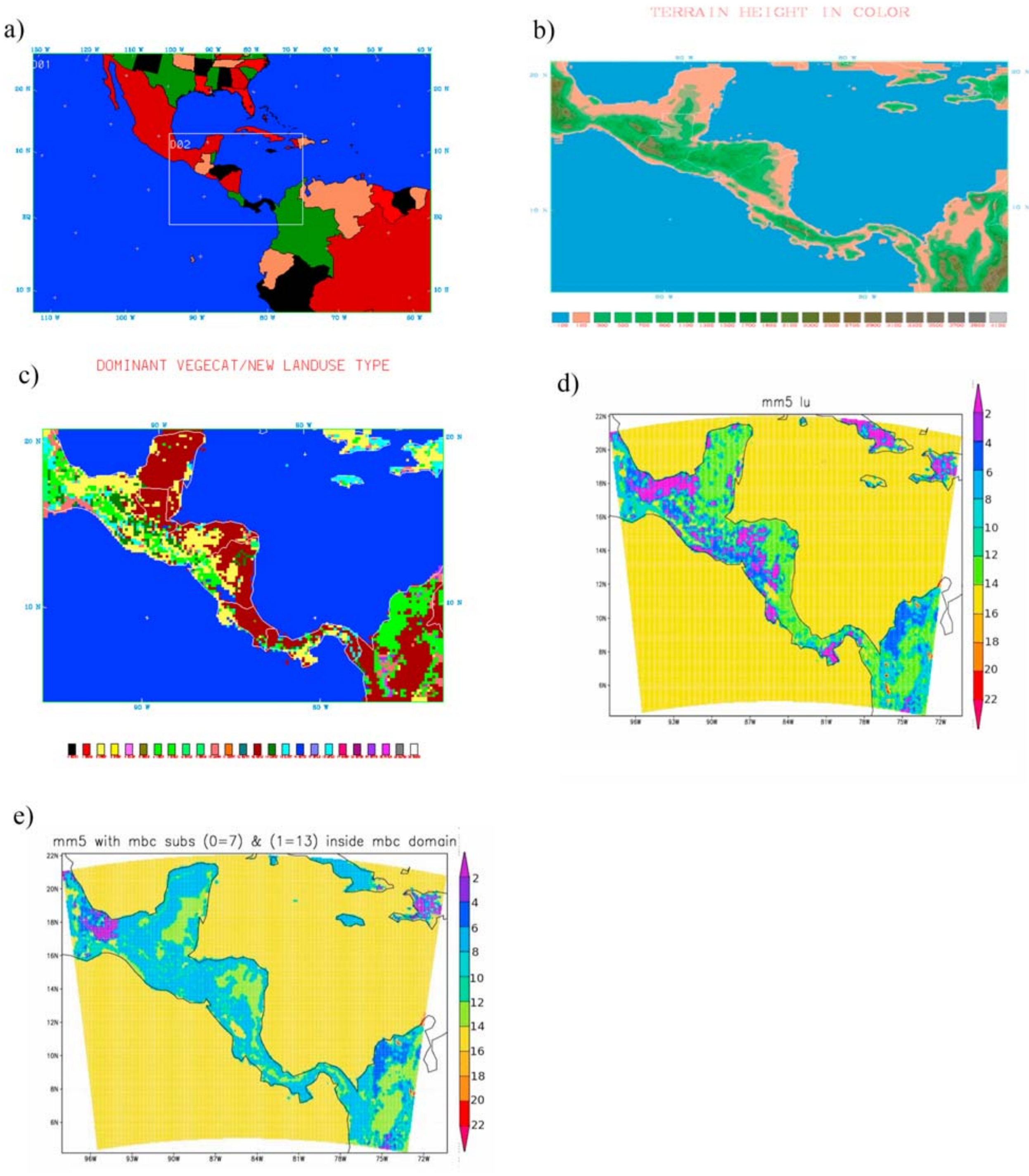

Figure 1. (a) The outer and inner domains used for the MM5 simulations. (b) The topography as resolved by the 12 km inner domain. (c) Land use category (default) as resolved by the 12 km inner domain. (d) Land use category circa 2000. (e) Land use category with complete deforestation except for proposed MBC corridor.

providing the large-scale forcing, as well as a run from 2000 to 2005 with Community Climate System Model, version 3 (CCSM3) providing the large-scale forcing (the years 2000–2005 represent the forcings used in the 20th to 21st century CCSM3 run described below. Thus, we have a control forced by the best “quasi-observational” state of the atmosphere available (i.e., the reanalysis) as well as one forced by the same global model we use to analyze naturally occurring drought.

