Future precipitation changes and their implications for tropical peatlands

Wenhong Li,[1] Robert E. Dickinson,[1] Rong Fu,[1] Guo-Yue Niu,[2] Zong-Liang Yang,[2] and Josep G. Canadell[3]

Received 4 October 2006; revised 30 November 2006; accepted 1 December 2006; published 12 January 2007.

[1] Carbon (C) in tropical peatlands over Southeast Asia and Amazonia, if released to the atmosphere, can substantially increase the growth rate of atmospheric carbon dioxide. Over Southeast Asia, where the most extensive tropical peatlands in the world occur, 11 climate models for the IPCC Fourth Assessment show an overall decrease of rainfall in future dry seasons. Over Amazonia, future rainfall changes in dry seasons are highly uncertain; five models predict increased rainfall, and the remaining models predict the opposite. We have further examined the UKMO-HadCM3, GISS-ER, and GFDL-CM2.1 models. Over Southeast Asia, all three models predict similar decreases of rainfall and evaporative fraction, implying an increase of water table depth and surface dryness during the dry season south of the equator. Such changes would potentially switch peat ecosystems from acting as C sinks to C sources. Over Amazonia, the two models with the best simulations of current rainfall produce conflicting results for the future of peat stability. **Citation:** Li, W., R. E. Dickinson, R. Fu, G.-Y. Niu, Z.-L. Yang, and J. G. Canadell (2007), Future precipitation changes and their implications for tropical peatlands, *Geophys. Res. Lett.*, *34*, L01403, doi:10.1029/2006GL028364.

1. Introduction

[2] Tropical peatlands have been acting as large carbon (C) sinks since organic matter first started accumulating around 26,000 years BP, with estimated current stores of 70 billion tons (Gt) of C [*Page et al.*, 2004, and references therein]. However, increased climatic seasonality and variability, amplified by land use and management, has the potential to switch tropical peatland ecosystems from net C sinks to net C sources [*Sorensen*, 1993; *Canadell et al.*, 2007]. For example, during the 1997–1998 El Niño, decreases in rainfall made the peatlands in Indonesia susceptible to fire brought about by human activities. Satellite imagery and ground measurements suggest that about 0.81–2.57 Gt of C was released to the atmosphere in Indonesia due to widespread peat combustion [*Page et al.*, 2002]. This release was equivalent to 13–40% of the mean annual global carbon emission from fossil fuels, and so contributed about 40% of the record growth in atmospheric CO_2 during that period [*van der Werf et al.*, 2004].

[3] As the earth's climate changes in the 21st century, we do not know whether tropical peatlands will continue accumulating C or will shift and begin releasing C to the atmosphere because of anticipated changes in rainfall and surface dryness. If more frequent drought events were to occur in the future associated with less rainfall and higher temperatures, the groundwater level would decrease, leading to a more flammable environment and accelerated oxidative loss of peat [*Page et al.*, 2004]. On the contrary, if future climates over tropical peatlands were more humid, then peatlands might continue removing C from the atmosphere. Therefore knowing how rainfall will change in tropical peatlands should clarify the future nature and magnitude of this carbon-climate feedback.

[4] Apparently, no studies have addressed how changes in future rainfall would impact tropical peatlands. Using the 11 coupled ocean-atmospheric models of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4), we analyze current and future climate over the two largest regions of threatened tropical peatland, i.e., Southeast Asia and Amazonia. Southeast Asia has the most extensive tropical peatlands in the world with an estimated area between 20 and 30 M ha largely distributed in Indonesia (Sumatra, Kalimantan, and Papua) and Malaysia (Peninsula Malaysia, Sarawak, and Sabah) [*Rieley et al.*, 1996; *Page et al.*, 2004; *World Energy Council*, 2004]. Small peatland areas remain in the Philippines, Thailand, Vietnam, and Brunei. The peatland area over Amazonia is estimated to be about 2.8 M ha largely occurring in the middle Amazon and marshy plains near the Bolivian border, and to a lesser extent in Venezuela and Colombia [*World Energy Council*, 2004]. Depths in excess of 10 m are characteristic of peatlands in Southeast Asia [*Page et al.*, 2002] and less in Amazonia.

[5] We examine the rainfall changes in three models of IPCC AR4 over these two regions. The three models, UKMO-HadCM3, GISS-ER, and GFDL-CM2.1, adequately simulate climatology of tropical rainfall and land surface parameters in the 20th century but project different future rainfall and land surface conditions [*Li et al.*, 2006]. We then discuss the potential impacts of these projected rainfall changes on the tropical peatlands of Southeast Asia and Amazonia.

