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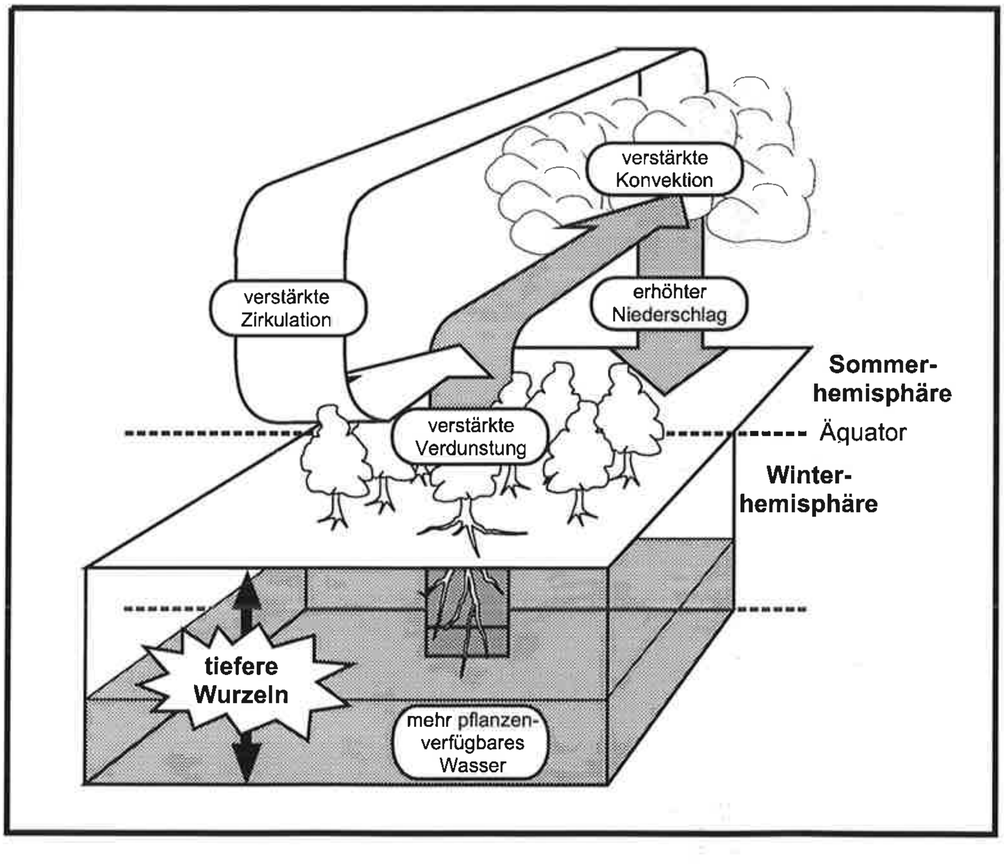

WURZELN UND KLIMA: BESTIMMUNG IHRER BEDEUTUNG DURCH MODELLSIMULATIONEN

(Roots and Climate: Assessing their Role with Model Simulations)

von

Axel Kleidon

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Dissertation zur Erlangung des Doktorgrades

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Wurzeln und Klima: Bestimmung ihrer Bedeutung durch Modellsimulationen

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Vorwort - Preface

Nach mehr als drei Jahren am Max-Planck-Institut ist es schwierig zu sagen, wo ich mit dem Dank anfangen soll. Natürlich bin ich meinem Betreuer, Dr. Martin Heimann, und dem Direktor des Instituts, Prof. Klaus Hasselmann, dankbar, da sie die vorliegende Arbeit erst ermöglichten. Allerdings scheint mir der Zeitpunkt auch angemessen zu sein, einen Moment innezuhalten und zurückzublicken. Gerade wenn man mit Wurzeln arbeitet, sollte man seine eigenen nicht vergessen. Also beginne ich mit einem Rückblick auf meine Zeit am Gymnasium. Dort habe ich enorm profitiert von meinem mitreißenden und herausfordernden Physiklehrer, Herrn Trinkl, der - durch Zufall oder Schicksal - ebenfalls ein Doktorand von Prof. Hasselmann vor etwa zwanzig Jahren war. Sein Enthusiasmus hat mein Interesse an der Physik geweckt. Nach einem kurzen Umweg von einem Jahr Elektrotechnik wurde ich Physikstudent und - seinem Rat folgend - belegte Meteorologie als Nebenfach.

Ein zweites, wichtiges Ereignis passierte während meines zweijährigen Aufenthalts an der Purdue Universität, an der ich mein Physikstudium abschloß. Im zweiten Jahr besann ich mich auf mein Nebenfach Meteorologie, als ich durch Zufall einen Kurs in Klimamodellierung entdeckte. Mehr als das Thema selbst, war es der Professor Bob Oglesby, der mich für einen Wechsel zur Klimatologie bewegte. Seine Begeisterung steckte mich sofort an. Ein großer Dank gilt ihm.

Den letzten Meilenstein auf meinem Weg passierte ich, als ich am Max-Planck-Institut angefangen habe. Ich empfand die Atmosphäre des Instituts als äußerst angenehm und produktiv. Ich danke besonders Prof. Hasselmann, der mir die Möglichkeit einer Promotion am Institut gab und meinem Betreuer, Dr. Martin Heimann. Er ließ mir während der gesamten Arbeit mehr Freiraum, als ich mir erhoffen konnte. Mit seinen kritischen Kommentaren, seinem Vertrauen in meine Arbeit, die Diskussionen und gelegentlichen Kurskorrekturen während der Zeit hat er einen entscheidenden Beitrag zu dieser Arbeit geleistet. Dank geht auch an Dr. Erich Röckner und Prof. Klaus Fraedrich, die mir mit Diskussionen und wertvollen Hinweisen bei der Analyse der Klimamodellsimulationen halfen. Ein weiteres Dankeschön geht an Prof. Schulze, der mir ein "echtes Wurzelerlebnis" im Bayrischen Wald vermittelte und dessen Anregungen mich inspirierten. Dankbar bin ich auch denen, die mir mit der Durchführung der

ECHAM Simulationen geholfen haben, insbesondere Martin Werner, Uwe Schulzweida und Monika Esch. Für Diskussionen über weit mehr als nur Arbeit und für die angenehme Zeit während gemeinsamer Dienstreisen danke ich besonders Bernadette Walter. Für anregende Gespräche bin ich außerdem Stefan Hagemann, Wolfgang Knorr, Jan-Peter Schulz und vielen anderen sowie Frau Radmann für ihre Unterstützung zu Dank verpflichtet. Ich werde mich auch gern an die angenehmen und inspirierenden Erfahrungen von zwei Jahren Zingst und die Lerngruppen erinnern, sowie der Gesellschaft während des Mittagessens in der Mensa, die das Essen tolerierbarer machten.

Dank geht an die Forscher im ABRACOS Projekt, die ihre Messungen frei zugänglich machten. Ihre Daten zeigten sich als sehr hilfreich für diese Arbeit.

Last, but not least, bin ich Ma-Li sehr dankbar für ihre kontinuierliche Unterstützung.

Hamburg im Februar 1998

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Zusammenfassung

Die vertikale Ausdehnung eines Wurzelsystems bestimmt, wieviel Bodenwasser der Landvegetation für die Verdunstung zur Verfügung steht und somit in die Atmosphäre zurückgeführt werden kann. Erst kürzlich wurde entdeckt, daß die immergrünen Wälder Amazoniens an manchen Orten Wurzeln bis zu 18 Meter Tiefe entwickeln und die Wasseraufnahme in diesen tiefen Bodenschichten beträchtlich zur Verdunstung während der Trockenzeit beiträgt. Unter Verwendung von Satellitenaufnahmen wurde sogar geschätzt, daß weite Teile der immergrünen Wälder in Amazonien von diesen tiefen Wurzeln (d.h. tiefer als ein Meter) abhängen und daß durch sie die grünen Kronendächer während der Trockenzeit beibehalten werden können. Im Gegensatz zu diesen Beobachtungen benutzen Modelle der Landbiosphäre ("TBM") und der allgemeinen atmosphärischen Zirkulation ("GCM") in der Regel Wurzeltiefen in der Größenordnung von einem bis zwei Meter.

Da Beobachtungen von Wurzeltiefen nur spärlich vorliegen und auch nicht unbedingt nur Anpassung an die Wasserbedürfnisse beschreiben (welches die Eigenschaft von Wurzeln ist, die in diesen Modellen berücksichtigt wird), stellt sich die Frage, wie eine globale Verteilung von Wurzeltiefen für solche Modelle bestimmt werden kann. Das Ziel dieser Arbeit ist es, die Rolle von Wurzeln als Wasserlieferant der Vegetation im Klimasystem zu untersuchen. Dazu wird zunächst eine Methode erarbeitet, die eine solche Verteilung bestimmt.

Die Methode basiert auf der Vorstellung, daß sich die Vegetation an ihre Umgebung in einer Weise anpaßt, die ihr Wohlergehen oder Überlebenspotential maximiert. Um diese Methode umzusetzen, wird angenommen, daß das Überlebenspotential charakterisiert werden kann durch das langjährige Mittel der Vegetationsproduktivität, wie es von einem einfachen Vegetationsmodell simuliert wird. Dieses Modell berechnet die Produktivität und die zeitliche Entwicklung der Bodenfeuchte ausgehend von atmosphärischen Eingangsgrößen. Es benötigt Wurzeltiefe als einen festen Parameter, der festlegt, wieviel pflanzenverfügbares Wasser im Boden gespeichert werden kann. Die Wurzeltiefe wird dann durch die Maximierung der mittleren jährlichen Produktivität in Abhängigkeit von der Wurzeltiefe bestimmt.

Diese Methode wird unter Verwendung von Klimadatensätzen auf globaler Skala

angewandt, um eine Verteilung von Wurzeltiefen zu erhalten. In vielen Teilen der Tropen wird Vegetation mit tiefen Wurzeln vorhergesagt. Durch die Vergrößerung des Speichervermögens an pflanzenverfügbarem Wasser im Boden erhöhen die tiefen Wurzeln die Wasserverfügbarkeit während der Trockenzeit und ermöglichen so erheblich mehr Verdunstung und Vegetationsproduktivität. Die Qualität der Verteilung wird auf verschiedene Weise untersucht. Ein direkter Vergleich zu Vegetationstypmittelwerten von beobachteter Wurzeltiefe zeigt, daß das allgemeine Muster gut reproduziert wird. Auf der anderen Seite führt die Zunahme der Verdunstung zur Reduzierung des mittleren Jahresabflußes von großen Flußeinzugsgebieten. Auch dies führt zu einer besseren Übereinstimmung mit Beobachtungen. Außerdem wird gezeigt, daß die Optimierung überwiegend durch den Wassermangel (Wasserüberschuß) während der Trockenzeit (Regenzeit) in humiden (ariden) Gebieten bestimmt wird.

Die Auswirkungen von tiefwurzelnder Vegetation auf das Klima werden durch die Anwendung der gleichen Methode auf ein Klimamodell (das globale Zirkulationsmodell ECHAM 4) untersucht. Dazu mußte eine Parameterisierung der Vegetationsproduktivität in das Klimamodell eingebaut werden. Wie zuvor wird eine erhebliche Zunahme der Verdunstung während der Trockenzeit festgestellt. Der damit verbundene erhöhte latente Wärmefluß führt zu einer Abkühlung der bodennahen Lufttemperatur von bis zu 8° Celsius im monatlichen Mittel. Diese kühleren Temperaturen und die dadurch reduzierte Saisonalität vergleichen sich erheblich besser mit Beobachtungen. Es wird ein allgemeiner Mechanismus vorgestellt, wie die Zunahme der Verdunstung während der Trockenzeit zu einer Verstärkung der tropischen Zirkulationsmuster führt. Wegen der Zunahme der Verdunstung auf der Winterhemisphäre wird feuchtere Luft mit den Winden der unteren Luftschichten zu den Konvektionsgebieten transportiert. Durch die Freisetzung von mehr latenter Wärme wird die Konvektion verstärkt, welches zu einer allgemeinen Anregung der Zirkulation führt.

Als Anwendung wird untersucht, wieviel der potentiellen klimatischen Auswirkungen durch die Abholzung tropischer Wälder Amazoniens auf die Entfernung tiefer Wurzeln zurückgeführt werden kann. Dazu wird eine Serie von Sensitivitätssimulationen mit dem Klimamodell durchgeführt, in denen Oberflächenparameter (besonders Wurzeltiefe und Albedo) Schritt für Schritt verändert werden, ausgehend von Werten des tropischen immergrünen Waldes zu solchen, die Grasland repräsentieren. Die Gesamtauswirkung wird überwiegend durch die Verringerung der Wurzeltiefe bestimmt. Es werden auch signifikante Fernwirkungen, wie zum Beispiel eine generelle Erwärmung über Nordamerika und trockenere Verhältnisse über Südostasien, beobachtet. Diese können wir zum Großteil auf die Abschwächung der tropischen Zirkulationsmuster als Konsequenz der verringerten Verdunstung während der Trockenzeit zurückführen.

Zusammenfassend finden wir, daß die Berücksichtigung von tiefen Wurzeln - wie sie von der hier vorgestellten Methode bestimmt wurden - zu einer Verbesserung der Simulationsergebnisse führt. Dies wurde aus dem Vergleich von einer Serie simulierter Größen mit Beobachtungen geschlossen. Die Ergebnisse lassen auch vermuten, daß natürliche Vegetation in vielen Teilen der Tropen tatsächlich am - oder zumindest nahe - dem Optimum bezüglich Wasserverfügbarkeit agiert. Wir folgern, daß tiefwurzelnde Vegetation einen wichtigen Bestandteil des Klimasystems darstellt, indem sie als großer Feuchtekondensator die Unterschiede in der atmosphärischen Wasserverfügbarkeit ausgleicht. Vernachlässigung von tiefen Wurzeln führt zwangsläufig zu einer Überschätzung der Saisonalität der bodennahen Lufttemperatur, wie sie nicht in Beobachtungen gefunden werden kann.

Summary

In the terrestrial biosphere the depth of a root system determines how much water can be extracted from the soil and recycled back into the atmosphere. Only recently it was discovered that evergreen forests in Amazonia develop deep roots of up to 18m and that the water uptake from these deep soil layers contribute significantly to dry season transpiration at some sites in Amazonia. With the use of satellite images, it has in fact been estimated that large parts of the evergreen forests in Amazonia depend on deep roots, that is, rooting depths of more than one meter, in order to maintain green canopies during the dry season. However, global models of the terrestrial biosphere and the general atmospheric circulation (GCMs) commonly use prescribed values for rooting depth which are typically of the order of one meter, and generally not exceeding 2 meters.

Considering that only sparse observations of rooting depth are available and that these do not necessarily reflect solely the adaptance to water needs (as are, however, only considered within these types of models), we ask how a global distribution of rooting depth can be obtained for such models. The aim of this thesis is to establish a methodology, based on an ecological principle and use it to obtain a global rooting depth distribution and investigate the role of roots in terms of water uptake in the global climate system.

The method is based on the idea that the vegetation has adapted to its environment in such a way that it's benefit or fitness is at a maximum. To implement this method, the fitness is measured by the long term mean of the vegetation's productivity, which is simulated by a simple vegetation model. This model computes productivity and soil moisture evolution from atmospheric quantities. It needs rooting depth as a fixed parameter to determine how much plant available water can be stored in the soil. Rooting depth is then obtained by maximising the mean annual productivity in respect to rooting depth.

This method is employed on a global scale to obtain a distribution of rooting depth using a global climatology. We find that deep rooted vegetation is predicted in many parts of the tropics. By increasing the storage capacity of plant available soil water, deep roots considerably enhance water availability during the dry season and hence transpiration and productivity. We assess the reasonability of the outcome by different means. A direct comparison to biome averages of observed rooting depths shows that the overall pattern is reproduced fairly well. The reduced annual discharge of large river basins resulting from the increase of basin transpiration complies better to observations. We also find that the optimisation process is primarily driven by the water deficit/surplus during the dry/wet season for humid and arid regions, respectively.

The climatic consequences of the presence of deep rooted vegetation is investigated by applying the same method to an atmospheric general circulation model. Here, it is necessary to incorporate the parameterisation of vegetation productivity into the climate model. Again, a considerable increase in the dry-season transpiration is found along with an enhanced latent heat flux. Consequently, mean monthly near-surface air temperatures during the dry season are lower by up to 8° Celsius and are found to be in much better agreement to observations. We also isolate a general mechanism by which the enhanced dry-season transpiration leads to an overall intensification of the tropical circulation patterns. Because of the increase of transpiration in the dry-season hemisphere, moister air is carried to the main convection areas in the lower atmosphere. The release of more latent energy leads to increased convection which in turn enhances the overall circulation.

Lastly, we assess how much of the climatic changes associated with Amazonian deforestation can be attributed to the removal of deep roots alone. This is done by conducting a series of sensitivity simulations with the climate model, in which some surface characteristics (mainly rooting depth and albedo) are subsequently modified from tropical evergreen forest values to ones representing grassland. The overall response is dominated by the reduction in rooting depth. Significant remote impacts, for instance, a warming over North America and drier conditions over Southeast Asia are also found. This can be attributed to the weakening of the tropical circulation patterns resulting from the reduction in dry season evapotranspiration.

To sum up, we found that the incorporation of deep roots - as predicted by the method - leads to an improvement of the simulations, as concluded from the comparison of a series of simulated quantities to observations. The results also suggest that the natural vegetation in many parts of the tropics indeed act at, or at least close to, the optimum, in terms of water availability. We conclude that deep rooted vegetation forms an important part in the climate system in that it acts as a large moisture capacitor levelling out differences in atmospheric moisture deficits. The neglection of deep roots inevitably results in an overestimation of air temperature seasonality in the humid tropics which cannot be found in observations.

Kapitel 1

Einleitung

1 MOTIVATION

Das globale Klimasystem ist eng mit den Kreisläufen von Wasser und Kohlenstoff verbunden. Während Wasser direkt eine aktive Komponente des Klimasystems darstellt, beeinflußt die Kohlendioxidkonzentration die chemische Zusammensetzung der Atmosphäre. Dadurch werden die Strahlungseigenschaften und folglich das Klima verändert (z.B. Schimel et al. 1996, Kattenberg et al. 1996). Über Land werden diese Kreisläufe stark durch das Vorhandensein von Vegetation geprägt. In diesem Zusammenhang wurde schon vor längerer Zeit vermutet, daß z.B. die Regenwälder Südamerikas ihr "eigenes" Klima erzeugen. Alexander von Humboldt (1849) berichtete von seiner Reise nach Südamerika am Anfang des letzten Jahrhunderts, daß

> "undurchdringliche Wälder [...] ungeheure Massen teils eingesogenen, teils selbsterzeugten Wassers aushauchen - alle diese Verhältnisse gewähren dem flachen Teile von [Süd] Amerika ein Klima, das mit dem afrikanischen durch Feuchtigkeit und Kühlung wunderbar kontrastiert."

Ein verbessertes Verständnis, wie Vegetation und Klima über die Stoffkreisläufe zusammenwirken, ermöglicht es uns besser abzuschätzen, wie sich eine veränderte Vegetationsbedeckung (z.B. durch Landnutzungsänderungen wie der Abholzung tropischen Regenwaldes) auf das Klima auswirkt, aber auch wie eine Klimaänderung (z.B. durch anthropogene Einflüsse oder während der Eiszeiten) die Zusammensetzung der Vegetation beeinflußt.

Um eine Idee über die allgemeine Bedeutung von Vegetation im Klimasystem zu bekommen, betrachten wir zunächst den globalen Wasserkreislauf, dargestellt durch seine jährlichen mittleren Flüsse (Abb. 1). Der Ozean stellt die Hauptquelle atmosphärischer Feuchte dar. Von dort gelangt Wasser durch Verdunstung in die Atmosphäre und wird zu den

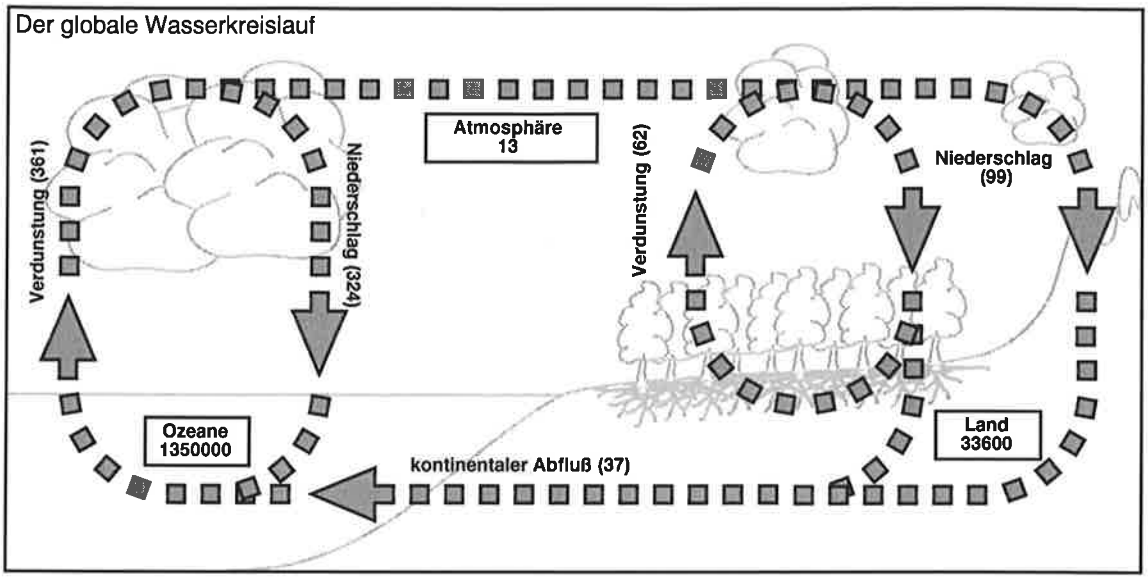

Abbildung 1: Der globale Wasserkreislauf. Das vereinfachte Diagramm (nach Peixoto und Oort 1992) zeigt die Jahresmittel der Flüsse zwischen den Speichern Ozean, Atmosphäre und Land. Wasserflüsse sind angegeben (in Klammern) in 10^{12} m^3/yr, Speichergrößen (in Kästen) in 10^{12} m^3.

Figure 1: The global water cycle. The simplified diagram (after Peixoto and Oort 1992) shows the annual mean fluxes between the reservoirs ocean, atmosphere and land. Water fluxes are given (in brackets) in 10^{12} m^3/yr, pool sizes (in boxes) in 10^{12} m^3.

Landflächen transportiert. Über Land regnet es ab und wird über den Abfluß von Flußsystemen zum Ozean zurückgeführt. Dadurch schließt sich der Wasserkreislauf.[1] Wir stellen aber auch fest, daß nur ein Drittel des Niederschlages über Land zum Ozean abfließt, während zwei Drittel durch Verdunstung in die Atmosphäre zurückgelangen, überwiegend durch die Transpiration von Pflanzen. Zwar trägt die Verdunstung direkt vom Boden auch zum Gesamtfluß bei, allerdings ist der Beitrag in der Regel gering, besonders in gut begrünten, humiden Gebieten (z.B. Hillel 1980). Deshalb wird ein Großteil dieser Rückführung aktiv von den Pflanzen durch die Aufnahme von Bodenwasser und anschließender Transpiration von den Blättern durchgeführt.

Die Transpiration von Wasser ist für die Pflanzen ein notwendiger Prozess (z.B. Larcher 1992): Er ermöglicht den Transport von Stoffen innerhalb der Pflanze, führt aber auch zur Kühlung durch Verdampfung. Dies kann für die Pflanzen entscheidend sein, um Hitzeschäden zu vermeiden. Transpiration ist außerdem ein unvermeidlicher Prozess, der bei

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[1] Prozesse im Zusammenhang mit Schnee, Eis usw. werden hier nicht berücksichtigt.

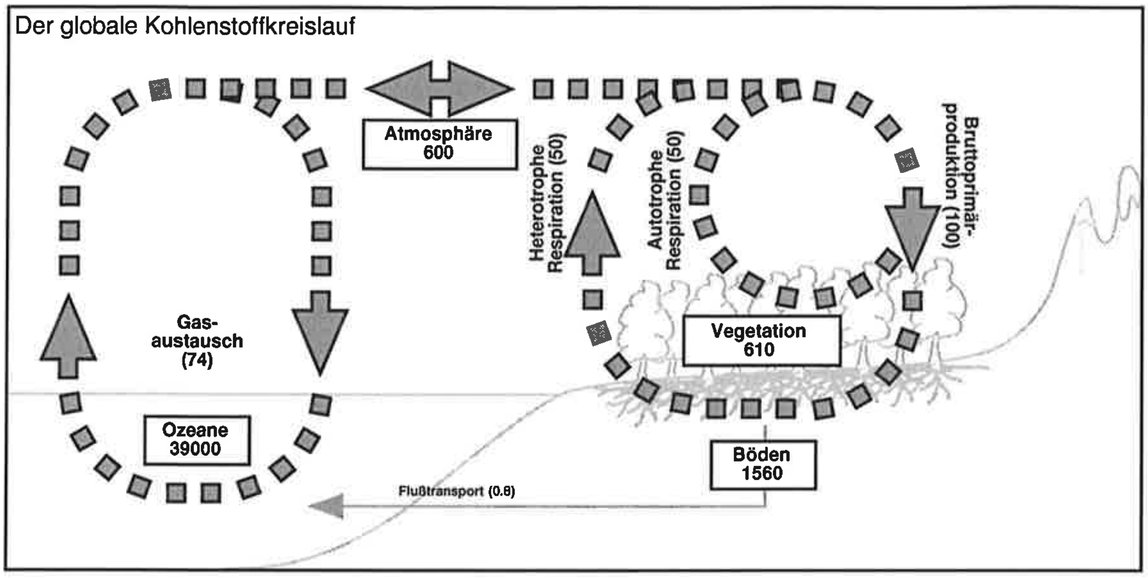

Abbildung 2: Der globale Kohlenstoffkreislauf. Das vereinfachte Diagramm (nach Siegenthaler und Sarmiento 1993) zeigt die vorindustriellen Jahresmittel der Flüsse zwischen den Speichern Ozean, Atmosphäre und Land. Kohlenstoffflüsse sind angegeben (in Klammern) in GtC/yr (Gigatonnen Kohlenstoff pro Jahr), Speichergrößen (in Kästen) in GtC.

Figure 2: The global carbon cycle. The simplified diagram (after Siegenthaler and Sarmiento 1993) shows the pre-industrial annual mean fluxes between the reservoirs ocean, atmosphere and land. Carbon fluxes are given (in brackets) in GtC/yr (gigatons carbon per year), pool sizes (in boxes) in GtC.

der Umsetzung von atmosphärischem Kohlendioxid in organische Substanzen bei der Photosynthese auftritt. Diese Aufnahme von Kohlenstoff durch die Vegetation (Bruttoprimärproduktion) ist ein Hauptbestandteil des globalen Kohlenstoffkreislaufs (Abb. 2). Pflanzen können die Aufnahme von Kohlenstoff und die daran gekoppelte Abgabe von Wasser durch eine Veränderung der Spaltöffnungen auf den Blattoberflächen, der Stomata, kontrollieren. Dies tritt ein, wenn nicht genügend Wasser im Boden verfügbar ist, mit der Folge, daß die Produktion von organischen Substanzen dann ebenfalls eingeschränkt werden muß.

Wie beeinflussen nun Wurzeleigenschaften der Vegetation diese Kreisläufe? Die Ausdehnung eines Wurzelsystems bestimmt, wieviel Wasser dem Boden entzogen werden kann und damit der Transpiration zur Verfügung steht.[2] Wie wir bereits gesehen haben, stellt das Vorhandensein von Vegetation die einzige Möglichkeit dar, große Mengen von

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[2] Andere Aspekte, wie Wurzeln diese Kreisläufe beeinflussen, z.B. durch die Zuführung von Kohlenstoff an den Boden, werden hier nicht berücksichtigt.

Bodenwasser in die Atmosphäre zurückzuführen. Ein gut entwickeltes und tiefreichendes Wurzelsystem erschließt einen größeren Bodenwasserspeicher und wirkt sich daher positiv auf die Vegetation aus, weil es Unterschiede in der Wasserverfügbarkeit zwischen Regenzeiten und Trockenperioden ausgleicht. Da große Gebiete der Erde ein saisonales Klima in Bezug auf Niederschlag besitzen, kann man daher erwarten, daß sich die natürliche Vegetation an das saisonale Klima angepaßt hat und genügend große Wasserspeicher im Boden erschlossen hat. Dies ist besonders in den Tropen der Fall, wo die höhere Sonneneinstrahlung zu einem intensiveren Wasserkreislauf führt. Der Vorteil der Vegetation dabei ist, daß sie die Kohlenstoffaufnahme über längere Zeiten durchführen kann, ohne unter Trockenstress zu leiden.

Erst kürzlich wurde entdeckt, daß der immergrüne Wald Amazoniens tiefe Wurzeln von bis zu 18 Metern entwickelt (Nepstad et al. 1994). Die Forschergruppe beobachtete, daß der Wald während einer ausgeprägten Trockenperiode durchweg nahe der potentiellen Rate transpirierte, indem Wasser aus tiefen Bodenschichten entzogen wurde. Unter Verwendung von Satellitenbildern wurde sogar geschätzt, daß große Teile des amazonischen immergrünen Waldes von tiefen Wurzeln abhängen, und damit die grünen Kronendächer unterhalten werden können.

Abgesehen von den Schlußfolgerungen dieser Forschergruppe wurde die Relevanz von Wurzeleigenschaften, z.B. ausgedrückt durch Wurzeltiefe, auf größerer Skala bisher kaum wahrgenommen. In globalen Modellen der allgemeinen atmosphärischen Zirkulation ("GCM's") und der terrestrischen Biogeochemie ("TBM's") ist die Wurzeltiefe generell kleiner als zwei Meter. Es wurde bisher von wenigen bemerkt, daß Wurzeleigenschaften (und/oder Bodeneigenschaften) einen gewissen Einfluß auf das simulierte Klima haben können (z.B. Milly und Dunne 1994, Stahmann 1996). Dies wurde geschlossen aus Sensitivitätsexperimenten bezüglich des Bodenwasserspeichervermögens. Allerdings können diese Sensitivitätsexperimente nicht beantworten, welche Werte für Wurzeltiefe generell benutzt werden sollten. Und wie können wir überprüfen, ob eine Verteilung von Wurzeltiefe in einem solchen Modell sinnvoll ist?

2 ZIELE DIESER ARBEIT

Die vorliegende Arbeit versucht die Bedeutung von Wurzeln - im Hinblick auf die Wasseraufnahme vom Boden - im Klimasystem zu bestimmen. Dies wird untersucht anhand der folgenden Fragen:

- Wie können wir eine globale Verteilung von Wurzeleigenschaften bestimmen, die die Effekte von tiefen Wurzeln, wie sie in gewissen Gebieten gefunden wurden, berücksichtigt? Wie kann eine solche Verteilung auf ihre Qualität hin getestet werden?

- In welchen Gebieten ist tiefe Bodenwasserspeicherung potentiell wichtig? Wie wichtig ist Bodenwasserspeicherung auf der globalen Skala?

- Welche Rolle spielen Wurzeleigenschaften im Klimasystem? Wie und wie sehr beeinflussen Wurzeln das Klima?

- Und als Anwendung: Was sind die klimatischen Auswirkungen, wenn tiefwurzelnde Vegetation entfernt wird, z.B. als Folge von Abholzung in Amazonien? Wie stark ist der Einfluß von Wurzeleigenschaften im Vergleich zu anderen Landoberflächeneigenschaften und wodurch unterscheidet er sich?

3 AUFBAU DER ARBEIT

Um diese Fragen zu beantworten, ist die Arbeit wie folgt aufgebaut:

In Kapitel 2 wird eine Methode vorgestellt, wie eine Verteilung von Wurzeltiefe mit Hilfe eines "TBM's" bestimmt werden kann. Hierbei steht Wurzeltiefe als Repräsentant von Wurzeleigenschaften innerhalb des Rahmens des einfachen verwendeten Modells. Die Methode benutzt ein bekanntes, evolutionäres Prinzip, wonach sich die Vegetation optimal an ihre Umgebung anpaßt und den besten Nutzen daraus zieht (z.B. Schulze 1982). Übersetzt in mathematische Schreibweise bedeutet dies, daß sich die Verteilung von Wurzeltiefe bestimmt aus der Maximierung des Wohlergehens oder der "fitness" der Vegetation, gemessen durch die vom Modell simulierte Produktivität. Diese Methode wird auf globaler Skala angewendet unter

Benutzung von beobachtetem Klima. Damit läßt sich der Effekt von Wurzeltiefe auf Produktivität und Transpiration abschätzen. Durch Vergleich mit Beobachtungen wird auch untersucht, ob die ermittelte Verteilung sinnvoll ist. In Abschnitt 2.2 werden theoretische Abschätzungen unter vereinfachenden Annahmen bestimmt, die das Funktionieren des Optimierungsansatzes verdeutlichen.

In Kapitel 3 untersuchen wir den Einfluß von veränderter Wurzeltiefe auf das Klima durch Anwendung der gleichen Methode auf ein "GCM". Dazu wird das einfache "TBM" aus Kapitel 2 in das "GCM" eingebaut. Der zugrunde liegende Mechanismus, wie Wurzeltiefe das lokale Klima und die tropische Zirkulation beeinflußt, wird ermittelt und diskutiert. Um zu testen, ob die Wurzeltiefenverteilung realistisch ist und ob sich die Simulation des Klimas verbessert hat, werden weitere Mittel der Überprüfung in Form von beobachtetem Oberflächenklima benutzt.

Die relative Bedeutung von Wurzeltiefe im Vergleich zu anderen Vegetationparametern wird in Kapitel 4 im Hinblick auf die klimatischen Auswirkungen von großskaliger Abholzung immergrüner Wälder in Amazonien abgeschätzt. Die Einflüsse der verschiedenen Parameter auf das Klima werden bestimmt durch weitere "GCM" Simulationen, in denen schrittweise die immergrünen Wald repräsentierenden Werte durch die für Grasland ersetzt werden. Die lokalen bis globalen Auswirkungen untersuchen wir anhand von direkten Änderungen des Oberflächenklimas und Änderungen der tropischen Zirkulation. Fernwirkungen von amazonischer Abholzung werden untersucht und erklärt durch den Mechanismus beschrieben in Kapitel 3.

Die Arbeit schließt mit einer Beantwortung der oben gestellten Fragen und mit einem Ausblick in Kapitel 5.

4 VERÖFFENTLICHUNGEN

Die meisten Abschnitte der folgenden Kapitel bestehen aus Manuskripten, die entweder zur Veröffentlichung eingereicht oder bereits veröffentlicht sind:

Abschnitt 2.1:	Global Change Biology, **4**(3), 275-286, © 1998 Blackwell Sciences
Abschnitt 3.1:	Geophysical Research Letters, **25**(3), 345-348 © 1998 American Geophysical Union
Abschnitt 3.2:	eingereicht bei Climate Dynamics
Abschnitt 4.1:	eingereicht bei Nature (in Überarbeitung)
Abschnitt 4.2:	eingereicht bei Climate Dynamics
Anhang B:	Physics and Chemistry of the Earth, **21**(5-6), 499-502, © Elsevier

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Kapitel 2

Optimale Wurzeltiefe

2.1 A Method of Determining Rooting Depth from a Terrestrial Biosphere Model and its Impacts on the Global Water- and Carbon Cycle[1]

Abstract: We outline a method of inferring rooting depth from a Terrestrial Biosphere Model by maximising the benefit of the vegetation within the model. This corresponds to the evolutionary principle that vegetation has adapted to make best use of its local environment. We demonstrate this method with a simple coupled biosphere/soil hydrology model and find that deep rooted vegetation is predicted in most parts of the tropics. Even with a simple model like the one we use, it is possible to reproduce biome averages of observations fairly well. By using the optimised rooting depths global Annual Net Primary Production (and transpiration) increases substantially compared to a standard rooting depth of one meter, especially in tropical regions that have a dry season. The decreased river discharge due to the enhanced evaporation complies better with observations. We also found that the optimisation process is primarily driven by the water deficit/surplus during the dry/wet season for humid and arid regions respectively. Climate variability further enhances rooting depth estimates. In a sensitivity analysis where we simulate changes in the water use efficiency of the vegetation we find that vegetation with an optimised rooting depth is less vulnerable to variations in the forcing. We see the main application of this method in the modelling communities of land surface schemes of General Circulation Models and of global Terrestrial Biosphere Models. We conclude that in these models, the increased soil water storage is likely to have a significant impact on the simulated climate and the carbon budget respectively. Also, effects of land use change like tropical deforestation are likely to be larger than previously thought.

1 INTRODUCTION

In the terrestrial biosphere, the depth (and the extent) of roots determine the maximum amount of water that can be stored in the soil for transpiration. Hence, rooting depth is an important parameter for large areas of the world's vegetation which are water limited during

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[1] Axel Kleidon and Martin Heimann, Global Change Biology 1998, 4(3), 275-286, © 1998 Blackwell Science

part of the year.

Land surface schemes of Atmospheric General Circulation Models (GCMs) (e.g. BATS(Dickinson et al. 1993), ECHAM(Roeckner et al. 1996), Sib2 (Sellers et al. 1996)) and models of the terrestrial biosphere (e.g. CASA (Potter et al. 1993), SILVAN (Kaduk and Heimann 1996), TEM (Raich et al. 1991)) both need rooting depth as a parameter to determine the storage size of the soil water pool. The storage capacity of the soil in turn determines how much water is available for transpiration during dry periods and thus affects the water stress of the vegetation in these periods. In present-day models, rooting depth is considered to be constant (within biomes and with respect to climatic forcing), usually not exceeding 2 meters. Little attention has been given so far to the question of how important this parameter is in the processes that determine fluxes of water and carbon between the vegetation and the atmosphere.

In contrast to the value of rooting depth used in global models, field studies show roots in some tropical regions going as deep as 60 m (Stone and Kalisz 1991). Also, it was estimated, that large parts of the Amazonian evergreen forests depend on deep roots to maintain green canopies during the dry season (Nepstad et al. 1994). During this period, Nepstad et al. (1994) also found a constant depletion rate of deep soil water, which indicates that water uptake by roots took place at that depth and suggests that transpiration was not restricted due to lack of soil water supply. These effects have not been included into present-day global models. This is partly due to lack of knowledge about the current distribution of rooting depth, which is difficult to obtain. Increasing rooting depth within global models should lead to higher water supply and hence have a pronounced effect on the hydrological cycle and Net Primary Production (*NPP*) of the vegetation. Also, enhanced transpiration increases the latent heat flux into the lower atmosphere, leading to a reduced near surface air temperature and an enhanced moisture flux within GCMs (Kleidon and Heimann, 1998).

Our aim in this paper is to outline a method of how to derive a global distribution of rooting depth by using a Terrestrial Biosphere Model. We base our approach on the idea, that there should be an optimum rooting depth depending mainly on soil texture and climate. This is motivated by the following reasons: On the one hand, deeper roots increase the vertical extent of the soil water storage accessible to plants, which in turn increases the ability of the vegetation to extract water. This is beneficial to the assimilation of carbon under water stress conditions. On the other hand, as roots grow deeper, more carbon needs to be allocated to the root system for construction and maintenance, which then reduces the amount of carbon available for aboveground growth and competition. With these two competing effects in mind, we may postulate that there should be an optimum rooting depth, at which the gain or survival power of the vegetation (e.g. expressed by *NPP*) is at a maximum.

However, costs of roots in terms of water- and nutrient uptake are mostly unknown and hence not implemented in present-day biosphere models (for one modelling approach see Kleidon and Heimann 1996). Therefore, we choose to demonstrate the method with a model, which is nevertheless capable of simulating the mechanism described above. This model consists of a simple parameterisation of *NPP*, depending on incoming Photosynthetically Active Radiation (*PAR*) and a drought stress factor. The drought stress factor is calculated by using a simple model for soil hydrology ("bucket model"). Within this model, increasing rooting depth first increases the soil water storage, but beyond a certain depth, productivity is not further increased by additional soil water storage. Thus, it is assured that there is an optimum rooting depth within this model. The model will be described in more detail below.