[11] The land surface scheme in MM5 has designated surface types; then a look-up table is used to assign values for physical parameters associated with each surface type.

Table 1. Description of (USGS) Vegetation Categories and Physical Parameters[a]

		Albedo (%)		Moisture Avail. (%)		Emissivity		Rough. Length (cm)		Thermal Inertia	
	Vegetation Description	Sum	Win	Sum	Win	Sum	Win	Sum	Win	Sum	Win
1	Urban	15	15	10	10	88	88	80	80	0.03	0.03
2	Drylnd Crop. Past.	17	23	30	60	98.5	92	15	5	0.04	0.04
3	Irrg. Crop. Past.	18	23	50	50	98.5	92	15	5	0.04	0.04
4	Mix. Dry/Irrg.C.P.	18	23	25	50	98.5	92	15	5	0.04	0.04
5	Crop./Grs. Mosaic	18	23	25	40	99	92	14	5	0.04	0.04
6	Crop./Wood Mosc	16	20	35	60	98.5	93	20	20	0.04	0.04
7	Grassland	19	23	15	30	98.5	92	12	10	0.03	0.04
8	Shrubland	22	25	10	20	88	88	10	10	0.03	0.04
9	Mix Shrb./Grs.	20	24	15	25	90	90	11	10	0.03	0.04
10	Savanna	20	20	15	15	92	92	15	15	0.03	0.03
11	Decids. Broadlf.	16	17	30	60	93	93	50	50	0.04	0.05
12	Decids. Needlf.	14	15	30	60	94	93	50	50	0.04	0.05
13	Evergrn. Broadlf.	12	12	50	50	95	95	50	50	0.05	0.05
14	Evergrn. Needlf.	12	12	30	60	95	95	50	50	0.04	0.05
15	Mixed Forest	13	14	30	60	94	94	50	50	0.04	0.06
16	Water Bodies	8	8	100	100	98	98	.01	.01	0.06	0.06
17	Herb. Wetland	14	14	60	75	95	95	20	20	0.06	0.06
18	Wooded wetland	14	14	35	70	95	95	40	40	0.05	0.06

[a] For Northern Hemisphere summer (15 April to 15 October) and winter (15 October to 15 April). Extraneous high-latitude categories are not shown. Our simulations focused on types 7 and 13. Win, winter; Sum, summer; Rough., roughness.

Figure 1c shows the default present-day surface types used for Central America, while Table 1 defines each surface type and gives the specific physical parameters used for each. The default surface types are based on USGS aerial surveys from the late 1970s and early 1980s (see the MM5 User's Guide for more details, obtainable from http://www.mmm.ucar.edu/mm5/doc1.html).

[12] Several MM5 runs designed to evaluate the impact of deforestation on climate were made. The first two simulations involved extreme scenarios, but not too far off reconstructions that suggest the Maya had almost completely deforested the zones where they lived. One run had all of Mesoamerica containing evergreen forest; the other had all of Mesoamerica containing grassland. Four years were simulated for each of the all forest and all grassland scenarios, with NCEP reanalysis for 1997–2000 providing the lateral forcing. Thus, these runs, besides being compared to each other, can also be compared to the control run described above.

[13] Two runs were also made with less extensive deforestation scenarios. One was a simulation with newly developed land use types for 2000 (http://servir.nsstc.nasa.gov/lcluc/index.html); this can be compared with the control run made using default MM5 land use types (from circa 1980 as noted above) to evaluate the effects of several decades of deforestation. The other run assumed complete deforestation outside the proposed "Mesoamerica Biological Corridor" (MBC) but complete forestation within the MBC [*Miller et al.*, 2001]. (The MBC would be a continuous, protected region of forest running northwest-southeast from southern Mexico through Panama.) As shown in Figures 1d and 1e, each of these deforestation scenarios are not too different than the circa 1980 control, and implications of this will be discussed below. These runs had lateral forcing provided by the CCSM3 and can also be compared to equivalent years from the CCSM3-forced control run described above.

2.2. The NCAR CCSM3.0

[14] The Community Climate System Model (CCSM), version 3, is a coupled model for simulating past, present, and future climates [*Collins et al.*, 2006]. In its present form, CCSM consists of four components for the atmosphere, ocean, sea ice, and land surface linked through a coupler that exchanges fluxes and state information among these components. Applications include studies of interannual and interdecadal variability, simulations of paleoclimate regimes, and projections of future anthropogenic climate change. The CCSM3 atmosphere and land models are formulated on Eulerian spectral grids with T85 wave number truncation (about 1.4° latitude and longitude) and ocean and sea ice models on grids with a nominal equatorial resolution of 1°.