2. Models and Experiments

[6] We use the standard outputs from coupled Ocean-Atmosphere General Circulation Models for the IPCC AR4 and the National Oceanic and Atmospheric Administration

[1] Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA.

[2] Department of Geological Sciences, University of Texas at Austin, Austin, Texas, USA.

[3] Global Carbon Project, CSIRO Marine and Atmospheric Research, Canberra, ACT, Australia.

0094-8276/07/2006GL028364$05.00

(NOAA) Climate Prediction Center (CDC) Merged Analysis of Precipitation (CMAP) data. CMAP data are available from the NOAA CDC website and were estimated by combining satellite observations of clouds and rain gauge measurements [*Xie and Arkin*, 1996, 1997].

[7] We have examined the rainfall variations in the 21st century simulations under the emission scenario A1B (SRES A1B) for 11 available models for the IPCC AR4 compared to their 20th century runs (20C3M). This study focuses on whether or not there is an overall agreement between the future climates projected by the models. The period from January 1950 to December 1999 is analyzed to represent the second part of the 20th century, and for future climate we study rainfall changes from January 2050 to December 2099. Three of the 11 models (UKMO-HadCM3, GISS-ER, and GFDL-CM2.1) were analyzed in depth for the following periods: 1970–1999 and 2101–2130. The latter is the first 30-year period after the atmospheric CO_2 is stabilized at 720 ppm according to the SRES A1B.

[8] Southeast Asia spans an extensive spatial domain of complex terrain with different rainfall climatologies [*Haylock and McBride*, 2001; *Aldrian and Susanto*, 2003; *Hendon*, 2003; *Chang et al.*, 2004]. This entire region is analyzed for changes in rainfall and land surface conditions. The monsoon region of Indonesia (0°–10°S 100°E–120°E) is emphasized as it is more readily influenced by the El Niño–Southern Oscillation (ENSO) [*Hendon*, 2003; *Chang et al.*, 2004]. The peatland region of Amazonia is 0°–10°S 75°W–50°W, where a large portion of peatlands are located [*World Energy Council*, 2004]. We focus on the peak dry season (July, August, and September) in both regions when peatland is most vulnerable to potential climate change [*Page et al.*, 2002].

3. Results

3.1. Future Changes of Rainfall Compared to the 20th Century

[9] Figure 1 shows the averaged dry season rainfall and the variability over the peatland regions of Indonesia and Amazonia for 11 models and for the last 50 years in the 20th (1950–99) and the 21st (2050–99) centuries. These climatological dry season rainfalls in the 20th century are also compared to those observed by CMAP data (1979–99). All models overestimate the rainrate over Indonesia. The dry season rainfall in the 20th century varies from 4.3 to 8 mm day^{-1} among the 11 models compared to 3.3 mm day^{-1} suggested by CMAP data (Figure 1a). The amplitude of interannual to decadal variations of rainfall, as indicated by the standard deviations of the dry season rainfall in most of the models, is weaker than that of CMAP (1.6 mm day^{-1}) except for MPI, GFDL-CM2.1, and UKMO-HadCM3. In the last 50 years of the 21st century, 7 out of 11 models (i.e., CNRM-CM3, GFDL-CM2.1, GISS-ER, MPI, MRI, NCAR-CCSM3, and UKMO-HadCM3) predict a decrease of the dry season rainrate. Two models (IPSL and INMCM) have no significant change, while the remaining two models, GISS-EH and MIROC, predict an increase of the dry season rainfall. The amplitude of interannual to decadal variations of the future dry season rainfall also increases in 9 out of 11 models. Thus these climate models suggest a high probability of decreasing rainfall during the future Indonesian dry seasons.

