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The impact of the parameterization of heterogeneous vegetation on the modeled large-scale circulation in CCM3-BATS

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Abstract. This letter reports evidence of an unexpected large change in the planetary-scale circulation as a consequence of modifying the land cover within the Community Climate Model (CCM3). Three 10-year simulations were analyzed using (i) default land cover, i.e., a single dominant vegetation in each land grid cell; (ii) aggregate land cover that includes a representation of subpixel heterogeneity; and (iii) aggregate land cover for aerodynamic properties, but default land cover otherwise. Simulations (ii) and (iii) were similar, indicating that aerodynamic properties are influential at the planetary scale. Comparing these two runs with (i), there are significant differences in the boreal summer. These include a northward shift of the Northern Hemisphere jet that relates to a decrease in the zonally averaged aerodynamic roughness around 60^oN, and a perturbation of the Southern Hemisphere jet. Field significance tests suggest these changes are likely a remote influence of the Northern Hemisphere perturbation, not a sampling fluctuation.

Introduction

Proper representation of the land-surface cover is essential for accurate parameterization of the lower boundary of an atmospheric General Circulation Model (GCM) [*Garratt*, 1993]. At the grid scale of a GCM, the land-surface cover is strongly heterogeneous. This can be accounted for by the use of pre-defined "aggregation rules" in combination with a high-resolution land-cover data set [*Arain et al.*, 1997; *Shuttleworth et al.*, 1997]. These aggregation rules are used to define grid-averaged land-cover parameters in such a way that the surface energy fluxes are similar to those found using an explicit representation of the individual patches of vegetation. Results of recent studies [*Arain et al.*, 1996, 1997] showed that, for most parameters, a weighted linear averaging rule is adequate. However, if the fluxes are not proportional to the parameters (e.g., in the case of aerodynamic roughness length and minimum stomatal resistance), more complex averaging procedures are required [*Shuttleworth et al.*, 1997].

Aggregate land-cover parameters were used within NCAR's CCM3 coupled with BATS [*Arain et al.*, 1999]. Comparing this model run with results from a run with the land-cover parameters defined to be those of a single dominant vegetation in each land grid cell, *Arain et al.* [1999] found regional changes in the land surface diagnostics (e.g., surface air temperature) which directly related to regional changes in the land-surface parameters. However, there were also unexpectedly significant changes in large-scale circulation. It is the impact of altering the vegetation parameterization on the planetary-scale circulation that is reported here.

Other studies have suggested that changing the land cover may affect global circulation [*Chase et al.*, 1999; *Zhang et al.*, 1996]. *Chase et al.* [1999] changed the global vegetation distribution so as to remove any anthropogenic impact. Resulting CCM3 model runs showed changes in high latitude boreal winter climate, which included a northward shift of the Northern Hemisphere zonally averaged jet stream.

Materials and methods

The version of CCM3 used in this study has 18 vertical levels extending up to 2.9 mb and a horizontal grid of approximately $3^0 \times 3^0$. *Kiehl et al.* [1996] described the physical parameterizations and numerical algorithms used in the model. BATS is a comprehensive Soil Vegetation Atmosphere Transfer (SVAT) scheme designed for use within the NCAR CCMs [*Dickinson et al.*, 1993]. It has 18 land-surface cover types, each type with 15 associated parameters that describe in detail the properties of the vegetation. BATS is driven by the atmospheric variables generated by CCM3 and returns the lower boundary conditions, such as water and heat fluxes, to CCM3.

Aggregate surface-cover parameters for each CCM3 grid box were derived using the aggregation rules defined by *Shuttleworth et al.* [1997] and land-cover classification data at 1 km resolution [*EDC DAAC*].

Three multi-year CCM3-BATS simulations were analyzed. The first, "default parameter" simulation used a single dominant cover type to define the 15 BATS parameters for each grid cell, and was run for 11 years. The second

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Table 1. Global averages of the aggregate and default land-cover parameters.