The model runs on a daily time step and is forced with incoming solar radiation, precipitation and atmospheric potential evapotranspiration. The forcing variables are derived from a global monthly climatology. Maximisation is done numerically by "Golden Section Search" (Press et al. 1992). Subsequently, we compare the rooting depth distribution obtained by maximisation to averages maximum rooting depth from field studies (Canadell et al. 1996).

As a sensitivity study, we also calculate optimised rooting depths under a setup with increased water use efficiency (*WUE*, = assimilated carbon / transpired water). This can be viewed as the vegetation response to an increase in atmospheric carbon dioxide concentration (CO_2), since the *WUE* is likely to increase (see e.g. Mooney et al. 1991). We model the effect of changed *WUE* in two extreme ways: In the one extreme, the increase of *WUE* is accomplished by reduction of transpiration. In the other extreme case, carbon assimilation (i.e. *NPP* within the model) is increased by a reduction of water stress. In this way *WUE* is also changed. We show the impacts on both of these cases for the determination of optimum rooting depth and on *NPP* and hydrology.

2 METHODOLOGY

2.1 Model Description

To demonstrate the method, we apply it to a simple, prognostic formulation of Net Primary Production (*NPP*) with a hydrological submodel. It does not contain processes like allocation, root-shoot communication, or nutrient uptake. The limitations of the model (and the method) and its consequences on the results are discussed in more detail in the discussion section below. The formulation of NPP is based on a common approach used in diagnostic studies (e.g. (Heimann and Keeling 1989), where NPP depends on the absorbed PAR (Photosynthetically Active Radiation) only:

$$NPP(fPAR) = A \times fPAR \times PAR \tag{1}$$

where A is the globally constant light use efficiency and $fPAR$ is the fraction of absorbed PAR. We argue, that $fPAR$ mainly reflects limitations or modifications of the vegetation such as water stress, nutrient stress, land use (e.g. agriculture) and temperature limitations (phenology), which do not allow the vegetation to convert all of the incoming PAR into carbon assimilates. Here, we consider water limitation only, and write NPP as

$$NPP(D) = A \times \alpha(D) \times PAR \tag{2}$$

with $\alpha(D)$ being the water stress factor, which depends in some way on the rooting depth D (see below for details) . The NPP calculated in this way could be called potential, water limited NPP.

To obtain an estimate for the water stress factor, we make use of a bucket model to simulate soil hydrology. We use the model of Prentice et al. (1993). In the following we outline the model (and its forcing) only to an extent that is necessary to understand the mechanisms described in the later sections.

The water stress factor is parameterised as

$$\alpha(D) = \min\left[\frac{SUPPLY(D)}{DEMAND};1\right] \tag{3}$$

where $DEMAND$ is the demand for transpiration from the atmosphere and $SUPPLY$ is the soil water supply for transpiration. $DEMAND$ is set to the “equilibrium evapotranspiration rate” calculated fom the approach of McNaughton and Jarvis (1983), where this rate is estimated from the energy budget. $SUPPLY$ is calculated following Federer (1982) by :

$$SUPPLY(D) = c \times \frac{W}{W_{MAX}(D)} \tag{4}$$

Here, c is the maximum soil water supply rate for transpiration, set to be 1mm/h and W the amount of plant available water stored within the rooting zone. Maximum plant available soil water storage W_{MAX} ("bucket size") is given by

$$W_{MAX}(D) = D \times PAW \tag{5}$$

where PAW is the difference between field capacity and permanent wilting point for 1 meter of soil, taken from a global data set (Batjes 1996).

The change of soil water ΔW in a time step Δt is described by

$$\Delta W = PRECIP - TRANS - RUNOFF \tag{6}$$

where $PRECIP$ is precipitation, $TRANS$ the transpiration and $RUNOFF$ the runoff and the drainage from the soil column during this time step. $TRANS$ is calculated as the minimum of supply of soil water (given by eqn. 4) and demand for transpiration:

$$TRANS = \min[SUPPLY, DEMAND] \tag{7}$$

By combination of eqn.(4) and eqn. (7) we see, that within this formulation, drought stress sets in if W falls below a critical water content of W_{crit} given by

$$W_{crit} = \frac{W_{MAX} \times DEMAND}{c} \tag{8}$$

If W is greater than W_{crit}, transpiration is only limited by the atmospheric demand and NPP is not water-limited. $RUNOFF$ is taken as the excess of soil water whenever W exceeds the maximum soil water storage W_{MAX}:

$$RUNOFF = \max[0, W - W_{MAX}] \tag{9}$$

For simplicity, effects of snow and bare soil evaporation are neglected.

2.2 *Forcing of the Model*

The biosphere model runs on a daily time step on a global grid with a half-degree horizontal resolution. We assume all land points to be covered by vegetation (i.e. including deserts). The model is forced by a monthly climatology of precipitation, cloudiness and air temperature of Cramer and Leemans (pers. comm., updated version of Leemans and Cramer (1991)). While precipitation is a direct forcing variable of the hydrologic submodel (*PRECIP*), cloudiness is used to calculate solar radiation (Linacre 1968), which together with air temperature is used to compute $DEMAND$ (McNaughton and Jarvis 1983). PAR is taken to be half of the incoming solar radiation. A "weather generator" (Geng et al. 1986) in connection with a global data set of wet days (i.e. days with precipitation events) (Friend 1996) was used to simulate day-to-day variations in precipitation. Annual global NPP is set to a value of 60 GtC for the experiment with a rooting depth of D = 1m to obtain the light use efficiency constant A. We do this only to formulate the impacts on NPP on an absolute scale; the relative changes resulting from the optimisation are independent of the value of A.

2.3 *Determination of Rooting Depth*

We calculate the optimum rooting depth by maximising NPP (i.e. eqn.(2)) with respect to D. The maximum is obtained numerically by ten iterations using the "Golden Section Search" algorithm (Press et al, 1992). During each iteration, the model runs for 10 years to damp the noise introduced by the weather generator. The ten year mean of annual NPP is used as the maximisation variable. We compare the results with a run of the model under the same setup but using a rooting depth of one meter.

2.4 *Sensitivity to Increased Water Use Efficiency*

The computation of optimum rooting depth has also been performed with an increased water use efficiency (WUE). Within the formulations used here, WUE can be expressed by

$$WUE = \frac{NPP}{TRANS} \propto \frac{\alpha}{\min[SUPPLY, DEMAND]} \tag{10}$$

The increase of WUE has been implemented in two different ways:

- In the numerical experiment "0.5*DEMAND", WUE is increased by reduction of $DEMAND$ by an arbitrary factor of 2
- In the numerical experiment "2*ALPHA", WUE is increased by inserting a factor of 2 into eqn. (3), so that it becomes

$$\alpha(D) = \min\left[2 \times \frac{SUPPLY(D)}{DEMAND}; 1\right] \tag{11}$$

In both experiments, *WUE* is doubled in water stressed conditions. While the first experiment has strong impacts on the water cycle because of the reduction of *DEMAND*, the latter experiment will affect *NPP* only. Both experiments could be seen as simulations of an environment of elevated atmospheric carbon dioxide concentration; in the experiment "0.5*DEMAND" the stomatal conductance is affected by the elevated concentration ("downregulation") while it is not affected in the experiment "2*ALPHA".

3 RESULTS

3.1 Optimum Rooting Depth

The calculated rooting depths are shown in Fig. 1. A noticeable feature is that even relatively wet regions like the Amazon basin in South America or the Congo basin in central Africa show depths substantially larger than one meter. All desert regions show a noisy estimate - this is mainly due to the stochastic precipitation in the forcing. To assess the quality of this estimate, we calculate biome averages using a land cover data set (Wilson and Henderson Sellers 1985) and compare it to averages of observations of maximum rooting depths (Canadell et al. 1996) in Fig. 2. The values for forested biomes are generally well reproduced, considering the high scatter of observed rooting depths even within the same biome. Rooting depth is overestimated for biomes (temperate grassland, shrubs, and tropical deciduous forest), where the vegetation might use leaf-shedding as a drought-avoidance strategy.

The simple formulation of hydrology affects the arctic regions: Since snow hydrology is not included in the bucket model, a considerable water deficit during the summer months in some arctic regions (parts of Alaska and Northern Canada) is created. This, in turn, causes the optimisation process to "create" deep roots in these regions since water availability and the maximum in irradiation are out of phase (see below for a general description of the mechanism). However, these regions are strongly affected by other limitations of root growth such as permafrost and low productivity, so that the formation of deep roots under the present climate is unlikely.

The high scatter in the observed biome averages also stresses the need for a conceptual approach rather than measured values in the field of modelling. It is important to notice, that the maximisation process in fact determines the optimum plant available water

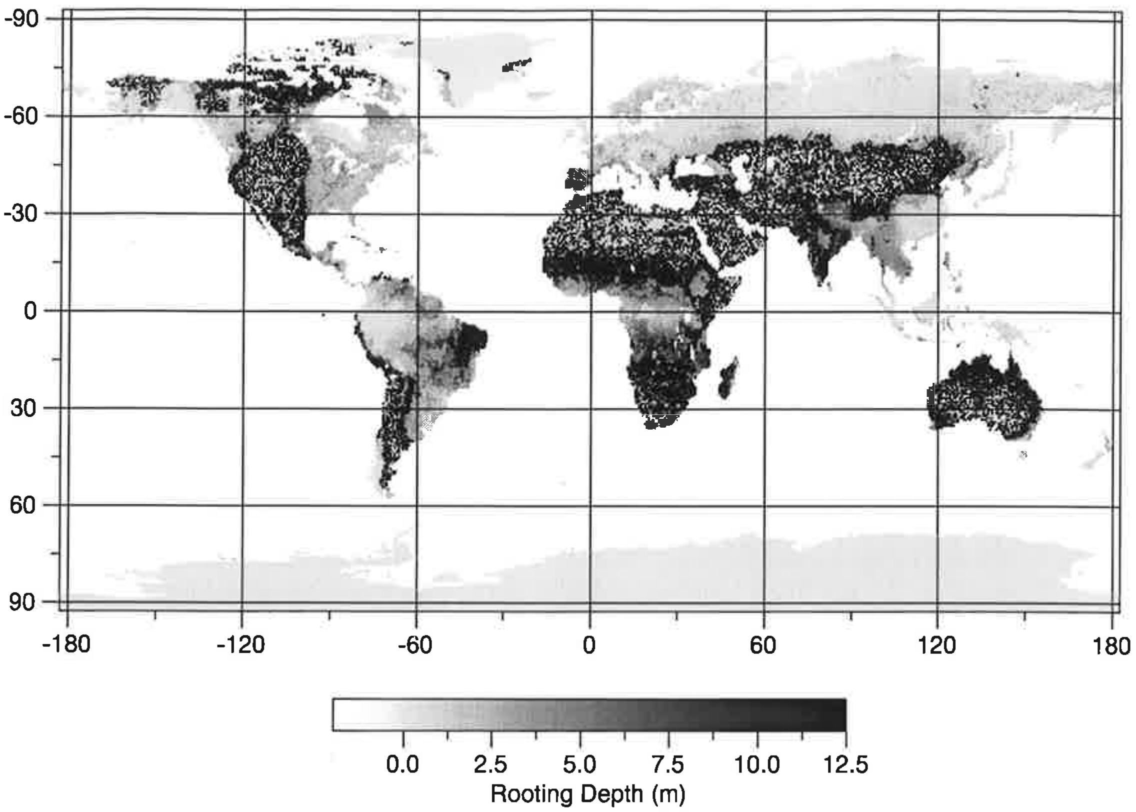

Figure 1: Global distribution of rooting depth obtained from the maximisation of NPP. The scattered values in desert ecosystems are due to the stochastic precipitation generated by a weather generator.

storage of the soil ("bucket size", W_{MAX}). The corresponding optimum rooting depths are then calculated from W_{MAX} by using eqn. (5) and a soil texture data set. This means, that the obtained values for optimum rooting depth depend on the soil texture data set, while the values of optimum W_{MAX} (and the model results) are unaffected when using a different soil texture data set. This is useful, since available data sets of soil textural parameters vary substantially, e.g. Batjes (1996), Dunne and Willmott (1996), and Webb et al. (1991).

The comparison of the calculated biome averages of optimum rooting depth to the observed averages should be taken with caution: The high scatter in the averages calculated from observations indicate that rooting depth is probably mainly driven by site specific characteristics (including the local climate) and cannot be classified on a biome level. This was also stated in Stone and Kalisz (1991). It is also not clear whether the observed rooting depths represent plant strategies to increase water uptake capability. Therefore, a simple incorporation of this data set into the model can lead to inconsistencies within the model with the above principle of maximisation of *NPP*. In contrast to the observations, the scatter in the biome

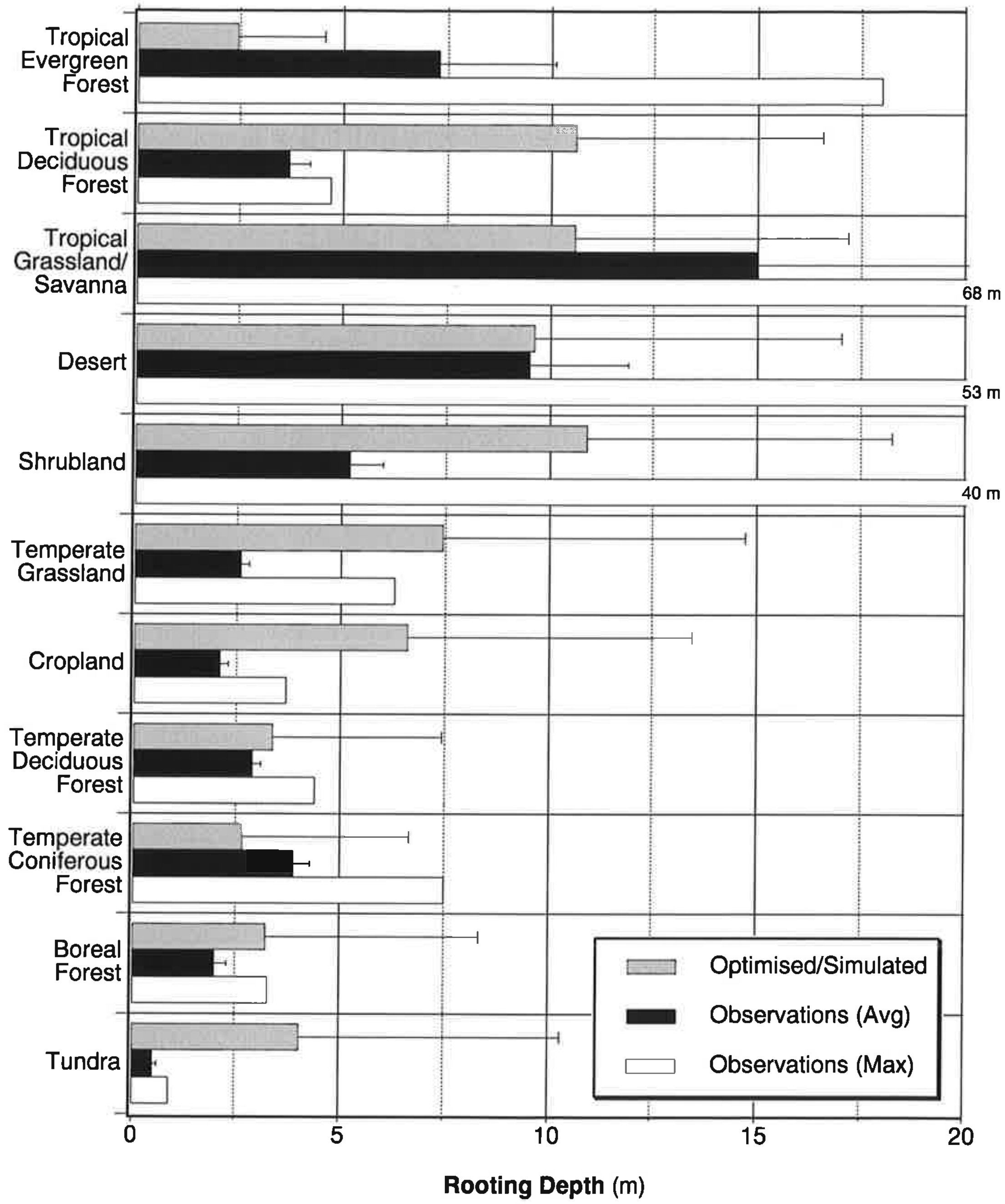

Figure 2: Comparison of biome averages of optimum rooting depth obtained by the described method to biome averages of rooting depth and maximum rooting depth found in each biome (Canadell et al. 1996). Error bars indicate one standard deviation.

Experiment	Rooting Depth (m)	NPP (GtC/yr)	Evapotranspiration (mm/d)	Runoff and Drainage (mm/d)
Standard WUE				
Standard	1.00	60.0	0.99	1.15
Optimised	6.91	69.6	1.17	0.97
Increased WUE "0.5 DEMAND"				
Standard	1.00	72.8	0.61	1.53
Optimised	4.33	80.6	0.69	1.45
Increased WUE "2 ALPHA"				
Standard	1.00	63.0	0.99	1.15
Optimised	9.36	76.9	1.17	0.97

Table 1: Global average of rooting depth, global annual Net Primary Production (*NPP*), and global averages of evapotranspiration and runoff for the different runs. Global *NPP* has been set to 60.0 GtC/yr for the standard case and a rooting depth of 1 m. The scaling constant (light use efficiency) obtained this way was used by the other experiments to calculate global *NPP*. Averages are weighted by area.

averages calculated from the optimum rooting depths primarily reflects the differences in the climatic forcing (see also discussion below) and, to a lesser extent, variations in the soil texture.

3.2 Impacts on NPP

To investigate changes in annual Net Primary Production (*ANPP*), we first scale the global sum of *ANPP* for the standard model run (i.e. with a rooting depth of 1m) to 60 GtC/year. The scaling constant obtained in this way is applied to all other experiments. With the use of the optimum rooting depth distribution, global *NPP* increased by 16% (see Table 1). We plotted the distribution of *ANPP* for the standard run in Figure 3a. Increases in *ANPP* caused by the use of the optimised rooting depth distribution is mainly concentrated on tropical

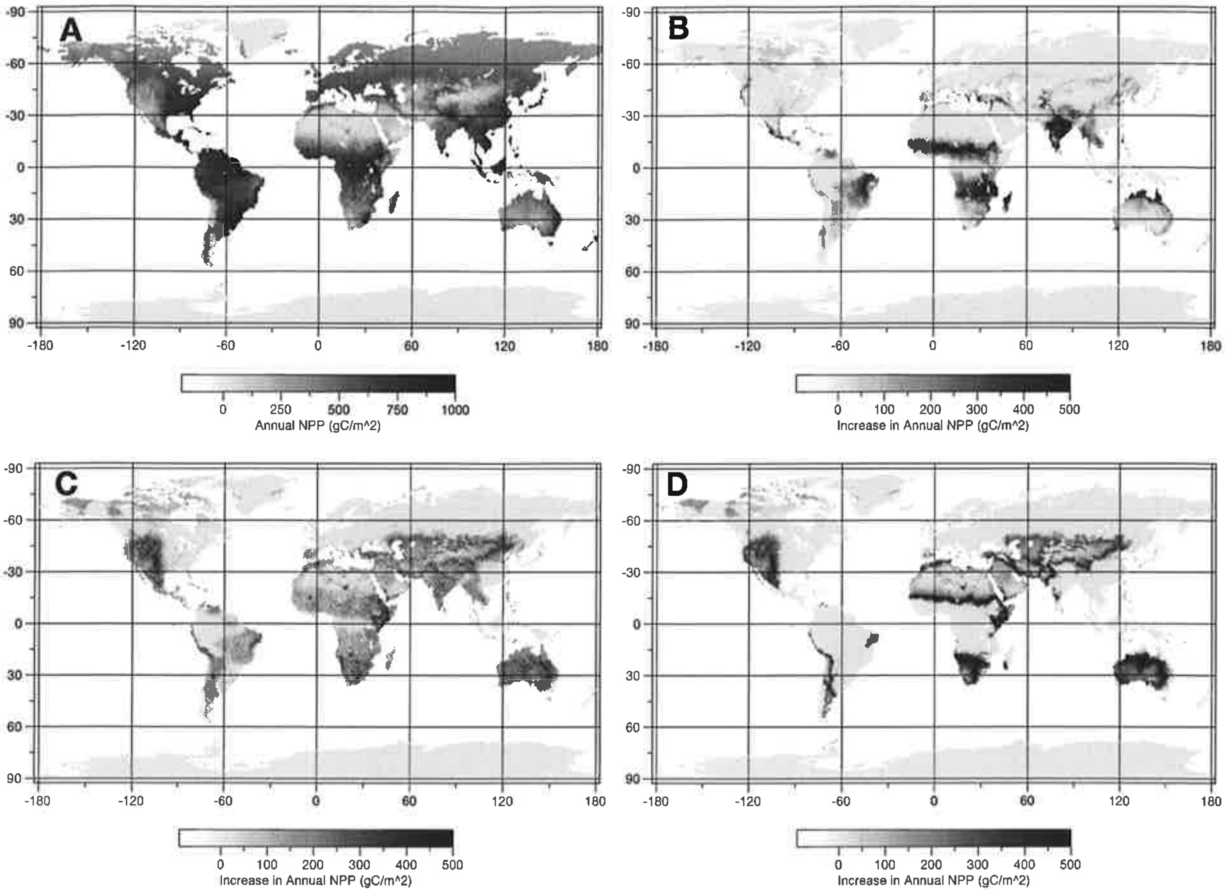

Figure 3: Distribution of mean Annual Net Primary Production (*ANPP*) for the standard case (rooting depth D = 1m) (a), and changes by using an optimised rooting depth distribution (b). In (c) and (d) are shown the changes of *ANPP* resulting from a decreased atmospheric demand (potential evapotranspiration) for the standard rooting depth and optimised rooting depth distribution respectively. This can be interpreted as the sensitvity of the model to deceased stomatal conductance in an elevated CO_2 environment. The standard case (a) was scaled to yield a global *ANPP* of 60 GtC.

regions that experience longer drought periods, such as eastern Brazil, large parts of Africa, India and northern Australia (see Fig. 3b). We visualize the seasonal effect of deep roots on *NPP* in Fig. 4 for a grid point in eastern Brazil. It is clearly seen that the seasonality in transpiration and hence in *NPP* is removed by the optimisation process. The seasonal persistence - in contrast to the strong seasonality of the meteorological forcing - has been observed by Nepstad et al. (1994) for this particular region.

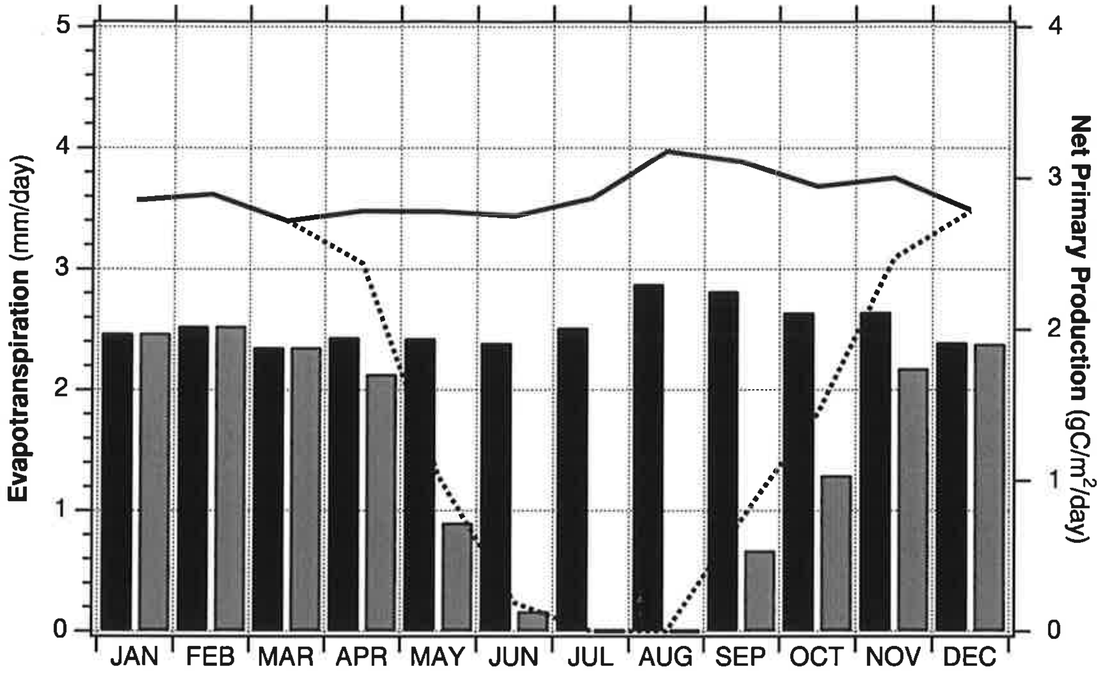

Figure 4: Evapotranspiration (bars) and Net Primary Production (lines) for the standard rooting depth of 1 m (grey/dashed) and the optimised rooting depth (black, solid) shown for one grid point in eastern Brazil (grid point 10°S, 45°W).

3.3 Impacts on watershed hydrology

On the global scale, transpiration is increased over land areas by 18% with the use of optimised rooting depths (Table 1). The increase in transpiration shows the same spatial and temporal distribution as the change in *ANPP* (shown in Figs. 3 and 4). Increased transpiration leads to a decreased runoff, which is also reflected in the reduction of annual river basin discharge (that is equal to the annual sum of runoff taken over the drainage basin). In Fig. 5 we show the annual river basin discharge resulting from uniform (D=1m) and optimised rooting depth for 11 drainage basins that show the largest changes in runoff. For all river basins shown, discharge is reduced substantially and the resulting calculated discharge compares much better with observations (Dümenil et al. 1993). Here, again, the comparison to observations have to be taken with caution, since the model does not include several effects (such as swamps in river basins, e.g. Niger and Nile, irrigation of land, and dams) that modify the water budget of drainage basins.

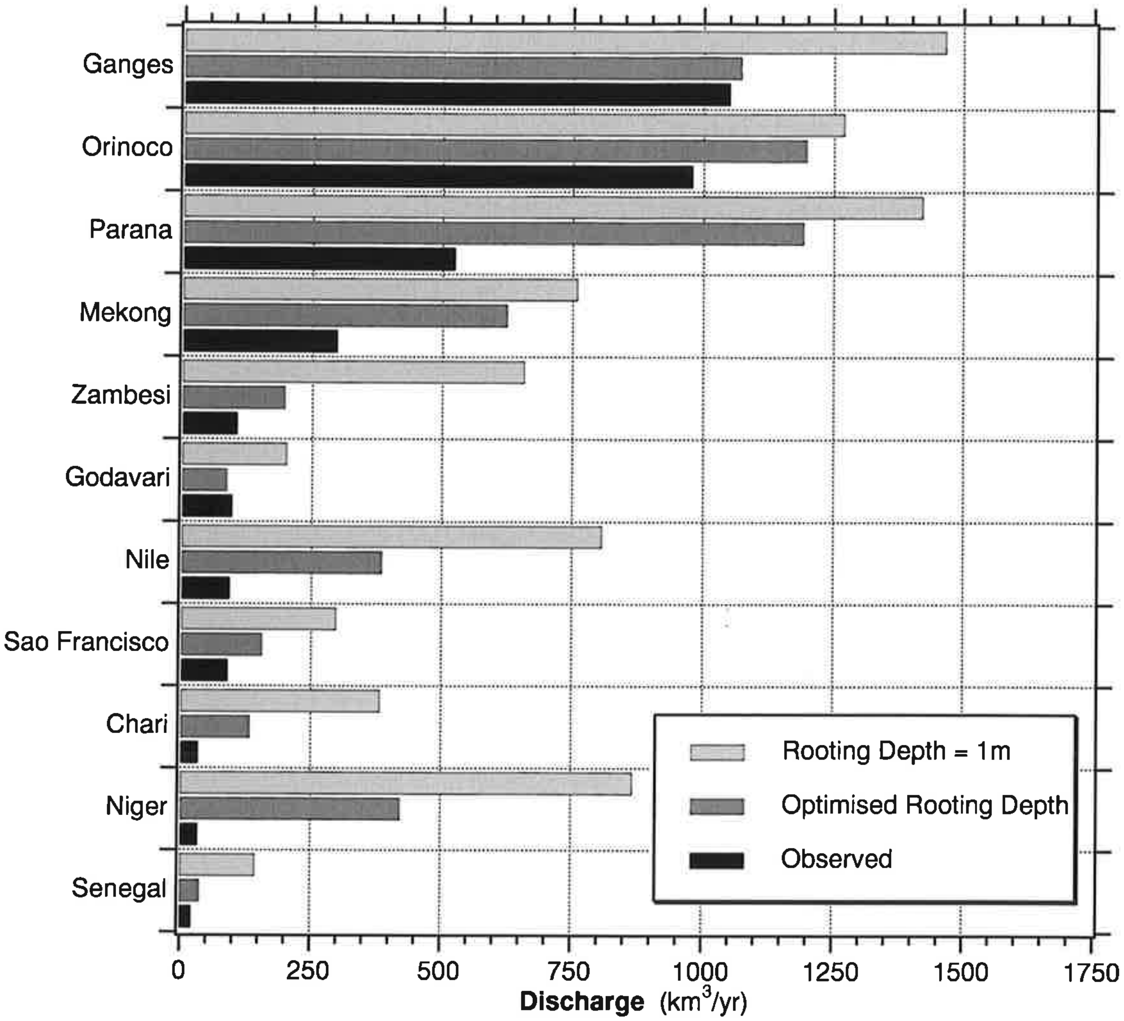

Figure 5: Comparison of annual river basin discharge (for the standard rooting depth of 1m and the optimum rooting depth) compared to observations (Dümenil et al. 1993). We selected only river basins with significant changes in runoff due to the modified rooting depth.

3.4 Mechanism behind the optimisation process

We have already shown one aspect of the effects on the seasonality in water availability at one site in Fig. 4. This effect can be generalised by considering the water budget of regions with dry periods:

We consider humid regions first, i.e. regions that have a balanced water budget on an annual scale. These regions are characterised by the property that annual *PET* (potential evapotranspiration, taken to be equal to *DEMAND*) is less or equal to annual *PRECIP* (precipitation):

$$\int_{year} PET\,dt \le \int_{year} PRECIP\,dt \tag{12}$$

For grid points that meet this criterion, we calculate the water deficit of the dry period by integrating monthly means of *PET* - *PRECIP* for months where *PET-PRECIP* > 0:

$$DEFICIT = \int_{PET>PRECIP} (PET - PRECIP)\,dt \tag{13}$$

In Fig. 6a we depict the optimised soil water storage (bucket size) against the water deficit of humid regions. The bucket sizes for the case of a rooting depth of 1 meter ranges from 30 mm to 350mm for organic soils with an average value of 72mm. One can clearly see in Fig. 6a that the optimisation process creates bucket sizes that are at least as large as the water deficit. This enables the vegetation to transpire at potential transpiration rates, implying, that drought stress is eliminated. More formally speaking, all points lie above the line $DEFICIT = W_{MAX}$. There are two reasons, why the points do not lie exactly on this line: First, the water deficit calculated in the described way does not completely remove drought stress. In order to completely remove water stress, the rooting depth needs to be adjusted in such a way that W never falls below W_{crit} given by eqn. (8). Since W_{crit} differs for each grid point (since it depends on *DEMAND*), we cannot derive a general expression for a "minimum soil water storage capacity of potential vegetation". However, the condition $DEFICIT = W_{MAX}$ assumes a critical water content of 0, so that this condition is a valid lower estimate. The second factor influencing the scatter of optimised bucket sizes in Fig. 6a is due to the stochastic precipitation. The conclusions we can draw from this is, that climate variability enhances the estimates of an optimum rooting depth and that the optimum rooting depth is mainly a result of the atmospheric forcing.

We now consider arid regions, i.e. regions where annual *PET* is larger than annual *PRECIP*:

$$\int_{year} PET\,dt > \int_{year} PRECIP\,dt \tag{14}$$

For the grid points that meet this criterion, we calculate the water surplus in the wet season by integrating monthly means of *PRECIP* - *PET* for months where *PRECIP* - *PET* > 0:

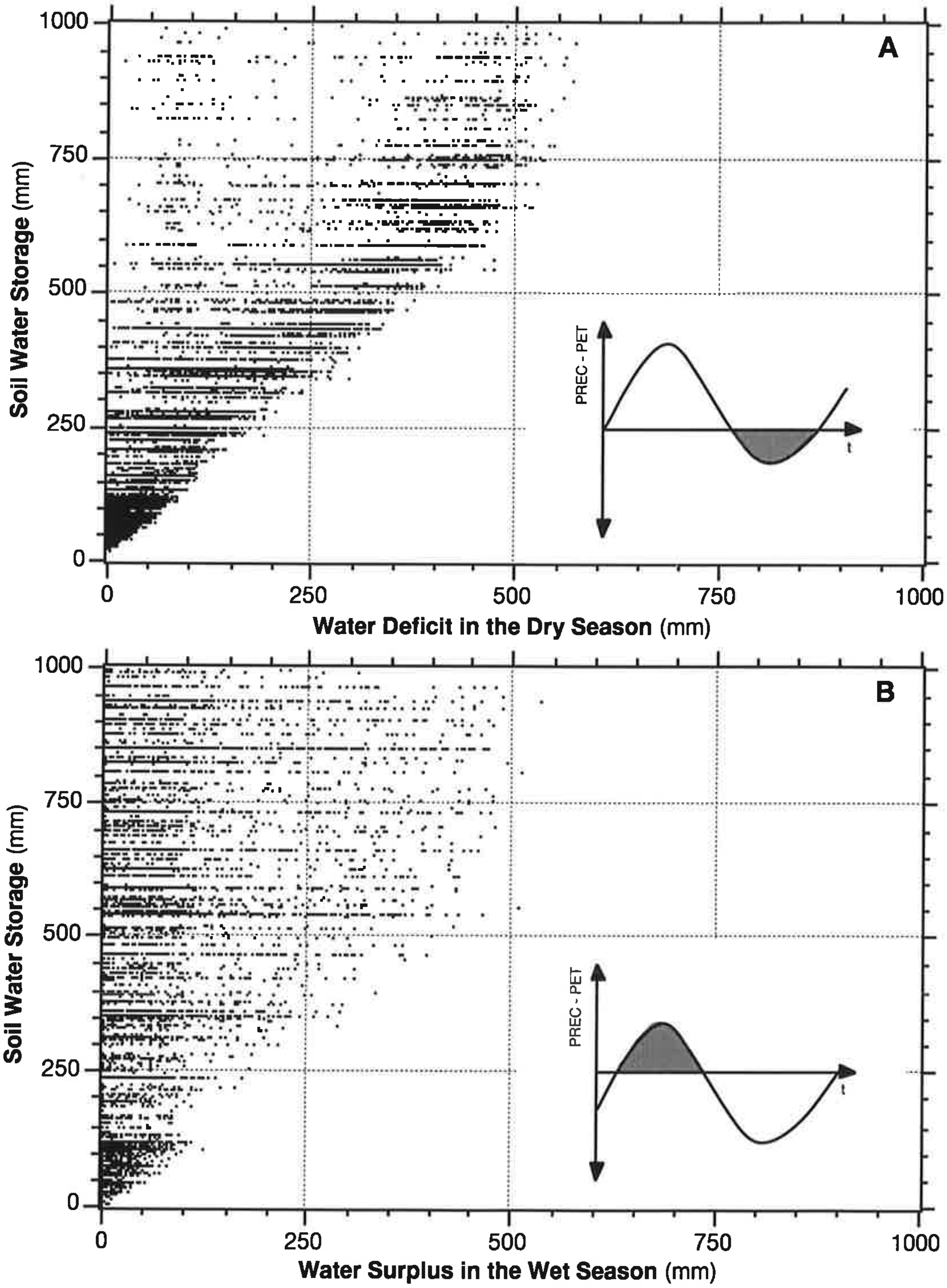

Figure 6 : Water deficit (for humid regions, a, see eqn. 13) and water surplus (for arid regions, b, see eqn. 15) plotted against optimised soil water storage. The water deficit during the dry season was calculated by integrating *PET* (potential evapotranspiration) - *PRECIP* (precipitation) during months where *PET* - *PRECIP* >0 (see inlet in a). The water surplus during the wet season was calculated correspondingly by *PRECIP* - *PET* when *PRECIP* - *PET* > 0 (see inlet in b).

$$SURPLUS = \int_{PET<PRECIP} (PET - PRECIP)\,dt \qquad (15)$$

In Fig. 6b we plot the optimised soil water storage (bucket size) against the water surplus of arid regions. Again, we can see that all points lie above the line $SURPLUS = W_{MAX}$. The interpretation here is slightly different to the one for the humid regions: In arid regions, the optimisation process enlarges the soil water storage to an extent that enables the vegetation to hold as much water as possible, thus minimising drought stress. Here, the stochastic precipitation is the only reason for the high scatter.

In summary, the optimisation process for both cases adjusted the bucket size in such a way that the water availability is maximised throughout the year. Hence, the optimisation of *NPP* led to a maximisation of transpiration (with a given atmospheric demand).

3.5 Sensitivity to increased water use efficiency

For the two different setups of increased *WUE* (as described in the methodology section above) we optimised *NPP* again in respect to rooting depth. The global average of rooting depth is shown in Table 1. In the "0.5*DEMAND" experiment, rooting depth was reduced in a rather uniform way in most regions (not shown, the patterns of change are very similar to those in changes in *NPP*, see below), while in the "2*ALPHA" experiment rooting depth did not change for most regions except at the transition to desert regions, where it increased (not shown).

In the "0.5*DEMAND" experiment, global *ANPP* increased by 21% using the standard distribution ($D = 1$m) and 16% in the presence of optimised rooting depth. In contrast to this, the increases in the "2*ALPHA" experiment were lower with 5% and 10% for the standard and optimised rooting depth distribution respectively (see Table 1). The patterns of *ANPP* increase were quite different: When using the standard rooting depth, ANPP increased mainly in regions with a distinct dry season and rather uniformly in both cases, with a larger magnitude of change for the "0.5*DEMAND" experiment (Fig. 3c). In contrast to this, the increases in *ANPP* for the optimised distribution reached peak values at the boundary to desert regions. Again, the pattern is similar for both cases, with higher magnitude for the "0.5*DEMAND" experiment (Fig. 3d). The annual average of global transpiration did not change in the "2*ALPHA" experiment, while for it decreased in the "0.5*DEMAND" experiment by 38% and 41 % for the standard and optimised rooting depth distribution (Table 1).

4 DISCUSSION

Deep roots have been found by field workers in many parts of the tropics (Stone and Kalisz 1991), but have yet been neglected by the global modelling community. The results of our study suggests, that deep roots as suggested by the optimisation process are important especially for tropical ecosystems, mainly because of two mechanisms: First, the increased soil water storage capacity induced by the deep roots supply sufficient water for the dry seasons. This removes the drought stress from the vegetation and consequently the productivity of those ecosystems with a drought period is substantially increased. Secondly, a larger soil water storage reacts more slowly and the productivity is less affected by climatic variations. Even though we used a simple model, these two mechanisms are not only inherent properties of this simple model, but rather fundamental. Hence, they are very likely to have similar impacts on more sophisticated models as well. They also suggest, that rooting depth should preferably be classified on a water-deficit basis and not on a biome basis.

In summary, vegetation with an optimised rooting depth distribution is less vulnerable. In fact, a (fixed) rooting depth of the order of 1 meter can be seen as a region where the vegetation is not in equilibrium with its environment. This is the case e.g. for deforestation (or general changes in land use). Considering the changes we described here resulting from an optimised rooting depth distribution, deforestation is likely to have much larger effects on climate and hydrology as previously thought (e.g. Henderson-Sellers et al. (1993), Nobre et al. (1991)). From this point of view, a vegetation without an optimised rooting depth distribution is more affected by climatic variations, experiences enhanced water stress during the dry season, evaporates less water and, consequently, runoff is increased.

The stabilising effect of optimised rooting depth can also be seen in the sensitivity experiments: The response in *ANPP* is much more dependent on the implementation of a doubled *WUE* in the presence of a standard rooting depth than for the optimised rooting depths. Since the optimisation process reduces the extent of drought stressed vegetation and “pushes” the limit towards desert-like environments, less areas are affected by an increased *WUE*. In fact, the response, in terms of *ANPP* changes, is concentrated only on regions where annual potential evapotranspiration exceeds precipitation. In areas of dry periods with no annual water deficit only the rooting depth estimates are affected by a modified *WUE*. The modification of rooting depth, however, can affect the carbon cycle within the soil. The impact of doubled *WUE* on the water cycle is strongly dependent on how it is implemented in both cases.