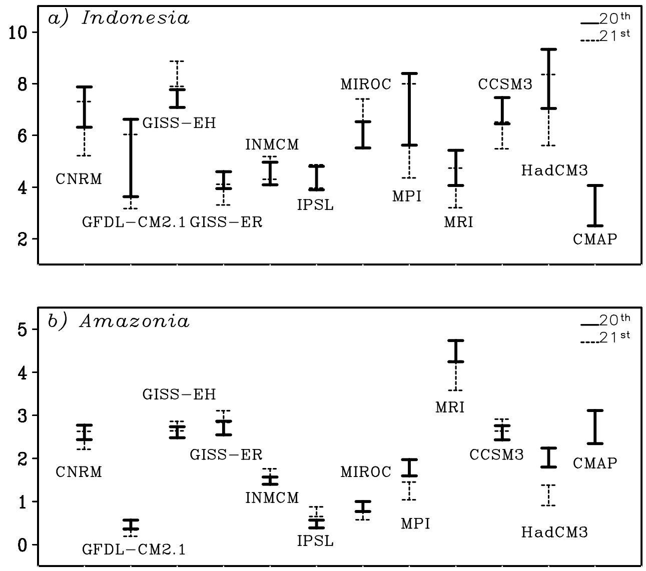

Figure 1. Dry season (JAS) rainfalls and their standard deviation for each of the 11 models for the periods of 1950–99 (solid) and 2050–99 (dotted) respectively over (a) Indonesia (0°–10°S 100°E–120°E), and (b) Amazonia (0°–10°S 75°W–50°W) peatland areas, respectively. The observed dry season rainfall and its standard deviation derived from CMAP (1979–99) are also plotted. Units: mm day^{-1}.

[10] Over Amazonia, the dry season rainfall and its interannual variability in the 20th century are underestimated by most models compared to those suggested by CMAP data (2.7 ± 0.8 mm day^{-1}, Figure 1b). In the future climate, rainfall during the dry season increases in five models, i.e., the GISS-EH, GISS-ER, IPSL, MRI, and NCAR-CCSM3, but it decreases in the remaining models. The interannual variability of the future dry season rainfall remains essentially unchanged for these models except for that of the CNRM, MPI, and MRI models.

[11] We choose three models, the UKMO-HadCM3, GISS-ER, and GFDL-CM2.1 (hereinafter referred to as models 1, 2, and 3, respectively), for a further assessment of the future climate changes over Southeast Asia and Amazonia. These three models simulate reasonably well the rainfall seasonality in the 20th century but predict different changes of rainfall in the 21st century [*Li et al.*, 2006]. Southeast Asia is impacted by more than one climate system [*Hendon*, 2003; *Chang et al.*, 2004], and therefore its rainfall change is not uniform and is usually different in different seasons. Figure 2 compares the climatological dry season rainfall in the 20th century and the dry season rainfall change during the period of 2101–30 from 1970–99 for the three models over Indonesia. Compared to the CMAP data, the three models tend to overestimate the dry season rainfall over Papua New Guinea and Sulawesi outside of the main peatland areas in the maritime region. All three models predict a future decrease of rainfall during the dry season from 1 to 3 mm day^{-1} in southern Indonesia including South Sumatra and southern Borneo (Figure 2) where most peatland is located. North of the equator, two models show an increase of future rainfall; model 3 has no significant change.