[15] We used output from two long global climate model runs made with the CCSM3 to analyze the occurrence of natural drought in the Maya region. A global model is required to simulate naturally occurring drought, as climate is a global phenomenon, and therefore, the controls on it can include many far-field factors such as sea surface temperatures (SST) throughout the Atlantic or Pacific basins. One run was a 100 year present-day "control" run. That is, the model was run with invariant present-day forcing and surface boundary conditions through 100 seasonal cycles to estimate the model mean climate and, importantly for our purposes, its variability. The other run was designed to simulate the actual climate from 1870 through 1999. That is, known year-by-year variations in forcings and boundary conditions such as greenhouse gas concentrations, fluctuations in solar output, and ash from volcanic eruptions during this period were imposed on the model. See *Collins et al.* [2006] and http://www.ccsm.ucar.edu/experiments/ccsm3.0/ for more details about these runs.

3. Results

3.1. Validating MM5: Comparison to Observations

[16] *Hernandez et al.* [2006] performed a comprehensive evaluation of how well MM5 simulates the climate of Central America. They focused on all available daily station observations and found that, at least where these relatively sparse observations exist, the model does an acceptable job in

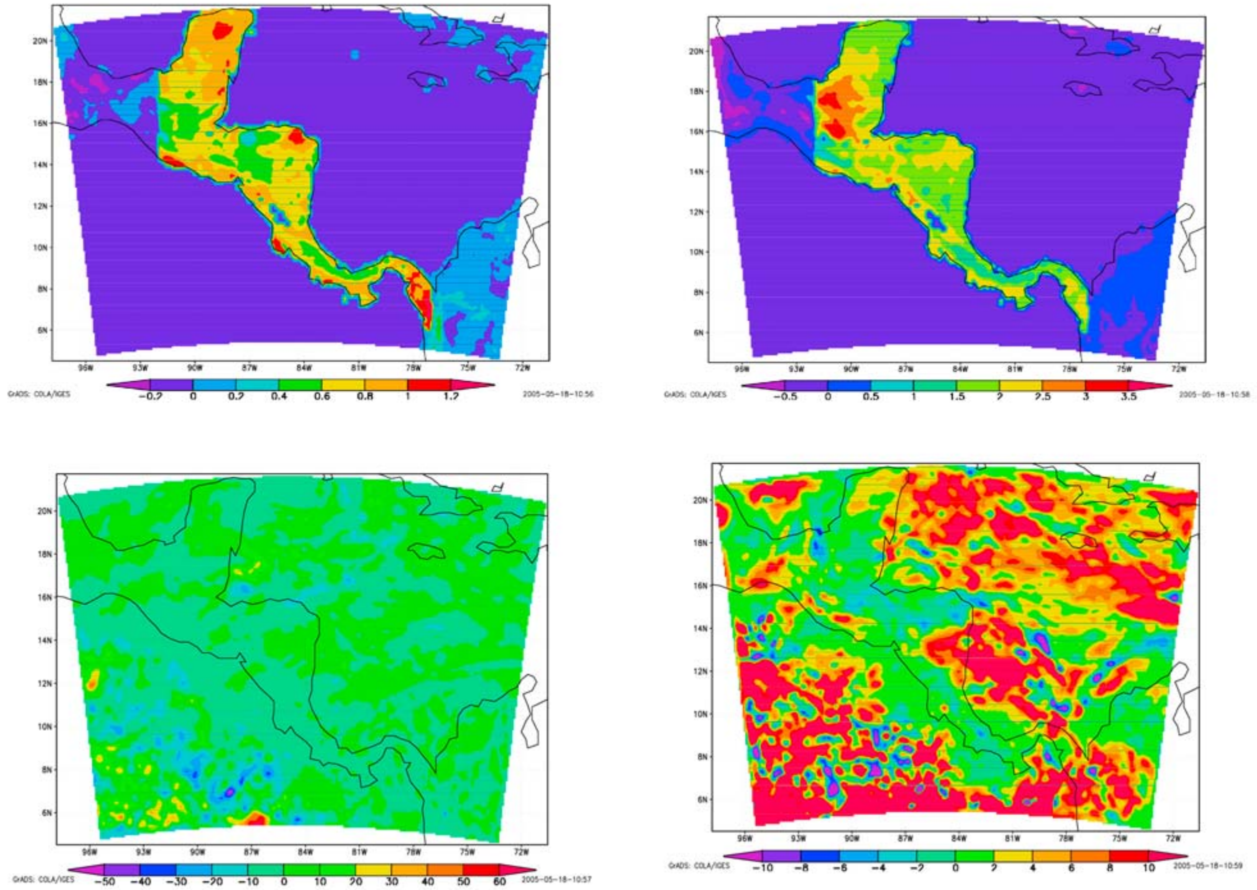

Figure 2. Surface temperature differences (in °C) for the MM5 simulation with all grassland minus all forested MM5 runs for (a) January and (b) July. Precipitation differences (in cm) for (c) January and (d) July.