Further implications of the presence of deep roots cannot be investigated in the scope of this study, since we have a fixed climatic environment, which is given by observed distributions of the climatic parameters. A next step is to apply this method to a Atmospheric General Circulation model to study the impacts of enhanced (and less seasonal) fluxes of latent heat on the simulated climate.

4.1 Limitations of the model

Since we applied the method to a simple model, the results are subject to several limitations and should be taken as a demonstration of the method. We discuss the main limitations, how important they are and how they could be resolved in the following:

Net Primary Production: *NPP* is parameterised in a very simple way. It could be easily replaced by a more sophisticated model, which explicitly simulates processes like photosynthesis, nutrient cycling, phenology (such as budburst and leaf-shedding for temperate deciduous trees) and stomatal control. However, the main driving force in the maximisation process was the water availability and not the productivity itself. Therefore it seems more reasonable to include a more realistic water uptake scheme. Since most present-day models of the terrestrial biosphere use hydrology schemes that are similar in its simplicity to the one used in this study, the distribution of optimum rooting depth calculated from these models and the impacts are probably comparable.

Vertical Heteorogeneity of Soil Water Distribution/Groundwater: We used a simple model to simulate soil hydrology. Since the model consists of one soil layer only, impacts on rooting depth (and on the water stress factor) resulting from a heterogeneous vertical soil water distribution are ignored. The simulation of soil hydrology could be improved by increasing the vertical resolution, i.e. by the use of a multilayer model. This requires knowledge about the global distribution of soil and plant parameters that determine the fluxes between the soil layers and water uptake by roots. Other sources of water such as ground water or lateral transport by rivers are also not considered within the model. However, the estimates of optimum soil water storage patterns and the impacts on hydrology and *NPP* are unlikely to change substantially, since after all the main driving factor for optimum soil water storage was the atmospheric water deficit/surplus (see figure 6).

Bare Soil Evaporation: In this study it is assumed that the vegetation completely covers each grid point. In reality, water evaporates also from the soil directly. This effect becomes more important in arid regions, where the vegetation cover decreases. However, bare soil evaporation affects the top part of the soil column only and its impacts on the results of this study seems minor. In a multi-layer soil hydrology model this process could easily be incorporated. In a bucket model, where soil water is simulated by one layer only, this process would likely to be overestimated in the presence of deep roots, since too much water from greater depths would be available for bare soil evaporation.

Bedrock/Impermeable Soil Layers: Bedrock or the presence of an impermeable soil layer would also limit the development of a root system to some extent. Limitations by bedrock are likely to be present in mountainous regions. It is difficult to obtain the global distribution of impermeable soil layers but also how much the presence is limiting to root growth. For example, Lewis and Burgy (1964) showed, that an oak stand extracted significant amounts of groundwater from the underlying fractured rock by roots going deeper than 20 meters (see also other examples in Stone and Kalisz (1991)). If the depth of bedrock/impermeable layer were known, this could be used as an additional constraint for the maximisation process. This, however, would not resolve the question of how limiting their presence is to the development of root systems.

Nutrient Uptake: Nutrient uptake and its effect on *NPP* has not been implemented in the model either. We have seen earlier, that the maximisation of *NPP* led also to a maximisation of transpiration for most grid points. If we assume, that nutrients are taken up as ions that are dissolved in the soil water and nutrients are available at the same rate throughout the year, a maximum uptake of nutrients is also assured. Under this condition, nutrients are of minor importance for the estimation of rooting depth. If the availability of nutrients is out of phase with the demand of soil water (or the distribution is not constant with depth), the uptake of nutrients is not at a maximum. This would then require a more sophisticated model, where the formulation of *NPP* considers both, a water stress factor and a nutrient stress factor (which both might depend to some degree on the rooting depth).

Snow: Snowfall, accumulation and melt is not considered in the model. As already mentioned before, the neglection of these processes creates an artificial water deficit in some arctic regions. Incorporation of a snow module would eliminate this limitation; however, the results in this study do not indicate drastic changes in productivity or within the water cycle by the use of optimum soil water storage in the arctic regions. This is sensible, since these regions are more limited by temperature and light.

Frozen Soil: Frozen soil sets a physical boundary for rooting depth. If the distribution of (maximum) thaw depth is known, it could be used as an additional constraint for the maximisation process. This again affects arctic regions only and this limitation is unlikely to have a large impact on productivity or the water cycle.

4.2 *Limitations of the method*

While the above limitations result from the simplicity of the model and could easily resolved by the use of more sophisticated models, there are also limitations to the method itself, which are more serious:

Equilibrium of Vegetation/Potential Vegetation: The optimisation method assumes that the vegetation is in equilibrium with its environment, which is not necessarily the case even for natural vegetation. Surely, this method fails where mankind influences the presence of species, such as agricultural areas. We should therefore call the optimum rooting depth a "potential" rooting depth.

Drought-Avoidance Strategy: In the way the method has been set up, it is assumed that in every grid cell evergreen vegetation is present and that it is subject to the atmospheric demand of transpiration throughout the year. In the real world, however, there are plants that simply shed leaves (or die) to avoid drought stress. This is the case for biomes such as grasslands and dry-deciduous forests. Probably this is one reason why the rooting depth is overestimated in the tropical deciduous forest biome, for shrubs and for the temperate grasslands. To incorporate leaf-shedding as a mechanism, it would be necessary to have an explicit representation of the carbon costs of root growth/water uptake, so that it can be evaluated whether it is "worth" for the vegetation to develop deep root systems.

Optimal Behaviour: We used an optimisation approach in this study, which implies that the vegetation makes optimum use of its environment. This, to some degree, also implies that the vegetation can "foresee" the future development of the climatic forcing. Nevertheless, since the model is not optimised at each time step but rather over a long time interval (10 years), the outcome of the optimisation reflects an adaption of rooting depth to a mean climate only. It has been suggested (e.g. Reynolds and Chen, 1996) that plants allocate in a way ("coordination theory") where the imbalance between supply and demand of different plant variables (such as carbon and nitrogen) is reduced in each time step in contrast to an optimum behaviour. Applied to the problem of rooting depth, it would mean, that allocation would correct the imbalance between carbon and water supply. To do so, an explicit representation of carbon costs for water uptake is required.

5 SUMMARY AND CONCLUSION

We have shown that applying an optimisation principle to a simple biosphere model is capable of reproducing observed patterns of rooting depth. This way, the rooting depth distribution is consistent within the model (and its forcing) to the idea, that the vegetation has adapted to its environment and maximises carbon gain. Evidently, larger rooting depths make the vegetation less vulnerable to day-to-day and seasonal fluctuations, which has large impacts on productivity and the hydrological cycle in tropical regions with a dry period. We have found, that the main driving force for deep roots within the optimisation process is the water deficit during the dry season. Even though a simple soil hydrology model has been used, the increased soil water storages are likely to cause similar impacts in other global models of the terrestrial biosphere. The increased soil water storages and the associated increases in latent heat flux are likely to have a significant impact on the simulated climate within General Circulation Models. This in turn suggests that impacts on the climate and the hydrological cycle by deforestation might be stronger than previously thought.

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2.2 Theoretical Estimates of Optimum Rooting Depth

Abstract: The purpose of this section is to analytically derive expressions of optimum rooting depth. To do so, four hydrologic domains are defined from the mean seasonal components of the climatic forcing. Annual Net Primary Production (NPP) is then maximised analytically for each of those domains under some simplifying assumptions. The obtained expressions are in agreement to the findings of the previous chapter. While no soil storage is needed in humid environments, the storage size in semihumid environments is primarily given by the water deficit during the dry season. In arid regions, the optimum storage size is given by the largest surplus of water during a wet period.

1 INTRODUCTION

In this section, it is investigated in more detail of how the optimisation process from the last section works. In the following, optimum rooting depths are calculated for different hydrologic domains for the model described in section 2.1 under some simplifying assumptions. These examples illustrate the mechanism behind the optimisation process and help to understand the results of the following chapters. Since the model does not explicitly depend on rooting depth *D*, the optimisation is discussed in terms of the bucket size W_{MAX}, which could be called a soil texture independent rooting depth. Rooting depths can be calculated from W_{MAX} by use of equation (section 2.1 - 5).

In the following subsection, the hydrologic domains are defined, based on the expressions (12) - (15) used in section 2.1. In the subsequent three subsections, the optimisation is conducted for these domains. Some simplifications are made in the derivation: Radiation and potential evapotranspiration (or *DEMAND*, as in the last section) are assumed to be constant throughout the year. Vegetation exerts complete control over evapotranspiration so that runoff is mainly formed by drainage and surface runoff can be neglected. In that case, runoff can be controlled by the vegetation by changing the extent of the rooting zone. Thus, the maximisation conducted here turns out to be a maximisation of transpiration. This section closes with a discussion of the findings and a comparison to the results of the previous section.

2 DEFINITION OF THE HYDROLOGIC DOMAINS

Four regions are classified by their annual water balance AWB and the seasonal components given by

$$\begin{aligned} AWB &= \int_{year} (P - PET)dt \\ &= SURPLUS - DEFICIT \end{aligned} \tag{1}$$

with $SURPLUS$ and $DEFICIT$ given by equations (2.1 - 15) and (2.1 - 13):

$$SURPLUS = \int_{P>PET} (P - PET)dt \tag{2}$$

and

$$DEFICIT = \int_{PET>P} (PET - P)dt \tag{3}$$

where P is precipitation and PET is the potential evapotranspiration rate. When monthly means of P and PET are used, $SURPLUS$ describes the water surplus of water during the wet season and $DEFICIT$ the water deficit during the dry season, assuming that only one wet and dry season exists.

Based on expressions (1) - (3), four hydrologic domains can be defined:

- **arid**: $AWB \leq 0$ and $SURPLUS = 0$
- **semiarid**: $AWB \leq 0$ and $SURPLUS > 0$
- **semihumid**: $AWB > 0$ and $DEFICIT > 0$
- **humid**: $AWB > 0$ and $DEFICIT = 0$ (4)

For these four hydrologic domains, optimum rooting depths are obtained under some simplifying assumptions. In the derivations, it is assumed that PET and PAR are constant throughout the year and that P is constant (zero) during the wet (dry) season, respectively. In non-seasonal environments P is assumed to be constant throughout the year. Since PAR is assumed to be constant, the maximisation of NPP is equivalent to a maximisation of evapotranspiration, ET.

3 OPTIMISED ROOTING DEPTH FOR ANNUAL MEAN FORCING

If all forcings are assumed to be constant (i.e. P, PET, and PAR), annual NPP is independent of soil water storage (except a infinitely small storage to prevent numerical problems). This can be seen from the water budget equation (2.1 - 6). On a mean annual time scale, ET and R balance P:

$$\frac{dW}{dt} = P - ET - R = 0 \tag{5}$$

If P exceeds PET, then $ET = PET$ and $R = P - PET$, and annual NPP is equal to the unstressed rate. This is the case for the humid climate as defined in (4). In arid conditions, annual P is less than annual PET, and, with the same assumption about R, $ET = P$ and $R = 0$. In this case, annual NPP is given by the unstressed rate, reduced by a factor of P / PET:

$$\begin{array}{lllll} \textit{humid}: & ET = PET & R = P - PET & NPP = NPP_{POT} & d_{R,OPT} \approx 0 \\ \textit{arid}: & ET = P & R = 0 & NPP = P/PET \cdot NPP_{POT} & d_{R,OPT} \approx 0 \end{array} \tag{6}$$

with $NPP_{POT} = A\ PAR$. This simple example illustrates, that rooting depth only plays a role in the presence of variability in terms of water supply and demand.

4 OPTIMISED ROOTING DEPTH FOR A SEMIARID REGION

In a water-limited environment, NPP is clearly increased by utilising all available water. This is accomplished by a suitable minimum choice of W_{MAX} such that drainage out of the rooting zone is avoided (i.e. $R = 0$). The water balance equation (2.2) in this case reduces to

$$\frac{dW}{dt} = P - ET \tag{7}$$

In the following derivation, first the time development of the soil water content W is obtained before it is used to get an expression for NPP. The details of the calculations are given in Appendix A. ET is assumed to be less than PET at all times, so that (2.1 - 7) can be used and substituted into (7). The resulting differential equation is solved by (see eqn. A - 5),

$$W(t) = P\tau + (W_0 - P\tau)e^{-\frac{t-t_0}{\tau}} \tag{8}$$

which describes the soil water depletion and/or recharge with time t. Here, $\tau = W_{MAX} / c$. is a time constant, and W_0 is the initial soil water content at $t{=}t_0$.With this expression for $W(t)$, NPP_{DRY}, the net primary production during the dry period (when $P = 0$) and NPP_{WET}, the net primary production during the wet period, is calculated (eqn. A - 10):

$$NPP_{DRY} = NPP_{POT} \frac{W_0}{PET}\left(1 - e^{-t_2/\tau}\right)$$

$$NPP_{WET} = NPP_{POT}\left[\frac{P}{PET}(t_A - t_2) + \frac{W_2 - P\tau}{PET}\left(1 - e^{-(t_A - t_2)/\tau}\right)\right] \tag{9}$$

with $t_A = 1$ year and t_2 being the end (and length) of the dry season. When equations (9) are simplified and added, we find that annual NPP is independent of W_{MAX}:

$$ANPP = NPP_{POT} \frac{AP}{APET} \tag{10}$$

where AP ($APET$) is the annual mean precipitation (evapotranspiration) rate, respectively. This result is equivalent to the case of an arid region under annual mean forcing (equation 6), with the difference that W_{MAX} needs to be of suitable size to ensure $R = 0$. This condition is satisfied for any bucket size $W_{MAX,OPT}$ exceeding $SURPLUS$ (given by (2)):

$$W_{MAX,OPT} > EXCESS \tag{11}$$

4 OPTIMISED ROOTING DEPTH FOR A SEMIHUMID REGION

In the semihumid case, there is sufficient water available on an annual basis, since $AP > APET$ by definition. Hence, PET could be maintained during the dry season if the soil water storage is sufficiently large. Unstressed conditions are maintained if the soil water content does not fall below a critical value W_C, which can be determined by equating the supply, given by equation (2.1 - 4), with PET (see also Appendix A, equation 6):

$$c \cdot \frac{W_C}{W_{MAX}} = PET$$

$$W_C = PET \cdot \frac{W_{MAX}}{c} \quad (= PET \cdot \tau) \tag{12}$$

Here, $\tau = W_{MAX} / c$ as in the semiarid case. Sufficient water for dry season *ET* is then available if W_{MAX} is at least as large as (also eqn (A - 17)):

$$\begin{aligned} W_{MAX,OPT} &= W_C + PET\, t_2 \\ &= c\, t_2 \frac{PET}{c - PET} \end{aligned} \tag{13}$$

with t_2 being the length of the dry season. With W_{MAX} given by (13), annual *NPP* is at its potential value, and the expression for annual *NPP* is again independent of W_{MAX}, equivalent to the humid case (equation (6)). This result can also be obtained from a detailed maximisation, which is performed in Appendix A.

Equation (13) can be further simplified and generalised: Since on a daily basis c (= 24 mm/d) is much larger than *PET* (≈ 4 mm/d), $c / (c - PET) \approx 1$, and a lower boundary of optimum bucket size for the semihumid case is given by

$$W_{MAX,OPT} > DEFICIT \tag{14}$$

using $PET\ t_2 = DEFICIT$ under the simplified assumptions made. Note that $W_{MAX,OPT}$ is always larger than *DEFICIT* since $W_C > 0$.

5 EFFECT OF CLIMATIC VARIABILITY

It is already evident from the examples given above, that soil water storage is only needed in the presence of climatic variability, expressed, for instance, in terms of the seasonality in *P* and *PET*. In a seasonal environment, optimised rooting depths act to level out periods of water surplus and demand. How does the optimisation process react to larger degrees of variability, for example on a day-to-day or interannual time scale?

For humid regions, the effect of variability, for instance expressed by interannual variations in the length of the dry season t_2, is clear: The period with the greatest water deficit will dominate the optimisation process since a larger W_{MAX} does not decrease productivity in years with a less intense dry season. Variability of *PAR* has no effect on the outcome of the optimisation since in the presence of sufficient water availability, *NPP* is solely determined by *PAR* which is assumed to be a forcing variable and is not affected by the optimisation.

Arid regions react differently to variability: The optimisation process is driven by the largest water surplus in the wet season. Creating a sufficiently large soil water storage guarantees to capture the water surplus and makes best use of it for *ET* (and *NPP*), avoiding water loss by R. Since the environment is in general water limited, variations in *PAR* can have an effect on optimum W_{MAX}: If the maximum of *PAR* occurs during a different period than the water availability, the decline in soil water can be altered by modifying the time constant τ, which depends on W_{MAX}. This could then lead to a higher overall *NPP*. However, this mechanism seems unrealistic, since the depletion should rather be controlled by a modified extraction rate, represented by c, which was kept constant throughout the optimisation.

6 DISCUSSION

These features are clearly seen in the outcome of the optimisation process of the previous section. Optimised rooting depths are generally low in humid areas, such as the Amazon or Congo basin, but also in temperate regions like western Europe. The more seasonal the climate gets, the larger the rooting depths, which can be seen in the transitional regions of South America and Africa. In arid regions, the optimum rooting depth is primarily driven by the variability introduced by the stochastic weather generator and thus shows a noisy distribution.

It is interesting to note, that the equations obtained for evapotranspiration (6) are similar to those of Budyko (1974). When examining estimates of annual evapotranspiration, he distinguished between radiation controlled (humid) and precipitation controlled (arid) environments. The introduction of optimised rooting depths can therefore be seen as an extension to shorter time scales of his work.

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Kapitel 3

Auswirkungen von Wurzeltiefe auf das Klima

3.1 Optimised Rooting Depth and its Impacts on the Simulated Climate of an Atmospheric General Circulation Model[1]

Abstract. Rooting depth determines how much water can be stored in the soil which is accessible to the vegetation for transpiration. Here, we derive a global distribution of rooting depth with an optimisation principle: A simple formulation of Net Primary Production (*NPP*) is incorporated into a General Circulation Model and then *NPP* is maximised in respect to rooting depth. The obtained rooting depths are considerably larger to those used in present-day models but are consistent with observations. *NPP* increases substantially with the use of optimised rooting depths, mainly in tropical regions during the dry season accompanied with enhanced transpiration. The increased flux of latent heat leads to a considerable decrease in 2m air temperature, which leads to a better agreement with observations. We conclude that rooting depth is an important vegetation property, especially in the tropics, and tropical deforestation might have a much larger impact on climate than previously thought.

1 INTRODUCTION

The depth of the rooting zone plays a vital role in the terrestrial hydrological cycle. Rooting depth, combined with soil texture, determines the size of maximum soil water storage which is accessible to plants and hence controls how much precipitation can be stored and transpired back into the atmosphere. The water flux into the atmosphere, in turn, has a large impact on the surface climate, affecting cloudiness, moisture transport, precipitation and surface temperature to a large extent (e.g. Shukla and Mintz 1982, Milly and Dunne 1994). The size of the soil water storage becomes especially important for regions with a pronounced dry season, like large parts of the tropics. For example, it has been estimated that in large parts of the Amazon basin the vegetation developed deep roots in order to hold sufficient water in the

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[1] Axel Kleidon and Martin Heimann, Geophysical Research Letters 1998, 25(3), 345-348, © American Geophysical Union.

soil to maintain green canopies during the dry season and to transpire near the potential rate (Nepstad et al. 1994). Also in other parts of the tropics it is known that vegetation can develop roots reaching deeper than 60 metres (Stone and Kalisz 1991). However, up to now not much effort has been given to the effects of rooting depth on ecosystem productivity and on hydrology on a regional to global scale.

Most present day land surface schemes of atmospheric General Circulation Models (GCMs) (e.g. BATS/CCM (Dickinson et al. 1993), ECHAM (Roeckner et al. 1996), SiB2 (Sellers et al. 1996)) do not incorporate deep roots; the values of rooting depth are typically taken as less than two metres. In these models, the distribution of rooting depth is prescribed according to a biome distribution. In this way, rooting depth is taken as a fixed surface property which is not able to adapt to the local, environmental conditions as it would be the case for natural vegetation in equilibrium with the climate.

Instead of using fixed rooting depths from field studies, we take a different approach (Kleidon and Heimann 1998): We use a well known ecological principle, i.e. that the vegetation adapts to the climate in an optimum way. In order to use this principle to estimate the distribution of rooting depth and its potential impacts on climate, we first incorporate a simple formulation of Net Primary Production (*NPP*) into the model which we take as a measure for the benefit or survival potential of the vegetation. Secondly, we maximise *NPP* in respect to rooting depth, which then is the realisation of the above principle. The existence of an optimum rooting depth is motivated by the following reasons: On the one hand, deeper roots increase the vertical extent of the soil water storage accessible to plants, which in turn increases the ability of the vegetation to extract water. On the other hand, as roots grow deeper, more carbon needs to be allocated to the root system for construction and maintenance. This reduces the amount of carbon available to aboveground growth which then leads to disadvantages for the whole plant survival.

We use the ECHAM 4 GCM in this study. Subsequently, we compare biome averages of the computed rooting depths to averages from observations by Canadell et al. (1996). Note that this comparison can only give a general idea of the quality, since rooting depth within the model should be seen as a large-scale quantity and its value is determined only to the extent to which it is relevant for water storage. Impacts on the simulated climate are investigated in terms of direct changes (such as *NPP* and evapotranspiration) and indirect effects (precipitation, 2m air temperature).

2 METHODOLOGY

We use the ECHAM 4 GCM (Roeckner et al. 1996) in its T21 resolution (i.e. a resolution of ca. 5.5° * 5.5°). In this model, total evapotranspiration over land is the sum of four fractions: evaporation from snow, from intercepted water in the canopy, from bare soil and transpiration. Transpiration is calculated by using the bulk transfer method and is affected by the vegetation by its stomatal resistance in a nonlinear way. Stomatal resistance is parameterised by an empirical function following Sellers et al. (1986) and decreases proportional to the water stress factor α given by:

$$\alpha(D) = \begin{cases} 1 & ; W_{CR} \le W_S \\ \dfrac{W_S - W_{PWP}(D)}{W_{CR}(D) - W_{PWP}(D)} & ; W_{PWP} \le W_S \le W_{CR} \\ 0 & ; W_S \le W_{PWP} \end{cases} \tag{1}$$

where W_S is the total water content of the soil, W_{PWP} (set to 35% W_{MAX} in the model) is the soil water content at the permanent wilting point, W_{CR} (75% W_{MAX}) is the critical soil water content at which transpiration is reduced, and W_{MAX} is the maximum soil water content of the rooting zone ("bucket size"), depending on the rooting depth D:

$$W_{MAX}(D) = D \times SWC \tag{2}$$

SWC is the soil water storage capacity, expressed as the maximum amount of water which can be stored per metre of soil depth. It is calculated from a global data set of Batjes (1996).

2.1 Parameterisation of Net Primary Production

We use the same formulation of NPP as in Kleidon and Heimann (1997) which is based on a common approach used in diagnostic studies (e.g. Monteith 1977, Heimann and Keeling 1989):

$$NPP(D) = A \times \alpha(D) \times PAR \tag{3}$$

with A being the globally constant light use efficiency (that is the conversion efficiency of radiation into organic carbon assimilates), $\alpha(D)$ being the water stress factor (eqn. 1) and PAR being the Photosynthetically Active Radiation. PAR is taken to be 55% of the incoming solar radiation at the surface, which is calculated by the GCM. The *NPP* calculated in this way could be called potential, water limited *NPP*.

2.2 Determination of Rooting Depth

We calculate the global distribution of optimised rooting depth by maximisation of the vegetation's *NPP* (eqn. 3), averaged over a long time period, in respect to rooting depth (Kleidon and Heimann 1998). The maximum of *NPP* is obtained iteratively by "Golden Section Search" (Press et al. 1992). Within each iteration, the GCM runs for six years and *NPP* is averaged over the last five years. For easier comparison, the scaling constant A is determined by setting global annual *NPP* of the control run to 60 GtC (gigatons of carbon). The outcome of the maximisation and the relative increases of *NPP* are unaffected by this scaling. All runs are initialised with the same soil wetness (i.e. W_S / W_{MAX}), which is taken from the initialisation of the control experiment.

The carbon costs of water uptake by plant roots are poorly understood. In order to restrict the extent of the root system, as represented by W_{MAX}, the carbon costs are incorporated into the optimisation process in a very simple way: The optimisation is set up in such a way that it finds the minimum W_{MAX} for which long-term *NPP* is at a maximum. By this procedure, a unique value of the optimum is ensured. It is justified by the mechanism stated in the introduction, that is, that vegetation cannot "afford" to have an excessive root system.

3 RESULTS AND DISCUSSION

We calculate biome averages of optimised rooting depth by using a land cover data set (Wilson and Henderson Sellers 1985) and compare it to biome averages of observations of maximum rooting depth (Canadell et al. 1996) in Fig. 1. The obtained averages lie within the range of observations; however, rooting depth for extratropical biomes are generally overestimated. This might mean that other limitations are more important such as temperature, phenology, nutrients, bedrock or permafrost.

The statistical significance of the changes presented below are assessed with the student's t-test. All changes reported below are significant on a 95% level.

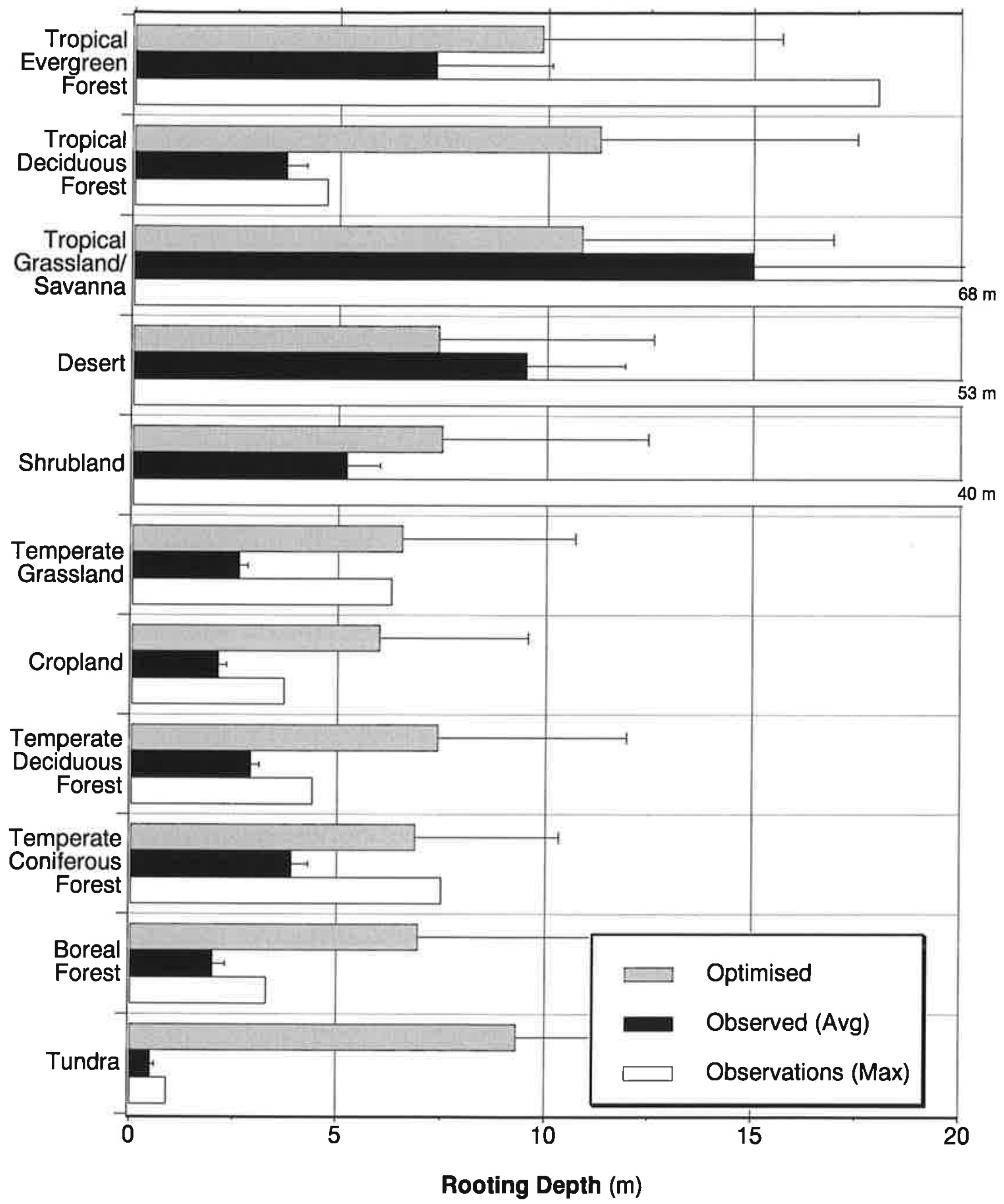

Figure 1: Comparison of biome averages of optimum rooting depth obtained by maximisation of *NPP* (grey bars) to observations (black bars) by Canadell et al. (1996). Also shown are maximum values reported in field studies for each biome (white bars). Error bars show one standard deviation.

Impacts of optimised rooting depths on *NPP* and the hydrological cycle are greatest in the tropics compared to the standard distribution. Therefore, we choose to focus on the regions between 30°N and 30°S. We show zonal averages of *NPP* in Fig. 2a and b for the northern (December to February) and the southern (June to August) tropical dry season respectively. *NPP* increases substantially during the dry seasons. It is noteworthy that *NPP* is considerably increased even in regions with a less pronounced dry season (i.e. close to the equator). A small decrease of *NPP* occurs during the wet season which is caused by a reduction of incoming solar radiation due to enhanced cloud cover (see Fig. 2e and f and below). The global annual average of *NPP* increases by 26%.

In Fig. 2c and d we show the zonal means of evapotranspiration (negative) and precipitation (positive) for both dry/wet seasons. Evapotranspiration is only affected during the dry season where it almost doubles due to the increased water storage capacity of the soil. This seasonal persistence of transpiration from evergreen tropical forest is consistent with the observation of Nepstad et al. (1994). The increase in transpiration leads to a decrease in surface runoff/drainage with a subsequent decrease in river basin discharge (not shown) which is in part compensated by increases in precipitation. Precipitation is increased in the wet seasons and unaffected in the dry seasons. Note that the increase in precipitation is an indirect effect which is due to increased "recycling" of precipitation (i.e. more evapo-transpiration leads to increased atmospheric water content which favours increases in precipitation). To summarise, the seasonality of the divergence of the moisture transport of the atmosphere, which is roughly equal to evapotranspiration minus precipitation, is strengthened.

Increased evapotranspiration also has a strong impact on the surface energy balance. In Fig. 2e and f we show the zonal means of incoming solar radiation, latent and sensible heat for both seasons. Solar radiation is decreased during the wet season only and is caused by enhanced cloud cover (not shown) which, however, does not affect 2m air temperature (see fig. 2g and h). During the dry seasons, latent heat fluxes increase with an accompanying decrease in the sensible heat fluxes. This decrease in sensible heat flux is also reflected in the 2m air temperature (Fig. 2g and h). The zonal mean of 2m air temperature decreases considerably by more than 2K, with local decreases of up to 4K (not shown), which is in fact consistent with observations (Legates and Wilmott 1990) for the southern hemisphere dry season.

The results are subject to some limitations. A broad discussion of the limitations is given in Kleidon and Heimann (1998). Here, we focus on the limitations of the method: The method in its present form neglects vegetation which simply sheds leaves to avoid water stress.

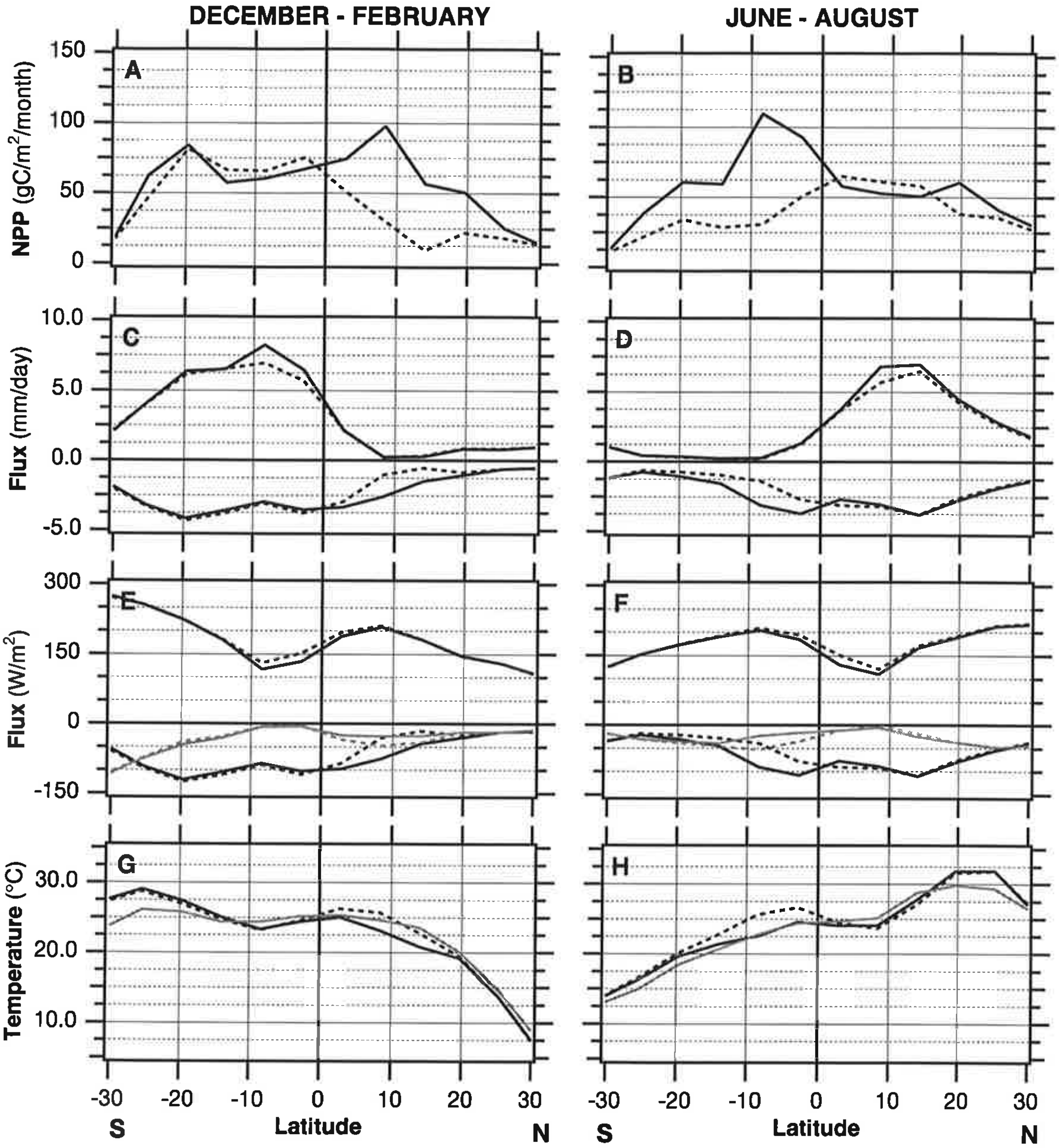

Figure 2: Zonal seasonal averages of *NPP* (a and b), precipitation (displayed positive) and evapotranspiration (displayed negative) (c and d), incoming solar radiation (displayed positive), latent (black) and sensible (grey) heat flux (e and f), and 2m air temperature (g and h). On the left (right), seasonal averages of the December - February and June - August season are shown, respectively. The zonal averages of the standard and optimised model are shown as dotted and solid lines, respectively. Also shown are averages of 2m air temperature (g and h) from observations (grey line, Legates and Wilmott, 1990).

This is likely to be the main reason why the biome average of optimum rooting depth for dry deciduous forests is overestimated (see Fig. 1). Hence, the impacts of rooting depth on climate presented here are likely to be overestimated for the regions where this biome type is present. Also, the method assumes that the vegetation is in equilibrium with its environment and makes best use of it. This is not the case, for instance, for regions which are affected and modified by humans (e.g. agriculture). Another problem might be the interaction of grid points via the atmosphere. The increased evaporation, caused by the larger soil water storages, modifies the latent heat flux and thus affects the moisture transport to some extent. This, in turn, could cause other effects in adjacent grid boxes which could result in several maxima of *NPP*, so that the maximisation process does not lead to a unique result.

4 CONCLUSION

The results show that it is possible to reproduce observed patterns of rooting depth fairly well with a simple method. More importantly, the calculated rooting depths are much larger than those previously used and significantly change the seasonal cycle in the tropics. The changes induced by the optimised rooting depth pattern are consistent with observations, so that we might conclude that the calculated distribution is more realistic than a prescribed rooting depth of less than 2 metres.

The results presented here could have considerable consequences for tropical land use changes and deforestation: A large reduction of rooting depth caused by deforestation could affect the regional climate more than previously thought.

In summary, we conclude that rooting depth is an important vegetation parameter and more attention should be paid to it in the field of atmospheric modelling.

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3.2 The Effect of Deep Rooted Vegetation on the Simulated Climate of an Atmopsheric General Circulation Model. Part I: Mechanism and Comparison to Observations[2]

Abstract. Deep rooted vegetation was found to maintain dry-season evapotranspiration near the potential rate in some tropical regions and thus is thought to form an important part of the terrestrial hydrological cycle. In contrast, models of the general atmospheric circulation (GCMs) usually use rooting depths of less than 2 metres in their land surface parameterisations. How does the incorporation of deep roots into such a model affect the simulated climate? We assess this question by using a GCM. We find a pronounced seasonal climatic response. During the dry season, evapotranspiration and the associated latent heat flux are considerably increased when deep rooted vegetation is considered leading to a cooling of up to 8K. The enhanced atmospheric moisture is transported towards the main convection areas where it supplies more energy to convection. In total, we find that deep rooted vegetation acts to intensify the tropical circulation patterns. The reasonability of the outcome is assessed by different means of verification. The incorporation of deeper roots seem realistic in terms of 2m air temperature seasonality and the seasonal variation of basin wide soil water storage in some parts of the tropics. We conclude that deep rooted vegetation is an important part of the tropical climate system.

1 INTRODUCTION

Land surfaces are distinctively different to oceans in that water is not abundantly available for evapotranspiration but limited by precipitation input and soil storage. Only in the presence of vegetation with a well developed root system can considerable amounts of water be extracted from the soil and transpired back into the atmosphere. This soil storage of plant-available water becomes increasingly important with greater seasonality in precipitation. Thus, the extent of the rooting zone, or rooting depth, is an important vegetation parameter in land surface parameterisations in regions with a seasonal climate. Nepstad et al. (1994) found that an evergreen forest at the margin of the Amazon basin developed deep roots of up to 18 metres and consequently was capable of transpiring considerable amounts of water throughout the dry season. From the greenness of the vegetation observed by satellites and the seasonality of precipitation they estimated that the deep-rootedness of the vegetation could be common to large parts of the Amazon basin.

However, land surface parameterisations in General Circulation Models (GCMs) of the atmosphere generally use values of less than 2 metres for rooting depth (e.g. BATS

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[2] Axel Kleidon and Martin Heimann, Climate Dynamics 1998, submitted (also: Max-Planck-Institut für Meteorologie, Report 249)

(Dickinson et al. 1993), SiB (Sellers et al. 1996), ECHAM (Roeckner et al. 1996)). This is in contrast to the findings of Nepstad et al. (1994). Consequently, the model simulations likely contain errors in the computation of dry-season evapotranspiration and the associated heat fluxes (e.g. Hahmann and Dickinson 1997). The importance of evapotranspiration from the land surface for the climate simulation has been pointed out before, for instance, by the sensitivity study conducted by Shukla and Mintz (1982).