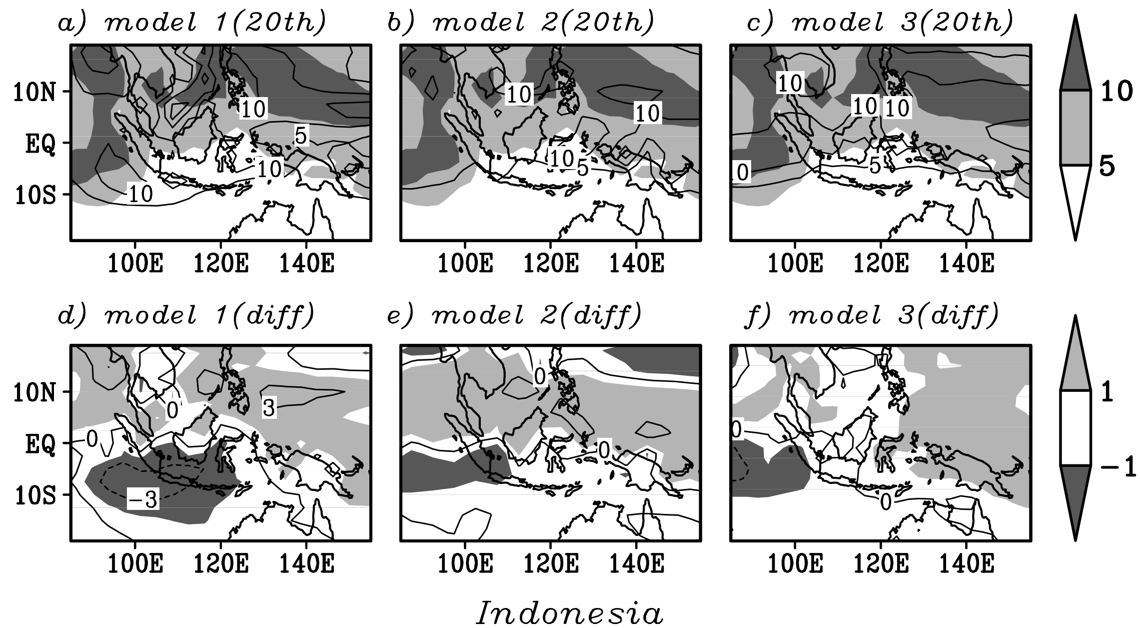

Figure 2. Climatological dry season (JAS) rainfall in the period 1970–99 simulated by (a) model 1, (b) model 2, and (c) model 3, and its change during the period of 2101–30 from those of 1970–99 over Southeast Asia simulated by (d) model 1, (e) model 2, and (f) model 3, respectively. The observed dry season rainfall derived from CMAP is also shaded from Figures 2a to 2c. The areas where differences of rainfall are greater (less) than 1 mm day^{-1} are shaded from Figures 2d to 2f. Contours intervals in Figures 2a to 2c and in Figures 2d to 2f are 5 and 3 mm day^{-1}, respectively.

[12] The rainfall change over Amazonia for each model is spatially more uniform than that over Indonesia. Figure 3 compares the climatological rainfall seasonality over Amazonia in the 20th century (1970–99) and during the period of 2101–30. Due to a significant dry bias in the dry and transition seasons in model 3 [*Li et al.*, 2006], we only examine future changes over Amazonia using models 1 and 2. The phases of rainfall seasonal cycle and the rainfall magnitude simulated by the two models agree with those of CMAP observations in the 20th century (Figure 3).

[13] Model 1 predicts a future decrease in rainfall mainly from May to December (Figure 3a). The largest decrease is during the transition period from the dry to the wet season and presumably delays the wet season onset. Model 2, however, predicts an increase of rainfall over Amazonia for the whole year. Its maximum increase of rainrate is during the wet season (Figure 3b). Thus Figure 3 along with Figure 1b indicates that the future changes of rainfall over Amazonia among current climate models are highly uncertain. This uncertainty is in part due to large discrepancies in projected changes of SST in the tropical Pacific and Atlantic Oceans between these two models [*Li et al.*, 2006].

3.2. Implications of Rainfall Changes for the Peatland Over Southeast Asia and Amazonia

[14] Changes in future rainfall could directly alter the distribution of water tables and the surface dryness of a peatland [*Roulet et al.*, 2005]. The distribution of water tables within the peat profile determines whether a peat ecosystem continues to store C or is a source of CO_2 and CH_4. A lowering of the water table in peat soils increases organic matter mineralization and a consequent enhancement of C losses [*Jauhiainen et al.*, 2005]. On the contrary, a higher water table decreases oxidic decomposition and consequently increases the net C uptake [*Belyea and Malmer*, 2004; *Chimner and Ewel*, 2004]. Since the IPCC AR4 output does not include water table depth, we have used soil moisture to diagnose the water table changes according to equation (10) of *Niu et al.* [2007]. The water table depth, defined as the depth from the land surface to the water table, changes inversely with the total soil moisture, i.e.,

$$\delta h = -\psi_{sat}\delta\left(S^{-b}\right) \tag{1}$$

where δh is the change in the water table depth (its increase means increased dryness), b is the Clapp-Hornberger

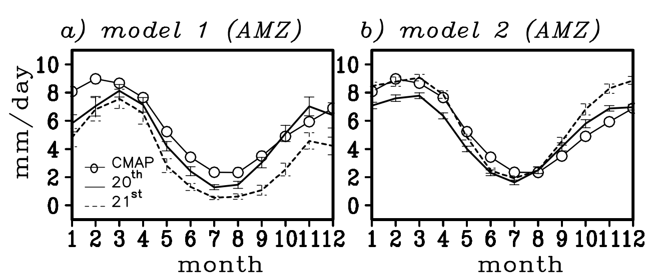

Figure 3. Climatological monthly rainfall and their error bars based on student-*t* test for (a) model 1 and (b) model 2, respectively, over Amazonia peatland region. The solid lines represent the rainfall climatology for the period of 1970–99 simulated by the current climate run; the dash lines represent the rainfall climatology for the period of 2101–30 simulated by the future climate run; the solid lines with circles represent the rainfall climatology observed by CMAP during the period of 1979–99.