describing the regional climate. In particular, they found that model simulated temperature, wind speed, and vapor mixing ratio agreed well with the observations. Precipitation, especially its magnitude, was handled less well overall, although this was attributed mainly to the lack of stations where sharp topographic features occur. The spatial patterns of precipitation showed much closer agreement. Because of the sparse network of reporting stations, especially in regions of complex topography, we also compared precipitation from the MM5 control run to precipitation obtained from the Tropical Rainfall Measurement Mission (TRMM). We used the TRMM6 blended product (http://trmm.gsfc.nasa.gov/); this combines data from TRMM itself as well as all other available, quality-checked precipitation data. This analysis provided little additional insight to that of Hernandez et al., suggesting that the spatial patterns were reasonably well simulated but the magnitude was more problematic. Other, quasi-proxy observations such as global reanalyses are not helpful because of their coarse spatial resolution (typically 1.0°–2.5° in latitude and longitude) and lack of assimilated station data for this region. Summarizing, while the lack of sufficient observations makes it difficult to fully assess the performance of MM5, what evidence we do have suggests that the model does at least a credible job.

3.2. Deforestation Scenarios

[17] The potential climatic impacts of deforestation are best demonstrated by the full deforestation versus completely forested cases (Figure 2). Replacing trees with grassland has two major effects: (1) an increase in surface albedo, which leads to cooling and stabilization of the atmosphere [*Charney*, 1975], and (2) a large reduction in evapotranspiration from the surface, leading to warming and stabilization of the atmosphere [*Henderson et al.*, 1993; *Suh and Lee*, 2004]. This occurs because the energy no longer used for evapotranspiration goes into heating the surface. The warmer surface then warms the air above, leading to rising parcels of air. These parcels of air, by themselves, stabilize the atmosphere by leading to higher pressure aloft (the "thermal mountain" effect of *Stern and Malkus* [1953]). (Destabilization is caused by large-scale changes in the environmental or background, vertical temperature structure of the atmosphere, not by rising parcels per se.) Both processes (1) and (2) therefore tend to stabilize the atmosphere and reduce precipitation [*Charney*, 1975; *Oglesby and Erickson*, 1989].

[18] To clarify their relative effects, we made an additional run in which only the albedo differences between forest and grassland were imposed. We found that the albedo increase led to a general 1°C–2°C cooling. Furthermore,

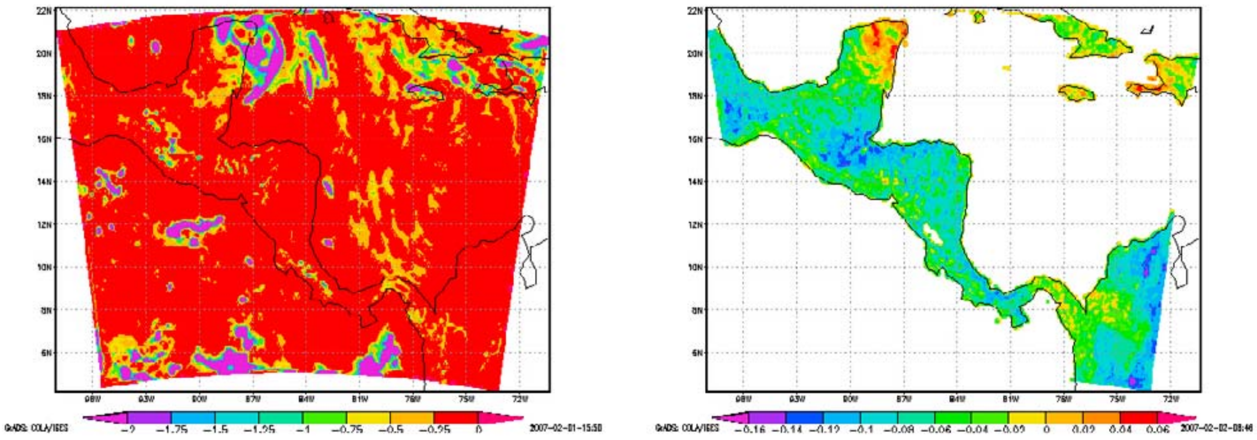

Figure 3. Differences for July for the run with 2000 land use types minus the "control" (circa 1980): (a) surface temperature differences (in °C) and (b) precipitation differences (in cm).