How can a reasonable rooting depth distribution be obtained which takes explicit account of the deep roots found in Amazonia and some other regions of the tropics (see e.g. Stone and Kalisz 1991 and Canadell et al. 1996)? On the one hand, observations of rooting depth are only sparsely available, and on the other hand, the hydrological significance of the reported values is not clear. Instead of using a distribution assembled from observations, we take a different approach (Kleidon and Heimann 1998a). We compute a distribution using an optimisation principle in which we maximise long-term mean of net primary production (NPP) in respect to rooting depth. In this approach, NPP serves as a measure of the vegetation's benefit or fitnes (Schulze 1982) and the method can be seen as an implementation of the evolutionary principle in which vegetation makes best use of its environment. We applied this method to a simple biosphere model (which calculates NPP) embedded into a GCM and found that the obtained rooting depths were reasonable and had a considerable impact on the simulated climate, mainly in the tropics (Kleidon and Heimann 1998b).

The aim of the work presented here (which is a continuation of our earlier work (Kleidon and Heimann 1998b)) is to understand in more detail the mechanism by which deep rooted vegetation affects the tropical climate system. We use the same atmospheric GCM, that is, ECHAM 4 with prescribed climatological sea surface temperatures, in order to isolate this mechanism. We also assess whether the incorporation of deep roots leads to an overall improvement in the climate model's performance. This helps us to see whether, why and where deep rooted vegetation is climatically relevant. The mechanism described here also has direct implications for the climatic effects of large-scale land use change/tropical deforestation, that is when deep rooted vegetation is replaced by a grassland vegetation type. The consequences with respect to Amazonian deforestation are presented in an accompanying paper (Kleidon and Heimann 1998c).

In the following section, our methodology is described in more detail. In section 3 we compare the model simulation which includes deep roots to the one with the standard rooting depth distribution and describe the mechanism involved. In section 4 we try to assess whether and where the incorporation of deep roots leads to an improvement of the model's performance. The findings are discussed in section 5. We close with a brief summary and conclusion in section 6.

2 METHODS

In this study, we use the ECHAM 4 General Circulation Model (Roeckner et al. 1996) in its T21 resolution (≈ 5.6° lat * 5.6° lon). This model simulates the general circulation of the atmosphere by solving the equations of motion in spectral space.

2.1 Description of the Land Surface Parameterisation

The land surface of the model is characterised by a set of surface parameters, which include albedo, fraction of vegetation cover, total roughness length (i.e. the composite of both, roughness from orography and vegetation cover), forest fraction, a heterogeneity parameter for runoff computation (see below) and soil water storage capacity. Total evapotranspiration over land is the sum of four fractions: evaporation from snow, from the skin reservoir (i.e. reevaporation of intercepted water from the canopy), from bare soil and from transpiration. Transpiration occurs from the part of the grid cell, which is not covered by snow and where no water is stored in the skin reservoir.

Transpiration (*ET*) is calculated by using the bulk transfer method:

$$ET = \rho C_H |v_H| \beta (q_S - q_A) \tag{1}$$

Here, ρ is the density of air, C_H the bulk transfer (or drag) coefficient of latent heat, v_H the horizontal wind speed, q_S the specific humidity at saturation under the surface conditions (specified by surface temperature T_S and pressure p_S), and q_A the specific humidity at an atmospheric reference level. The parameter β describes the decrease of transpiration as a response to water stress and is determined by

$$\beta = \left[1 + \frac{C_H |v_H| r_C}{\alpha(D)} \right]^{-1} \tag{2}$$

The stomatal resistance r_C of the canopy is parameterised by an empirical function, depending on Photosynthetically Active Radiation PAR (taken as 55% of net shortwave radiation at the surface) following Sellers et al. (1986).

The water stress factor α depends on soil moisture and, indirectly, on rooting depth D:

$$\alpha(D)=\begin{cases}1 & ; W_{CR}\leq W\\ \dfrac{W-W_{PWP}(D)}{W_{CR}(D)-W_{PWP}(D)} & ; W_{PWP}\leq W\leq W_{CR}\\ 0 & ; W\leq W_{PWP}\end{cases} \tag{3}$$

Here, W is the amount of water stored in the rooting zone of the soil, W_{PWP} is the soil water content at the permanent wilting point PWP (set to 35% W_{MAX} in the model), W_{CR} is the critical soil water content at which transpiration is reduced (set to 75% W_{MAX} in the model), and W_{MAX} is the maximum soil water content ("bucket size"), depending on the rooting depth D:

$$W_{MAX}(D)=D\times FC \tag{4}$$

FC is the field capacity of the soil, expressed as the amount of water stored per meter depth of soil.

Soil hydrology is simulated with a simple budget equation ("bucket" model). It includes a sophisticated computation of surface runoff (Dümenil and Todini, 1992), which accounts for sub-grid scale heterogeneity of the terrain height. Also, an explicit formulation for slow and fast drainage is used, depending on the water content of the rooting zone W. In the model's standard version, the distribution of rooting depth and the associated size of the soil water storage capacity of the rooting zone W_{MAX} is taken from Dunne and Willmott (1996). In this distribution, rooting depths are generally less than 2 metres, depending on the biome type. The simulation with the standard distribution of rooting depth is referred to as the "standard" simulation in the following.

2.2 *Incorporation of Deep Roots*

Deep roots are incorporated into the model by using optimised rooting depths which are taken from Kleidon and Heimann (1998b). These rooting depths were obtained by maximisation of long-term mean of net primary production. To do so, an explicit formulation of instantaneous productivity (NPP) was incorporated into the model, based on a simple parameterisation depending on solar radiation and water stress (Monsi and Saeki 1953, Monteith 1977, and e.g. Heimann and Keeling 1989):

$$NPP = A \cdot \alpha \cdot PAR \tag{5}$$

The formulation of water stress given by (3) was used for α and 55% of the net solar radiation at the surface for the photosynthetically active radiation PAR. The model was then run for six years, with the first year discarded to avoid spin up effects, and the mean of NPP over the last five years of the simulation was taken as a representative of the long term mean. The maximisation was then conducted iteratively by "Golden Section Search" (Press et al. 1992). Within each iteration, the model was run again for six years in order to compute the long term mean of NPP for a new distribution of adjusted rooting depth.

We decided to use the distribution of plant available water PAW, that is, PWP - FC, of Batjes (1996) instead of the distribution of field capacities of Dunne and Willmott (1996) in order to determine the "bucket" size for a given distribution of rooting depth (according to (4)). This is motivated by the general overestimation of tropical PAW values (e.g. Hodnett et al. 1995). While Batjes (1996) only gives ranges of PAW, we first associated values to each range according to (Batjes, pers. comm.):

RANGE (Batjes 1996)		VALUE (used here)	
0 - 60 mm/m	->	40 mm/m	
60 - 90 mm/m	->	75 mm/m	
90 - 120 mm/m	->	105 mm/m	
120 - 150 mm/m	->	135 mm/m	
150 - 200 mm/m	->	175 mm/m	
0 - 90 mm/m	->	45 mm/m	
90 - 150 mm/m	->	120 mm/m	
> 150 mm/m	->	200 mm/m.	(6)

Field capacities were then derived by

$$FC = \frac{PAW}{1-0.35} \tag{7}$$

following the definition of FC and PWP within the model.

These rooting depths obtained from the optimisation are considerably larger than those in the standard version and agree well with observations by Canadell et al. (1996) and those derived from satellite observed greenness (Knorr 1997). The distribution of rooting depth

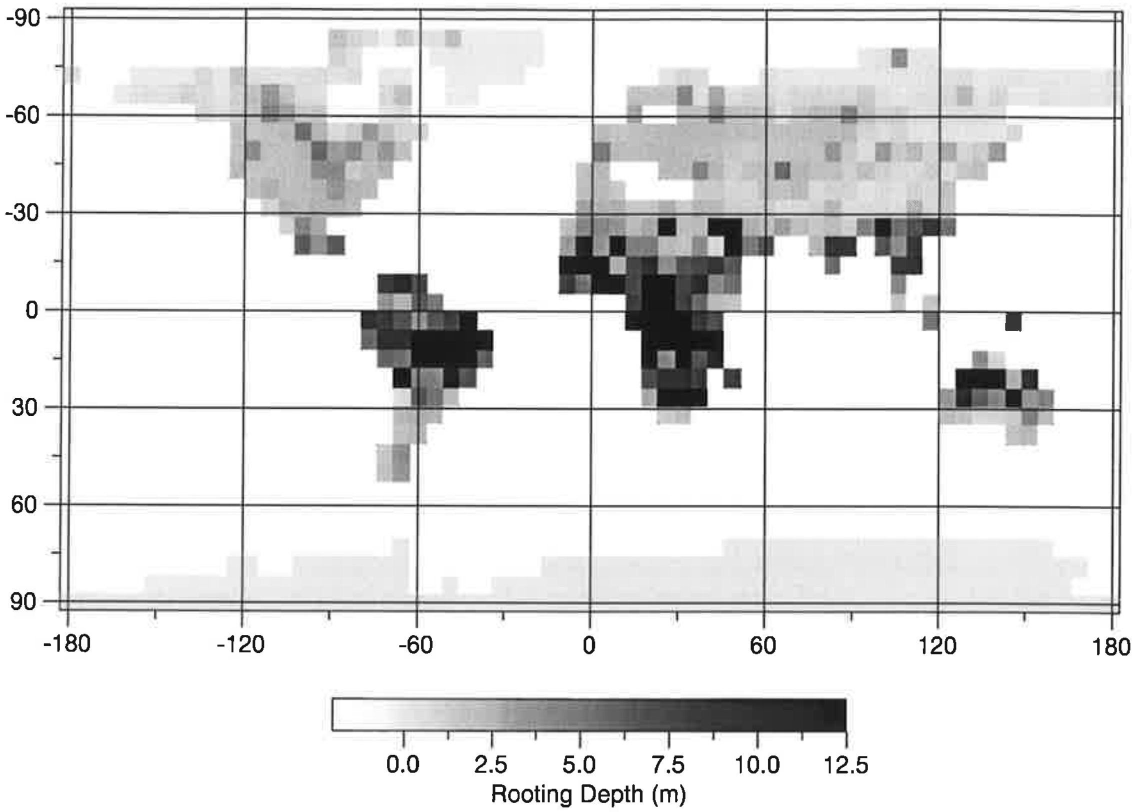


Figure 1: Distribution of rooting depths used in the "deep roots" simulation. Rooting depths exceed 2 metres in the extratropics because a different soil texture data set is used than in the standard version of the model.

is shown in Figure 1. Since consistent increases in evapotranspiration, resulting from the use of optimised rooting depths, were found mainly in the tropics, we incorporate optimised rooting depths only in the tropics, that is, between 30°N - 30°S. The rooting depths are left unchanged in the extratropics. The simulation using this distribution of rooting depth is referred to as the "deep roots" simulation.

All other surface parameters such as albedo, roughness length and vegetation cover are left unchanged. The two simulations are initialised with the same soil wetness (i.e. actual divided by maximum soil water content) and are conducted for 20 years. Sea surface temperatures are prescribed to their climatological values. In order to exclude spin-up effects, the first five years are discarded in the evaluation. The significance of the changes between the two simulations is assessed with the student's t-test. The comparison is focussed on seasonal averages from December to February ("DJF", which is roughly the dry (wet) season in the

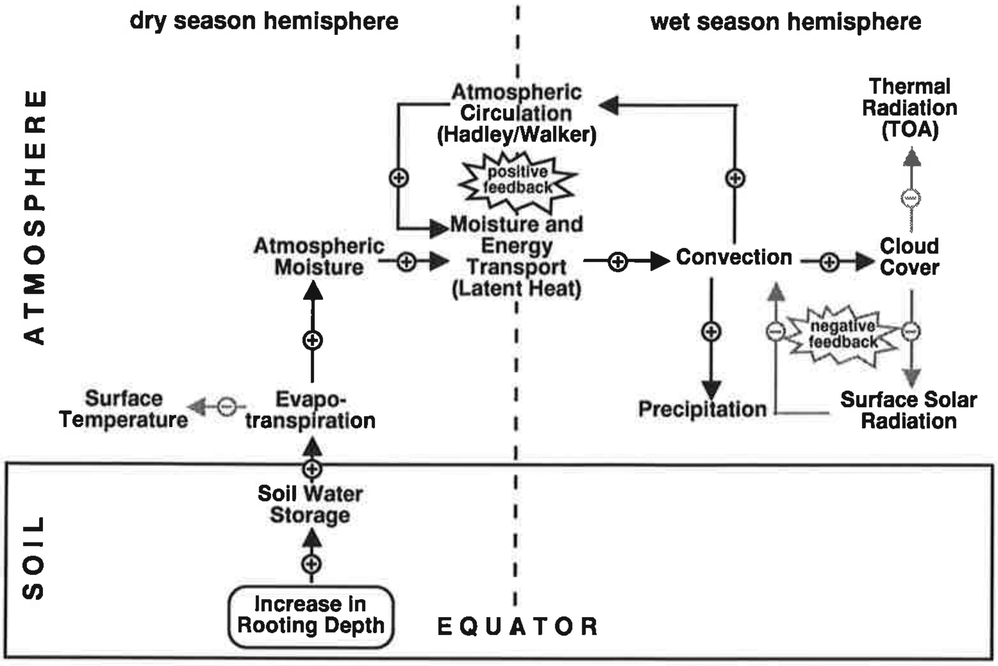


Figure 2: This Diagram illustrates the effect of increased rooting depth / deep roots on the atmosphere. Quantities in black (grey) increase (decrease) with an increase in rooting depth. A positive (negative) influence of one variable on another is indicated by a plus (minus) sign.

northern (southern) tropics) and June to August ("JJA", which is roughly the wet (dry) season in the northern (southern) tropics).

3 ATMOSPHERIC CHANGES

The atmospheric changes resulting from the incorporation of deep roots (compared to the standard simulation) can be understood by a simple mechanism which is shown in Fig. 2. In the following, we will follow the diagram step by step and show the difference between the corresponding variables of the two simulations in Fig. 3 and Fig. 4.

3.1 Direct Changes

The increase in rooting depth (associated with the incorporation of deep roots) leads to an increase in plant-available soil water storage capacity which then increases dry-season evapotranspiration (as long as evapotranspiration is limited by water storage). A large scale increase in evapotranspiration takes place on the dry season hemispheres (Fig. 3a, b). During DJF, the increases are concentrated over northern South America, Africa, and India/Southeast Asia, while small decreases are found over some parts of southern tropical South America, southern tropical Africa and Australia. This picture consistently changes during JJA, where the increases in evapotranspiration occur over southern tropical South America and southern tropical Africa. A decrease in evapotranspiration is also found over northern Africa. In addition, a large-scale increase in evapotranspiration occurs over the eastern tropical Pacific and Mesoamerica.

The enhanced latent heat flux associated with the increases in evapotranspiration leads to a cooling of the surface. Consequently, considerable decreases in near surface (2m) air temperatures (of up to 4K on the seasonal average and up to 8K on a monthly basis) are found for the respective dry-seasons (Fig. 3 c,d). The patterns of increases in dry-season evapotranspiration and decreases in near-surface air temperatures correspond very well. Apart from this direct effect, some changes (e.g. in temperature) can be found over the extratropics, on the northern hemisphere mainly during DJF and on the southern hemisphere mainly during JJA.

The increase in evapotranspiration during the dry season also leads to a consistent increase in atmospheric moisture over the affected region (not shown) and to enhanced moisture transport toward the Inter Tropical Convergence Zone (ITCZ). Thus, more energy is available in the ITCZ in form of latent heat, which then enhances convection and the mean cloud cover in the ITCZ. As a consequence, long wave radiation at the top of the atmosphere is reduced in these regions (Fig. 3 e, f) and precipitation is generally enhanced (Fig. 3 g, h).

3.2 Feedback processes

Fig. 2 also indicates a few feedback mechanisms which are further explored in the following. One positive feedback process involves the transport of moisture towards the ITCZ: The increased convection is associated with enhanced upward motion in the ITCZ which leads to enhanced wind flow towards the convection regions. It thus stimulates the general circulation patterns in the tropics (Hadley circulation in the zonal direction and Walker circulation in the meridional direction). The changes in circulation are investigated in terms of changes in the velocity potential near the surface (at the 850 hPa level, Fig. 4 a, b) and in the upper atmosphere (at the 200 hPa level, Fig. 4 c, d). We notice from Fig. 4 that the divergent wind

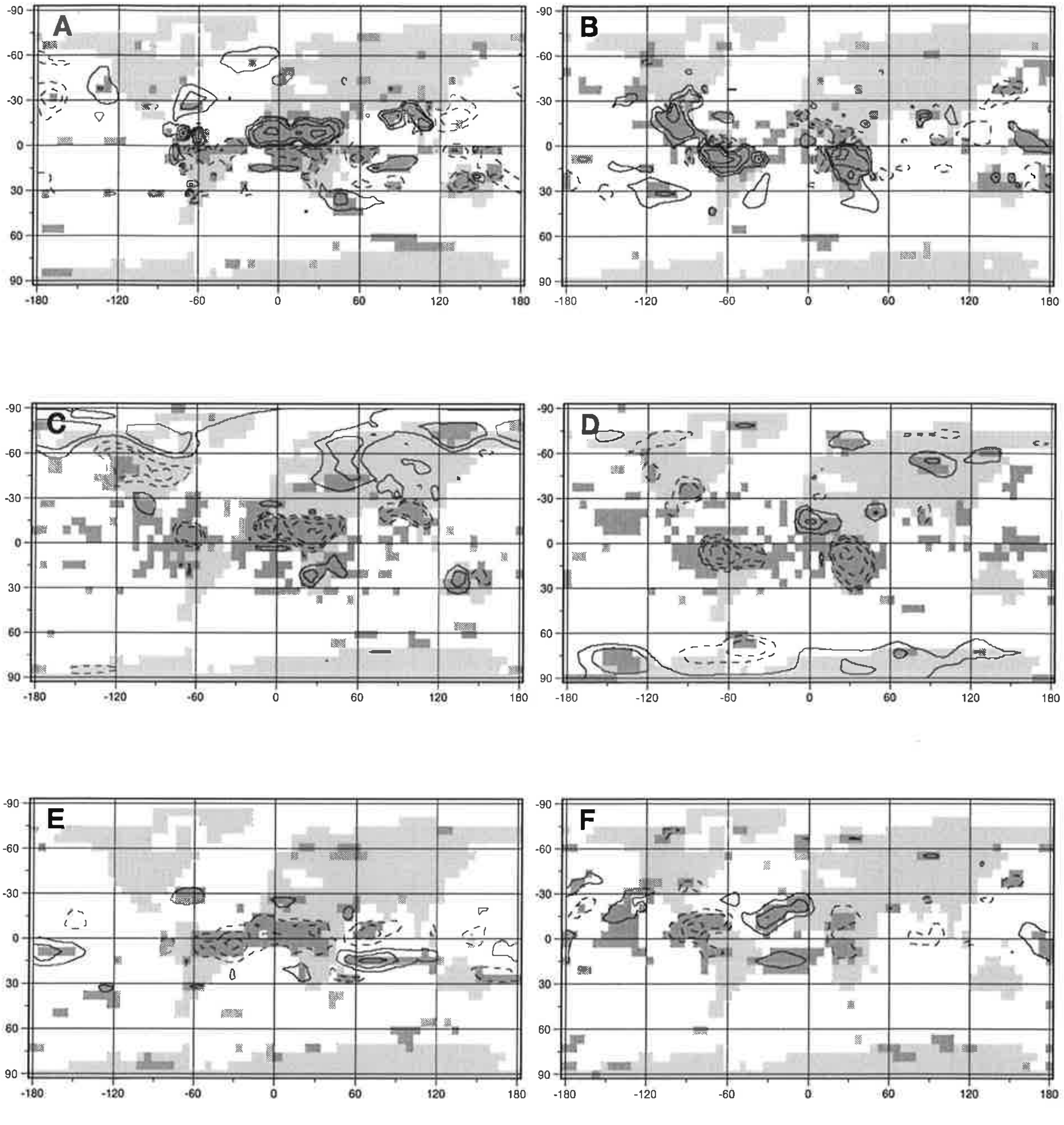


Figure 3: Mean seasonal changes in evapotranspiration (a, b), 2m air temperature (c, d), long wave outgoing radiation at the top of the atmosphere (e, f) and precipitation (g, h, next page) for the December - February (left) and June - August (right) season respectively. Solid (dashed) contour lines denote positive (negative) changes. Significant changes are shown in grey (student's t-test, $p \leq 0.05$). Contours are at ± 0.25, 0.5, 1, 2, 4 mm/day for water fluxes and ± 0.5, 1, 2, 4 K for air temperature. The contour interval in the longwave radiation plots is 5 W/m^2 (zero line is omitted). Light grey areas indicate land regions in which no significant changes take place.

flow (i.e. the gradient of the velocity potential) is increased towards the convection areas (cf. Fig. 3 e, f) thus providing a positive feedback to further enhance near-surface moisture transport towards the ITCZ. This feedback is most pronounced (in terms of absolute magnitude and statistical significance) over South America during the JJA season.

The reduction of solar radiation at the surface in the ITCZ as a consequence of increased cloud cover forms a negative feedback process in that it reduces the net amount of energy at the surface thus decreasing convection. The spatial patterns of change in solar radiation (not shown) are similar to those of the changes in longwave radiation at the top of the atmosphere (Fig. 3e, f). The reduction in solar radiation at the surface can explain the decrease found in evapotranspiration during the wet periods seen in Fig. 3a, b.

There is also a positive feedback process on an interseasonal time scale (which is not indicated in Fig. 2): The increases in precipitation during the wet season leads to increased storage of soil water which then further enhances evapotranspiration during the following dry season. This feedback mechanism is mainly found in the semiarid regions of northeastern tropical Africa (not shown).

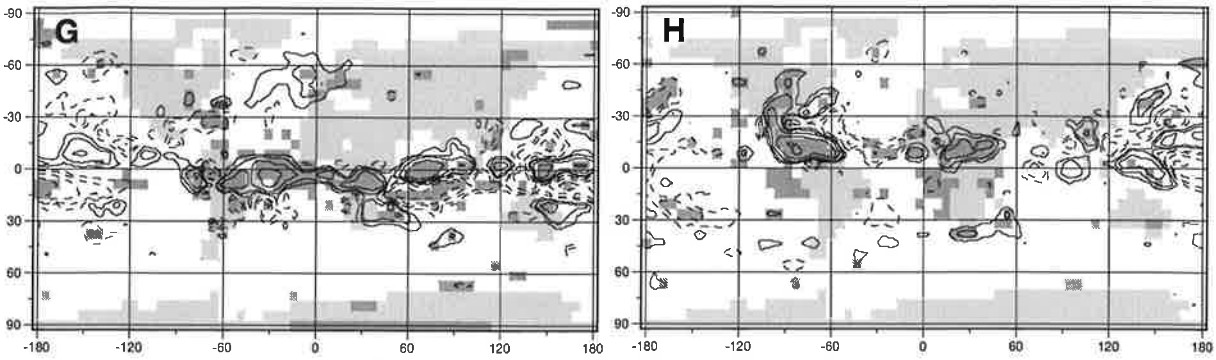
4 MEANS OF VERIFICATION

Are the climatic changes associated with the incorporation of deep roots reasonable? Assessing this question helps us to estimate if the overall performance of the model is improved and whether deep rooted vegetation forms an important part in large-scale modelling.

4.1 Local Observations of Surface Climate

Next, we compare the hydrologic effect associated with the use of deep roots. As observed by Nepstad et al. (1994), the deep roots provide sufficent access to soil water and, as a consequence, the transpiration is maintained throughout the dry season. We demonstrate this effect by showing the seasonal course of evapotranspiration for two model grid cells in South America in Fig. 5a and b. It is evident from Fig. 5, that the incorporation of deep roots leads to a considerable increase of dry season evapotranspiration. The selected grid cells cover two sites where observations in evergreen forest were taken during the ABRACOS project (Gash et al. 1996). While rooting distributions and, consequently, rooting depth were not measured at these sites (although the site of Marabà lies relatively close to the site at which Nepstad et al. (1994)

Figure 3 cont.



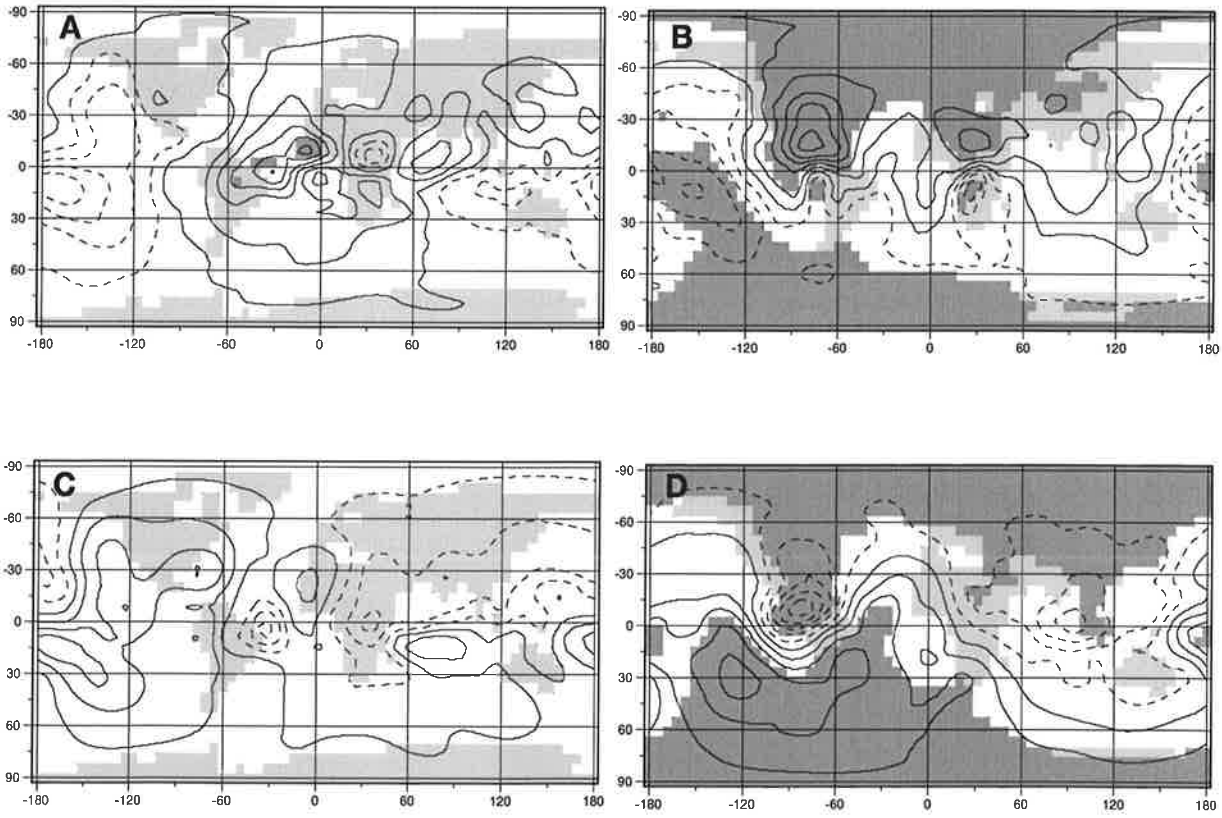


Figure 4: Mean seasonal changes in convergence in divergent wind flow at the 850 hPa level (a, b) and at the 200 hPa level (c, d) for the December - February (left) and June - August (right) season respectively. Solid (dashed) contour lines denote positive (negative) changes. Significant changes are shown in grey (student's t-test, $p \leq 0.05$). Contour interval is 0.2 10^6 m^2/s for (a, b) and 0.4 10^6 m^2/s for (c, d). Positive changes mean enhanced convergent wind flow. Light grey areas indicate land regions in which no significant changes take place.

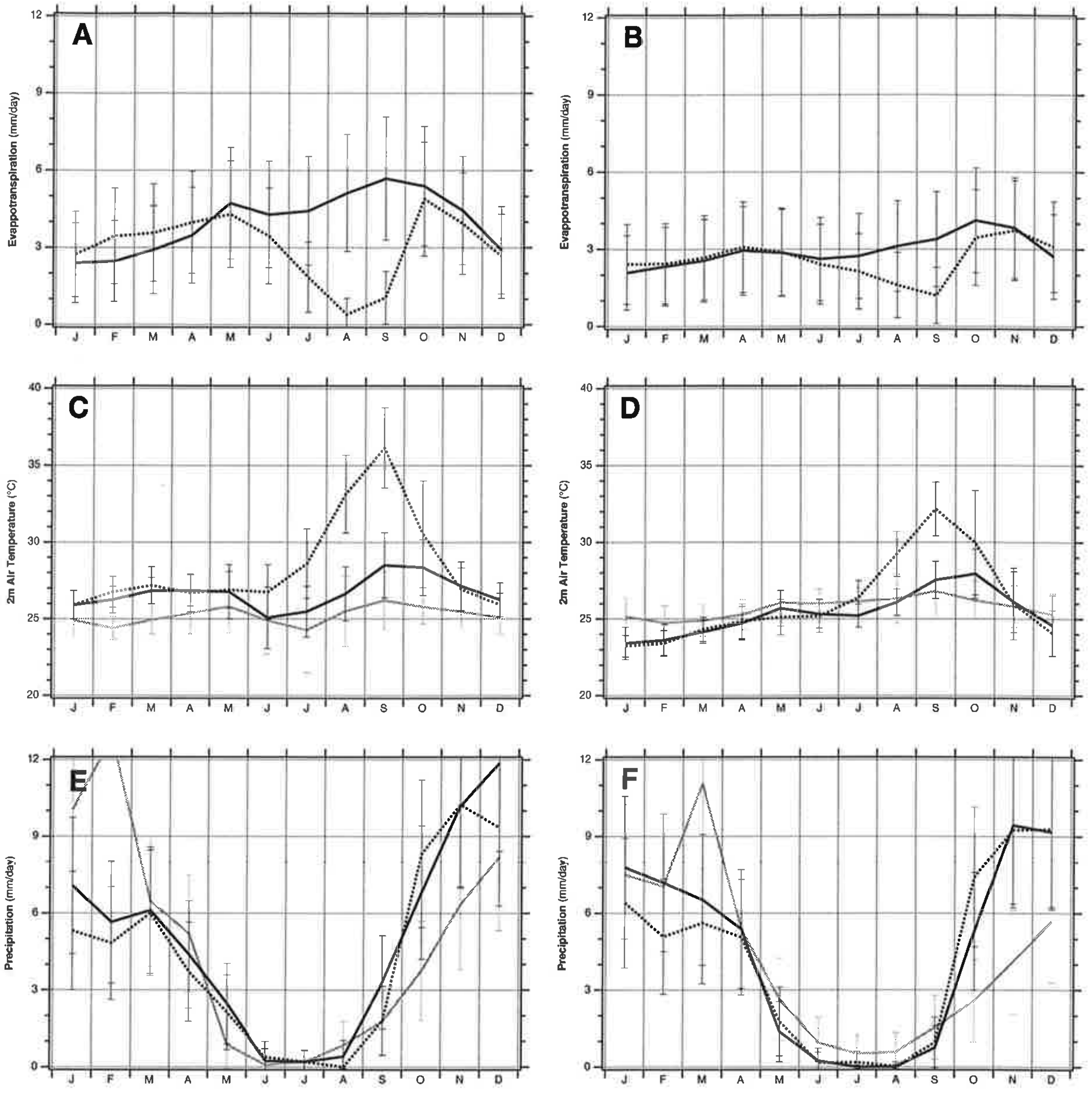


Figure 5: Simulated seasonal course of evapotranspiration (a, b), near surface (2m) air temperature (c, d) and precipitation (e, f) at two grid cells in South America. These grid cells cover two sites at which observations were taken during the ABRACOS project (Gash et al., 1996, left: Ji-Paranà, right: Marabà). Shown are the seasonal course of the standard simulation (dotted) and the simulation with deep roots (solid). Observations of air temperature and precipitation are shown in grey. Error bars indicate one standard deviation. Up to six years of daily data were used to calculate the seasonal course and the standard deviation for the observations. The meteorological data were collected under the ABRACOS project and made available by the UK Institute of Hydrology and the Instituto Nacional de Pesquisas Espaciais (Brazil). ABRACOS is a collaboration between the Agencia Brasileira de Cooperacao and the UK Overseas Development Administration. The data are available via the Internet by http://yabae.cptec.inpe.br/abracos/ available.html.

observed deep roots), we can get an idea about the reasonability of the seasonal course of evapotranspiration by comparing the simulated near-surface air temperatures to observations. Up to six years of daily data from automatic weather stations were used to calculate the seasonal course of air temperature and precipitation. The seasonal courses of near-surface air temperature show a noticeable improvement when deep roots are used in the model simulation at both sites (Fig. 5c and d). The effect of deep roots within the model does not originate from errors in the model's simulation of precipitation. The simulated length and strength of the dry season, as reflected by dry season precipitation, agrees well with the observations at these sites (Fig. 5e and f) for both simulations, while wet season precipitation is somewhat underestimated. The latent heat flux was also measured at some times during the ABRACOS project. It remained almost constant throughout the dry season similar to our "deep roots" simulation. A comparison of solar net radiation at the surface reveals that the model somewhat overestimates the seasonality. Considering this, we might expect the evapotranspiration rates during the dry season to be overestimated. This overestimation is nevertheless minor compared to the first order changes resulting from the incorporation of deep roots (see also below).

Considerable amounts of evapotranspiration during the dry season was also observed at other sites. Edwards (1979) found in a forest catchment in East Africa, that the forest transpired all year round with roots as deep as 8.2m in an area with a 6 months dry period. On an annual basis, actual evapotranspiration was about 90% of open pan evaporation over several years and evidence for deep soil water uptake was found. On a larger scale, Kreuels et al. (1975) noticed that the Bowen ratio (i.e. the ratio of sensible to latent heat flux) over the evergreen forests of South America was simular to oceanic values, implying that sufficient water was available for evapotranspiration throughout the year. Considering that a seasonal climate exists, sufficient soil water storages (explored by the root systems of the vegetation) are needed.

4.2 Seasonal Variation of Amazon River Basin Storage

Enhanced dry season evapotranspiration in a river basin also leads to an increased seasonal variation in the basinwide storage of water. We compute the seasonal variation of the storage of the Amazon basin (approximated by ten grid cells, taken as ≈ 75°W - 55°W, 0° - 10°S and 70°W - 60°W, 5°N - 0°) from the amplitude of the variation in the soil water content and compare it to the seasonal change of the water storage calculated from observations (Matsuyama 1992) in Fig. 6. Note that the exact size of the basin is not crucial since the variations are compared on a unit area basis. It is evident from this comparison, that the incorporation of deep roots into the model leads to a considerable improvement in the variation

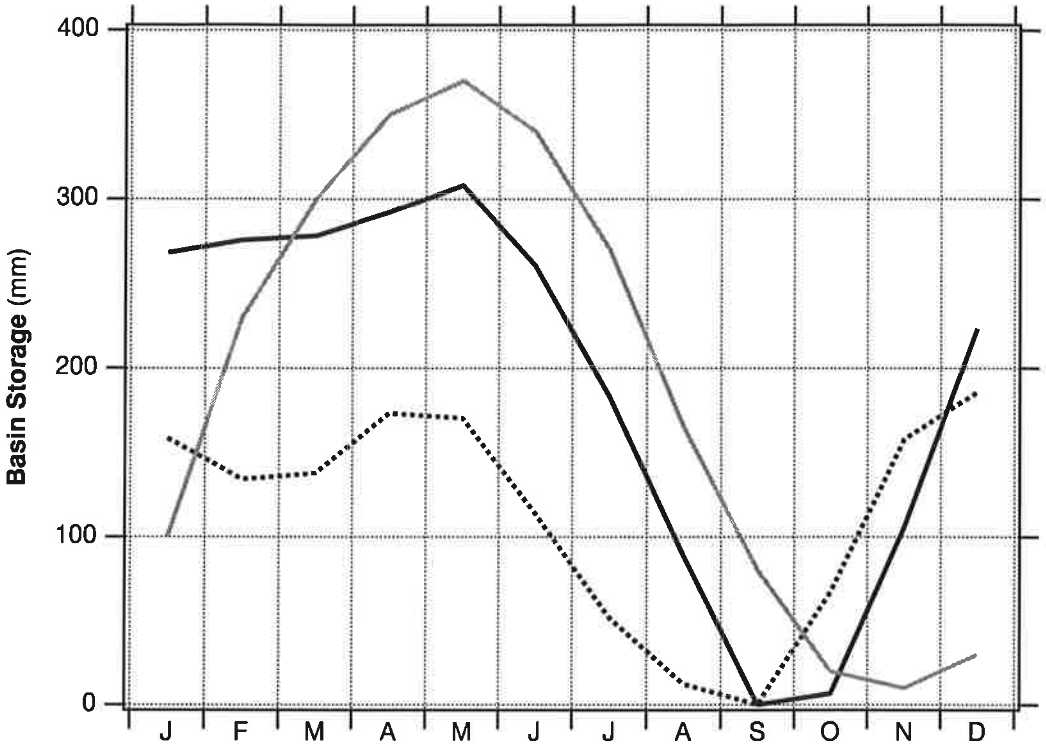


Figure 6: Seasonal variation of the water storage of the Amazon basin. Shown is the mean seasonal course of the simulation with optimised rooting depths (solid line), with standard rooting depths (dotted line) and observations (grey line, taken from Matsuyama, 1992).

and the seasonality of basin wide storage. In the standard simulation, the seasonal variation is clearly constrained by the bucket size, while in the simulation with deep roots, the variation is limited by precipitation which is somewhat underestimated. The observed variation in soil water depletion by Nepstad et al. (1994) is also of this order (≈ 500 mm during the dry season). However, Matsuyama and Masuda (1997) attribute the seasonal variation to flooding and changes in river levels.

4.3 Large Scale Observations of Air Temperature

As a final step, we compare the large-scale seasonal course of air temperature to observations. In order to do so, averages are computed over land for each hemisphere for five regions which cover the areas where the largest changes occur (see also Fig. 3 c, d and Fig. 7 f). The regions are: northern tropical South America (≈ 0° - 10°N, consisting of a total of seven

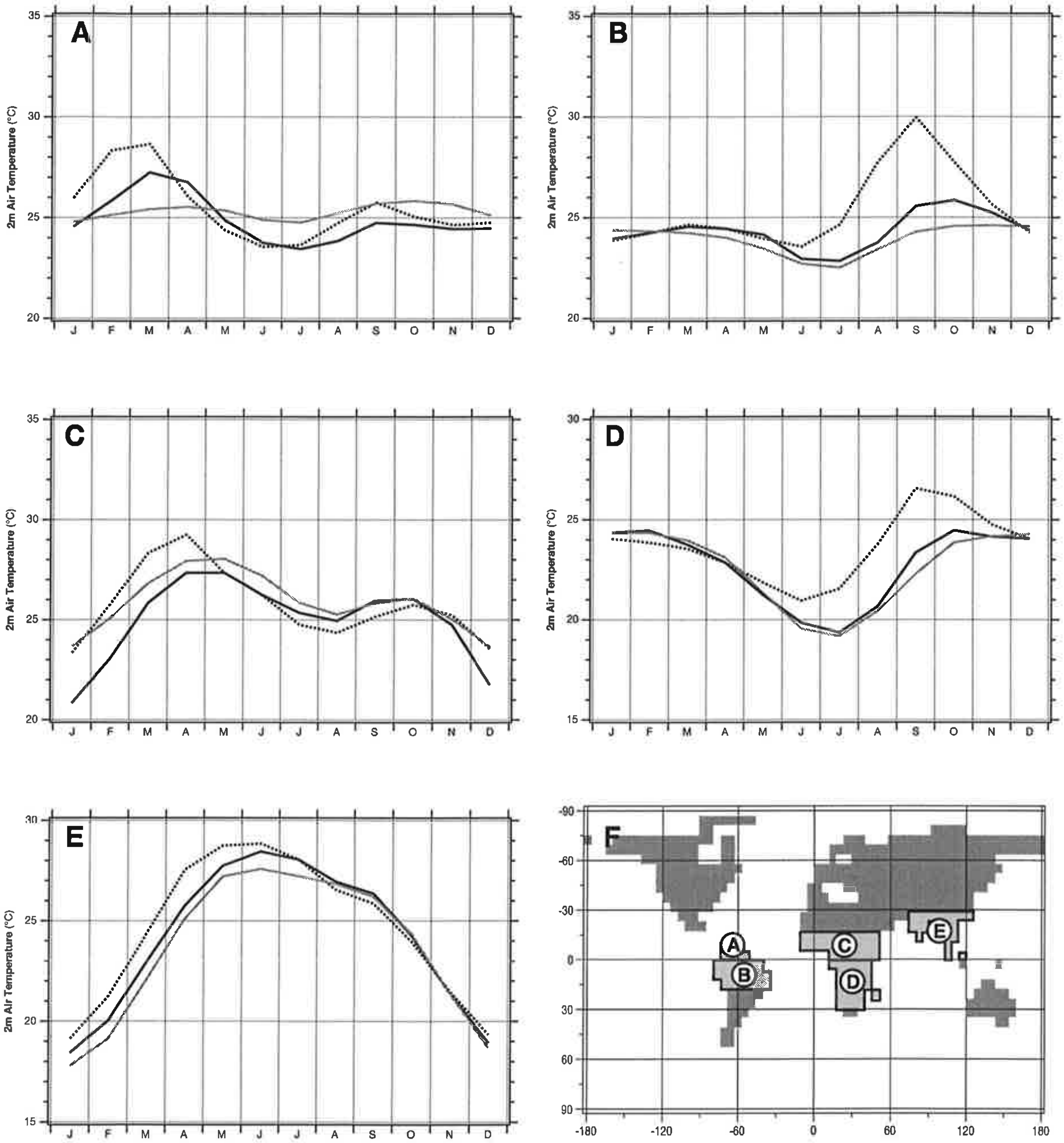


Figure 7: Seasonal course of 2m air temperature (a - e) for five different regions (shown in f). Shown are the mean seasonal course for the simulation with optimised rooting depths (solid line), with standard rooting depths (dotted line) and observations (grey line, Legates and Willmott, 1990a).

grid cells), southern tropical South America (≈ 0° - 15°S, 22 grid cells), northern tropical Africa (≈ 0° - 15°N, 29 grid cells), southern tropical Africa (≈ 0° - 30°S, 21 grid cells) and Southeast Asia (≈ 0° - 30°N, east of 70°E, 25 grid cells). Tropical Australia is not included into the comparison because the effects are far less pronounced. The seasonal course of near-surface air temperatures of the five regions for the two simulations and for observations (Legates and Willmott 1990a) are shown in Fig. 7. The southern hemisphere regions of South America (Fig. 7b) and Africa (Fig. 7d) show a clear improvement in the simulation of the seasonal course of air temperature when deep roots are included. The improvement is less in the northern hemisphere, and for northern tropical Africa (Fig. 7c), no improvements can be found.