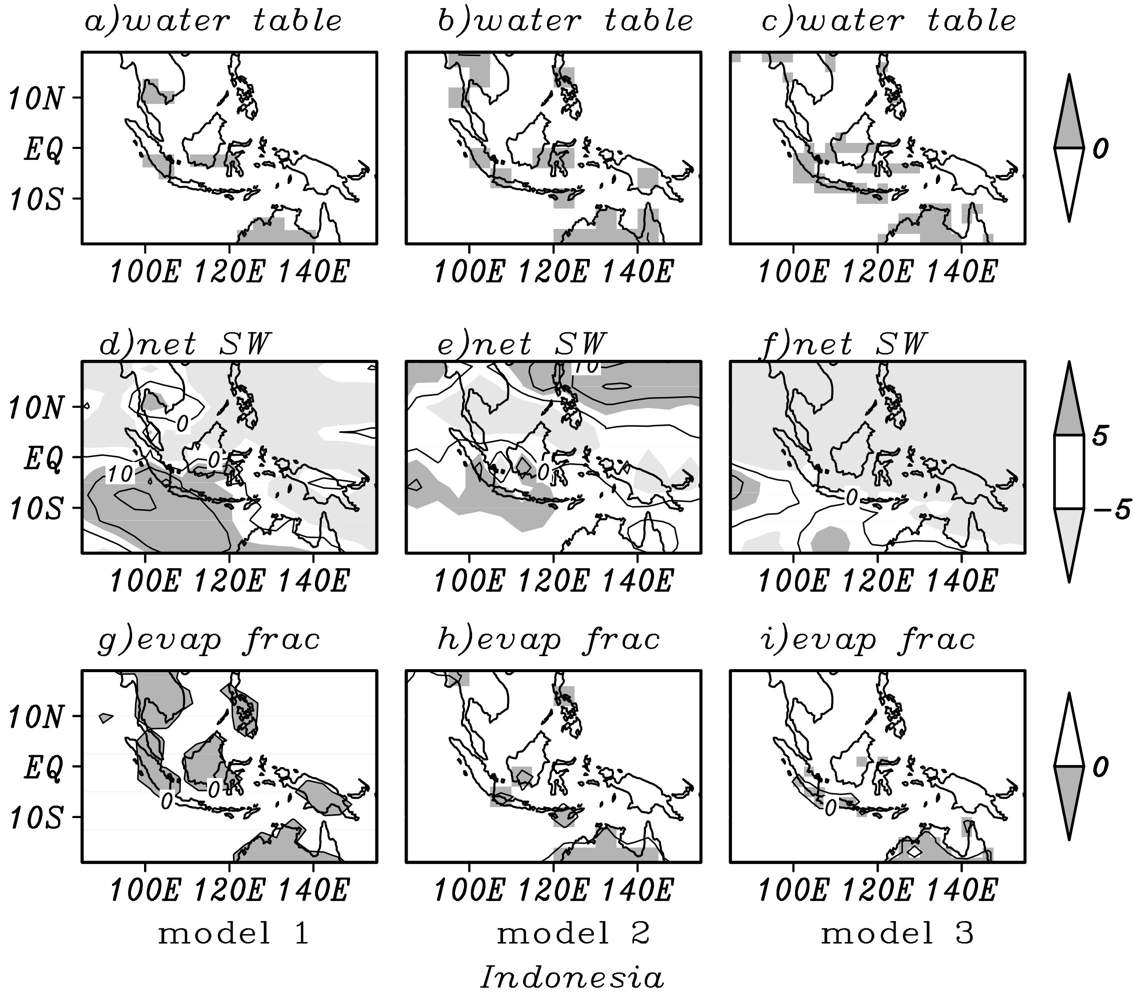

Figure 4. Climatological changes of dry season (JAS) (top) water table depth (unit: m), (middle) surface solar radiation (unit: W m^{-2}), and (bottom) EF simulated by (a, d, and g, respectively) model 1, (b, e, and h, respectively) model 2, and (c, f, and i, respectively) model 3. The differences of water table depth (EF) greater than (less than) 0 are shaded. The differences of net solar flux greater (less) than 5 (−5) W m^{-2} in magnitude are shaded; contours interval is 10 W m^{-2}.

parameter, about 2.7 for peatland [*Letts et al.*, 2000], and ψ_{sat} is the saturated soil matric potential. Water table depth changes are inferred from $\psi_{sat} \cong -0.12$m [*Beringer et al.*, 2001] and modeled *S*.