while many previous deforestation studies have been made, they generally focused on large landmasses (e.g., the Amazon or tropical Africa). A key purpose of our study is to see how deforestation might affect a region that is much smaller and closer to large water bodies (oceans). Other more minor effects also occur, such as a reduction in surface roughness when grassland replaces forest, which affects winds, and also inhibits evaporative fluxes from the surface. While small, these act to enhance the overall effects of deforestation.

[19] Warmer and drier conditions occur in both the dry (Figures 2a and 2b) and wet (Figures 2c and 2d) seasons, but, not surprisingly, the impact is much larger in the wet season for both temperature and rainfall. That is, during the dry season, precipitation and surface evaporation are both at relative minimums regardless of the nature of the land cover. Temperatures warm by 1°C–2°C during the dry season, and precipitation generally shows a modest decrease. During the wet season, on the other hand, temperatures warm by up to 3°C–5°C, and precipitation is reduced by up to 15%–30%. Temperatures increase everywhere (except for a small region around Lake Nicaragua). Approximately 78% of the overall Maya region (southwest Mexico, Guatemala, southern Yucatan, and Honduras) shows a precipitation decrease. Relative to the mean, precipitation decreases an average of 17% throughout this region, with maximum decreases of 29%. Unfortunately, even 5 year model simulations are insufficient for robust statistical significance testing, but a 5 year 17% decrease would generally be considered at least drought-like (see, for example, http://www.ndmc.unl.edu).

[20] These changes are largest where the landmasses are largest and smallest over Panama and Costa Rica, where landmasses are smaller and nowhere far from the ocean. Furthermore, in general, the precipitation decrease is largest where the temperature increase is also largest. The precipitation increases are smaller, and indeed in some places increase, where the increase in temperature is also smaller. This is consistent with the physical effects of deforestation described above; we would expect them to vary simultaneously, and indeed, this is what occurs. Physically, the larger the landmass, the larger the change in forestation and, importantly, the smaller the ameliorating effects of adjacent oceans. This also means that the largest changes in both temperature and precipitation generally coincide with those regions most populated by the Maya. The reduction in rainfall means it would have been more difficult for the Maya to store enough water to survive the dry season, while the warmer temperatures would increase evaporation stress, as well as stress agriculture, livestock, and people.

[21] While precipitation decreases strongly over land, it also shows an overall increase over the adjacent oceans. When averaged over the domain as a whole, the net precipitation change is quite small. While the cause is not certain, this is likely a question of compensation. As noted by *Rogers* [1988] and *Magana et al.* [1999], the wet season for much of Central America crucially depends on convection that originates over adjacent ocean waters and then drifts over land. The increase in surface heating due to deforestation in general tends to block convection [e.g., *Stern and Malkus*, 1953]. Therefore, the most likely reason for the increased oceanic precipitation is simply that the convective storms are inhibited from moving over land and instead remain over the ocean.

[22] Therefore, our results are best considered a sensitivity study that sets overall limits on the role of deforestation in affecting Mesoamerica climate, with implications for the collapse of Maya civilization. Certainly, the complete deforestation case may be a valid model for the latter stages of the classic Maya civilization, at least in those regions they occupied, but even before the earliest human settlements, it is likely that not all of Mesoamerica was completely forested. Furthermore, as noted by *Pielke* [2001], a patchwork of forest and grassland may affect mesoscale circulations and hence have an effect on convective activity. To gain a more modern-day perspective, we compared temperature and precipitation for land use patterns in 2000 versus circa 1980 (Figure 3) and complete deforestation except for the MBC versus circa 1980 (Figure 4). Noteworthy in Figures 3 and 4 is that the changes are very small. Indeed, the changes between 1980 and 2000 are almost trivially small, while even those between 1980 and the MBC case are hard to distinguish from year-to-year variations within each simulation. Consideration of the land use plots shown in Figure 1 leads to the realization that by