It is worth investigating, whether the changes in air temperature associated with deep roots reflect an improved simulation of evapotranspiration (and thus surface climate in general) or whether the changes are artefacts of errors in the simulated climate in either energy or water supply (i.e. incoming solar radiation at the surface and precipitation respectively). For instance, too little dry-season precipitation is compensated by larger soil water storages as long as the climate remains humid. However, the impact of errors in radiation are less easy to estimate. If the seasonality of radiation is too great, for instance, evapotranspirational demand in the dry season is overestimated which, again, would be compensated by larger soil water storages. On the other hand, wet-season evapotranspiration is consequently underestimated so that these effects might cancel each other.

In order to assess potential errors in the simulations we compute regional averages of precipitation (Fig. 8) and incoming solar radiation (Fig. 9) from both model simulations and compare them to observations (precipitation: Legates and Willmott 1990b, Rudolf et al. 1996; incoming solar radiation: Schiffer and Rossow 1985). While the annual means compare fairly well to the observations, we find that the modelled seasonality in radiation is generally overestimated. Considering the discrepancies in observations of precipitation (as indicated by the two data sets), the dry seasons are fairly well simulated in most regions. The beginning of the wet season generally occurs too early which favours an underestimation of the length of the dry season and consequently of the optimum soil water storage sizes.

The largest errors occur in South America and the northern part of tropical Africa. In South America, the simulaton of the dry seasons seems too pronounced which might overemphasise the role of deep roots but is in contrast to the comparison of the local observations (see above and Fig. 5e and f). This inconsistency could be attributable to an underestimation of orographic rainfall in the equatorial Andes mountain range (of up to 10mm/day for individual grid cells during the JJA season compared to Rudolf et al. 1996),

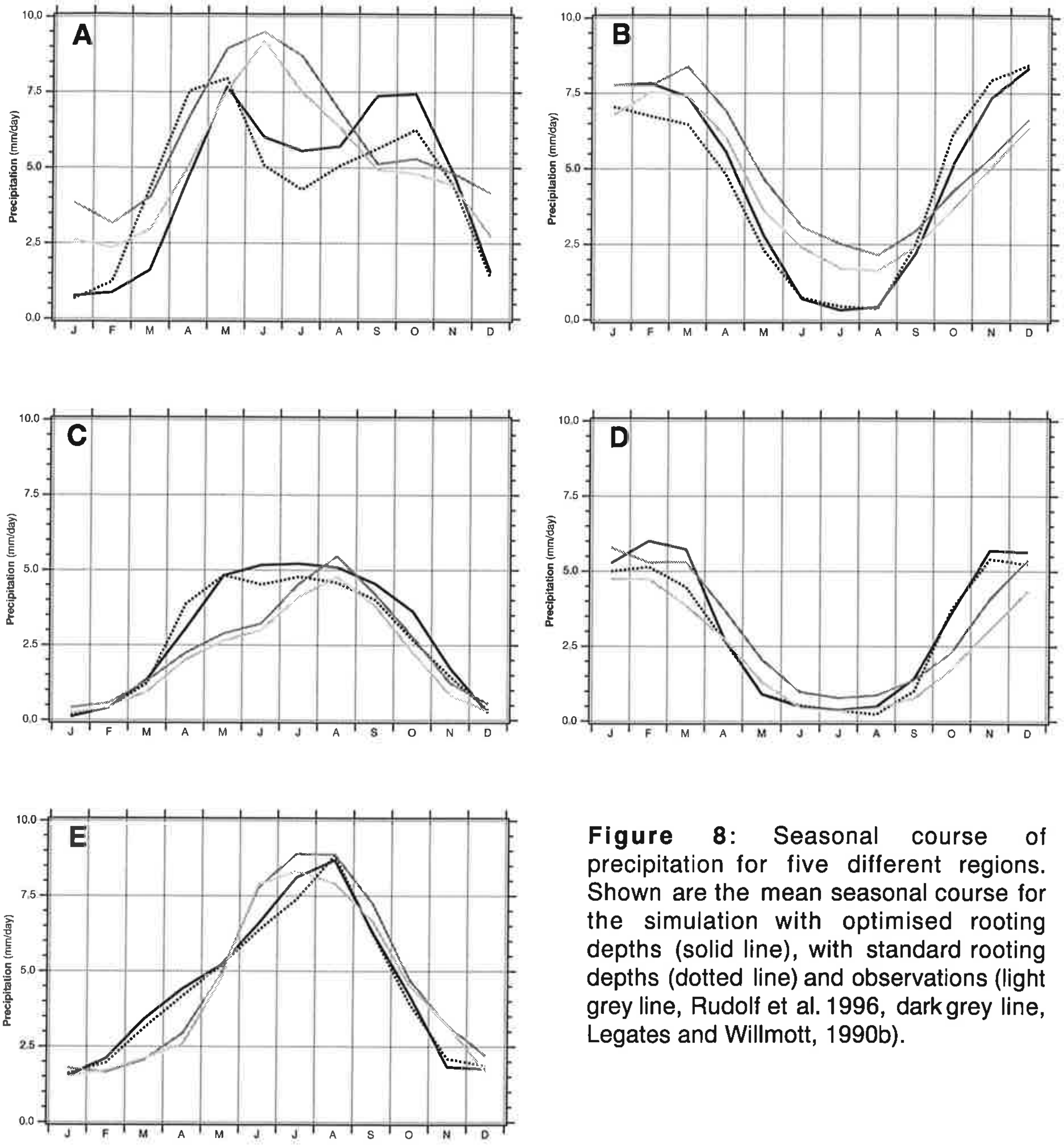


Figure 8: Seasonal course of precipitation for five different regions. Shown are the mean seasonal course for the simulation with optimised rooting depths (solid line), with standard rooting depths (dotted line) and observations (light grey line, Rudolf et al. 1996, dark grey line, Legates and Willmott, 1990b).

presumably because the low model resolution does not resolve the Andes very well. Considering this systematic error in the simulation, the strong impact of deep roots on evapotranspiration seems to be realistic in large parts of tropical South America. In northern tropical Africa, the solar radiation at the surface is underestimated (and consequently the energy

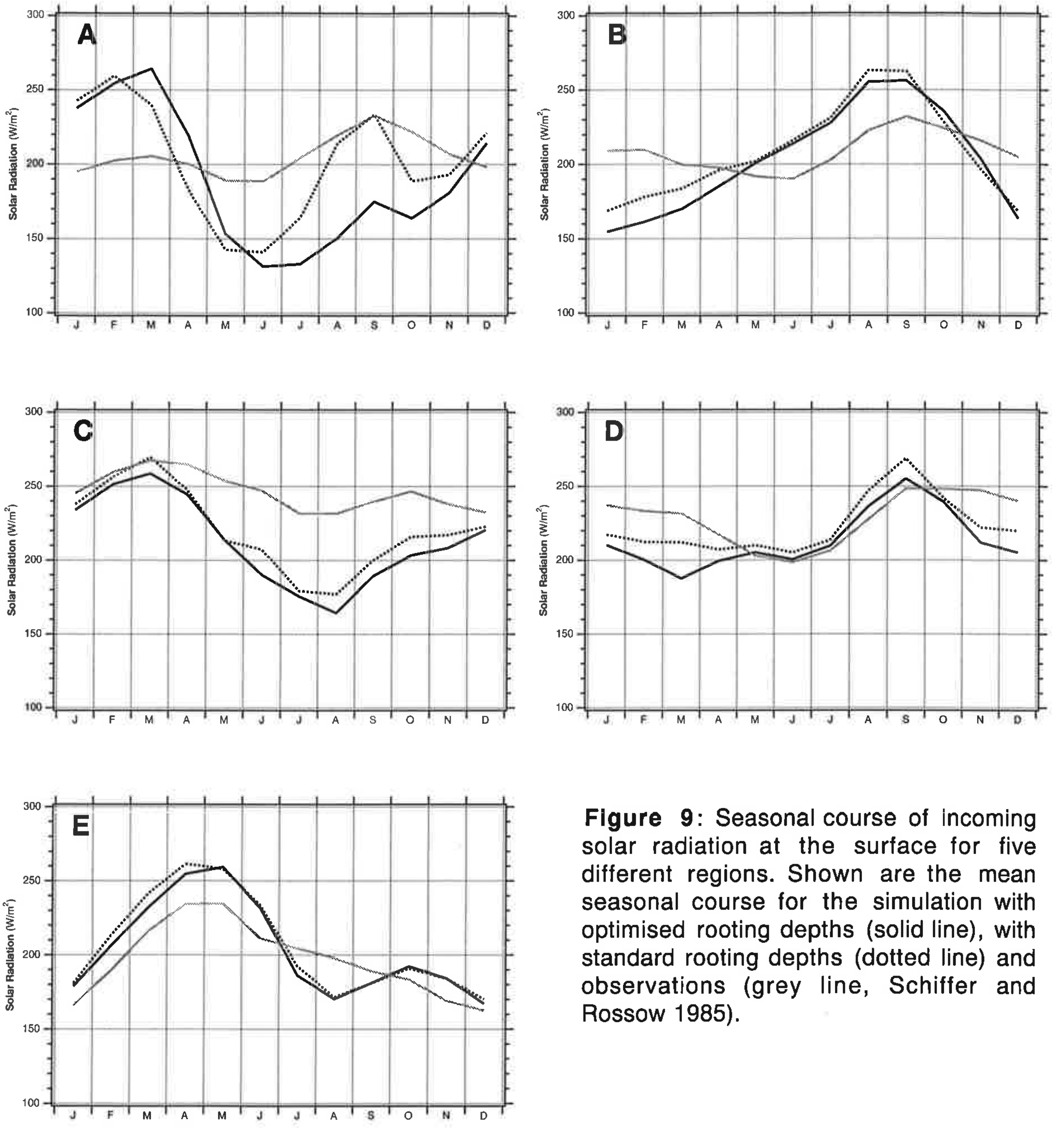


Figure 9: Seasonal course of incoming solar radiation at the surface for five different regions. Shown are the mean seasonal course for the simulation with optimised rooting depths (solid line), with standard rooting depths (dotted line) and observations (grey line, Schiffer and Rossow 1985).

supply for evapotranspiration) and precipitation is overestimated during the wet season. This error causes an excess of water availability in the dry-season which could explain the deviations in the temperature seasonality (i.e. too low in the presence of deep roots).

5 DISCUSSION

We found that changes in rooting depth cause a pronounced seasonal signal on the simulation of the climate which makes it distinct from other surface parameters such as albedo or roughness length. The patterns of change which we found are similar to those obtained in earlier sensitivity studies (e.g. Shukla and Mintz 1982, Milly and Dunne 1994), even though this study here is not a sensitivity study per se since we compare a model simulation with deep roots, which we assume of having a more realistic distribution of rooting depth, to the standard model simulation. The optimisation approach which we used in deriving the rooting depth distribution delivers a spatial pattern and thus isolates regions which are sensitive to water storage/rooting depth and is thus not equivalent to simply doubling the soil water storage capacity as it is commonly done in sensitivity studies. The simulation with the deep roots can be seen as one where the vegetation makes optimum use of water. Even though the vegetation's productivity was optimised in the derivation of rooting depth instead of transpiration (see Kleidon and Heimann 1998b), the outcome using the simple biosphere model is close to a maximisation of evapotranspiration. With the conservation of water at the land surface in mind, the logical consequence is that evapotranspiration is controlled by radiation in humid environments and by precipitation in arid ones. It is interesting to note that Budyko (1974) established these limits for annual estimates of evapotranspiration. In this sense, the use of optimised rooting depths is a logical extension to shorter time scales of Budyko's work.

The comparison performed in the previous section strongly suggests that natural vegetation indeed acts at an optimum in terms of soil water storage and that the incorporation of deep roots consequently leads to an improvement in the surface hydrology and climate in large parts of the tropics. However, excluding the comparison of biome averages of rooting depth, most of the evidence is connected with the increase in evapotranspiration. In principle, other processes could contribute to evapotranspiration as well, for instance, in the case of evaporation from open water surfaces such as rivers, lakes or wetlands (which was suggested by Matsuyama and Masuda (1997) in the case of the Amazon basin). Since open water bodies only cover a small fraction of the total land area in most regions (Matsuyama and Masuda (1997) cite a value of 7% maximum inundation for the Brazilian part of Amazonia), they are likely to be able to account for only a small part of the total evapotranspiration flux of a large region (especially in the humid tropics) and their impact consequently appears minor. Another way of assessing the quality of the hydrological changes associated with the presence of deep roots is to compare the seasonal course of large river basin discharge to observations (see e.g. Hagemann and Dümenil 1997). However, because of the low spatial resolution used here, we did not conduct this comparison in this study.

A remaining, more fundamental question is whether the observed values of rooting depth can be directly translated into soil storage of plant-available water, or if the total water uptake capability needs to be weighted by root biomass density as it is commonly done in models which use multiple soil layers. In the simple soil hydrology model within the GCM used in this study, the assumption is made that water can be extracted by roots within the soil column independent of depth and, hence, root biomass. The comparison of the optimised rooting depths to observations and the ones obtained from satellite observed vegetation greenness (and the observations by Nepstad et al. 1994) supports the latter idea. This could mean that the presence of roots is more important than their quantity. The implication of this is that the effects seen here are likely to remain even if a more sophisticed land surface scheme were used. Ultimately, it is the net amount of soil water accessible to plants which is underestimated in the standard simulation.

The results reported here have certain implications for the effects of land use change on climate. After land clearing (e.g. of evergreen tropical forest), the vegetation replacing the natural vegetation (usually grassland) is associated with lower rooting depths which dies during the dry season thus reducing dry season transpiration (see e.g. Nepstad et al. 1994). This effect is incorporated into simulation studies of tropical deforestation (e.g. Nobre et al. 1991, Henderson-Sellers et al. 1993). However, most models do not have deep roots in their standard simulation which consequently leads to underestimations of the dry season evapotranspiration and overestimation of air temperature in the simulation of the present-day climate (e.g. Hahmann and Dickinson 1997). The neglection of deep roots is partly compensated in some of the studies (e.g. Lean and Rowntree 1997) by an overestimation of the field capacity of tropical soils (e.g. Tomasella and Hodnett 1996, Batjes 1996). The consequences of deep root removal associated with tropical deforestation are nevertheless likely to be underestimated. It is thus interesting to ask what the climatic consequences of deep root removal in Amazonia are. Using the mechanism described above, we might speculate in the "reverse" direction that the removal of deep rooted vegetation causes a strong seasonal warming and a reduction in the tropical circulation, with consequent decreases in precipitation. This aspect is investigated in more detail in the accompanying paper (Kleidon and Heimann 1998c).

6. SUMMARY AND CONCLUSION

We found that deep rooted vegetation acts as a large water capacitor levelling out seasonality in evapotranspiration in seasonal environments in the tropics. In this sense, the inclusion of deep roots makes a land surface appear more like an ocean surface in terms of its evaporative behaviour. The local consequence is a constant air temperature, which is not expected from the seasonality of precipitation and solar radiation. The persistance in evapotranspiration during the dry season is associated with a net energy transfer in the form of latent heat towards the convective regions, so that the convection is enhanced and the overall tropical circulation patterns are strengthened. Since it is the net storage of soil water accessible to the vegetation which is underestimated in the standard model it seems that the effects found in this study should be fairly model independent. Especially the (non)seasonality of near surface air temperature in the tropics appears to be a strong indicator for the presence of deep rooted vegetation on a large scale. We may therefore suggest that larger rooting depths should be used in the tropics within other climate models.

We consider this work as a first step to include more realistic vegetation behaviour in a climate model. Nonetheless, we need more observations for comparison in order to be more confident about the model's prediction in the simulated regional scale behaviour of evapotranspiration (and its relation to rooting properties), but also about the importance of dry season evapotranspiration from land areas as a source of energy for the ITCZ. The Large scale Biosphere-atmosphere experiment in Amazonia (LBA) is an ideal project for gathering this sort of data on the appropiate scales. We hope that this data will provide additional means of testing the proposed mechanism.

We can draw an additional conclusion from the results of this study. Considering that the inclusion of the optimised rooting depths lead to a general improvement of the simulated surface climate, we may also conclude that the vegetation in large areas does indeed act optimal. This does not answer the question of how the vegetation actually achieves its optimum behaviour. Recent studies showed that the variability of the exchange fluxes was reduced in ecosystems with a higher biodiversity (e.g. McGrady-Steed et al. 1997), that is, that the ecosystem as a whole "works" more stable - an effect which we also found in the climate model when optimised rooting depths were incorporated. Does this mean that we implicitely assumed a sufficiently large biodiversity? If this is the case, a loss of species could have a direct impact on climate.

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Kapitel 4

Anwendung auf Amazonische Abholzung

4.1 Deep Roots, Amazonian Deforestation, and Global Climatic Effects[1]

Abstract. A climate model is used to investigate the significance of deep rooted vegetation and the climatic changes associated with its removal by large scale Amazonian deforestation. By transpiring throughout the dry season, deep rooted vegetation provides a considerable source of atmospheric moisture, enhancing and stabilising the convection and the tropical atmospheric circulation. We show that its removal leads to a pronounced seasonal response and causes remote effects by changing the tropical circulation.

Land surfaces are distinctively different to oceans in that water is not abundantly available for evapotranspiration but limited by precipitation and soil water storage. Only in the presence of vegetation with a well developed root system can considerable amounts of water be extracted from the soil and transpired into the atmosphere. This soil storage of plant-available water becomes increasingly important with greater seasonality in precipitation. This is especially the case in the tropics where deep reaching root systems have been reported at various sites[1, 2] and the Amazon basin[3] in particular. They allow the vegetation to extract water from deep soil layers for transpiration throughout the dry season[3,4], leading to evapotranspiration near the potential rate[5]. The importance of deep rooting is amplified by the low ability of some tropical soils to store plant available water despite their high clay contents (e.g. Ref. 6, 7). By supplying stored water near the potential rate during the dry season, deep rooted vegetation provides a considerable source of atmospheric moisture and latent heat to the atmosphere. On the one hand, the increased latent heat flux leads to cooler temperatures during this period, while on the other hand, the increased transport of latent heat from the dry season

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[1] Axel Kleidon and Martin Heimann, submitted to Nature, revised version

regions to the convection areas supplies additional energy for convection which enhances the tropical circulation patterns[8]. Consequently, one might expect that the large-scale removal of deep rooted vegetation, for instance by Amazonian deforestation, could have a pronounced - and possibly far reaching - effect on climate.

There are numerous studies which have investigated the impact of tropical deforestation on climate using Atmospheric General Circulation Models (GCM's) [9, 10, 11, 12, 13, 14, 15, 16]. All of them have been conducted in a similar way, where surface parameters such as albedo, vegetation cover, roughness length and rooting depth were modified to those representing degraded grassland in a selected region of the central Amazon basin in South America. The results were consistent in that all found a reduction of evapotranspiration, increase in sensible heat flux and an increase in surface temperature in the deforested region. These effects have been attributed mainly to the increased albedo and reduced roughness length. Since the energy balance at the surface was modified, some changes of the atmospheric circulation over Amazonia were also found.

However, all studies used land surface schemes where the tropical evergreen forest is represented by a rooting depth of less than 2 metres, therefore neglecting the presence and the significance of deep roots. While some studies have reported underestimated dry season evapotranspiration in the climate simulation in the presence of evergreen forest [16], others compensate artificially for the neglection of deep roots by considerably overestimating the net storage capacity of the soil [12, 15] which is also the case in the standard version of the model used in this study (ECHAM). For instance, in ECHAM values of about 240 mm/m are used for plant available water while observed values are typically within 70 - 150 mm/m in the upper part of the soil profile [17, 4] but can be as low as 30mm/m[4]. Both kind of errors evidently result in an underestimated climatic sensitivity to rooting depth changes in these simulations.

Here we report the results of a study in which we explicitly incorporated deep roots and the water holding characteristics of tropical soils into the climate model. This allows us to investigate the climatic significance of the deep rooted vegetation in the Amazon basin and to assess the climatic conseqeuences associated with its removal. From conducting a series of sensitivity simulations we find that most of the climatic changes can be attributed to the reduction of rooting depth. Besides a strong seasonal response over the whole of tropical South America, we also find that the tropical circulation patterns are affected strongly enough to cause climatic changes in regions remote from the deforested area such as North America and Southeast Asia.

Incorporation of Deep Roots

We use the ECHAM 4 GCM [18] in its T21 resolution (≈ 5.6° * 5.6° resolution) to conduct the climate simulations. In order to estimate the distribution of deep roots, we employ an ecological principle that vegetation adapts to its climatic environment in such a way that its benefit or fitness is at a maximum [19, 20]. We incorporate a formulation of net primary productivity (NPP) into the climate model and use the long term mean of NPP as a measure for fitness. The principle is then implemented by numerical maximisation of long term NPP in respect to rooting depth to yield an estimate for the distribution of deep roots[21]. Also used is a recent data set of the soil's storage capacity of plant available water[17], which explicitly accounts for the considerably lower values found for tropical soils. The rooting depths obtained in this way are considerably deeper (≈ 10 - 20m) than those currently used in global models. They are consistent with observed values of rooting depth [3, 2] and show a similar distribution to one which was obtained by using satellite-derived greenness of the vegetation [22].

The simulated surface climate considerably improved with the use of deep roots [8], as reflected in the persistence of transpiration throughout the dry season [3, 4, 5], no seasonality in observed near surface air temperature [23] and basinwide storage of water [24]. To illustrate the pronounced effect of rooting depth on evapotranspiration and air temperature, we show the simulated surface climate of one grid in the Amazon basin and compare it to observations taken during the ABRACOS project [25] in Fig. 1. Evapotranspiration considerably increases during the dry season with the use of deep roots (Fig. 1a) because of increased plant-accessible soil water. The simulated net solar radiation at the surface and the length and intensity of the dry season are reasonably well simulated (Fig. 1b, c) so that this change in evapotranspiration cannot be attributed to model biases in the forcing variables but rather to the underestimation of rooting depth in the standard model. The increase in latent heat flux associated with enhanced evapotranspiration leads to a noticeable cooling during the dry season which leads to an improved seasonal course in air temperature (Fig. 1d).

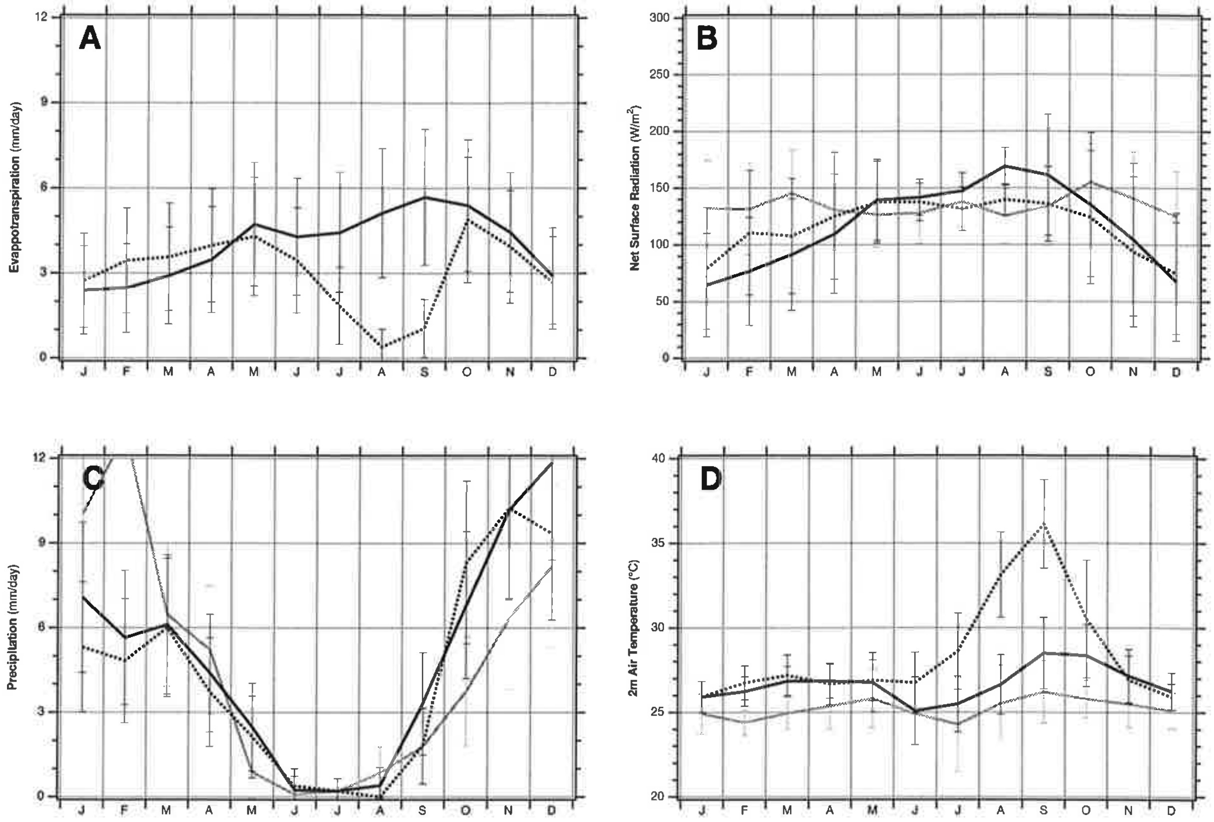

Figure 1: Seasonal course of surface climate at one grid point in the Amazon basin: A evapotranspiration, B net surface radiation, C precipitation and D 2m air temperature. The solid line shows the model simulation including deep roots, the dotted line for the simulation with the standard rooting depth and the grey line represents observations taken during the ABRACOS project[25] at the Reserva Jaru, near Ji-Paraná, Rondonia. Error bars indicate one standard deviation. The meteorological data were collected under the ABRACOS project and made available by the UK Institute of Hydrology and the Instituto Nacional de Pesquisas Espaciais (Brazil). ABRACOS is a collaboration between the Agencia Brasileira de Cooperacao and the UK Overseas Development Administration. The data are available via the Internet by http://yabae.cptec.inpe.br/abracos/available.html.

Deforestation Simulation

To simulate the climate in the presence of a deforested landscape, we modify the vegetation parameters of central Amazonia as in Nobre et al. (Ref. 5). There, rooting depth was reduced to 60cm and albedo increased to 0.20 along with other parameters. We perform three scenario simulations to assess the extent to which the effects of deforestation on climate can be

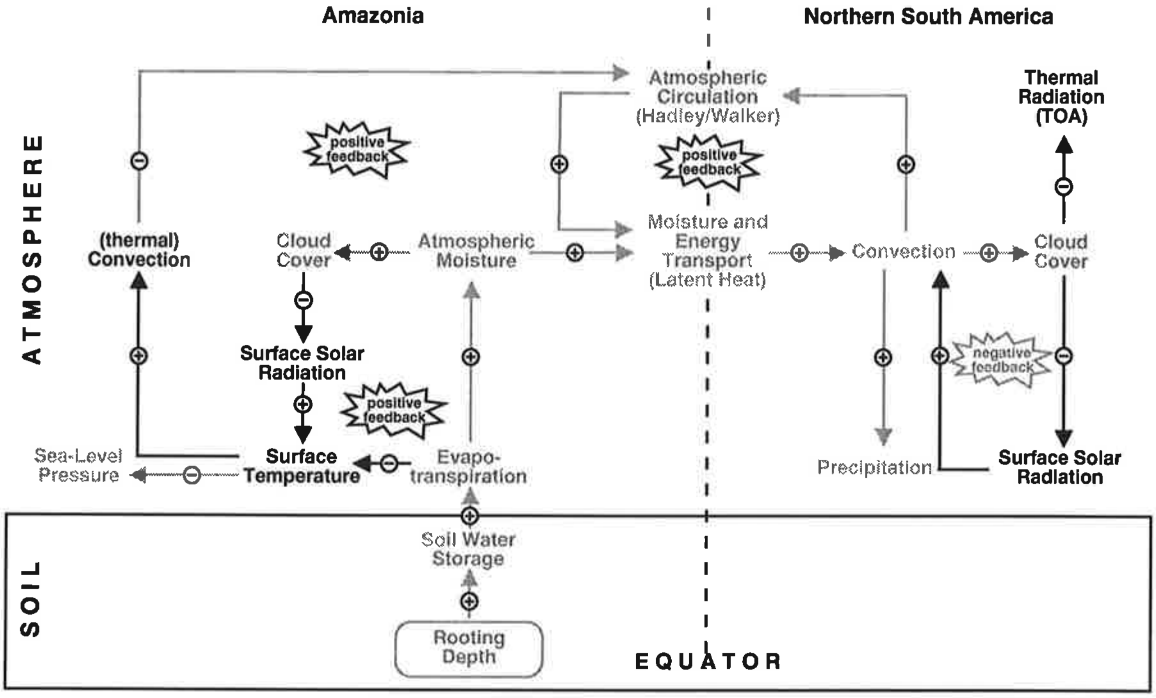

Figure 2: Effect of a reduction of rooting depth on the climate during the Amazonian dry season (during June-August). Quantities in grey (black) decrease (increase) with a reduction in rooting depth, respectively. A positive (negative) influence of one variable on another is indicated by a plus (minus) sign.

attributed solely to the removal of deep rooted vegetation: In a first run, we reduce rooting depth only, in a second run we increase the albedo only, and in a final run we include all modifications. All model simulations run for 20 years and averages are taken over the last 15 model years to discard spin-up effects. To investigate atmospheric feedback processes only, climatological sea-surface temperatures are used.

The effect of reduced rooting depth on the regional climate is summarised in a schematic diagram (Fig. 2). In the absence of deep roots, less soil water is accessible to the vegetation leading to a considerable reduction in evapotranspiration (Fig. 3a), mainly during the dry season of the southern hemisphere in June to September. The reduction in

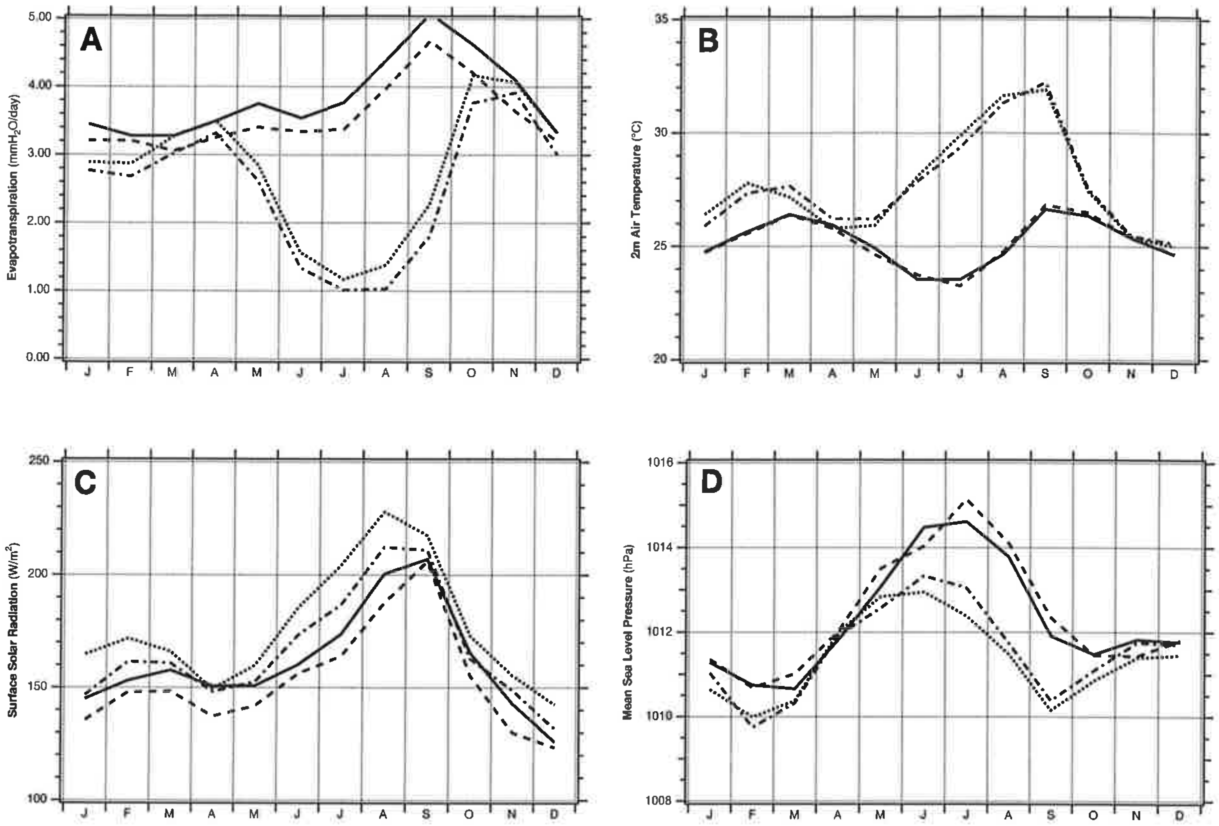

Figure 3 : Seasonal course of regional quantities: A evapotranspiration, B 2m air temperature, C net solar radiation at the surface and D mean sea level pressure. The values are averaged over the deforested region which consists of ten model grid points in central Amazonia (enclosed by 75°W - 55°W and 0° - 10°S and an area 70°W - 60°W and 5°N - 0°). The control simulation (including deep roots) is represented by the solid line, the simulation with increased albedo by the dashed line, the simulation with a shallow rooting depth by the dotted line and the deforestation simulation by the dash-dotted line.

evapotranspiration eliminates an effective way of cooling the surface by the associated latent heat flux, so that a considerable warming takes place over the region (Fig. 3b). Less evapotranspiration also leads to a reduced input of moisture into the atmosphere resulting in drier air. This is accompanied by a reduced cloud cover and increased net solar radiation at the surface (Fig 3c) which amplifies the warming. With a warmer surface, more thermally driven convection takes place over the region manifesting itself in lower air pressures (Fig. 3d). The overall export of moisture and energy in the form of latent heat out of the region is reduced because of less moisture in the atmosphere, but also because of a weakened circulation as a

Simulation	ΔE (mm)	ΔP (mm)	ΔT (°C)	ΔRAD (W/m^2)	Change in Moisture Sink
Shallow Roots	-383	+50	+2.5	+16.0	increase
Increased Albedo	-106	-194	-0.0	-8.3	decrease
Deforestation	**-474**	**-140**	**+2.5**	**+5.5**	**increase**

Table 1: Annual changes of evapotranspiration (ΔE), precipitation (ΔP), near surface air temperature (ΔT) and net solar radiation (ΔRAD) for each of the sensitivity simulations. Note that the net radiation in the "deforestation" simulation increases despite an increase in albedo.

response to the enhanced convection over the deforested region.

In contrast, an increase in albedo leads to a reduction of net solar radiation throughout the year (Fig 3c), which, since water is sufficiently available in the presence of deep roots, mainly leads to a continuous reduction in evapotranspiration (Fig 3a) and has no effect on air temperature (Fig 3b) and air pressure (Fig 3d). Nonetheless, it also results in a decreased export of moisture during the dry season as in the case of the simulation with the reduced rooting depths. The total response of the deforestation simulation can be understood by the combined effects of the reduction of rooting depth and the increase of albedo, with the reduction in rooting depth dominating the overall response (Table 1). On an annual basis, the reduction of net radiation resulting from the albedo increase is more than compensated for by the reduction of cloud cover and the associated increase in solar incoming radiation, which is in contrast to other studies.

Remote Effects

Climatic changes remote from the deforested region can be understood by atmospheric circulation changes which are caused by the mechanism also shown in Fig. 2. The decreased export of moisture affects the convective regions over South America by supplying less latent energy for convection, manifesting itself in decreased precipitation (Fig 4a). The reduced upward motion leads to a weakening of the Hadley circulation towards the convective region, further amplifying the reduction in moisture transport (Fig 4b). The large-scale

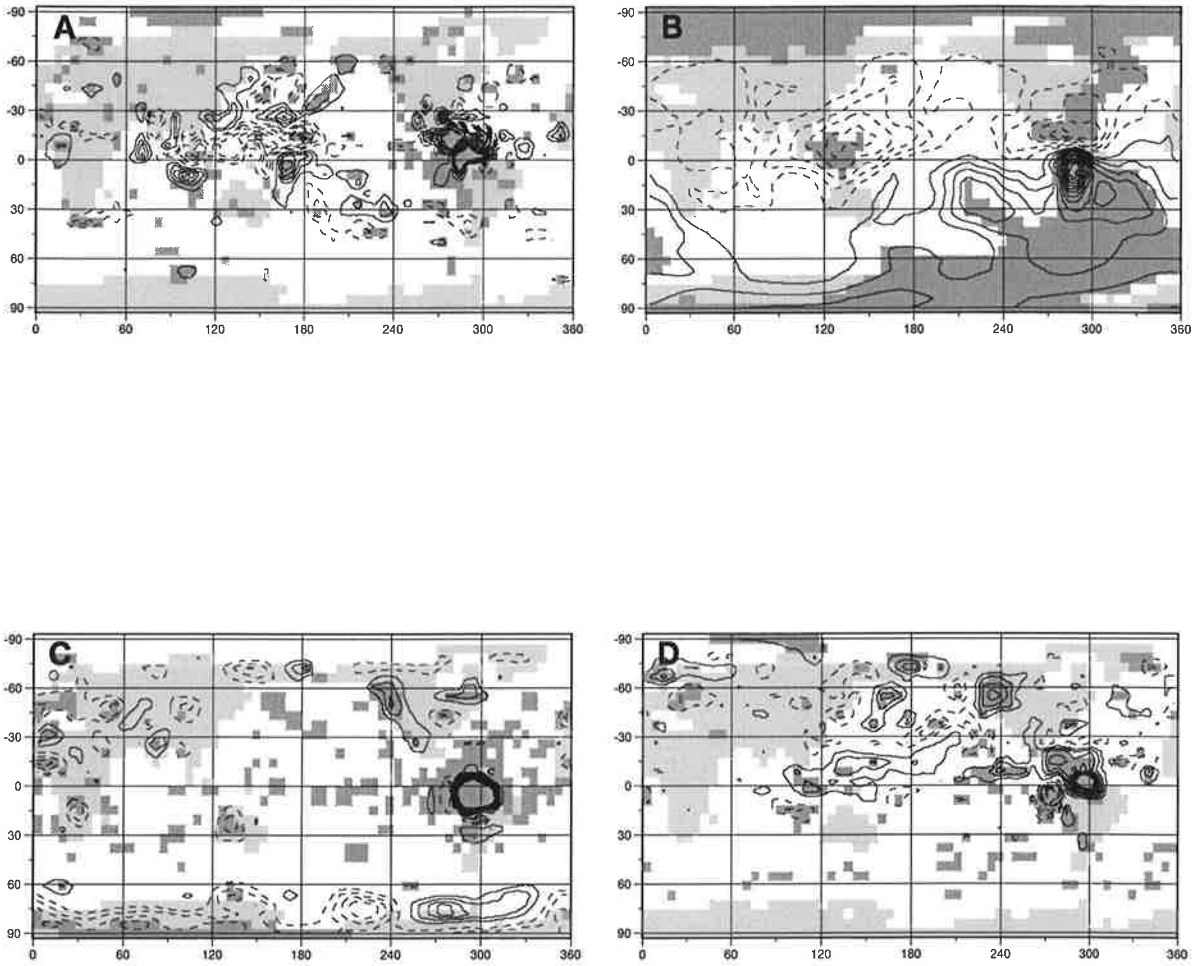

Figure 4: June-August mean climatic change resulting from the removal of deep roots for: A precipitation, B: the circulation (represented by the velocity potential at the 850 hPa level), C: 2m air temperature and D: net solar radiation. Solid (dashed) contour lines denote positive (negative) changes. The changes in velocity potential describe the changes in the divergent wind flow, with negative values representing more divergent winds (or less convergent) and postive values less divergent (or more convergent) winds. Patterns of change for the deforestation simulation are very similar. Significance was assessed using the student's t-test and changes with $p \leq 0.1$ are shown in grey. Land grid points are shaded light grey if no significant change occured. Contour intervals are 0.5 mm/day for A, 0.1 10^6 m^2/s for B, 0.25°C for C, and 5 W/m^2 for D. Changes in air temperature are small over the ocean because of prescribed sea surface temperatures.