[15] Figures 4a–4c shows the spatial changes in water table depth in the dry season over Southeast Asia. Because the land area is relatively small, the change in the water table depth is not as obvious as that of the net solar radiation. However, over south Sumatra and southern Borneo, all three models predict an increase of the water table depth (Figures 4a–4c). Such an increase in the water table depth will limit the rate of peat accumulation, enhance degradation and oxidation on peatlands, and consequently lead to a loss of stored C [*Waddington and Roulet*, 1996]. Evaporative fraction (EF, the ratio of latent heat flux to net radiation) has also been investigated as an index of surface dryness. Both observations [*Jacobs et al.*, 2002] and the Penman-Monteith equation suggest that a decreased EF over peatlands indicates water limited condition, usually drought. Over tropical land, surface dryness can be caused by either a decrease of rainfall or an increase of net solar radiation. Model 1 predicts an increase of surface solar flux due to decreased cloudiness over all peatland areas in Indonesia except for north Sumatra and New Guinea (Figure 4d) in agreement with the decrease of rainfall over the region (Figure 2d). The EF also decreases over the land areas in the future climate (Figure 4g). These changes collectively suggest a drier climate in the dry season over southern Indonesia.

[16] Models 2 and 3 predict future changes in surface net solar flux and EF that are weaker than those of model 1. In the model 2 simulation, the water table depth increases over south Sumatra, southern Borneo, and Papua New Guinea (Figure 4b). The surface net solar flux increases south of the equator especially over south Sumatra and southern Borneo, but decreases north of the equator and over Papua New Guinea (Figure 4e). Model 2 also predicts a decrease of EF south of the equator in the future climate (Figure 4h). The patterns of changes of water table depth, solar radiation, and EF are consistent with a reduction of future rainfall during the dry season (Figure 2e) in that region. Model 3 predicts a similar change of water table depth and EF over south

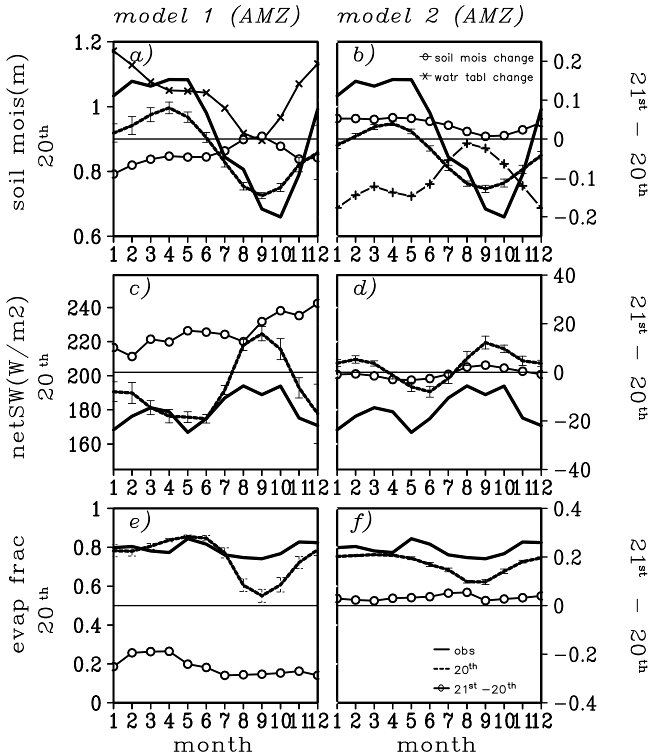

Figure 5. Climatology and the error bars based on student-*t* test (left y-axis) of (top) soil moisture (unit: m), (middle) net solar radiation (unit: Wm^{-2}) and (bottom) EF in the period of 1970–99, and their changes for the period of 2101–30 from those of 1970–99 (right y-axis) for (a, c, and e) model 1, and (b, d, and f) model 2, respectively, over Amazonia peatland region. The dashed lines represent the climatology of these variables for the period of 1970–99 simulated by the current climate run; the solid lines represent the climatology observed at the Jaru site (2000–02). The solid lines with circles represent the changes of soil moisture, net solar radiation and EF for the period of 2101–30 from those of 1970–99, respectively. The solid lines with x marks in Figures 5a and 5b represent the changes of water table depth (unit: m) for the period of 2101–30 from those of 1970–99.

Sumatra (Figures 4c and 4i) as model 2, a decrease in Central and East Borneo, but not a significant change of solar radiation south of Indonesia (Figure 4f). These models collectively predict decreases of rainfall and EF and increases of water table depth and surface net solar radiation either over the entire maritime continent (model 1) or over South Sumatra and the southern Borneo peatland regions (models 2 and 3).