Parameter	Default	Aggregate
Displacement height (m)	0.80	0.54
Aerodynamic roughness length (m)	0.13	0.09
Albedo	0.16	0.17
Min. leaf area index	0.44	0.34
Max. leaf area index	1.32	1.17
Min. stomatal resistance (s m^{-1})	197	216

and third simulations were 10-year runs and were initiated at the end of year 1 of the default parameter run. The "aggregate parameter" simulation used aggregate cover parameters for all of the land-cover parameters required by BATS, whereas the "aerodynamic parameter" simulation used aggregate cover parameters for aerodynamic roughness length and displacement height and dominant land-cover parameters for the remaining 13 vegetation parameters. Point-by-point tests of the statistical significance of the differences between the default and perturbed parameter runs were made by comparing the changes with the year to year variability [*Chervin and Schneider*, 1976]. Global field significance was evaluated using Monte Carlo techniques based on sub-samples of 6 years [*Livezey and Chen*, 1983]. A change is deemed field significant when the percentage of point-by-point tests passed exceeds the 95% tail of the probability distribution of the percentage of point-by-point tests passed for random differences between two default- parameter-simulation means.

Aggregate versus dominant parameters

A comparison of the two sets of land-cover parameters reveals large differences between the global-averaged aggregate and default parameters, examples of which are shown in Table 1. In particular, the aerodynamic roughness length decreases by 36%, and the displacement height decreases by 38%. Locally, the most notable differences are in semi-desert and forested regions, where there are patches of vegetation included within the aggregate parameter representation that have strongly contrasting characteristics compared with those of the dominant vegetation type [*Arain et al.*, 1999].

Modeled differences at the land surface

There are significant differences (at the 95% confidence level) in surface heat fluxes between the aggregate and default cover parameter simulations for the 10- year average of June, July, and August (JJA, Figure 1a - b). Many regions of significant difference appear to be a local response to changes in the land surface, e.g., in the Sahara Desert. However there are other areas, e.g., over Antarctica and the