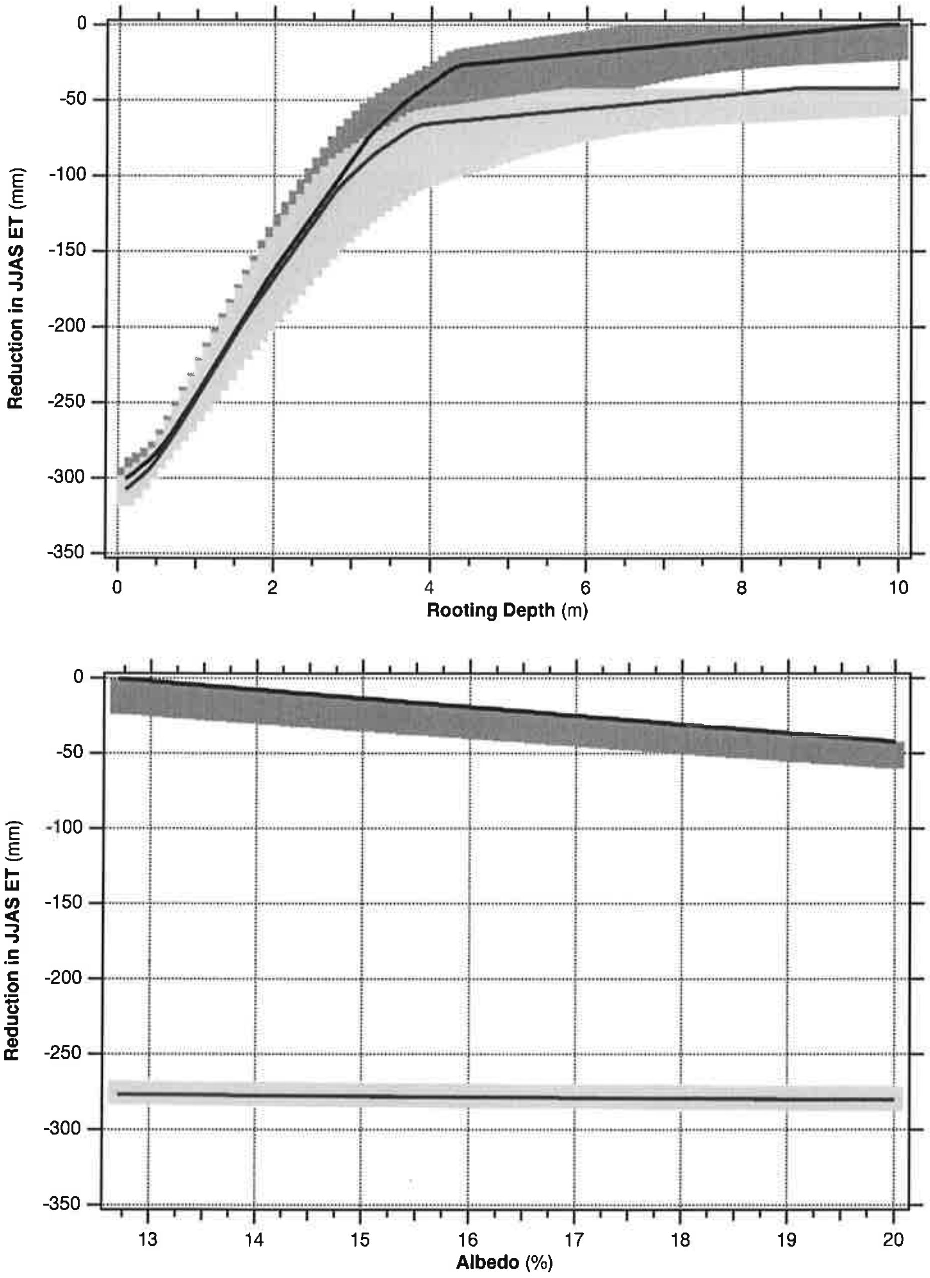

Figure 5: Sensitivity of dry season evapotranspiration (June to September integral) to a more moderate reduction in rooting depth (A) and increase in albedo (B). The sensitivity was computed with a simple budget model which.simulates the seasonal depletion of soil moisture using mean monthly values of precipitation and potential evapotranspiration. It was forced with the simulated climate of the "deep roots" simulation of the climate model. While a reduced rooting depth limits the seasonal soil water storage, an increase in albedo was incorporated by modifying potential evapotranspiration. The black (grey) line represents the sensitivity of one variable when the other is held at the value representing evergreen forest (deforested landscape) respectively. Dark (light) shaded areas indicate uncertainty resulting from errors in the plant available water holding capacity, assumed to be ± 50% of its value.

warming over South America (Fig 4c) also increases this effect in that it causes more thermal convection, which counteracts the atmospheric circulation. However, the effect is somewhat reduced by increased solar radiation due to the reduced cloud cover (Fig 4d).

As a consequence of decreased convection over South America, the Walker circulation across the tropical Pacific is also weakened (Fig 4b) resulting in decreased precipitation (Fig. 4a) and increased solar radiation (Fig. 4d) over Southeast Asia. These changes in the circulation also result in some other remote effects, such as a warming over North America. The changes share some similarities with the patterns found during an ENSO (El Niño/Southern Oscillation) warm event, with the difference that ENSO is a dynamical phenomenon while deforestation persists as a longer term change. We find a consistent strengthening of the Aleutean low pressure system over the North Pacific during the northern hemisphere winter (of about 4hPa, compared to 8-10 hPa during an average warm ENSO event [26]). These patterns are similar to ones reported by complete tropical deforestation studies[12, 14] (that is, where all tropical evergreen forests were removed). However, the ones shown here are distinct in that they can clearly be attributed to the removal of the deep rooted Amazonian forest.

Sensitivity to Parameter Changes

How sensitive is dry season evapotranspiration, as the main driving force for the circulation changes, to the choice of parameters used to represent grassland? We use a simple budget model to assess this question. With this model, the reduction in dry season evapotranspiration (taken as the integral from June to September) is calculated as a continuous function of a uniform rooting depth reduction (Fig. 5a) and albedo increase (Fig. 5b). It can be seen that the reduction of rooting depth to a wide range of values leads to a considerable decrease in dry season evapotranspiration. A change in albedo has its strongest effect in the presence of deep roots and its effect vanishes when the deforested value of rooting depth is used. The sensitivity to rooting depth reduction is likely to be underestimated since short and long term climatic variability as well as decreasing values of plant available water with depth [7] were not considered. The results suggest that similar changes in the circulation (and consequently remote effects) can be expected when the rooting depths in the basin are reduced to more moderate values in the simulation of the deforested landscape.

Conclusions and Implications

We found that the water availability during the dry season - determined by the depth of the root system - is a key component for understanding the regional to global scale implications of Amazonian deforestation. The strong response to rooting depth is a consequence of both, sufficient water availability in the "control" simulation due to the deep roots, and low water availability in the "deforestation" simulation resulting from shallow rooting depth. This is amplified by the low ability of the soil to store plant available water. Remote climatic changes can be understood in terms of a modified circulation, which is primarily attributable to the reduction of dry season evapotranspiration in the southern hemisphere. We conducted the simulations with prescribed sea surface temperatures. If tropical ocean-atmosphere feedbacks were allowed for, these global scale changes might be further intensified. It would therefore be an important step to conduct a simulation with an "active" ocean in future investigations in order to find out about further feedback mechanisms and interactions with ENSO and to assess the credibility of the remote changes.

In contrast, the presence of deep rooted vegetation in Amazonia acts as a large capacitor levelling out the water deficits during the dry season and interannual variability. It thus stabilises the convection over South America and the associated circulation patterns. Since the patterns of change associated with the removal of deep rooted vegetation show strong similarities to those during a warm ENSO event, it may be hypothesised that the Amazonian forest acts against warm ENSO events thus making them possibly less frequent and less severe. Additional information from field studies would be necessary to further substantiate the importance of deep rooted vegetation. The "Large scale Biosphere atmosphere experiment in Amazonia" (LBA) would provide a good opportunitiy to obtain more evidence.

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4.2 The Effect of Deep Rooted Vegetation on the Simulated Climate of an Atmospheric General Circulation Model. Part II: Implications for Amazonian Deforestation[1]

Abstract. In a companion paper we found that deep rooted vegetation affects circulation patterns in the tropics. Here, we use an atmospheric General Circulation Model (GCM) in order to investigate (i) how the climatic impact of deep root removal compares to other surface parameter modifications associated with large-scale tropical deforestation in Amazonia and (ii) whether the changes in the circulation are strong enough to cause remote impacts. The reduction of rooting depth leads to a strong seasonal response, mainly during the dry season of the southern hemisphere. The effects are amplified by positive feedbacks so that changes persist year-round. While the albedo increase contributes to the reduction in dry season evapotranspiration, on an annual basis the changes associated with the albedo increase counteract the changes resulting from rooting depth reduction. We also find significant impacts in regions remote from the deforested area. Most of these impacts can be understood primarily by the reduction of dry-season evapotranspiration of southern Amazonia and a consequent weakening in the tropical circulation patterns. We conclude that deep root removal accounts for the majority of climatic changes associated with large-scale Amazonian deforestation and might cause global scale changes in climate.

1 INTRODUCTION

Numerous studies have been conducted in order to investigate the climatic impacts of large-scale Amazonian deforestation (some recent studies include e.g. Nobre et al. 1991, Henderson-Sellers et al. 1993, Dirmeyer and Shukla 1994, Polcher and Laval 1994, Sud et al. 1996, Zhang et al. 1996a,b, Hahmann and Dickinson 1997, Lean and Rowntree 1997). These studies are all conducted in a similar way in that surface parameters in the climate model are modified in Amazonia from values representing tropical evergreen forest to grassland parameters (in some of the studies, evergreen forests are replaced in all tropical regions within the model). In most of the models a continuous decrease in evapotranspiration was found over the deforested region throughout the year which was attributed mainly to the reduction in net solar radiation at the surface resulting from the increase in albedo. The reduction in the net radiation also caused a decrease in convection and the low level convergence of moisture transport over the region resulting in decreases in precipitation. Most of the changes were confined to the modified region; only the simulations in which all the tropical evergreen forests were replaced, a few remote changes could be identified (e.g. changes in the geopotential height) and they were attributed to a weakening in the Hadley circulation and Rossby wave

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[1] Axel Kleidon and Martin Heimann, Climate Dynamics 1998, submitted (also: Max-Planck-Institut für Meteorologie, Report 249)

propagation (e.g. Zhang et al. 1996b, Sud et al. 1996).

However, all of the studies neglected the effect of deep rooted vegetation in the simulation of present-day climate, which is believed to play an important role in the hydrological cycle in Amazonia, especially during the dry season (Nepstad et al. 1994). Deep roots explore more soil volume and hence more soil water is accessible for dry-season transpiration. In the companion paper (Kleidon and Heimann 1998), we found that the inclusion of the deep roots into the model simulation yields a more consistent behaviour of the model climate in terms of the water budget and near-surface air temperature seasonality especially for regions in the southern hemisphere. Without the inclusion of deeper roots (larger soil water storage capacities) in the simulation of present-day climate, evapotranspiration was found to be too low during the dry season resulting in a strong increase in near-surface air temperatures (e.g. Lean and Rowntree 1993, Hahmann and Dickinson 1997, but also in the standard version of the model used in this study).

How does the climatic response to Amazonian deforestation change when deep rooted vegetation is considered? We concluded in the companion paper (Kleidon and Heimann 1998) that the incorporation of deep rooted vegetation enhances the tropical circulation patterns. If we were to invert this conclusion, we might hypothesise a weakening of the circulation when deep rooted vegetation, for instance by deforestation in Amazonia, were removed which could lead to climatic responses in remote areas far from the deforested region.

The scope of this paper is to test this hypothesis in respect to Amazonian deforestation. We try to assess whether the changes in the circulation are large enough to induce remote impacts but we also want to compare the effect of deep root removal to albedo and other surface parameter changes. In order to do so we conduct a series of sensitivity simulations with an atmospheric GCM. In a first simulation ("shallow roots" simulation), we only reduce rooting depth to values representing grassland while in a second simulation ("increased albedo" simulation), we increase albedo to grassland values. In a third simulation ("shallow roots and increased albedo" simulation), we include both changes (i.e. in rooting depth and albedo) and in a final simulation ("deforestation simulation"), we replace all vegetation parameters by values representing grassland. We take the simulation which includes deep roots (Kleidon and Heimann 1998) as our present-day simulation ("control").

In the GCM model simulations, we assume a large-scale (instantaneous) change from evergreen forest to degraded grassland all over the basin. How is the likely response to more moderate changes in the surface parameters? We try to estimate the sensitivity by a simple offline model which computes evapotranspiration as a function of soil water storage capacity and albedo under a fixed climate.

In the next section, we briefly describe the methods used. The simulated climate over the modified region of the four sensitivity simulations and the control are first compared in section 3 before remote impacts are investigated in section 4. In section 5 we discuss the findings and compare them to the outcome of other investigations. We close this work with a brief overall summary and conclusion in section 6.

2 METHODS

We use the ECHAM 4 GCM (Roeckner et al. 1996) in the T21 resolution (≈ 5.5° latitude * 5.5° longitude) throughout this study. The simulation with deep roots in the tropics (Kleidon and Heimann 1998) serves as our control climate, that is, the climate in the presence of natural vegetation. It was compared to observations in the companion paper (Kleidon and Heimann 1998).

With the help of four sensitivity simulations we try to assess the relative importance of deep roots and its removal in Amazonia in relation to other surface parameters:

- In the "shallow roots" simulation, the rooting depth is reduced to 60 cm. This value is translated into maximum soil water storage with a global data set of plant-available water (PAW) of Batjes (1996).
- In the "increased albedo" simulation, only the surface albedo is increased to a value of 0.20.
- In the "shallow roots + increased albedo" simulation, both of the above changes are incorporated.
- In the "deforestation" simulation, a whole series of surface parameters is changed to values representing degraded grassland (rooting depth to 60 cm, albedo to 0.20, vegetation roughness length to 0.08 m, fraction of vegetation cover to 0.85 and leaf area index to 2.2).

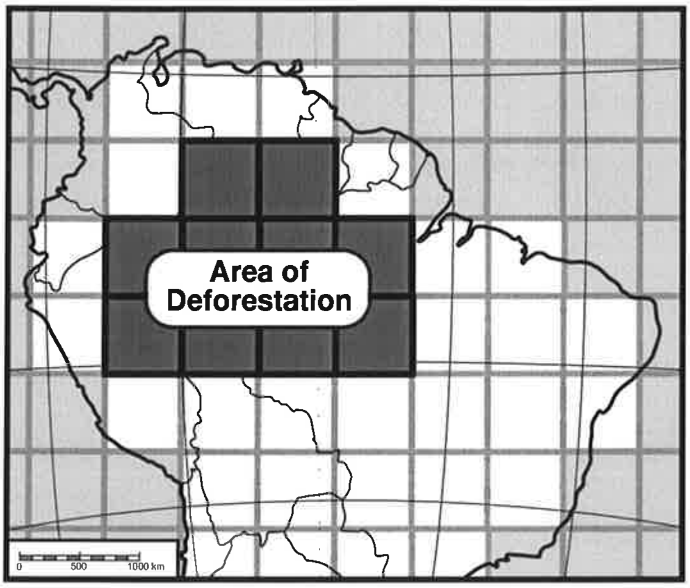

Figure 1 : A map of tropical South America. Shown is the representation of this area by the model and the region where changes in the surface characteristics are applied.

Simulation	**Albedo** (%)	**Rooting Depth** (m)	**Other Parameters**
Control	12.7	9.8	z_0: 1.1, f_V: 0.79, LAI: 6.3
Shallow Roots	12.7 (+0.0)	0.6 (-9.2)	z_0: 1.1, f_V: 0.79, LAI: 6.3
Increased Albedo	20.0 (+7.3)	9.8 (-0.0)	z_0: 1.1, f_V: 0.79, LAI: 6.3
Shallow Roots + Increased Albedo	20.0 (+7.3)	0.6 (-9.2)	z_0: 1.1, f_V: 0.79, LAI: 6.3
Deforestation	20.0 (+7.3)	0.6 (-9.2)	z_0: 0.06, f_V: 0.76, LAI: 2.2

Table 1 : Definitions of the simulations. The values represent basin averages of the surface variables used in each simulation. z_0 stands for the vegetation roughness length, LAI for leaf area index and f_V for the vegetation cover.

The values representing grassland and the region in which these changes take place (shown in Fig. 1) are adapted from Nobre et al. (1991). The values of the surface parameters in each simulation and the changes are summarised in Table 1. All simulations run for 20 years with the first five years discarded in order to avoid spin-up effects. Fixed climatological sea surface temperatures are used in all simulations. A student's t-test is used to assess the significance of all reported changes. The changes are considered significant if the value of the t-test p is less than 0.1.

3 REGIONAL CHANGES

We investigate the changes of the water fluxes and the atmospheric variables over the deforested area in terms of the seasonal cycle of the regional monthly means for each of the simulations. Note that the averaging region (see Fig. 1) crosses the equator so that the changes in part cancel because of opposing dry and wet seasons. The impacts are nevertheless dominated by the southern hemisphere response. A schematical diagram of the impacts of rooting depth reduction and albedo increase during the dry seasons is shown in Fig. 2. These changes are explained in more detail in the following two subsections before the combined impact of rooting depth reduction and albedo increase is investigated. The annual changes in evapotranspiration, precipitation and near-surface air temperature are summarised in Table 2.

3.1 Impact of Rooting Depth Reduction

In the shallow roots simulation, dry-season evapotranspiration is considerably reduced as a direct consequence of the reduction in soil water storage capacity (Fig. 3a). This reduction is most apparent during the southern hemisphere dry season, ranging from May to October. Minor changes occur in the northern hemisphere dry season in January and February. During these months, a consistent warming as reflected in 2m air temperature (Fig. 3d) is found originating mainly from the reduction in the latent heat flux associated with evapotranspiration. The warming causes increased thermally driven convection over the region resulting in lower sea level pressures (Fig. 3f). As a consequence of reduced evapotranspiration, atmospheric moisture content and cloud cover is lower leading to a persistent year-round increase in solar radiation at the surface (Fig. 3e). This increase further enhances warming and convection over the region (a positive feedback). During August, when the changes are strongest, this feedback contributes about 33% of additional energy at the

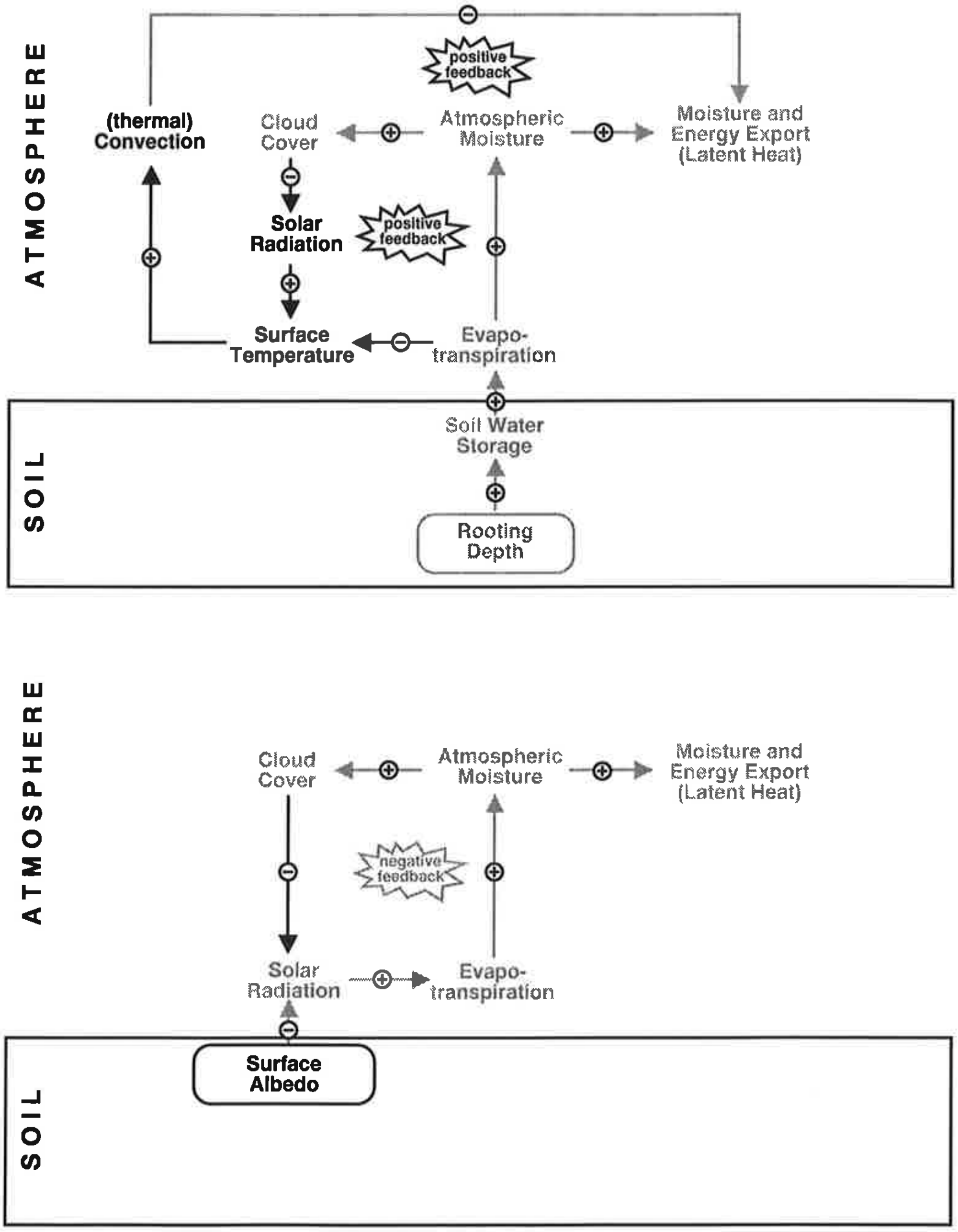

Figure 2: This diagram illustrates the effects of removal of deep rooted vegetation (top) and albedo increase (bottom) in Amazonia on the atmosphere. Quantities in grey (black) decrease (increase) with a decrease (increase) in rooting depth (albedo). A positive (negative) influence of one variable on another is indicated by a plus (minus) sign.

Simulation	ΔT (°C)	ΔP (mm)	ΔE (mm)	Change in Moisture Sink
Shallow Roots	+2.5	+ 50	-383	+
Increased Albedo	-0.0	-194	-106	-
Shallow Roots + Increased Albedo	+2.6	-177	-495	+
Deforestation	**+2.5**	**-140**	**-474**	+
Other Studies				
Nobre et al. (1991)	+2.5	-643	-496	-
Dickinson and Kennedy (1992)	+0.6	-504	-252	-
Henderson-Sellers et al. (1993)	+0.6	-588	-232	-
Polcher and Laval (1994)	-0.1	-186	-128	-
Dirmeyer and Shukla (1994) (Δalbedo = +0)	+2.0	+83	-76	+
Dirmeyer and Shukla (1994) (Δalbedo = +6)	+2.0	-101	-119	-
Dirmeyer and Shukla (1994) (Δalbedo = +9)	+2.0	-245	-137	-
Zhang et al. (1996)	+0.3	-403	-223	-
Sud et al. (1996)	+2.0	-540	-445	-
Hahmann and Dickinson (1997)	+1.0	-363	-149	-
Lean and Rowntree (1997) (increased albedo)	-0.1	-166	-50	-
Lean and Rowntree (1997) (deforestation)	+2.3	-157	-296	+

Table 2: Annual mean changes of the simulations averaged over the deforested region and comparison to the results of some recent studies. Note that in some studies, the temperature change refers to surface temperature change or surface soil temperature change. The changes reported from our study are changes in near surface (2m) air temperature.

surface which cannot be released by latent heat ($\approx$30 W/m^2 in increase in solar radiation compared to $\approx$90 W/m^2 resulting from the decrease in latent heat flux in August). The enhanced convection, as a result of the radiative energy increase, also manifests itself in increased precipitation, mainly during the wet seasons (Fig. 3b). As a result of the changes in evapotranspiration and precipitation, the overall sink of atmospheric moisture is considerably enhanced (Fig. 3c). The seasonal source of moisture (that is, evapotranspiration minus precipitation) during the southern hemisphere dry season is completely diminished since the soil is not capable of holding significant amounts of water which could be recycled by the vegetation. During this time, evapotranspiration is primarily given by the atmospheric input in form of precipitation. The increase in the sink of atmospheric moisture is also associated with a considerable increase in runoff and drainage, so that the total discharge of the basin is increased by 333mm on an annual basis (Table 2).

Naturally, some aspects are neglected when regional averages are considered. For instance, the small decrease in regional evapotranspiration during the northern hemisphere dry season (during December - February) reflects the combination of a strong decrease in the northern parts of the averaging region and a compensating increase in the southern parts which results from the overall increase in solar radiation. This compensating effect, although weaker, also takes place during the respective dry season of the southern hemisphere. The increase in precipitation found in the southern wet season is mainly located in the west of the region while some decreases take place over the southeastern part.

3.2 Impact of Albedo Increase

In the increased albedo simulation, the increase in albedo directly affects the amount of net solar radiation at the surface. A fairly uniform reduction of surface solar radiation can be seen during most parts of the year (Fig. 3e). Since water is not limiting at the surface because of the presence of deep roots, primarily the latent heat flux and evapotranspiration is reduced (Fig. 3a). This reduction does not lead to a change in air temperature (Fig. 3d). The reduction in radiative energy also leads to reduced convection over the area which, in turn, reduces precipitation throughout the year (Fig. 3b). The reduction in convection also manifests itself in a slight increase in sea-level pressure (Fig. 3f). Both, the reduced convection and the reduced water input into the atmosphere by evapotranspiration cause less cloud formation resulting in increased solar radiation at the surface (Fig. 3e), partly offsetting the initial effect of albedo increase (a negative feedback, especially in September). Because precipitation is more strongly affected than evapotranspiration, the overall sink of atmospheric moisture is reduced (Fig. 3c and Table 2). Consequently, runoff and soil drainage are reduced leading to decreased overall river basin discharge by 88mm (Table 2). Nevertheless, the region remains a source of atmospheric moisture during the southern hemisphere dry season as in the control simulation.

In the increased albedo simulation, the regional patterns of change over the deforested area are more uniform than in the shallow roots simulation. Also, the decrease in evapotranspiration is less compensated by other parts of the averaging region than in the case of decreased rooting depth.

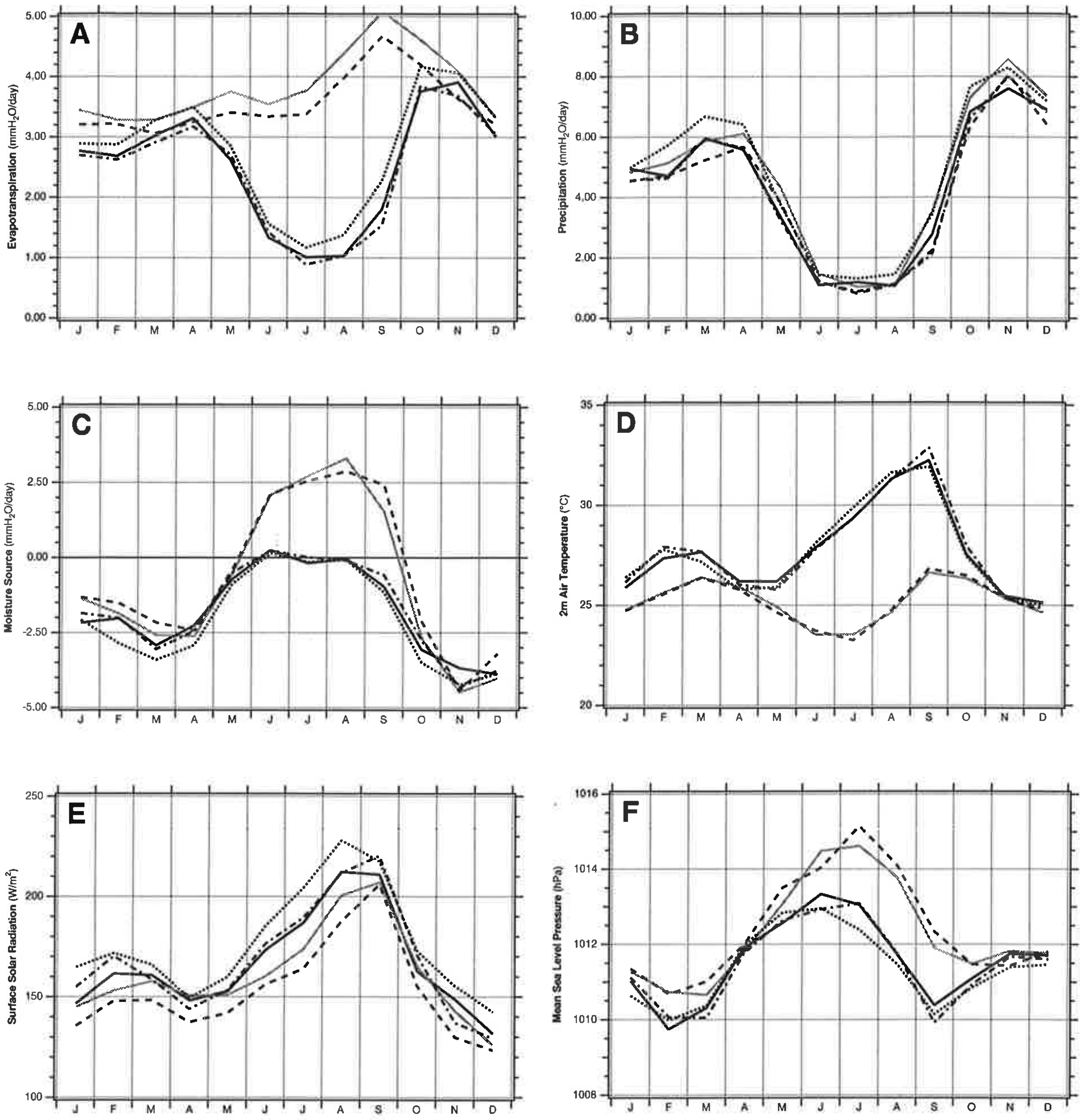

Figure 3: Mean seasonal course of evapotranspiration (a), precipitation (b), moisture source (c), 2m air temperature (d), net solar radiation at the surface (e) and mean sea level pressure (f) averaged over the region shown in Fig. 1. Shown is the seasonal course of the simulation with deep, roots ("control", grey line), shallow roots (dotted line), increased albedo (dashed line), shallow roots and increased albedo (dot-dashed line) and from the complete deforestation simulation (solid line).

3.3 Combined Impact of Rooting Depth Reduction, Albedo Increase and Other Parameters

When both effects (albedo increase and rooting depth reduction) are included, evapotranspiration is further reduced (Fig. 3a). The seasonal course mainly follows the one of the shallow roots simulation, with a fairly constant negative offset resulting from the albedo increase. The fairly uniform reduction with increased albedo is an artefact of the averaging procedure: In June-August, when in the southern hemisphere parts evapotranspiration is restricted by the low dry-season precipitation input and cannot further be reduced, the northern part of the averaging regions experiences the wet season, in which the albedo effect takes place. However, the changes over the whole region mainly reflect the composite effect of the individual changes resulting from shallow roots and increased albedo. While the changes in evapotranspiration add up (see above, Fig. 3a and Table 2), most other changes in part cancel, for instance, precipitation, moisture source, solar radiation and sea-level pressure (Fig. 3b, c, e, f). The response in solar radiation resulting from the positive feedback associated with the shallow roots outcompetes the response to increased albedo, so that in total an overall increase is found. More convection occurs over the region (with lower air pressures, as in the shallow roots simulation), and it is interesting to note, that this does not result in an overall increase in precipitation (Table 2). This can be attributed to the seasonality of the changes: The decrease in rooting depth leads to an increase in convection primarily during the dry season (thermally driven) thus not increasing precipitation by much. In contrast, the increase in albedo reduces the radiative energy for convection year round, but is dominant in the wet season because of the negative feedback during the dry season mentioned above (see section 3.2). The response in terms of atmospheric moisture sink is dominated by the rooting depth reduction. Thus, the total sink activity is enhanced, leading to increased runoff, soil drainage and river basin discharge of 318mm (Table 2).

The overall impact of all parameter changes is very similar to the response of the combined effect of rooting depth reduction and albedo increase. The effects of reduced roughness length and decreased leaf area index do not seem to further contribute substantially to the overall response.

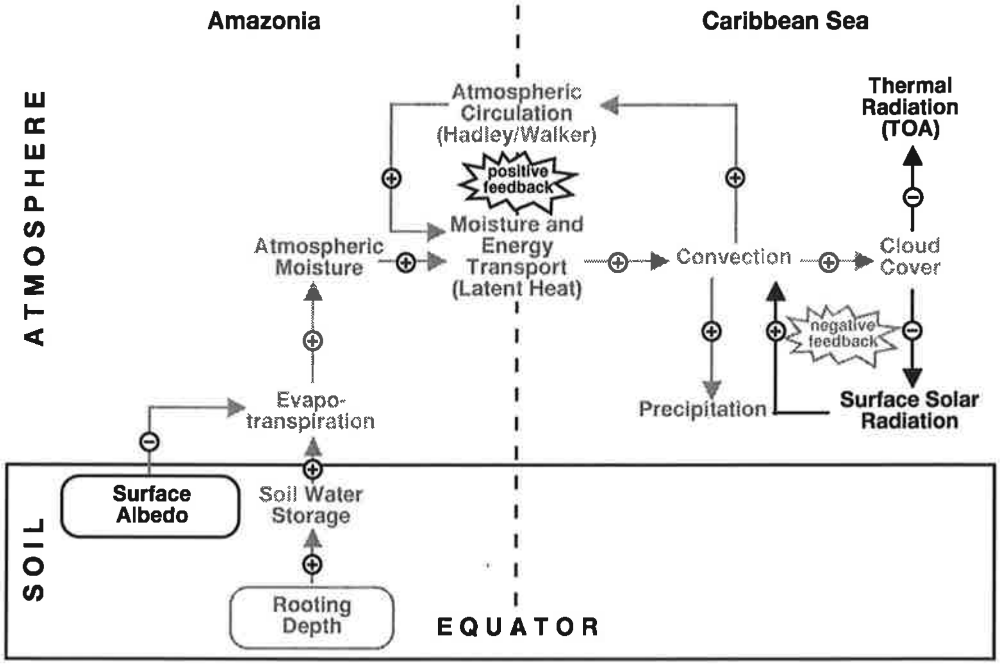

Figure 4: Diagram illustrating the mechanism of how the southern hemisphere dry-season (June - August) changes over Amazonia affect other regions. Quantities in grey (black) decrease (increase) with a decrease (increase) in rooting depth (albedo). A positive (negative) influence of one variable on another is indicated by a plus (minus) sign. Figure modified from Kleidon and Heimann (1998).

4 REMOTE CHANGES

Apart from atmospheric changes over the deforested region, we also find remote impacts, which involves changes in the general tropical circulation patterns. As hypothesised in the introduction, most of the remote effects can be understood with a simple mechanism. A schematic diagram of this mechansim is shown in Fig. 4 which is adapted from Kleidon and Heimann (1998). We start the investigation with the changes occuring during June to August, when the regional changes are strongest.

4.1 Changes during the Southern Dry Season

During June to August (JJA), both changes in parameters, the reduction in rooting depth and the increase in albedo, lead to an overall decrease of basinwide evapotranspiration (Fig. 3a). This decrease leads to a reduction of moisture and latent energy transport towards the

Inter Tropical Convergence Zone (ITCZ) which is located over the Caribbean sea/Northern South America during JJA. Consequently, less energy is available for convection. This reduction in convective activity manifests itself in a large-scale decrease of precipitation, which is apparent in all simulations (Fig. 5a, c, e). This effect is modified by two feedback mechanisms: On the one hand, the reduction in convection leads to reduced cloud cover leading to an increase in net solar radiation at the surface (not shown). This, in turn, partly counteracts the original decrease in energy available for convection. On the other hand, the overall decrease in convection reduces the wind flow towards the ITCZ.

In other words, the Hadley circulation is weakened in this period, which can be seen in the change of the velocity potential (i.e. the potential of divergent wind flow) in Fig. 6. This weakening shows up in a more (less) convergent wind flow over Amazonia (Caribbean sea) at the surface (850 hPa level, Fig. 6a, c, e) and more (less) divergent wind flow in the upper troposphere (200 hPa level, Fig. 6b, d, f) respectively. This pattern is most pronounced in the shallow roots simulation because of two effects: First, dry-season evapotranspiration is more substantially reduced, and second, the reduced moisture export leads to more energy available for thermally driven convection over the deforested region further enhancing the decrease in the Hadley circulation. While the changes in the circulation are just about not significant in some of the simulations, they are consistently present in both atmospheric layers and in all simulations. During this season a large-scale warming over North America can be found, which is less apparent in the increased albedo simulation (Fig. 5b, d, f).

The weakening of the ITCZ during JJA also induces remote impacts. In Fig. 6 we notice that the meridional circulation across the Pacific (Walker circulation) is also reduced, leading to decreased convection and precipitation over southeast Asia (Fig. 5 a, c, e). Again, these changes are just below the significance level but are present in all simulations. Other patterns are also consistently found in all simulations, for instance increased precipitaton over West Africa and decreased 2m air temperature over Europe, Africa and Australia.

4.2 Changes during the Southern Wet Season

We found in the previous section, that the regional changes of rooting depth reduction and albedo increase counteract in terms of net solar energy, especially during the southern hemisphere wet season in December - February (DJF). Consequently, distinct differences occur when the larger-scale patterns of change are investigated.