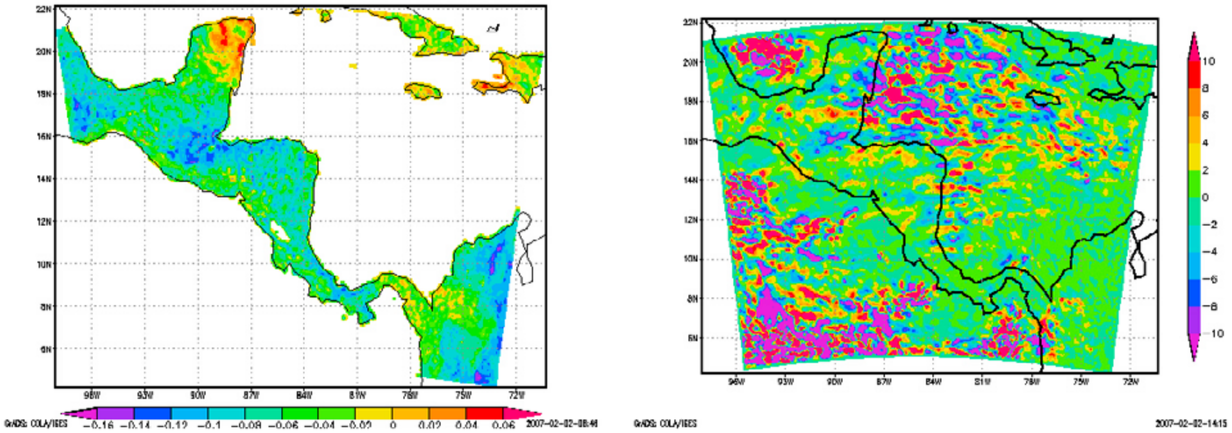

Figure 4. Differences for July for the run with proposed MBC land use types versus the “control” (circa 1980): (a) surface temperature differences (in °C) and (b) precipitation differences (in cm).

1980 much of Mesoamerica had already been deforested, thus subsequent loss of forest would have only a small impact on climate. This result is consistent with anecdotal evidence that, by the 1940s and 1950s, extensive deforestation had already taken place. What small changes in precipitation do take place have the same general spatial pattern as in the all grassland minus all forested case. This helps support the robustness of our overall results; we also see little impact of the patchwork forest effects of *Pielke* [2001] although our 12 km resolution may be insufficient to fully account for them.

[23] As a sobering aside, this result also implies that modern-day Mesoamerica is already experiencing the warming and drying that deforestation engenders. This further suggests that it may not be sufficient for the political entities that comprise Mesoamerica to simply discontinue deforestation; regions previously deforested must be replanted with new forest. Unfortunately, we do not know the pristine pre-Maya state of Mesoamerican forestation; we can only conjecture that it must have been much more extensive than the known circa 1980 forest extent.

[24] Figure 5 shows the possibility of natural drought in these regions where the Maya civilization flourished. Figure 5a indicates the area over which precipitation was averaged over the Mayan lowland region of Guatemala and the Yucatan. Shown in Figures 5b and 5c are time series of warm season rainfall (defined as rain from 1 June through 30 September). Figure 5b is from the 100 year “present-day” CCSM3 control run, that is, with constant boundary conditions and forcings, which allows an evaluation of natural climatic variability. In particular, this run had climatological SST prescribed, such that each model year had the same annual cycle of SST. Numerous dry periods are evident, although only a few extend for more than a few years. Figure 5c is from the simulation run for the period 1870–1999. This run prescribed observed year-to-year variations SST. Again, numerous dry periods are evident, but the key difference is that some prolonged periods of dry conditions occur, including one period of 24 of 30 years from 1952 through 1981. The obvious conclusion is two-fold: (1) Large year-to-year variations in precipitation can occur even in the absence of any specific change in forcing or especially SST. (2) When specific, known climatic forcings are used in the model, much more extensive periods of drought can occur. While further analyses are required to substantiate, the most likely implication is that specific SST patterns that persist for some time can lead to prolonged drought. Many studies have documented this for other regions, especially North America [e.g., *Feng et al.*, 2008, and references therein]. Overall, it is clear that naturally occurring drought undoubtedly plays a key role in this area.

4. Discussion and Conclusions

[25] The results presented here suggest that natural drought and human-induced drying due to deforestation both occurred and, in combination, may well have wreaked havoc on Maya civilization. Next, it was shown that complete deforestation of Mesoamerica has major impacts on temperature and precipitation. This experiment was an end-member test designed to bind the possible regional climate impacts; however, given the almost complete deforestation that apparently occurred during the height of Mayan civilization, it is not completely unrealistic. After the collapse, presumably much of the region became reforested. Furthermore, it may well be that Mesoamerica had again become so heavily reforested by the time that systematic, large-scale surveys were first undertaken during the last century that these are no guide as to how extensive forests were prior to human occupation. We have been through two cycles: original vegetated, devegetated by Mayans, revegetated post-Mayans, now again being devegetated. As suggested by the runs with realistic land use changes from 1980 to 2000, plus deforestation except for the proposed Mesoamerican Biological Corridor, we may well be headed again toward a scenario that devastated the Maya.