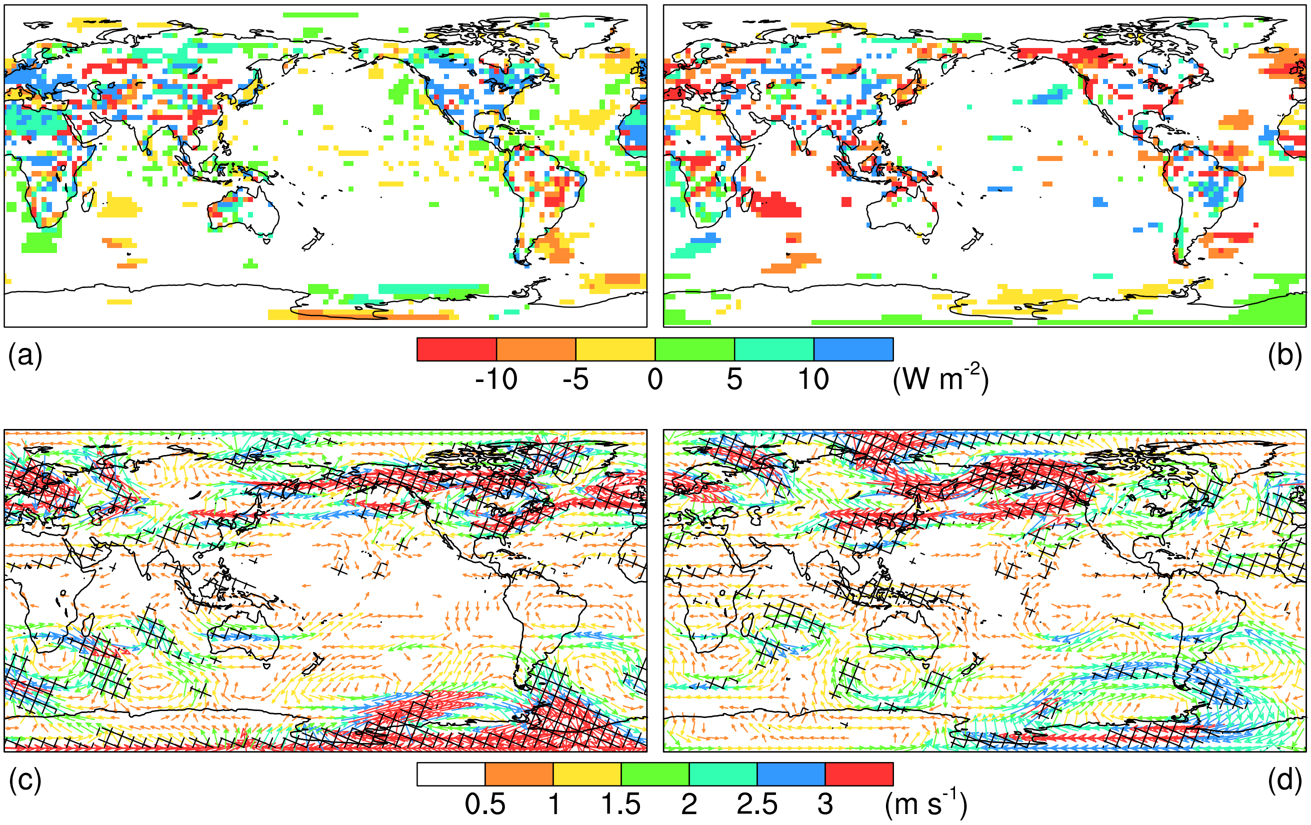

Figure 1. Differences in modeled (a) sensible heat flux; (b) latent heat flux; (c) 300 mb wind vector between the aggregate and default parameter simulations; and (d) 300 mb wind vector between the aerodynamic and default parameter simulations for the 10-year average of JJA. Only the regions where the differences are significant (at 95% confidence) are shown in (a) and (b), and the hatched area indicates significant differences in (c) and (d).

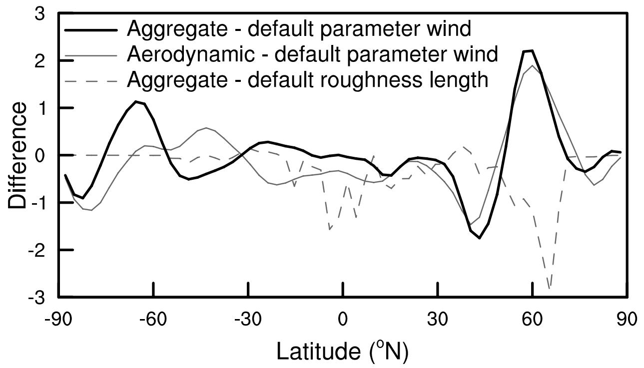

Figure 2. Difference between the zonally averaged east-west component of wind for the aggregate and default parameter runs and the aerodynamic and default parameter runs for the 10-year average of JJA (m s^{-1}); plus the difference between the roughness length (x 10 m) for the aggregate and default parameters.

Northern Atlantic Ocean, where the response is clearly not related to changes in the underlying land cover. It is the presence of the large-scale changes responsible for this non-local response which is of interest here.

Modeled differences in global circulation

Outside the tropics, there are statistically significant differences in wind vector between the aggregate and default parameter runs at the 300 mb level for the 10-year average of JJA (Figure 1c). These changes also pass global field significance tests. The differences between the 10-year average of December, January, and February (DJF, not shown) are similar, but fewer regions are statistically significant. The reduced area over which changes were significant in DJF compared to JJA is likely because there is greater land mass in the Northern Hemisphere over which forcing is greater in the boreal summer.

The path of the storm tracks in the Northern Hemisphere in JJA has been significantly altered, in response to the North Pacific and North Atlantic anticyclones being displaced northward. Similar effects appear at all levels in the atmosphere, indicating the response is equivalent barotropic. Changes in wind speed over the oceans may be responsible for some of the changes in the surface heat fluxes shown in Figure 1a-b. There is little change in the global precipitation distribution.

Figure 1c also shows changes in the patterns of the Easterlies in the Southern Hemisphere. The large natural variability in this region, particularly during the austral winter, suggests these changes should be treated with caution despite their point-by-point statistical significance. However, field significance testing suggests that the natural variability is less of an issue here. In addition, there is a remarkable similarity between Figure 1c and Figure 1d, which shows the difference between the aerodynamic and default parameter runs for the 10-year average of JJA, with a spatial correlation of 67% in nontropical latitudes. The ability to reproduce the spatial changes using a different combination of land-surface parameters lends support to the notion that the changes denote a dynamical response and not a sampling fluctuation. This similarity, and that in other model fields examined (not shown), also indicates that the modified aerodynamic characteristics have a major effect on the modeled global circulation pattern (Figure 1d) that is only perturbed slightly by differences in the 13 other parameters (Figure 1c).