[17] Figure 5 compares the seasonal changes of soil moisture/water table depth, surface net solar radiation, and EF over Amazonia with in situ observations at Jaru (10°05′S 61°57′W). The seasonal cycles of the soil moisture and net solar flux for both models are qualitatively similar to that observed. Soil moisture is overestimated in September–October by about 0.1 m by the two models and underestimated in December–May by 0.1 m and 0.2 m for models 1 and 2 respectively (Figures 5a and 5b). In austral spring and January–February, the two models overestimate the net solar radiation (Figures 5c and 5d) and underestimate the EF (Figures 5e and 5f). The future soil moisture (water table depth) in model 1 decreases (increases) during the year except August–September (Figure 5a). The future surface net solar radiation in model 1 increases by about 10–20 Wm^{-2} due to decrease of cloudiness. This increase of surface solar flux (Figure 5c) is balanced by an increase of surface sensible flux and decrease of latent flux (not shown). Figure 5e shows that the EF decreases from about 50% to 20% over the year and is the strongest during the transition from the dry to the wet season, coinciding with the period of largest rainfall decrease. Such a decrease of rainfall and persistent dryness over Amazonia along with an increase of the water table depth in peatlands would desiccate upper layers of plant material, increasing the potential flammability of the peat [*Jacobs et al.*, 2002]. Therefore the future climate implied by model 1 suggests an increase in the vulnerability of the peatland. In the model 2 simulation, soil moisture increases and water table depth decreases in the future climate (Figure 5b). The surface net solar flux (Figure 5d) does not change significantly. However, the latent heat flux increases by about 10% (not shown here), leading to a 10% increase of the EF in the dry and transition seasons (Figure 5f). Such increased EF and rainfall along with a decrease of the water table depth would enhance C uptake and maintain peatland ecosystems over Amazonia.

4. Conclusions

[18] We have analyzed changes in the dry season rainfall over Southeast Asia and Amazonia peatlands as part of the global climate change predicted by 11 models participating in the IPCC AR4 under the SRES A1B scenario. Over Indonesian peatlands, where the most extensive peatlands in the world occur, 7 models predict a decrease of future rainfall during the dry season. In addition, 9 of the 11 models suggest a greater interannual variation of future dry season rainfall. The more consistent decrease of rainfall during the dry season is found in South Sumatra and southern Borneo where most peatland in Indonesia is located. Water table depth and net solar flux are predicted to increase and EF is predicted to decrease over southern Indonesia accompanying rainfall decreases.

[19] Over Amazonia, model predictions disagree. Five models predict an increase of dry season rainfall and the remaining predict a decreased rainfall in the future dry season. Only three models suggest a greater interannual variation of rainfall.

[20] The changes predicted by climate models will result in the increase of C emissions from peat soils in southern Indonesia, hence reducing the strength of the net C sink of peatland regions and in same cases turning in net C sources to the atmosphere. The predicted climate trends will act in isolation in pristine ecosystems but in synergy with the acceleration of land use change and management of peatlands which also result in the lowering of water tables.

[21] Our results also illustrate the need for an accurate representation in Earth System models of the potential of large carbon-climate feedbacks from small regions in the

world with high carbon densities (hot spots). For the case of Amazonia, the disparities among different models highlight the need to better understand and represent the underlying controlling processes in climate models in these regions.

[22] **Acknowledgments.** We acknowledge the international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modeling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy. Jonathan Wright and Susan Ryan provided editorial assistance. This work is supported by a NSF ATM grant and a NASA Terra-Aqua-ACRIMSAT project. This work contributes to the activity on "Vulnerabilities of the Carbon Cycle" of the Global Carbon Project, a joint project of the Earth System Science Partnership (IGBP, IHDP, WCRP, Diversitas).

References

Aldrian, E., and R. D. Susanto (2003), Identification of three dominate rainfall regions within Indonesia and their relationship to sea surface temperature, *Int. J. Clim.*, *23*, 1435–1452.

Belyea, L. R., and N. Malmer (2004), Carbon sequestration in peatland: Patterns and mechanisms of response to climate change, *Global Change Biol.*, *10*, 1043–1052.

Beringer, J., A. H. Lynch, F. S. Chapin III, M. Mack, and G. B. Bonan (2001), The representation of Arctic soils in the Land Surface Model: The importance of mosses, *J. Clim.*, *14*, 3324–3335.

Canadell, J. G., D. Pataki, R. Gifford, R. A. Houghton, Y. Lou, M. R. Raupach, P. Smith, and W. Steffen (2007), Saturation of the terrestrial carbon sink, in *Terrestrial Ecosystems in a Changing World*, edited by J. G. Canadell, D. Pataki, and L. Pitelka, pp. 59–78, Springer, New York.

Chang, C.-P., Z. Wang, J. Ju, and T. Li (2004), On the relationship between western maritime continent monsoon rainfall and ENSO during Northern winter, *J. Clim.*, *17*, 665–672.