[26] Deforestation led to lower rainfall and higher temperatures; both factors would have been detrimental to Mayan life. The reduction in rainfall means it would have been more difficult for the Maya to store enough water to survive the dry season, while the warmer conditions put more stress on evaporation, vegetation, livestock, and people. These effects occurred during both the wet and dry seasons but were much larger during the wet season, when they were also arguably more important. This is because the Maya

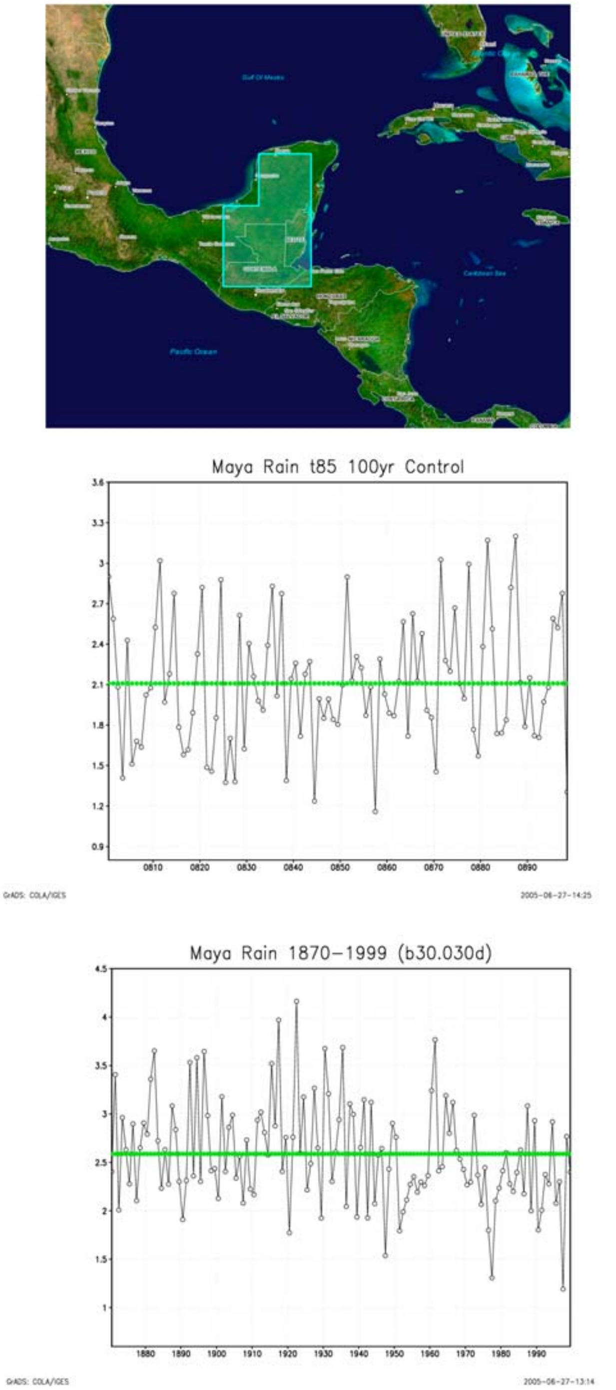

Figure 5. (a) Primary Maya region (denoted by the green-lined box) over which the CCSM3 results were averaged; larger map is for reference. (b) Time series of precipitation for the 100 year CCSM3 control run with present-day (circa 2000) conditions. (c) Time series of precipitation for the CCSM3 run with forcings from 1870 to 2000. In both Figures 5b and 5c averages are for the rainy season (units, in mm/d), and the line denotes the average over the length of each run.

societal structure depended on storage of water during the wet season, which in turn provided for them during the dry season. The small decreases in precipitation and increases in temperature during the dry season may have imposed a small additional stress, but given sufficient wet season storage, this was not likely to have been detrimental. It is also quite likely that, with deforestation, the wet season began later and ended earlier; our model runs do show some hint of this but are too short to adequately define if indeed this happened and by how much. Obviously, any decrease in the duration of the wet season would have imposed additional stress on water resources and overall storage, as well as prolonging the length of time for which water must be stored.