Figure 2 shows the zonally averaged east-west component of wind for the difference between the aggregate and default parameter runs and the aerodynamic and default parameter runs at 300 mb. The difference between the aggregate and default zonally averaged roughness length is also shown in this figure. Again, there is a remarkable similarity between the two perturbed model runs. The northward shift in the Northern Hemisphere jet stream between 40 and 70^{o}N is presumably related to the decrease in the roughness length around 60^{o}N and the slight increase in roughness length around 30^{o}N. In the Southern Hemisphere, there are zonally averaged changes in the 300 mb east-west wind but no changes in zonally averaged roughness length.

Figure 3 shows the 10-year average velocity potential and streamfunction for JJA for the default parameter run (contoured) and the difference between the aerodynamic and default parameter runs (colored) at the 300 mb level. [Note: the aerodynamic parameter run was used in this figure because it is a first-order effect.] There are large, coherent regions of significant difference in Figure 3. The velocity

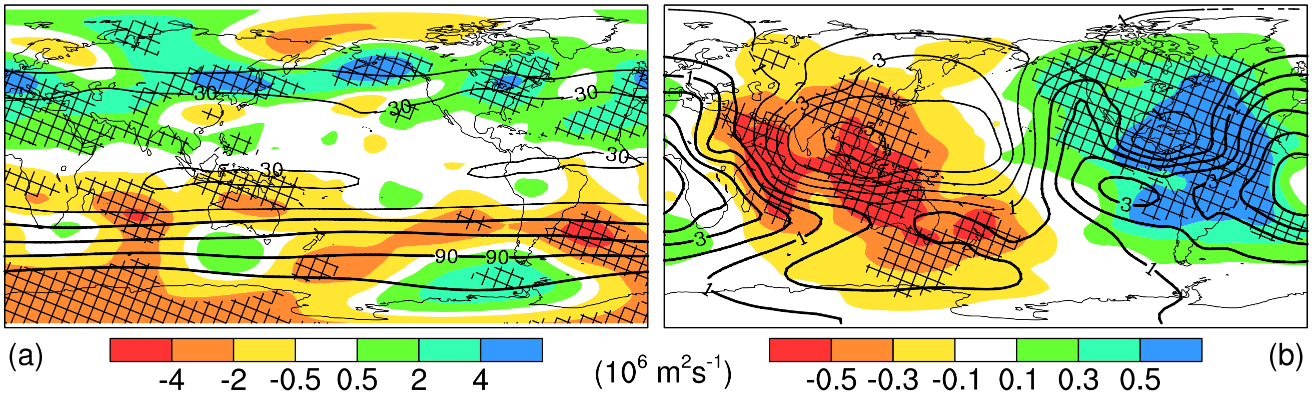

Figure 3. Difference between the aerodynamic and default parameter runs at 300 mb for the 10-year average of JJA of (a) the streamfunction (colored) superimposed on the default streamfunction field (contoured); and (b) the velocity potential (colored) superimposed on the default velocity potential field (contoured). The hatched areas indicate regions of significant difference at the 95% confidence level.

potential increases over the Americas and decreases over the Far East and Australia, while the streamfunction increases over the Northern Hemisphere jet stream and decreases in the Southern Hemisphere. These planetary-scale changes impact the divergence, and some of the modeled response in the Southern Hemisphere may result from the vorticity transport set up by this perturbed large-scale divergent field [*Chase et al.*, 1999]. Vorticity budget studies have shown that the transport of vorticity by the divergent field is an effective transport mechanism, especially for tropical- extratropical teleconnections [*Sardeshmukh and Hoskins*, 1987].