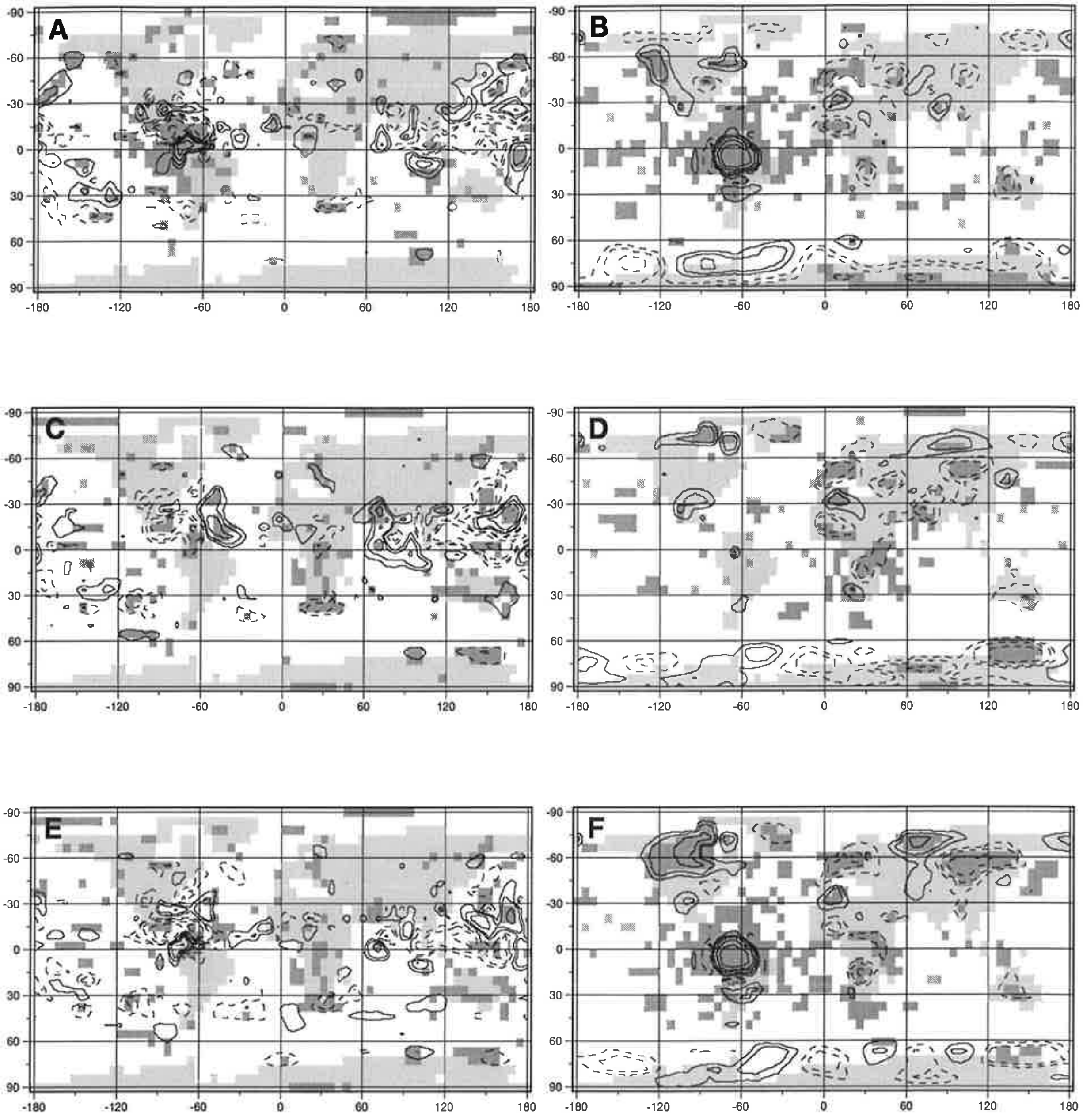

Figure 5: Changes in precipitation (a, c, e) and 2m air temperature (b, d, f) during JJA between the shallow roots simulation and the control (top), increased albedo simulation and the control (middle) and the deforestation simulation and the control (bottom). Solid (dashed) contour lines denote positive (negative) changes. Significant changes are shown in grey (student's t-test, $p \leq 0.10$). Contours are at ± 0.25, 0.5, 1, 2, 4 mm/day for water fluxes and ± 0.25, 0.5, 1, 2, 4 K for air temperature respectively. Zero lines are omitted. Light grey areas indicate land regions in which no significant changes take place. Note that sea surface temperatures are prescribed to their climatological values.

In the shallow roots simulation, convection is increased over Amazonia year round because of more available energy. This increase leads to a significant increase in low-level convergence of wind flow throughout all seasons, which, in DJF, leads to an intensification of the Hadley circulation. During this period, significant increases in precipitation over tropical Africa occur (not shown), which can be attributed to an enhanced Walker circulation across the Atlantic. In contrast, convection over Amazonia is decreased in the increased albedo simulation because of the reduction in net solar radiation. The simulation does not show a decrease in the convergent wind flow in the lower levels as one might expect. In terms of circulation (and associated) changes, the response of the deforestation simulation mainly reflects the effects of the shallow roots simulation.

Although different patterns of changes occur in the tropics, the extratropical response in all simulations is very similar. In the northern hemisphere, a significant strengthening of the Aleutean low pressure system can be found in connection with a PNA pattern (Fig. 7a, c, e). Consequently, large parts of North America exhibit an increase in surface temperature (and a cooling over northern Canada) while the temperatures are lower over Eurasia (Fig. 7b, d, f). A similar excitation of a pressure mode takes place over the Southern Ocean in all simulations.

5 DISCUSSION

In this section, we compare the results to the findings of other studies of Amazonian deforestation. The annual changes of the four sensitivity simulations (compared to the control) are shown in Table 2, together with some other recent investigations.

5.1 Regional Changes

When only albedo is increased, the climatic response is similar to many of the previous studies, that is, an increase in albedo results in a decrease in net solar radiation at the surface throughout the year causing a more or less constant decrease in evapotranspiration. Since the energy input into the atmosphere is reduced, precipitation consequently decreases, with the largest changes occuring during the wet season. In total, the basin-wide sink of atmospheric moisture decreases as it is reported in most of the other studies. The gross of the changes can be attributed to this mechanism (Charney 1975).

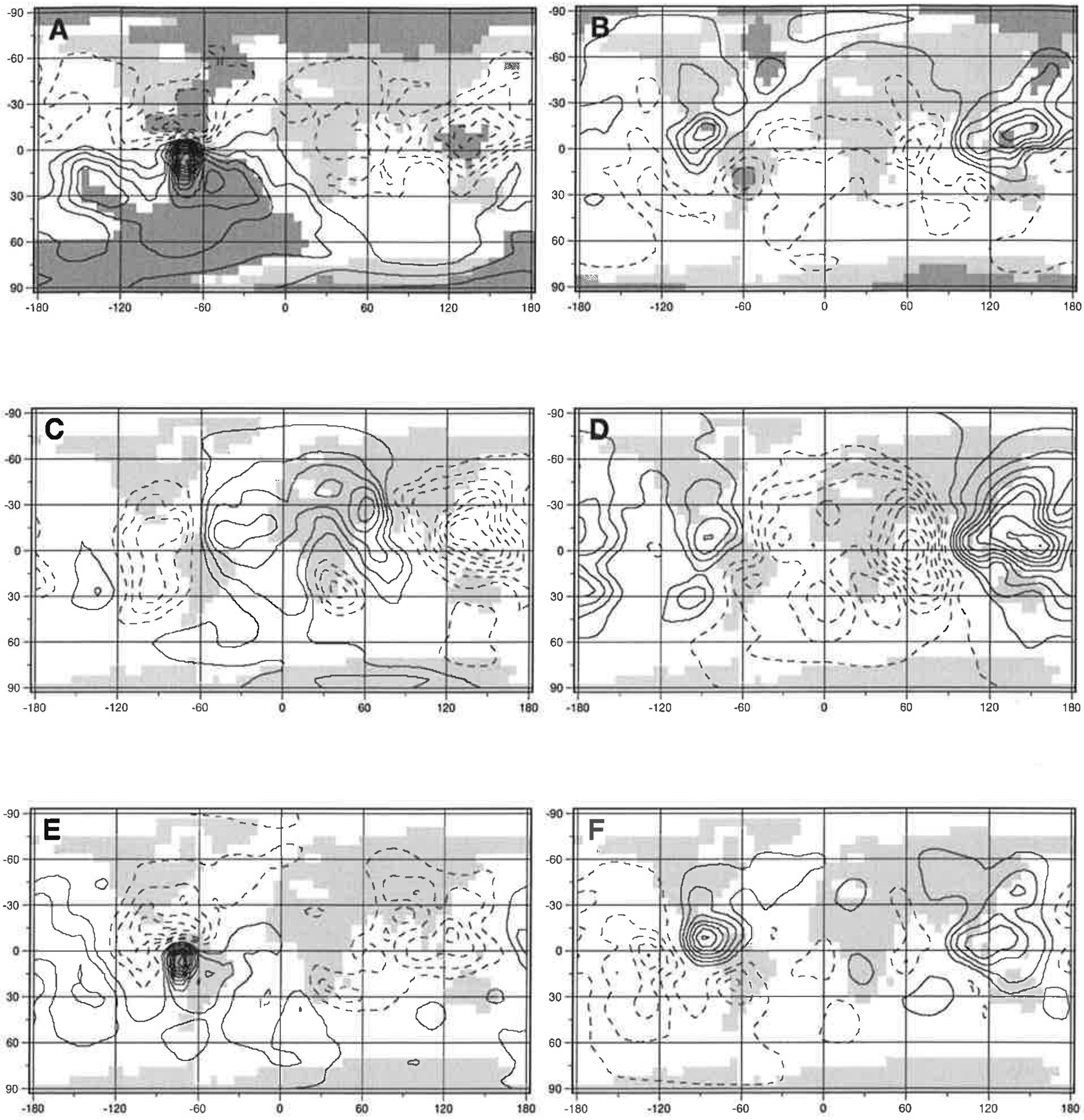

Figure 6: Changes in the circulation represented by changes in the velocity potential at the 850 hPa level (a, c, e) and 200 hPa level (b, d, f) during JJA between the shallow roots simulation and the control (top), increased albedo simulation and the control (middle) and the deforestation simulation and the control (bottom). Solid (dashed) contour lines denote positive (negative) changes. Significant changes are shown in grey (student's t-test, $p \leq 0.10$). Contour interval is 0.1 10^6 m^2/s for the 850 hPa level and 0.2 10^6 m^2/s for the 200 hPa level. Zero lines are omitted. Negative (positive) values indicate enhanced divergent (convergent) wind flow. Light grey areas indicate land regions in which no significant changes take place.

The removal of deep roots shows a much stronger response than all other studies. This can be attributed to two reasons: In some of the other models, rooting depths are simply not deep enough to store sufficient water for the dry season in the control simulation (examples are studies of Lean and Rowntree 1993, and Hahmann and Dickinson 1997). Consequently, no further strong reduction in evapotranspiration can take place during the dry season. On the other hand, some other models show a reasonable course of evapotranspiration even without the presence of deep roots (e.g. Lean and Rowntree 1997). This can be attributed to an overestimation of plant available water (that is the net amount of water stored in the soil per unit depth) more than 200% (they use a value of 240mm, while observed values are as low as 70mm, Hodnett et al. 1995, Batjes 1996). Under their setup, the climatic sensitivity to rooting depth reduction is obviously underestimated.

The simulation of both, the control and the deforested climate, are closest to the results of Lean and Rowntree (1997). However, they claim other processes (increased albedo and decreased infiltration rate) to be the main cause of the response. As mentioned above, changes in rooting depth apparently did not show up in their results since they used exaggerated values of plant available water. The attribution of the changes to the reduction in infiltration rate is dubious since ponding at the surface is presumably not simulated. Their overall response is nevertheless similar to the one reported here, which is not surprising since a reduction in infiltration rate in their simulation resulted in a strong reduction in soil water storage with a consequent decrease in dry season evapotranspiration.

The total response of deforestation found here differs considerably from most of the other studies. The dominant pattern of change over the region (and remote impacts, see below) originates from the reduction in rooting depth. While the effect of albedo increase can be found in the simulations, other parameter modifications (reductions in roughness length and leaf area) hardly show up. This is not surprising since the reduction of soil water storage capacities limit evapotranspiration to an extent to which other parameters cannot much further reduce evapotranspiration. This response is reasonable: For instance, Nepstad et al. (1994) observed that the managed pasture lost all its leaf area during the dry season thus not being able to transpire (the reduction in transpiration should not be seen as a consequence of leaf area loss but rather that the reduction of leaf area reflects the soil water status which in turn is likely the result of a shallow rooting depth).

We also find that most of the changes resulting from the rooting depth reduction counteract the albedo increase. This originates from the nature of the changes: While albedo directly reduces the amount of net solar radiation at the surface, a reduction in rooting depth

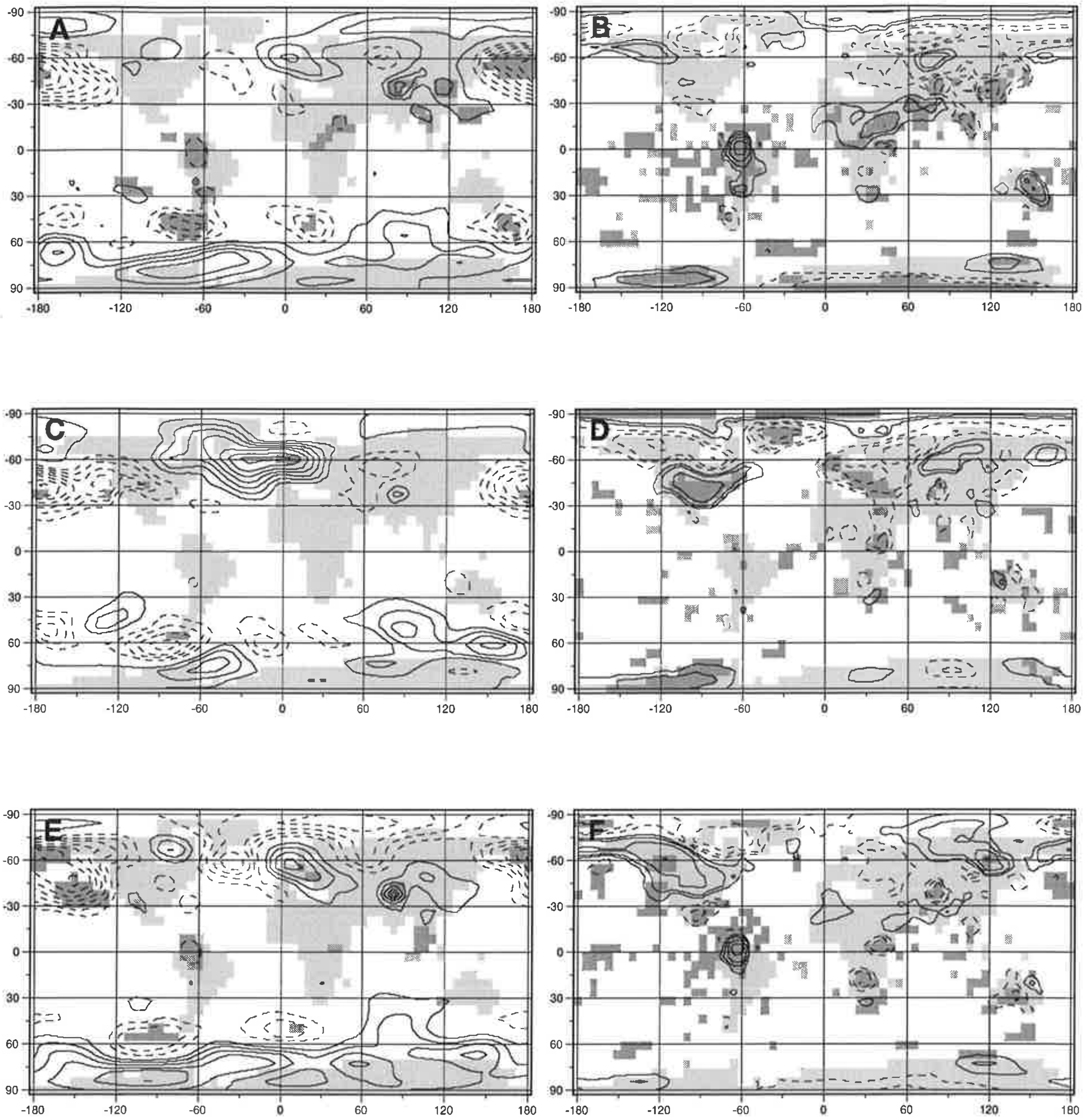

Figure 7: Changes in sea level pressure (a, c, e) and air temperature (b, d, f) during DJF between the shallow roots simulation and the control (top), increased albedo simulation and the control (middle) and the deforestation simulation and the control (bottom). Solid (dashed) contour lines denote positive (negative) changes. Significant changes are shown in grey (student's t-test, $p \leq 0.10$). Contour interval is 0.5 hPa for pressure and at ± 0.25, 0.5, 1, 2, 4 K for air temperature respectively. Zero lines are omitted. Light grey areas indicate land regions in which no significant changes take place. Note that sea surface temperatures are prescribed to their climatological values.

only affects the energy partitioning between latent and sensible heat. In fact, a rooting depth reduction leads to an overall increase in net solar radiation at the surface as a result of the feedback mechansim described in section 3.

The competing effect of albedo increase to other parameter changes (in our case rooting depth reduction) is consistent with the findings of Dirmeyer and Shukla (1994). They found in a deforestation simulation, which already contained other parameter changes, that a moderate increase of albedo led to an increase in precipitation and overall moisture sink over the deforested region (see also Table 2), which they attributed to the same mechanism (i.e. reduced cloud cover).

It is not surprising that the changes of albedo increase and rooting depth reduction counteract. After all, the surface albedo - at least in part - reflects the greenness of the vegetation, which in turn is controlled by the water availability. Thus, in a natural environment changes in albedo and rooting depth do not occur independently from each other. It is rather the difference in ecological survival strategy between evergreen forest and grassland which leads to the changes in the surface parameters. In the case of the evergreen forest, the low albedo reflects the sufficient water availability (and the ability to maintain deep root systems) while grasslands naturally “risk” the disadvantages of periods of water stress, reflected in their shallow dense rooting systems. For grasses, a higher albedo (and consequently less evaporative demand) is beneficial for their survival strategy.

5.2 *Remote Changes*

The remote changes can be explained by the reduction of evapotranspiration during the southern hemisphere dry season, and basically involves the reversal of the mechanism of how deep rooted vegetation affects the circulation described in the companion paper (Kleidon and Heimann 1998). Less moisture is supplied to the ITCZ, so that convective activity is reduced leading to a decreased Hadley circulation. This, in turn, weakens the Walker circulation across the Pacific accompanied with decreases in precipitation in Southeast Asia. Since decreased convection over Southeast Asia is also found during a warm phase of the El-Niño/Southern Oscillation (ENSO), it is not surprising to find a strenghtening of the Aleutean low pressure system and associated effects over the northern hemisphere (which correlate well with ENSO). Note though, that ENSO is a dynamical phenomenon while the change in boundary conditions associated with deforestation are permanent within the model simulation.

During the JJA season, the evapotranspiration changes caused by rooting depth reduction and albedo increase add up so that similar remote impacts can be found in all simulations. Because similar effects are also found during DJF in the extratropics even though the radiative changes counteract in the deforested region, one might speculate that the strengthening of the Aleutean low and other changes in the extratropics originate from the circulation changes found during the southern hemisphere dry season. This also seems plausible since the tropical changes associated with an El Niño event are quite similar to the JJA response, i.e. a weakening of the Walker circulation and decreased convection over Southeast Asia.

A few studies, in which all tropical evergreen forests were replaced, investigated global effects of deforestation (McGuffie et al. 1995, Zhang et al. 1996b, Sud et al. 1996). The results reported here differ in two aspects: First, surface parameters were modified *in Amazonia only*, and can therefore be attributed to originate from this particular region. Since all sensitivity experiments show the same patterns of change, we can be more confident about the significance of the changes. Second, the overall response is opposite to most studies, that is, we find an increase in radiative forcing over Amazonia despite the albedo increase as a result of a cloud feedback process. Nonetheless, we attributed the gross of the remote changes not to the changes in radiation over the deforested area but rather to the reduced evapotranspiration (and moisture export) during the southern hemisphere dry season.

6 THE EFFECTS OF MODERATE PARAMETER CHANGES

The basic assumption of a large-scale complete conversion of tropical evergreen forest into grassland across the whole Amazon basin is surely an exaggeration. Evidently, the outcome of the simulations depends on the choice of the parameter values used to represent grassland in the model simulations. It is therefore interesting to investigate, how sensitive the response of evapotranspiration (as the main driver of remote impacts) is to partial changes in rooting depth and albedo. Since GCM simulations are time consuming, we assess the sensitivity of the evapotranspiration response to the choices made for albedo and rooting depth by a simple budget model. This model simulates evapotranspiration as a function of atmospheric demand and soil water availability.

6.1 *Model Description*

In this model, evapotranspiration is computed as

$$ET = \min[PET, S] \tag{1}$$

with *PET* being potential evapotranspiration (or, more precisely, the evapotranspiration rate that would occur in a non-waterlimited environment) and *S* is the supply rate of the soil for evapotranspiration which is only constrained by the amount of plant available soil water within the rooting zone *W*. For simplicity, the effect of water-stress on evapotranspiration is not considered. The temporal evolution of the soil water content *W* is simulated for plant available water, i.e. between field capacity *FC* and permanent wilting point *PWP* ("bucket model"), according to

$$W(t+\Delta t) = \min[W_{MAX}, W(t) - (ET + P)\Delta t] \tag{2}$$

where *P* is the precipitation occuring during the time step Δt and W_{MAX} is the bucket size, given by

$$W_{MAX} = D \cdot PAW \tag{3}$$

Here, *PAW* is the maximum plant available water per unit soil depth (= *FC* - *PWP*) and *D* is the rooting depth.

This model runs for each of the deforested grid cells (see Fig. 1) on a daily time step in order to integrate (2). The forcing consists of interpolated mean monthly values of precipitation and evapotranspiration (taken as *PET*) from the control simulation of the GCM. The values of *PAW* are identical to the ones used in the GCM simulation (based on Batjes 1996). While modified rooting depth directly affects (3) and consequently the simulation of *W*, the effect of modified albedo *a'* is incorporated by changing *PET* to *PET'*, given by

$$PET' = \frac{1-a'}{1-a} \cdot PET \tag{4}$$

with *a* being the albedo of the control simulation. The underlying assumption in (4) is that the change in net radiation associated with a different albedo directly affects *PET*. Because the forcing is taken from the control simulation of the GCM, atmospheric feedback processes resulting from the parameter changes are neglected.

6.2 *Results and Discussion*

The response for evapotranspiration is computed with the offline model for a series of more moderate parameter changes. Note that this model does not include the feedback mechanisms described in the previous sections. The simple model is nevertheless capable of capturing the basic features of the seasonal changes associated with rooting depth and albedo change (Fig. 8a, c). The magnitude of change is underestimated (compare extreme values in Fig. 8b, d to those in Table 2) because the feedbacks are neglected (especially solar radiation and precipitation).

When rooting depth is reduced uniformly across the basin from the mean value in the control of 9.8m (Table 1) down to 0.6m, the decrease in annual evapotranspiration is first fairly small (Fig. 8b). This can be attributed to the heterogeneity of plant-available water which ranges from 50mm/m to 120mm/m across the basin, so that water limitation sets in at different times and different slopes (see also (3)). From a value of about 4.5m downwards, annual evapotranspiration is reduced considerably stronger, and this change takes place during the dry seasons (Fig. 8a). From this point onwards, water limitation sets in for extended periods across the basin. In fact, this critical value represents roughly the annual mean variation in soil water, and is in the order of the reported value of Nepstad et al (1994), who found a variation of about 500mm in evergreen forest during an extended dry season in 1992. At this lower end, the reduction in annual evapotranspiration is equal to the further decrease in plant available water storage. The start of stronger reduction and the slope might change with added degree of climatic variability. Using a higher albedo, the sensitivity of evapotranspiration to rooting depth is slightly decreased from 325mm down to 275mm.

This scaling behaviour is different (i.e. linear) compared to the logarithmic one reported by Milly and Dunne (1994). This likely results from the fact that their scaling function was obtained from sensitivity simulations, where the standard global "bucket" size distribution of the model was multiplied by different values. By doing so, regions affected more strongly by the "bucket" size are not distinguished from regions in which soil water storage is less important. Here, we use optimised rooting depths in the control simulation and these rooting depths, by definition, are the minimum values needed to avoid water stress. It is thus not surprising that we obtain a different scaling behaviour.

When albedo is increased uniformly across the basin, the mean reduction in annual evapotranspiration is directly proportional to the albedo change (Fig. 8d) which is not

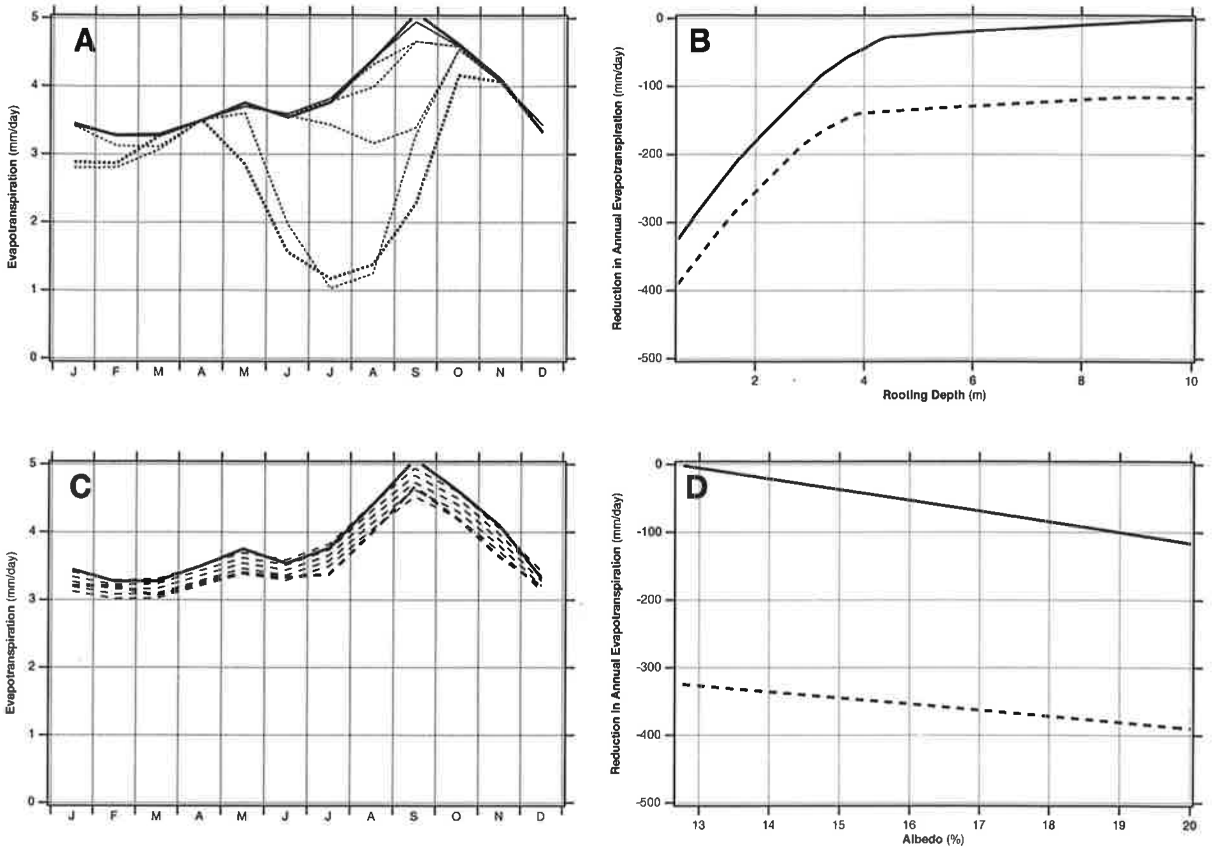

Figure 8: Offline simulation results for regional evapotranspiration with different parameter changes. The simulations of the GCM are shown in thick lines for comparison (solid: control simulation, dotted in (a): shallow roots simulation, dashed in (c): increased albedo simulation). The seasonal course of evapotranspiration for different values of rooting depth (albedo) is shown in a (c), respectively (thin lines, with values of 0.6m (20%) - strongest reduction, 2.9m (18.2%), 5.2m (16.3%), 7.5m (14.5%), 9.8m (12.7%) - no reduction, almost identical to the control simulation). The annual reduction of regional evapotranspiration as a function of rooting depth (with an albedo of 12.7%, solid, and 20%, dashed) and albedo (with a rooting depth of 9.8m, solid, and 0.6m, dashed) is shown in b (d), respectively.

surprising considering the way of how the albedo change is incorporated (see (4)). The annual reduction occurs fairly uniform throughout the year (Fig. 8c). When a shallower rooting depth is used, the slope (and the total sensitivity) decreases from 115mm down to 75mm over the albedo range.

These results stress the importance of soil water storage (and deep roots), which directly affects dry-season evapotranspiration. Any reduction in basin wide soil water storage will lead to some decrease in evapotranspiration (during the southern hemisphere dry season) and thus favour some remote impacts by the mechanism described above. In both cases, the overall sensitivity of the parameter decreases only slightly when the other parameter is modified. This can be explained by the opposing dry and wet seasons across the basin. In the presence of small soil water storages (i.e. shallow roots), the effect of albedo on evapotranspiration primarily occurs in the wet-season regions. Nevertheless, this decrease also contributes to the total, basinwide reduction in evapotranspiration during the southern hemisphere dry season.

6. SUMMARY AND CONCLUSION

We found that the total climatic response resulting from large-scale Amazonian deforestation can be attributed mainly to the reduction in rooting depth. On a regional level, the effect of increased albedo is overruled by a cloud feedback process initiated by the strong reduction in dry-season evapotranspiration caused by the shallow rooting depths. We also detected some significant remote impacts which are similar to those occuring during an ENSO warm phase. These are explained by a mechanism in which the decrease in evapotranspiration during the southern hemisphere dry season is the main driving force. Since increased albedo reduces evapotranspiration, this change adds to the total response even though not as strongly as the reduction in rooting depth. The strength of the effect associated with deep root removal is not surprising. After all, the Amazon basin forms of a large region, and during the southern hemisphere dry season, the presence of deep roots determines whether the surface behaves like an ocean surface or like (semi-) arid land.

All experiments are conducted with fixed sea-surface temperatures. Consequently, climatic variability is likely to be underestimated and ocean-atmosphere interactions are not included. The investigation of such effects would be an interesting task for the future, which would also allow to examine the interactions between deforestation (as a permanent change in forcing) with ENSO (as a dynamical phenomenon) in general. Also not included are possible changes and feedback mechanisms that arise from a transient change from closed evergreen forests over patchy landscape to degraded grassland. Results from the Large scale Biosphere-atmosphere experiment in Amazonia (LBA) might provide sufficient data to associate different stages of deforestation within a region (with similar dimensions as a GCM grid cells) to the appropiate parameter changes in order to conduct such a transient deforestation simulation.

Another unanswered question is whether the deforestation is an irreversible process on time scales of human thinking and acting. Recovery will certainly be slowed by the positive cloud feedback as a response to reduced evapotranspiration, which exposes the vegetation within the deforested landscape to increased atmospheric demand. Also, as hypothesised in the accompanying paper, the loss of biodiversity associated with deforestation might lead to an additional slowdown on recovery. This topic will be another interesting prospect for future investigations.

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Kapitel 5

Abschließende Bemerkungen

1 ZUSAMMENFASSUNG

Das Ziel dieser Arbeit war es, den Einfluß von Wurzeln - in Hinblick auf die Wasseraufnahme aus dem Boden - auf das Klimasystem zu untersuchen. Es wurde in der Einleitung (Kapitel 1) durch eine Reihe von Fragen näher präzesiert. Hier wird versucht, auf diese Fragen mit Hilfe der Ergebnisse der vorangegangenen Kapitel zusammenfassend zu antworten. Dabei wird Wurzeltiefe und die damit verbundene Bodenwasserspeicherung als repräsentativ für Wurzeleigenschaften verstanden.

- **Wie kann man eine globale Verteilung von Wurzeltiefe bestimmen?**

  In Kapitel 2 wurde eine Methode vorgestellt, die es ermöglicht, eine Verteilung von Wurzeltiefe unter Verwendung eines Simulationsmodells der terrestrischen Biogeochemie zu errechnen. Diese Methode basiert auf der Annahme, daß sich die Vegetation optimal an die Umgebung anpaßt. Umgesetzt wird diese Idee, indem wir das Langzeitmittel der simulierten Produktivität als Maß für die optimale Anpassung in Abhängigkeit der Wurzeltiefe maximieren.

- **Wie kann eine solche Verteilung auf ihre Qualität hin getestet werden?**

  Verschiedene Mittel der Überprüfung wurden im Abschnitt 2.1 und im Kapitel 3 verwendet, um die berechnete Wurzeltiefenverteilung zu beurteilen.

  Beobachtete Wurzeltiefen: Als erstes haben wir die berechneten Wurzeltiefen zu Biommittelwerten von Beobachtungen verglichen. Die Übereinstimmung war in der Regel gut, besonders für wasserlimitierte, also überwiegend tropische

Ökosysteme. Der Nachteil dieser Art der Überprüfung ist, daß die eigentlich von der Methode berechnete optimale Verteilung der Bodenwasserspeicherkapazität auch von der Textur abhängt, die stark innerhalb eines Bioms variieren kann. Außerdem repräsentieren beobachtete Werte von Wurzeltiefe nicht notwendigerweise die optimale Anpassung an den Wasserbedarf. Insofern kann diese Art der Überprüfung nur qualitativen Zwecken dienen.

Mittlerer Jahresabfluß großer Flußsysteme: Die Simulation der Bodenhydrologie beinhaltet auch die Simulation von Abfluß (bestehend aus oberirdischem Abfluß und Drainage). Wird der Abfluß über ein Flußeinzugsgebiet und über eine hineichend lange Zeit gemittelt und mit Beobachtungen verglichen, so erhält man Informationen über die Qualität des simulierten hydrologischen Kreislaufs des Einzugsgebiets. Da der Abfluß aus dem Wasser besteht, das nicht verdunstet, gewinnt man dadurch auch eine Aussage über das Verdunstungsverhalten innerhalb dieser Region. Wurde der simulierte Wasserkreislauf des Modells mit fest vorgegebener Wurzeltiefe von einem Meter verglichen mit dem in der Gegenwart von optimierten (tiefen) Wurzeltiefen, so zeigte sich, daß wegen der Zunahme der Verdunstung durch die optimierten Wurzeltiefen der Abfluß von Flußeinzugsgebieten abnahm, was allgemein den Beobachtungen näherkam. Daraus läßt sich indirekt schließen, daß das Verdunstungsverhalten in der Gegenwart optimierter Wurzeltiefen besser simuliert wurde. Nachteil dieser Überprüfungsmethode ist, daß andere Quellen von Verdunstung (z.B. von Feuchtgebieten, Staudämmen und künstlich bewässerten Gebieten) nicht berücksichtigt wurden.

Bodennahe Lufttemperatur: Bei der Anwendung der Methode auf das in das Klimamodell eingebettete "TBM" zeigte sich, daß die bodennahe Lufttemperatur ein guter Indikator für das Verdunstungsverhalten und daher auch der Wasserverfügbarkeit im Boden ist. Der Vergleich mit Beobachtungen auf lokaler und regionaler Ebene zeigte, daß die Modellsimulation mit den optimierten (tiefen) Wurzeltiefen in großen Regionen zu einer wesentlich verbesserten simulierten Saisonalität der Lufttemperatur führte. Andere Landoberflächenparameter, wie z.B. Albedo, wirken kontinuierlich auf die Energiebilanz und können somit diese Überschätzung der Saisonalität nicht beheben. Ein Nachteil dieses Vergleichs ist wiederum, daß andere Quellen von Verdunstung nicht eingeschlossen wurden.

Weitere Möglichkeiten der Überprüfung, auf die in dieser Arbeit nicht weiter eingegangen wurde, sind:

Satellitenbeobachtungen: Die Verwendung vom satellitenbeobachteten Zustand der Vegetation läßt indirekt auf den Wasserstatus der Vegetation schließen. Diese Methode wurde u.a. verwendet von Nepstad et al. (1994) und Knorr (1997).

Saisonalität des Abflußes großer Flußsysteme: Die Saisonalität des Abflußes enthält zusätzliche Informationen über das Verdunstungsverhalten größerer Einzugsgebiete. Um den saisonalen Gang des Abflußes zu simulieren, wird jedoch ein weiteres Modell benötigt, welches den lateralen Abfluß der Flußsysteme simuliert (z.B. Hagemann und Dümenil 1998). Diese Methode wurde wegen der geringen Auflösung des Klimamodells hier nicht benutzt.

- **In welchen Gebieten ist tiefe Bodenwasserspeicherung potentiell wichtig?**

Anhand der Simulationsergebnisse, aber auch durch theoretischen Überlegungen in Abschnitt 2.2, wurde gezeigt, daß die Speicherung von Wasser im Boden nur in der Gegenwart eines saisonalen Klimas in Hinblick auf atmosphärische Wasserverfügbarkeit (also Niederschlag minus potentieller Verdunstung) notwendig ist. Es ist deshalb nicht verwunderlich, daß die Saisonalität einen großen Einfluß auf das Ergebnis der Optimierung hat. Je ausgeprägter die Saisonalität ist, desto größer waren die berechneten optimalen Wurzeltiefen. Zusätzliche Variabilität, ausgedrückt z. B. durch die Länge der Trockenperiode, führt in der Regel zu einer Erhöhung der optimalen Wurzeltiefe. Deshalb sind große Bodenwasserspeicher der Vegetation (erschlossen durch tiefe Wurzeln) überwiegend in Regionen hoher Variabilität und Saisonalität, also überwiegend in den Übergangsregionen zu den humiden Tropen, zu erwarten.

- **Wie wichtig ist Bodenwasserspeicherung auf der globalen Skala?**

Da es weltweit große Gebiete gibt, die ein saisonales Klima bezüglich Wasserverfügbarkeit besitzen, stellt Bodenwasserspeicherung einen wichtigen Prozess dar. Die Bedeutung nimmt mit stärkerer Saisonalität und Variabilität zu und ist daher überwiegend in den Übergangsregionen zu den humiden Tropen wichtig. Die Bedeutung kann aus der Zunahme der Produktivität und der Transpiration abgeschätzt werden, wenn tiefere (optimierte) Wurzeltiefen innerhalb der verwendeten Modelle benutzt werden: In Kapitel 2 nahm die simulierte jährliche globale Nettoprimärproduktion um 16% zu (wobei der Antrieb durch eine beobachtete monatliche Klimatologie gegeben war), in Kapitel 3 um 26% (wobei der Antrieb vom Modell simuliert wurde und dementsprechend auf die verstärkte Verdunstung reagierte). Die Verdunstung nahm jeweils in ähnlicher Größenordnung zu.

- **Welche Rolle spielt Wurzeltiefe im Klimasystem?**

Mit Hilfe eines Klimamodells wurde in Kapitel 3 untersucht, wie sich die Berücksichtigung von tiefen (optimierten) Wurzeltiefen auf das Klima auswirkt. Durch die größeren Bodenwasserspeicher wird in weiten Gebieten mit saisonalen Klimaten der Vegetation ein kontinuierlicher Transpirationsfluß ermöglicht. Damit verbunden ist eine Änderung der Energiebilanz an der Oberfläche hin zu verstärktem latenten Wärmefluß innerhalb der Trockenperioden. Dies hat zur Folge, daß die Saisonalität der bodennahen Lufttemperatur nahezu verschwindet. Vegetation mit tiefen Wurzeln kann daher als großer Kondensator verstanden werden, der Saisonalität ausgleicht. Man kann auch sagen, daß durch Berücksichtigung der tiefen Wurzeln die Landoberfläche - in Bezug auf ihr Verdunstungsverhalten - mehr einer Ozeanoberfläche gleicht.

- **Wie und wie sehr beeinflussen Wurzeln das Klima?**

Im Abschnitt 3.2 wurde ein Mechanismus beschrieben, wie die Zunahme der Transpiration in der Trockenzeit die allgemeine tropische Zirkulation beeinflußt. Die feuchtere Luft wird zu den Konvektionsgebieten transportiert, wo die Freisetzung der zusätzlichen latenten Energie die Konvektion anregt. Dies führt in den Konvektionsgebieten zu einer Erhöhung des Wolkenbedeckungsgrades und des Niederschlags. Dieser Effekt wird durch eine allgemeine Anregung der Zirkulation in Richung der Konvektionsgebiete verstärkt.