[27] The warmer and drier conditions we obtain in response to deforestation are also consistent with the results of previous modeling studies conducted for regions elsewhere in the tropics. Early on, *Stern and Malkus* [1953] identified the so-called “thermal mountain effect.” The increased/decreased surface sensible/latent heating leads to warming of the air immediately above the surface, which then rises through the lower and middle troposphere, leading aloft to higher pressures and stable conditions. These higher pressures aloft act to divert atmospheric flow, much as does an actual mountain, hence the name. This paradigm remains relevant; more recent studies have largely just examined and refined the relevant physical processes involved. For example, *Henderson-Sellers et al.* [1993] found that deforestation in the Amazon reduced surface evaporation, runoff, and soil moisture, which in turn reduced available moist static energy. *Clark et al.* [2001] found that land surface “degradation” (devegetation) over tropical North Africa reduced surface evaporation and moisture convergence, with little change in large-scale forcing. Both studies also address the difficulty in directly assessing precipitation recycling, especially because of the strong dependence on spatial scale.

[28] The underlying physical processes identified in the above (and other related) studies are nicely summarized by *Pielke* [2001] and, importantly, are not fundamentally different than those expounded on by *Stern and Malkus* [1953]. What has been accomplished since this seminal study is a considerable refinement and quantification of when and how land use changes, especially deforestation, are important. Our study contributes to this ongoing discourse in two ways: (1) We have used a regional climate model to demonstrate that deforestation can have important climatic consequences even for a fairly small, narrow landmass; the physical mechanisms are the same as those identified previously for much larger landmasses and even in our domain, their effect is proportional to continentality. (2) These climatic effects due to deforestation are large enough that they may have played a significant, if not dominant role, in the demise of the Maya civilization between 800 and 900 A.D.

[29] Therefore, these model results are robust and consistent with many previous studies noted above looking both at the explicit effects of deforestation and more generally what occurs when the land surface dries out, regardless of what originally causes the drying [e.g., *Oglesby and Erickson*, 1989]. Furthermore, although we investigated only regional impacts, it is possible that large-scale or far-field teleconnections may act to enhance the drying. Exploration of this would involve either two-way nesting or more likely use of a global model and is left for future work.

[30] The results from the global climate model simulations also demonstrated that long, naturally occurring droughts are likely an occasional but ubiquitous feature of this region. The paleo-record indicates that it is quite likely that, in the distant past, even more prolonged periods of drought occurred. The causes of and controls on these droughts, both past and present, are still keenly debated. Proposed mechanisms range from slight fluctuations in "convergent wind regimes" [*Hunt and Elliott,* 2005] to cyclical changes in solar output [*Hodell et al.*, 2001] to large-scale climate forcing from phenomena such as the NAO and/or AMO. Natural variability of the highly complex, largely fluid climate system, without any definable "cause" may also simply be the major player. Regardless of the specific cause, the simple fact that these severe and prolonged natural droughts occur is to the point.

[31] The key question, yet to be completely answered, is whether either deforestation-induced drought or a naturally occurring drought by themselves could have caused sufficient stress on water resources to precipitate the collapse of the Maya. While our work to date is not yet definitive, a simple argument suggests that neither type of drought could have been solely responsible. Evidence suggests that deforestation by the Maya had been ongoing for centuries and that their homeland was essentially free of trees long before the collapse, with sources of wood coming from far-off regions. Furthermore, while the drought of the ninth century A.D. was certainly significant and prolonged, it was almost certainly not an isolated event, but one of many that must have occurred during the time of the Maya. We suggest, instead, that the conjunction of continuous and likely increasing stress on water resources due to essentially complete deforestation and a major natural drought caused sufficient stress that the sociopolitical structure of the Maya could not endure and quickly collapsed. This conjunction of events was also likely to have been aided by the steadily increasing population of the Maya.

[32] In future work, we will analyze a CCSM3 model run covering the past 6000 years that is currently being made. We will then use years with naturally occurring drought to drive the high-resolution MM5 model and better quantify impacts of these droughts for the Maya, analogous to what we have already done for deforestation scenarios. Finally, we will run the MM5 forced with naturally occurring drought with complete deforestation. This will allow us to distinguish the relative impacts of natural and human-induced drought as well as the combined impacts. While we will probably never know the complete story of what caused the collapse of the Maya, we can hope to increase our knowledge of how various events may have happened and what were the likely implications of these events. Besides the compelling questions surrounding the rise and fall of the Maya, this knowledge and understanding may be very important in preventing such a scenario from occurring again in the near future.

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