Chimner, R. A., and K. C. Ewel (2004), Differences in carbon fluxes between forested and cultivated Micronesian tropical peatlands, *Wetlands Ecol. Manage.*, *12*, 419–427.

Haylock, M., and J. McBride (2001), Spatial coherence and predictability of Indonesia wet season rainfall, *J. Clim.*, *14*, 3882–3887.

Hendon, H. H. (2003), Indonesia rainfall variability: Impacts of ENSO and local air-sea interactions, *J. Clim.*, *16*, 1775–1790.

Jacobs, J. M., S. L. Mergeksberg, A. F. Lopera, and D. A. Myers (2002), Evapotranspiration from a wet prairie wetland under drought conditions: Paynes Prairie Preserve, Florida, USA, *Wetlands*, *22*, 374–385.

Jauhiainen, J., H. Takahashi, J. E. P. Heikkinen, P. J. Martikainen, and H. Vasander (2005), Carbon fluxes from a tropical peat swamp forest floor, *Global Change Biol.*, *11*, 1788–1797.

Letts, M. G., N. T. Roulet, N. T. Comer, M. R. Skarupa, and D. L. Verseghy (2000), Parameterization of peatland hydraulic properties for the Canadian land surface scheme, *Atmos. Ocean*, *38*, 141–160.

Li, W., R. Fu, and R. E. Dickinson (2006), Rainfall and its seasonality over Amazonia in the 21st century as assessed by the coupled models for the IPCC AR4, *J. Geophys. Res.*, *111*, D02111, doi:10.1029/2005JD006355.

Niu, G.-Y., et al. (2007), Development of a simple groundwater model for use in climate models and evaluation with GRACE data, *J. Geophys. Res.*, doi:10.1029/2006JD007522, in press.

Page, S. E., F. Siegert, J. O. Rieley, H. V. Boehm, A. Jaya, and S. Limin (2002), The amount of carbon released from peat and forest fires in Indonesia during 1997, *Nature*, *420*, 61–65.

Page, S. E., R. Wuest, D. Weiss, J. Rieley, W. Shotyk, and S. H. Limin (2004), A record of Late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): Implications for past, present and future carbon dynamics, *J. Quat. Sci.*, *19*, 625–635.

Rieley, J. O., A. A. Ahmad-Shah, and M. A. Brady (1996), The extent and nature of tropical peat swamps, in *Tropical Lowland Peatlands of Southeast Asia*, edited by E. Malby, C. P. Immirizi, and R. J. Safford, pp. 17–53, World Conserv. Union (IUCN), Gland, Switzerland.

Roulet, N. T., S. Frolking, B. Ouyang, F. St.-Hilaire, P. Lafleur, and J. Wu (2005), Hydrology—The key to modeling a peatland's carbon cycle in a changing or variable climate, paper presented at Annual Meeting, Can. Geophys. Union, Calgary, Alberta, Canada. (Available at http://www.acs.ucalgary.ca/~cguconf/2005webs/Program/Roulet.pdf).

Sorensen, K. W. (1993), Indonesian peat swamp forests and their role as a carbon sink, *Chemosphere*, *27*, 1065–1082.

van der Werf, G. R., J. T. Randerson, G. J. Collatz, L. Giglio, S. Prasad, P. S. Kasibhatla, A. F. Arellano, S. C. Olsen, and E. S. Kasischke (2004), Continental-scale partitioning of fire emissions during the 1997 to 2001 El Niño/La Niña period, *Science*, *303*, 73–76.

Waddington, J. M., and N. T. Roulet (1996), Atmosphere-wetland carbon exchanges: Scale dependency of CO_2 and CH_4 exchange on the developmental topography of a peatland, *Global Biogeochem. Cycles*, *10*, 233–245.

World Energy Council (2004). Peat, in *Survey of Energy Resources*, 20th ed., chap. 8, Elsevier, New York.

Xie, P. P., and P. A. Arkin (1996), Analysis of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions, *J. Clim.*, *9*, 840–858.

Xie, P. P., and P. A. Arkin (1997), Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs, *Bull. Am. Meteorol. Soc.*, *78*, 2539–2558.

J. Canadell, Global Carbon Project, CSIRO Marine and Atmospheric Research, GPO Box 3023, Canberra, ACT 2601, Australia.

R. E. Dickinson, R. Fu, and W. Li, Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Drive NW, Atlanta, GA 30332, USA. (wenhong@eas.gatech.edu)

G.-Y. Niu and Z.-L. Yang, Department of Geological Sciences, University of Texas at Austin, Austin, TX 78712, USA.