Conclusions

This letter reports the results from a comparison of three, 10-year CCM3-BATS model simulations. These were a default simulation (using the parameters of the dominant land cover in each grid cell); an aggregate simulation with a high-resolution data set to incorporate subpixel heterogeneity into the land-cover parameters; and a simulation where only the aerodynamic parameters were set to aggregate values. The impact of these changes were seen both locally over the changed land surface and remotely in the planetary-scale atmospheric circulation. Differences between default and aggregate parameter CCM3 simulations include a northward shift in the modeled Northern Hemisphere storm tracks (which is likely linked to zonally-averaged changes in roughness length), and a perturbation of the modeled Southern Hemisphere jet stream. These changes are field significant and reproducible in the aggregate and aerodynamic parameter runs. Statistical significant, reproducible patterns suggest that the perturbations are most likely a physical response dominated by the modified aerodynamic parameters. Modeled results show planetary-scale perturbations in the velocity potential and streamfunction fields that may provide the basis for a possible teleconnection mechanism between the Northern Hemisphere, where most of the land-cover changes are situated, and the Southern Hemisphere, where significant changes in the planetary-scale wind field also occur.

Results shown here demonstrate that subpixel heterogeneity needs to be carefully considered when determining the land-cover parameters for GCM simulations.

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References

Arain, M. A., J. D. Michaud, A. J. Dolman, and W. J. Shuttleworth, Testing of vegetation aggregation rules applicable to the Biosphere Atmosphere Transfer Scheme and the FIFE site, *J. Hydrol., 177,* 1-22, 1996.

Arain, M. A., W. J. Shuttleworth, Z.-L. Yang, J. D. Michaud, and A. J. Dolman, Mapping surface cover parameters using aggregation rules and remotely sensed cover classes, *Q. J. R. Meteorol. Soc., 123,* 2235-2348, 1997.

Arain, M. A., E. J. Burke, Z.-L. Yang, and W. J. Shuttleworth, Representing heterogeneous vegetation cover in the CCM3 global climate model–regional response at the land surface, *Hydrol. Earth Syst. Sci.,* in press, 1999.

Chase, T. N., R. A. Pielke, T. G. F. Kittel, R. R. Nemani, and S. W. Running, Simulated impacts of historical land cover changes on global climate in northern winter, *Climate Dynamics,* in press, 1999.

Chervin, R. M. and S. H. Schneider, Determining statistical significance of climate experiments with general circulation models, *J. Atmos. Science, 33,* 405-412, 1976.

Dickinson, R. E., A. Henderson-Sellers, and P. J. Kennedy, Biosphere-Atmosphere Transfer Scheme (BATS) version 1e for NCAR Community Climate Model, *Tech. Note NCAR/TN-387+STR,* 72 p., National Center for Atmospheric Research, Boulder, CO, 1993.

EDC DAAC, Earth resources observing system Data Center Distributed Active Archive Center, *http://edcwww.cr.usgs.gov/landdaac/glcc/glcc.html.*

Garratt, J. R., Sensitivity of climate simulations to land-surface and atmospheric boundary layer treatments–a review, *J. Climate, 6,* 419-449, 1993.

Kiehl, J. T., J. J. Hach, G. B. Bonan, B. A. Boville, B. P. Briegleb, D. L. Williamson, and P. J. Rasch, Description of the NCAR Community Climate Model (CCM3), *Tech. Note NCAR/TN-382+STR,* 152 p., National Center for Atmospheric Research, Boulder, CO, 1996.

Livezey, R. E. and W. Y. Chen, Statistical field significance and its determination by Monte Carlo techniques, *Mon. Wea. Rev., 111,* 46-49, 1983.

Sardeshmukh, P. D. and B. J. Hoskins, The generation of global rotational flow by steady idealized tropical divergence, *J. Atmos. Sci., 45,* 1228-1251, 1987.

Shuttleworth, W. J., Z.-L. Yang, and M. A. Arain, Aggregation rules for surface parameters in global models, *Hydrol. Earth Syst. Sci., 2,* 149-158, 1997.

Zhang, H., A. Henderson-Sellers, and K. McGuffie, Impacts of tropical deforestation, part II: the role of large scale dynamics, *J. Climate, 10,* 2498-2521, 1996.

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