Die Stärke des Einflußes zeigt sich z.B. in den Änderungen der Temperatur (lokal) und des Niederschlags (Fernwirkung). Während der Trockenzeit führt die Berücksichtigung von tiefen Wurzeln zu Abkühlungen der bodennahe Lufttemperatur von bis zu 8°C im Monatsmittel. In den Konvektionsgebieten nimmt der Niederschlag um bis zu 2 mm/Tag im saisonalen Mittel zu. Somit können Wurzeleigenschaften stark zu den saisonalen Komponenten einer Klimamodellsimulation beitragen.

- **Was sind die klimatischen Auswirkungen, wenn die tiefwurzelnde Vegetation entfernt wird, z.B. als Folge von Abholzung in Amazonien?**

Zur Untersuchung dieser Frage wurden im Kapitel 4 weitere Simulationen mit dem Klimamodell durchgeführt. Die Entfernung von tiefwurzelnder Vegetation in Amazonien führte zu einer starken Abnahme der Verdunstung und einer großskaligen Erwärmung, überwiegend während der Trockenzeit der Südhemisphäre. Dieser Effekt wurde noch verstärkt durch erhöhte solare Einstrahlung als Folge eines verringerten Wolkenbedeckungsgrades. Neben den regionalen Effekten wurde auch die großskalige Zirkulation in den Tropen verändert. Daraus ergaben sich Klimaänderungen fern vom Abholzungsgebiet. Die Fernwirkungen ähnelten den Mustern eines El-Niño Ereignisses (z.B. Abnahme der Konvektion über Südostasien und Verstärkung des Aleutentiefs). Allerdings ist hierbei zu beachten, daß für die Abschätzung der Auswirkungen amazonischer Abholzung zwei Gleichgewichtszustände des Klimas (jeweils in der Gegenwart von tiefwurzelndem Wald und Grasland) verglichen wurden, während ENSO ein dynamisches Phänomen der Ozean-Atmosphäre Wechselwirkung ist.

- **Wie stark ist der Einfluß von Wurzeleigenschaften im Vergleich zu anderen Landoberflächeneigenschaften und wodurch unterscheidet er sich?**

Die Simulationen von amazonischer Abholzung im Kapitel 4 wurden auch dazu benutzt, den Einfluß von Wurzeltiefenverringerung mit anderen Parameteränderungen zu vergleichen, insbesondere der Albedo. Die Änderungen des regionalen Klimas wurden überwiegend durch die Verringerung der Wurzeltiefe hervorgerufen. Es stellte sich auch heraus, daß die Abnahme der Wolkenbedeckung (als Folge verringerter Verdunstung aufgrund der Wurzeltiefenverringerung) dem Effekt der Albedo entgegenwirkte. Da nur eine Albedoerhöhung aber auch zu einer verringerten Verdunstung während der Trockenperiode in der Südhemisphäre führte, wurden ähnliche Fernwirkungen gefunden wie wenn nur die Wurzeltiefe verringert wird. Änderungen von anderen Vegetationseigenschaften, wie z.B. Rauhigkeitslänge, spielten innerhalb der Simulationen eine untergeordnete Rolle.

Im Gegensatz zu anderen Vegetationsparametern (insbesondere Albedo) zeigt sich der Einfluß von Wurzeltiefe durch ein stark ausgeprägtes saisonales Signal. Während Albedo direkt und kontinuierlich die verfügbare Strahlung an der Oberfläche bestimmt, ändert Wurzeltiefe lediglich die Aufteilung in latente und fühlbare Wärme während Perioden mit Wasserdefizit.

3 SCHLUSSFOLGERUNG

Aufgrund der Ergebnisse der vorangegangenen Kapitel können wir nun folgende Schlußfolgerungen ziehen:

- **Tiefwurzelnde Vegetation stellt einen wichtigen Teil des tropischen Klimasystems dar.** Vegetation mit tiefen Wurzeln gleicht aufgeprägte Saisonalität im Niederschlag aus und läßt die Landoberfläche mehr als eine Ozeanoberfläche erscheinen. Die ungebremste Verdunstung während Trockenperioden hat Auswirkungen auf die Konvektionsaktivität der anderen Hemisphäre und damit auf die allgemeine tropische Zirkulation.

- **Das Vorhandensein tiefwurzelnder Vegetation kann, zumindest zum Teil, durch optimale Anpassung an Wasserbedürfnisse verstanden werden.** Tiefwurzelnde Vegetation erscheint als eine sinnvolle Anpassung an saisonales Klima.

4 OFFENE FRAGEN UND AUSBLICK

- **Hängen die Schlußfolgerungen dieser Arbeit von den verwendeten Modellen ab?**

Obwohl wir die Plausibilität des Einflußes tiefer Wurzeln anhand mehrerer Überprüfungsmethoden aufgezeigt haben, ist es trotzdem sinnvoll zu untersuchen, ob in anderen Modellen die Einführung von tiefen Wurzeln ebenfalls zu Effekten gleicher Größenordnung führt. Die Optimierung wurde auch mit zwei anderen terrestrischen biogeochemischen Modellen durchgeführt: In SILVAN (Kaduk und Heimann 1996) führte die Optimierung zu einer Erhöhung der jährlichen globalen Nettoprimärproduktion (NPP) von 15% mit ähnlichen Mustern wie denen im Abschnitt 2.1. Dies wurde durch die Optimierung des SDBM (Knorr und Heimann 1995) bestätigt (Zunahme der NPP von 10%). Beide Modelle benutzen in ihrer Standardversion Wurzeltiefen von einem Meter. Knorr (1997) führte eine Anpassung der Bodenwasserspeicherkapazität des BETHY Modells an Satellitenbeobachtungen der "Vegetationsgrünheit" durch, was ebenfalls zu einer Zunahme der simulierten NPP von etwa 10% führte. Die auf diese Art bestimmte Verteilung von Bodenwasserspeicherkapazitäten zeigt viele Gemeinsamkeiten mit der durch die Optimierung bestimmten Verteilung.

Die Auswirkungen der Wurzeltiefe auf das Klima scheinen auch nicht ein Resultat der verwendeten Auflösung oder des verwendeten Modells zu sein. Vorläufige Ergebnisse mit dem Klimamodell in einer höheren Auflösung (T42, entsprechend ca. 2.8° * 2.8°) zeigen in der Standardversion eine ähnliche Überschätzung des Jahresgangs der bodennahen Lufttemperatur in den Tropen. Wie bereits im Abschnitt 4.2 erwähnt, zeigen auch andere Klimamodelle diese Überschätzung (z.B. CCM2 (Hahmann und Dickinson 1997), UKMO (Lean and Rowntree 1993)).

- **Wie kann erhöhte Klimavariabilität die Ergebnisse beeinflussen?**

Innerhalb der hier durchgeführten Simulationen wurde die Klimavariabilität eher unterschätzt, da mit vorgeschriebenen, klimatologischen Meeresoberflächentemperaturen ("SST's") gearbeitet wurde. Aufgrund der Ergebnisse der theoretischen Ausführungen im Abschnitt 2.2 könnten die optimierten Wurzeltiefen daher unterschätzt sein. Die Optimierung könnte erneut durchgeführt werden mit einem atmosphärischen Antrieb, der solche Variabilität berücksichtigt.

- **Hat die tropische Vegetation einen Einfluß auf ENSO?**

Der im Abschnitt 3.2 offengelegte Mechanismus, wie tiefwurzelnde Vegetation die tropische Zirkulation verstärkt (und entsprechend bei Abholzung abschwächt), läßt vermuten, daß es Wechselwirkungen mit ENSO (El-Niño/Southern Oscillation) geben könnte. Zum Beispiel gibt es in Ostbrasilien während einer Warmphase ("El-Niño") eine längere, intensivere Trockenperiode. In der Gegenwart von tiefen Wurzeln steht der Vegetation genügend Bodenwasser zur Verfügung, sodaß sich eine solche ausgeprägtere Trockenperiode trotzdem nicht auf die Verdunstung auswirkt (genau dies haben Nepstad et al. (1994) während der 1992 ENSO Warmphase gemessen). Damit stehen den Konvektionsgebieten unveränderte Mengen an latenter Energie zur Verfügung trotz der ausgeprägteren Trockenperiode. Dies könnte möglicherweise der Abschwächung der Walker Zirkulation über dem tropischen Pazifik entgegenwirken und so einen dämpfenden Einfluß auf ENSO haben.

- **Wie kann die Beschreibung der Landoberfläche im Klimamodell verbessert werden?**

Das Konzept des Bodenwassermodells ("Bucket" Modell), welches in verschiedener Weise in dieser Arbeit benutzt wurde, gelangt in der Gegenwart von tiefen Wurzeln an seine Grenzen, da die vertikale Verteilung von Bodenfeuchte nicht berücksichtigt (oder als mit der Tiefe konstant angesehen) wird. Dies führt z.B. zu Problemen, wenn in ariden Gebieten die Regenzeit einsetzt. Nach dem Ende der Trockenzeit füllt sich ein tiefer, fast leerer (da das Gebiet arid ist) "Bucket" langsamer auf, sodaß die Vegetation nach Einsetzen der Regenzeit womöglich innerhalb des Modells weiterhin unter Trockenstreß leidet. Um dies Problem zu lösen, muß die vertikale Verteilung der Bodenfeuchte explizit modelliert werden. Dies wirft dann auch Fragen auf, in wie weit die Wasseraufnahme in einzelnen Bodenschichten von Wurzelbiomasse und -wachstum abhängt. Ein möglicher Ansatz wird im Anhang B gezeigt.

- **Wie kann die Methode verbessert werden?**

Eine gegenwärtige Schwäche der Methode ist, daß eine andere evolutionäre Strategie zur Vermeidung von Wasserknappheit vernachlässigt wird, nämlich das Abwerfen von Blättern. Diese Strategie zeigt sich in Gräsern und Trockenwäldern. Es stellt sich die Frage, ob diese Strategie, also das Abwerfen von Blättern und das Neubilden in der nachfolgenden Regenzeit, "billiger" ist als das Unterhalten eines tiefreichenden Wurzelsystems. Wenn das der Fall ist, könnte diese Strategie berücksichtigt werden, indem die Kohlenstoffkosten von Blättern und Wurzeln gegeneinander abgewogen werden. Ein Ansatz für die Formulierung von Wurzelkosten ist im Anhang B aufgeführt. Unbekannte Parameter innerhalb dieser Kostenformulierungen könnten möglicherweise anhand des Vorkommens von Grasland und Trockenwäldern bestimmt werden.

- **Wie kann die Optimierung des Klimamodells effizienter durchgeführt werden?**

Die Optimierung des gesamten Klimamodells, wie es in Abschnitt 3.1 durchgeführt wurde, ist selbst in der geringen Auflösung sehr rechenintensiv. Es könnte ein effizienteres Verfahren benutzt werden, indem zunächst die Vegetationsproduktivität unter fest vorgegebenen Klima des Standardmodells optimiert wird (ähnlich zu Abschnitt 2.1). Anschließend wird die berechntete Wurzeltiefeverteilung für eine erneute Klimasimulation verwendet. Mit dem so simuliertem Klima wird die Optimierung erneut durchgeführt und das Verfahren wird dann iterativ fortgeführt, bis man einen Gleichgewichtszustand erhält. Ein solches Verfahren wurde z.B. von Claussen (1994) zur Simulierung von Biom-Klima Wechselwirkungen benutzt. Dieses Verfahren ist insbesondere dann effizienter (bezüglich der Rechenzeit), wenn mehrere Parameter optimiert werden sollen (siehe unten).

- **Kann die Methode auch für die Bestimmung anderer Vegetationsparameter benutzt werden?**

Da im Rahmen dieser Arbeit ein Optimierungsansatz erfolgreich zur Bestimmung einer Verteilung von Wurzeltiefe eingesetzt wurde, läßt sich vermuten, daß sich auch andere Landoberflächenparameter mit diesem Ansatz bestimmen ließen, z.B.

Vegetationsbedeckungsgrad oder Albedo. Mit einem Satz von optimierten Parametern läßt sich ermitteln, ob sich Vegetation auch unter anderen Aspekten optimal anpaßt. Ist dies der Fall, so kann diese Methode allgemein dazu dienen, ökologisch sinnvollere Parameter für natürliche Vegetation für das Klimamodell zu bestimmen, insbesondere unter anderen Bedingungen (z.B. Eiszeiten, erhöhter Treibhauseffekt). Allerdings stellt sich bei einer mehrdimensionalen Optimierung auch die Frage nach der Eindeutigkeit der Lösung. Mit zunehmender Komplexität des zu optimierenden Modells erhöht sich womöglich auch der Grad an Redundanz von Parametern.

- **Hängt die optimale Anpassung von der Gegenwart hinreichender Artenvielfalt ab?**

Die Verwendung eines Optimierungsansatzes beantwortet nicht die Frage, wie die Vegetation die optimale Anpassung an ihre Umgebung erzielt. Unlängst wurde gezeigt, daß die Variabilität der Austauschflüsse in Ökosystemen mit höherem Artenreichtum ("biodiversity") geringer ist (z.B. McGrady-Steed et al. 1997), das heißt, daß ein artenreicheres Ökosystem als Ganzes stabiler arbeitet. Diesen Effekt (ausgedrückt in Transpiration und NPP) haben wir auch gefunden, wenn optimierte Wurzeltiefen verwendet wurden. Bedeutet das, daß wir unbewußt ein hinreichendes Maß an Artenreichtum vorausgesetzt haben? Wenn dies der Fall ist, könnte eine Verringerung der Artenvielfalt direkte Folgen auf das Klima haben, neben möglichen Auswirkungen auf die chemische Zusammensetzung der Atmosphäre (z.B. Abschnitt 6.2.4 in Mooney et al. 1995).

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Anhang

Anhang A

Derivation of Analytical Expressions for Optimum Rooting Depth

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1 SOIL WATER DEPLETION UNDER CONSTANT FORCING

In this appendix, optimum rooting depth, or soil water storage, is calculated analytically in two simplified environments. As a first step, the soil water depletion is calculated under constant forcing (i.e. P = const. and PET = const.). We start from the equation of state for the soil water depletion given by the budget equation:

$$\frac{dW}{dt} = P - ET - R \tag{1}$$

The runoff term R is neglected in the following calculations, assuming that runoff consists mainly of drainage and is thus controlled primarily by the extent of the rooting zone. Then, soil water depletion (or recharge) in an unstressed environment is simply given by

$$W(t) = W_0 + (P - PET)(t - t_0) \tag{2}$$

where W_0 is the soil water content at the time t_0. In a stressed environment, ET depends on W, and by using equation (section 2.1 - 4) for ET the following differential equation describes the soil water depletion:

$$\frac{dW}{dt} = P - \frac{W}{\tau} \tag{3}$$

with a decay constant τ given by

$$\tau = \frac{W_{MAX}}{c} \tag{4}$$

Equation (3) can easily be solved by separation of variables, and $W(t)$ is given by

$$W(t) = P\,\tau + \left(W_0 - P\,\tau\right) e^{-\frac{t-t_0}{\tau}} \tag{5}$$

The transition from unstressed to stressed *ET* (or vice versa) takes place at a critical water content W_C, which can be obtained by equating stressed *ET* , given by (2.1 - 4) with *PET*:

$$\begin{aligned} c\frac{W_C}{W_{MAX}} &= PET \\ W_C &= PET\,\tau \end{aligned} \tag{6}$$

2 AN EXAMPLE FOR A SEMIARID/ARID REGION

The expressions for soil water depletion/recharge are now being used to calculate annual *NPP* and then to derive the optimum rooting depth for a semiarid (or arid) environment. This environment is assumed to have a dry period with a length t_2, in which $P = 0$. During the wet period of length t_A - t_2,(with t_A = 1 yr), *P* is constant. *PET* and *PAR* are assumed to be constant throughout the year. Whether $P > PET$ or not does not influence the following derivation; hence it is valid for both, semiarid and arid environments. Furthermore it is assumed that water stressed conditions prevail throughout the year, i.e. $W \le W_C$ at all times, which is reasonable for at least some semiarid/arid environments.

Under these forcings, the evolution of soil water content with time is described by

$$W(t) = \begin{cases} W_0\, e^{-\frac{t-t_0}{\tau}} & ;\ 0 \le t \le t_2 \\ P\,\tau + \left(W_2 - P\,\tau\right) e^{-\frac{t-t_0}{\tau}} & ; t_2 < t < t_A \end{cases} \tag{7}$$

using (5). The soil water contents W_0 and W_2 at the beginning of the dry (wet) season respectively are given by

$$W_0 = P\,\tau + \left(W_2 - P\,\tau\right) e^{-\frac{t_A - t_2}{\tau}}$$
$$W_2 = W_0\, e^{-\frac{t_2}{\tau}} \tag{8}$$

The equations (8) can be solved for W_0 and W_2, and yield the following expressions:

$$W_0 = P\,\tau\, \frac{1 - e^{-(t_A - t_2)/\tau}}{1 - e^{-t_A/\tau}}$$
$$W_2 = P\,\tau\, \frac{e^{-t_2/\tau} - e^{-t_A/\tau}}{1 - e^{-t_A/\tau}} \tag{9}$$

Net primary production during the dry (wet) period NPP_{DRY} (NPP_{WET}) respectively, is calculated by using (2.1 - 2), (2.1 - 3) and (7) from above:

$$\begin{aligned} NPP_{DRY} &= \int_0^{t_2} NPP_{POT} \frac{W(t)}{PET\,\tau}\, dt \\ &= NPP_{POT} \frac{W_0}{PET}\left(1 - e^{-t_2/\tau}\right) \end{aligned}$$

$$\begin{aligned} NPP_{WET} &= \int_{t_2}^{t_A} NPP_{POT} \frac{W(t)}{PET\,\tau}\, dt \\ &= NPP_{POT}\left[\frac{P}{PET}\left(t_A - t_2\right) + \frac{\left(W_2 - P\,\tau\right)}{PET}\left(1 - e^{-(t_A - t_2)/\tau}\right)\right] \end{aligned} \tag{10}$$

where $NPP_{POT} = A\;\; PAR$ is the potential, light limited rate of NPP. When annual NPP is calculated by adding NPP_{DRY} and NPP_{WET} and using the expressions for W_0 and W_2 given by (9), most terms cancel except

$$\begin{aligned} ANPP &= NPP_{POT} \frac{P}{PET}\left(t_A - t_2\right) \\ &= NPP_{POT} \frac{AP}{APET} t_A \end{aligned} \tag{11}$$

with AP and $APET$ (= PET) being the annual mean precipiation (evapotranspiration) rate respectively.

We notice that (11) is independent of W_{MAX} and rooting depth d_R. This is even true when W is allowed to exceed W_C, which can be shown by numerical simulations (it is not possible to show this in an analytical way because of transcendental expressions). Hence, optimum bucket size (and consequently rooting depth) in this simplified environment is the minimum size at which runoff R is just about avoided.

3 AN EXAMPLE FOR A SEMIHUMID REGION

This example makes similar assumptions as above, i.e. the environment is assumed to have a dry period with a length t_2, in which $P = 0$. During the wet period of length t_A - t_2,(with t_A = 1 yr), P is constant. PET and PAR are assumed to be constant during the year. Furthermore it is assumed that conditions are not water stressed during the wet season and that the bucket is filled at the beginning of the dry season (i.e. $W_0 = W_{MAX}$). These assumptions are reasonable, since in a semihumid environment, annual precipitation AP exceeds annual potential evapotranspiration $APET$, which means that runoff must occur during the wet season.

Since ET is unstressed during the wet period, soil water depletion is considered only during the dry period. Using (2) and (5), $W(t)$ is described by

$$W(t)=\begin{cases} W_{MAX}-PET\,t & ;\ 0 \le t \le t_1 \\ W_C\, e^{-\frac{(t-t_1)}{\tau}} & ;t_1 < t < t_2 \end{cases} \tag{12}$$

with t_1 being the time at which water stress sets in. t_1 is determined from $W(t_1) = W_C$ yielding

$$t_1=\frac{W_{MAX}-W_C}{PET}=t_{POT}-\tau \tag{13}$$

where t_{POT} describes the time needed to deplete the bucket at potential rate, τ given by equation (4) and W_C given by (6).

Net primary production during the dry (wet) period NPP_{DRY} (NPP_{WET}) respectively, is calculated by using (2.1 - 2), (2.1 - 3) and (12):

$$
\begin{aligned}
NPP_{DRY} &= \int_0^{t_2} NPP_{POT} \frac{W(t)}{PET\,\tau} dt \\
&= \int_0^{t_1} NPP_{POT} \frac{(W_{MAX} - PET\,t)}{PET\,\tau} dt \\
&\quad + \int_{t_1}^{t_2} NPP_{POT} \frac{W_C\, e^{-(t-t_1)/\tau}}{PET\,\tau} dt \\
&= NPP_{POT}\left(t_1 + \tau\left(1 - e^{-(t_2-t_1)/\tau}\right)\right)
\end{aligned}
$$

$$NPP_{WET} = NPP_{POT}\left(t_A - t_2\right) \tag{14}$$

where $NPP_{POT} = A\ PAR$ is the potential, light limited rate of NPP. In the calculation for NPP_{WET} the assumption is used that ET (and thus NPP) is unstressed during the wet period. Note that it is sufficient to consider NPP_{DRY} for the maximisation of NPP, since NPP_{WET} does not depend on the bucket size.

In order to compute the optimum bucket size, NPP_{DRY} is first rewritten in terms of W_{MAX}:

$$NPP_{DRY} = NPP_{POT} \frac{W_{MAX}}{c}\left(\frac{c}{PET} - e^{c/PET-1}\, e^{-t_2 c/W_{MAX}}\right) \tag{15}$$

NPP_{DRY} does not explicitely depend on the rooting depth D, but only on W_{MAX} (which in turn depends on D). Hence, the maximum of NPP_{DRY} is obtained in terms of W_{MAX}:

$$\frac{\partial NPP_{DRY}}{\partial W_{MAX}} = \frac{NPP_{POT}}{c}\left[\frac{c}{PET} - e^{c/PET-1}\, e^{-t_2 c/W_{MAX}}\left(1 + \frac{t_2\, c}{W_{MAX}}\right)\right] \overset{!}{=} 0 \tag{16}$$

The solution of (16) is given by

$$
\begin{aligned}
W_{MAX,OPT} &= W_C + PET\,t_2 \\
&= c\,t_2\left(\frac{PET}{c - PET}\right)
\end{aligned}
\tag{17}
$$

With this value of W_{MAX}, the value of NPP_{DRY} indeed reaches a maximum value:

$$NPP_{DRY} = NPP_{POT}\, t_2 \tag{18}$$

that is, water stress throughout the dry season is just about avoided. However, since with this W_{MAX}, $t_1 = t_2$, this also means that any other bucket size $W_{MAX} > W_{MAX,OPT}$ also leads to the same value of NPP_{DRY}. This makes it necessary to define the optimum rooting depth as being the least of all possible rooting depths which leads to an optimum in NPP. This restriction is ecologically meaningful: An excessive root system is surely not beneficial for aboveground competition. Clearly, the amount of evapotranspired water during the dry season ET_{DRY} is equal to the unstressed rate, i.e.

$$\begin{aligned} ET_{DRY} &= \int_0^{t_2} ET(t)\,dt \\ &= PET\, t_2 \end{aligned} \tag{19}$$

Anhang B

Simulating Root Carbon Storage with a Coupled Carbon- Water Cycle Root Model[1]

Abstract. Is it possible to estimate carbon allocation to fine roots from the water demands of the vegetation? We assess this question by applying a root model which is based on optimisation principles. The model uses a new formulation of water uptake by fine roots, which is necessary to explicitly take into account the highly dynamic and non-steady process of water uptake. Its carbon dynamics are driven by maximising the water uptake while keeping maintenance costs at a minimum. We apply the model to a site in northern Germany and check averaged vertical fine root biomass distribution against measured data. The model reproduces the observed values fairly well and the approach seems promising. However, more validation is necessary, especially on the predicted dynamics of the root biomass.

1 INTRODUCTION

Carbon stored in the soil forms a major carbon pool of the terrestrial biosphere. This carbon pool is estimated to be around 1500 GtC (Gigatons Carbon, Schimel et al. 1995) and consists of soil organic matter, plant litter and living biomass in form of plant roots. Fine roots are responsible for the water and nutrient uptake and exhibit a high seasonal and spatial variation. While extracting water, the soil dries locally around the root ends which are thought to be the main extraction parts of the root system. Once the water (or nutrient) resources are depleted, the roots either have to grow towards new resources or are disposed. Hence fine roots show a high variation and a substantial amount of annual NPP is invested into the root system to meet the water and nutrient demands of the vegetation.

While most of the aboveground processes are reasonably understood (e.g. photosynthesis, stomata control) little is known about the carbon costs of plant roots. Once having a formulation of these costs, one can approach the problem of carbon allocation in the

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[1] Axel Kleidon and Martin Heiman (1996), Phys. Chem. Earth, **21** (5-6), 499-502 © Elsevier

terrestrial biosphere by optimisation principles which will lead to a more "intelligent" description of the vegetation. Currently most terrestrial biosphere models use a fixed root-shoot ratio to allocate carbon to the above-and belowground carbon pools.

In this paper we suggest a way of modelling carbon costs of roots. We approach this problem with the assumption that the root system is at minimum extent at all times which is necessary to supply the plants with sufficient water for transpiration. A crucial part of this approach is the way of how water extraction of plant roots is modelled. Most approaches to describe the water uptake of roots is based on solving the water diffusion equation under the steady state situation. They also assume a uniform and static distribution of roots within the soil layer and that all parts of the roots contribute to the water uptake in the same way (see e.g. Gardner 1968). As Caldwell (1976) points out, these models fail to reproduce observations, mainly because these models cannot reproduce localized rhizospheric resistances. We use a new approach in which we assume that water is solely extracted by the root ends. This leaves dry areas of soil around the root ends and hence a steady extraction rate can only be maintained when the roots grow.

Using an estimate of potential evapotranspiration for the transpiration demand we determine the amount of carbon that is necessary to be invested to supply the vegetation with sufficient water. We compare the allocated carbon to an observation at a site in Northern Germany to check whether this approach leads to reasonable amounts of allocated carbon.

2 MODEL DESCRIPTION

The root model consists of three components, describing the root structure, water extraction and root dynamics. Daily input data consist of a soil moisture profile, the water demand and the carbon that is available to invest. It returns the transpiration rate for each soil layer, the amount of carbon that is actually invested into the root system and the total carbon allocated to fine roots.

The model closely interacts with the water cycle in the soil. Therefore we need to apply another model that predicts vertical soil moisture distribution. Here we use a simple soil water model based on solving the vertical water diffusion equation. A detailed description of the soil water model is beyond the scope of this paper.

2.1 *Root Structure*

The assumed structure of the root system is rather simple. In each soil layer the root system is described by the number of root ends n and the maximum length of the roots k measured from the centre of the patch. Within the rooted zone (i.e. within the radius k), the root ends are uniformly distributed. The calculation of the carbon stored in such a root system is based on the pipe model approach of Shizuki et al. (1964a,b). Each root tip is connected to the centre of the patch and then to the top of the soil column by a sequence of unit pipes.

2.2 *Water Extraction*

The basic concept we follow is that at the top of the soil column a certain root potential Ψ_R is applied to the root system. This potential is varied such that the overall water uptake from all soil layers is maximised. We neglect transport resistances within the root system and adjust the root potential for each soil layer by the gravitational potential. Within each soil layer we assume that the main extracting parts of the root system are the root ends. The volumetric water content $\theta_{R,i}$ at the surface of the root end in layer i is obtained by the parametrization of the matric potential as it is used by Saxton et al. (1986):

$$\theta_{R,i} = \left(\frac{\Psi_{R,i}}{A_i} \right)^{\frac{1}{B_i}} \tag{1}$$

where A_i and B_i are soil texture dependent parameters.

We then assume that the water content around each root end increases linearly up to a certain radius $r_{2,i}$, which we will call the extraction radius

$$\theta_i(r) = \min\left[\theta_{S,i}; \max\left[\theta_{R,i}; \theta_{R,i} + \frac{\theta_{S,i} - \theta_{R,i}}{r_{2,i} - r_1}(r - r_1) \right]\right] \tag{2}$$

with r_1 being the radius of the root end and $\theta_{S,i}$ being the water content of the soil outside the extraction area. $\theta_{S,i}$ is adjusted in such a way, that the total water content (i.e. eqn. (2) integrated over the soil layer volume) of the soil layer equals the water content of the soil water model (see below). This approximation of the water content around the root ends will allow us to solve the water diffusion toward the root end explicitly, which we will outline in the following. (We will omit the soil layer index i from now on.)

During a time period Δt the extraction radius changes from r_2 to r_2' and the change in soil moisture ΔW around one root end during this time period is given by:

$$\Delta W = \int_{r_1}^{r_2'} \left[\theta(r,r_2) - \theta(r,r_2')\right] 2\pi r \, \Delta z \, dr \tag{3}$$

with Δz being the length of the root end that is active in water uptake, taken to be 1 cm (see e.g. Strasburger 1991). On the other hand, the amount of extracted water is also given the flux from horizontal diffusion using Darcy's law

$$\frac{dW}{dt} = K(r_1)\frac{d\Psi}{d\theta}\frac{d\theta}{dr}A \tag{4}$$

with A being the cross section at the radius r_1 and Ψ the matric potential of the soil. The hydraulic conductivity $K(r_1)$ is parameterised as a function of soil moisture and soil texture as in Saxton et al. (1986). By using the above expressions (2), (3) for θ and ΔW and by using the functional dependance of the matric potential as mentioned above, we obtain a differential equation for the extraction radius r_2, which can be solved analytically.

The overall water uptake during the time period Δt of the root system ΔW_{TOTAL} is given by the amounts of extracted water ΔW_i of each soil layer and is found by varying the root potential Ψ_R such that ΔW_{TOTAL} is maximised. In addition, the root potential is constrained by a maximum potential of 1.5 MPa (see e.g. Larcher 1994) and negative values of the uptake are set to zero.

2.3 *Root Dynamics*

Root dynamics within the model are solely motivated by water demands and maintenance costs. Root growth is initiated if the daily supply of water for transpiration is less than the atmospheric demand. The actual growth is restricted to the carbon which is available to be invested (input parameter). Carbon is allocated in the layer which promises maximum increase in water uptake and it is distributed to branching (i.e. an increase in n) and extension (i.e. an increase in k) in such a way that water uptake is maximised. With an increase in either k or n we adjust the extraction radius such that the total water in the root zone of the soil layer remains constant. Extension of the root system within the layers and in the downward direction is limited by a maximum growth rate of 5 cm/day (see e.g. Köstler et al. 1968).

Maintenance costs for roots are calculated by using a constant cost of 4 10^{-8} gC/(s gC biomass) based on values given by Ryan (1991). Construction costs are taken to be 0.67 gC/(gC new biomass) (Ryan 1991). If the investment of carbon in layer *j* promises a larger uptake than the maintenance of roots in layer *i*, then roots in layer *i* are reduced until the following condition is met

$$\frac{c_{M,i}}{c_{C,j}} W_j \leq U_i \tag{5}$$

with $c_{M,i}$ the maintenance costs of carbon in soil layer *i*, $c_{C,j}$ the total carbon necessary to construct new roots in layer *j*, W_j the increase in water uptake per invested carbon in layer *j* and U_i the water uptake in layer *i*.

3 EXPERIMENTAL SETUP

With the root model we try to reproduce vertical biomass distribution as reported by Scherfose (1990) for a *Pinus sylvestris* stand in northern Germany close to the town of Celle. Therefore we use the same soil layer limits as in the data. The soil at the location is a ferro-humic podsol and the soil texture is described by the author as well as the bimonthly values of precipitation and temperature of a weather station nearby. The soil texture is used by the soil model to parametrise the hydraulic variables (such as $K(\theta)$, $\Psi(\theta)$) according to Saxton et al. (1986) and is driven by the observed climate variables. Evapotranspirational demand is calculated as in Knorr and Heimann(1995) and is splitted according to the fractional cover of the vegetation. The values for the fractional cover are taken from Gallo(1992) for the corresponding grid box. Available carbon, which is required by the root model, is taken as the Net Primary Production at the corresponding grid point from Knorr and Heimann(1995).

The model works on a daily time step. It is initialised with no roots in the soil and is run for 10 years. The forcing is kept the same for each year. A steady state is reached after the first year. Given the vertical soil moisture distribution, as predicted by the soil water model, carbon is allocated to the root system at each time step such that it is capable of meeting the demand. Subsequently the transpiration rates for each soil layer predicted by the root model are fed back to the soil water model.

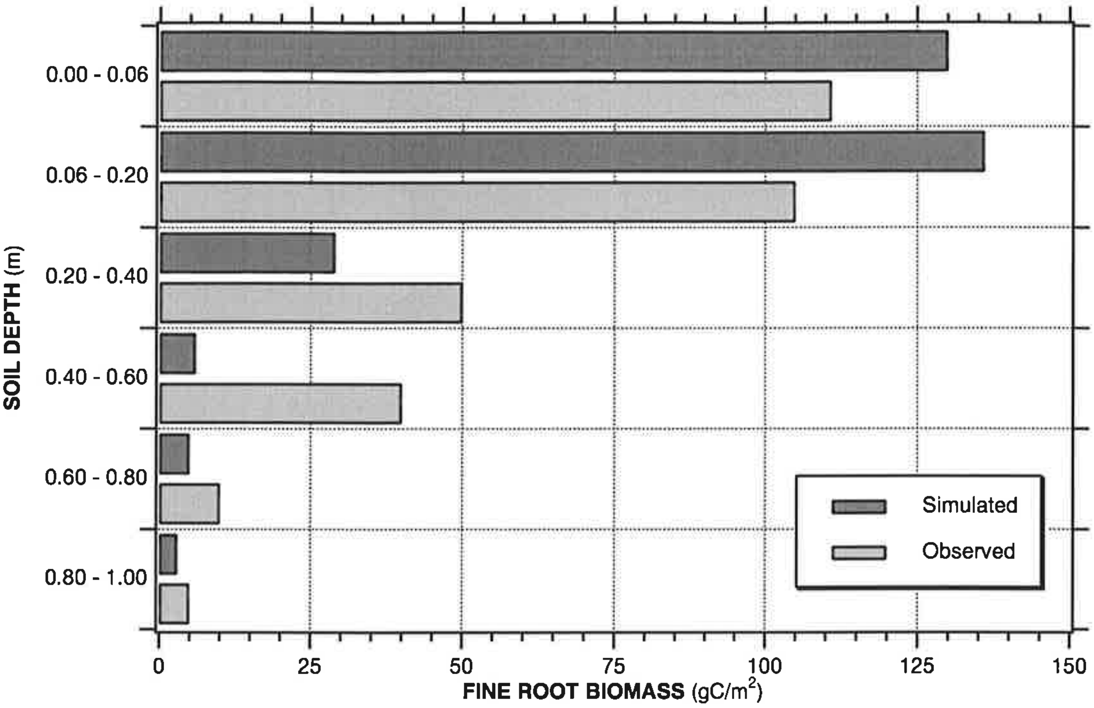

Figure 1: Averaged vertical fine root biomass distribution (simulated and observed).

4 RESULTS AND DISCUSSION

In the following we present two selected results from the model run at the site described above. First, the only tuning parameter in the model (which is the density of roots, or, equivalently, the weight of one unit pipe) is chosen such that the total allocated carbon in the model matches the observation. Best agreement is found for a unit pipe weight of $1.6\ 10^{-3}$ gC/cm. It was found, that a larger value leads to a more flat root biomass distribution with a larger total amount of allocated carbon (which also led to periods of drought stress) and a smaller value to a deeper distribution with an overall lesser amount of allocated carbon.

In Figure 1 we show the vertical distribution of fine root biomass (observed and May/November average of the model output). The simulated profile compares well with the observation. In Figure 2 the predicted root growth activity (monthly averaged) is plotted against the NPP input data. Integrated over the year, 26% of the NPP is invested into fine root production. Also shown in Figure 2 is the root-shoot ratio, i.e. the ratio of root investment to total NPP. Peaks of the root-shoot ratio occur in early spring (March) and in the summer

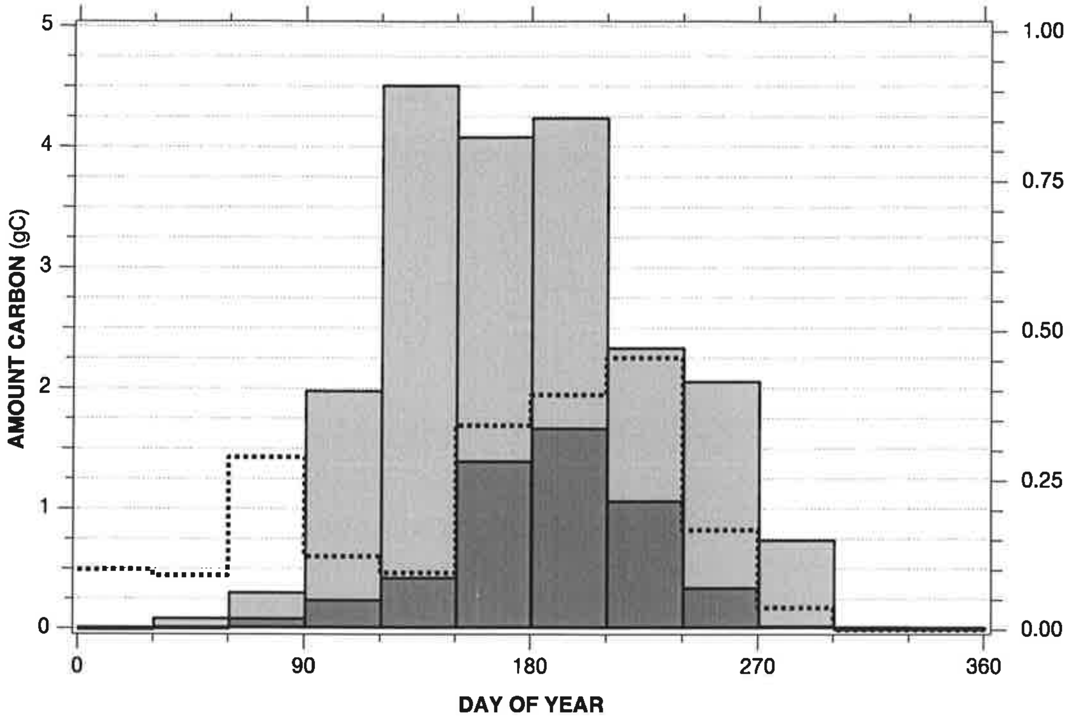

Figure 2: Mean monthly carbon supply (NPP, input, light grey), root investment (dark grey), and Root-Shoot Ratio (dotted line).

months (June - August), when the transpirational demand is high.

We have not yet tested of how sensitive the model reacts to changes in the forcing. For example, one question is whether the carbon input should be constrained to average daily NPP or accumulated NPP over the year. Another problem arises from the monthly averaged input data. The sensitivity of the model (esp. the soil water part) to different ways of obtaining daily input data has not yet been studied. Here we assume for simplicity, that precipitation events take place every third day. We intend to use a stochastic weather generator in the future.

The main problem of applying this model on a global scale or of incorporating it into existing Terrestrial Biosphere Models is the large amount of computing time needed by the various optimisations. Therefore one of the next steps will be to simplify the model without destroying its dynamic character.

5. SUMMARY AND CONCLUSION

We presented a process based model to simulate the dynamics and the water uptake of fine roots. This model is based on a new approach of water uptake by roots, which incorporates the highly dynamic and inhomogenous process of water uptake. Root dynamics are solely motivated by the water demand and maintenance costs. The total fine root biomass is tuned such that it reproduces the observed value. The resulting vertical distribution in the soil compares well with the observation. As an application of the model, we showed the predicted amount of carbon invested into fine roots and the predicted root-shoot ratio.

We conclude that the proposed approach seems promising to obtain information about fine roots without a detailed knowledge of physiological parameters of roots. Applied on a global scale, the model may be used to obtain maps of rooting depths, information about fine root turnover and soil carbon storage.

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