# Irrigated Afforestation of the Sahara and Australian Outback to End Global Warming

Leonard Ornstein

Department of Pathology, Mount Sinai School of Medicine, New York, NY 10029, USA

5 Biltom Road, White Plains, NY 10607, USA

914-592-9622

e-mail: lenornst@pipeline.com


Igor Aleinov

Earth Institute, Columbia University, New York, NY 10025, USA

NASA Goddard Institute for Space Studies

2880 Broadway, New York, NY 10025, USA

212-678-5587

e-mail: ialeinov@giss.nasa.gov


David Rind

Department of Earth and Environmental Science, Columbia University, New York, NY 10025

NASA Goddard Institute for Space Studies

2880 Broadway, New York, NY 10025, USA

212-678-5593

e-mail: drind@giss.nasa.gov

**Abstract**  Each year, irrigated Saharan- and Australian-desert forests could sequester

amounts of atmospheric $CO_2$ at least equal to that from burning fossil fuels.

Without any rain, to capture $CO_2$ produced from gasoline requires adding about

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$1 to the per-gallon pump-price to cover irrigation costs, using reverse osmosis (RO), desalinated, sea water. Such mature technology is economically competitive with the currently favored, untested, power-plant Carbon Capture (and deep underground, or under-ocean) Sequestration (CCS). Afforestation sequesters $CO_2$, mostly as easily stored wood, both from distributed sources (automotive, aviation, etc., that CCS can not address) and from power plants.

Climatological feasibility and sustainability of such irrigated forests, and their potential global impacts are explored using a general circulation model (GCM). Biogeophysical feedback is shown to stimulate considerable rainfall over these forests, reducing desalination and irrigation costs; economic value of marketed, renewable, forest biomass, further reduces costs; and separately, energy conservation also reduces the size of the required forests and therefore their total capital and operating costs. The few negative climate impacts outside of the forests are discussed, with caveats.

If confirmed with other GCMs, such irrigated, subtropical afforestation probably provides the best, near-term route to complete control of green-house-gas-induced, global warming.

# 1      Introduction

About $7.2 \pm 0.3$ Gigatonnes[1] (Gt) of carbon (C) from fossil fuel (estimated for 2000-2005), and an additional increment of about $1.6 \pm 0.9$ GtC/yr (estimated for the 1990's) consumed by burning and/or biodegradation following deforestation and 'land use', have been introduced annually into the atmosphere as $CO_2$ (Alley et al. 2007). About 58% of this (5.3 GtC/yr $\approx$ 19 Gt $CO_2$/yr $\approx$ 2 ppm $CO_2$/yr) presently remains airborne (Hansen and Sato 2004). The rest of the anthropogenic $CO_2$ is absorbed from the atmosphere by the oceans and biosphere (Battle et al. 2000). This increasing atmospheric concentration of $CO_2$, is the major cause of global warming (Hansen et al 1981). Although gradual in its

effects, unabated, it may pose the greatest environmental challenge to humanity since the development of modern civilization.


Afforestation of temperate regions seems to have been rejected as a practical solution to warming because the additional net warming, from albedo decrease, almost cancels the cooling effects produced by the sequestration of $CO_2$ by the trees (Bala et al. 2007).


But afforestation of subtropical regions, with broad-leaf evergreen trees with the potential for 12-month growing-seasons, is entirely another matter. The Sahara and the Australian Outback are two Hadley-Cell deserts; vast, subtropical, continental areas, where human occupation, agricultural food and fiber resources and competing natural biomes are minimal (only the Antarctic land mass is comparably vast and barren). Were either, or both, planted with irrigated forests, very large $CO_2$ sinks would be generated.


In addition to proposing this 'cure', this report will provide a preliminary examination of other possible climatological impacts of such projects, and their potential for sustainability.


## 2      The Model


If we define the Sahara as a swath, about 16° Latitude x 50° Longitude, (sum of the yellow and orange areas in Figure 1a) this encompasses about $9.8 \times 10^8$ ha. At such latitudes, 5 to 8 year-old Eucalyptus plantations of about 1,000 trees/ha can sequester aboveground, net, primary productivity (ANPP), from about 1 to $2 \times 10^7$ g dry mass/ha/yr ($\approx 0.5$ to $1 \times 10^7$ gC/ha/yr). This is achieved with about 1,000 mm/yr precipitation; the variation was attributed largely to differing soil fertility (Stape et al. 2004). Underground

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carbon adds about another 20% to give the total NPP. High-efficiency irrigation (Howell 2001), can be at least twice as efficient as rainfall in delivering water to trees. Such irrigation is scheduled to just replace moisture consumed, so that virtually no losses occur due to runoff at the surface, to the soil below the root zone or to evaporation from wet foliage. This is managed by estimating local evapotranspiration, using either observations derived from satellites, local pan-evaporation or soil-moisture sensors in the root-zone[2]. Therefore, irrigated with about 500 mm/yr, the Sahara might sequester from about 6 to 12 GtC/yr in wood, bark, leaves and roots. Such a forest (of $\approx$100 m-tall trees; e.g., *Eucalyptus grandis*) can accumulate carbon at such a rate for about a century, reaching a steady-state, when photosynthetic $CO_2$ in = respiratory $CO_2$ out. However, within a few decades of planting, a growing portion of such a forest could be harvested (and replanted), ramping up to a yield of about 7.2 GtC/yr, providing a 'forever' renewable carbon source, for marketing at less than the taxed prices of coal, oil and gas. Used for direct burning, conversion to liquid fuel (as a substitute for non-renewable, fossil fuels), conversion to synthetic feed-stock, construction use and/or storage, as credits against the burning of unrenewed biofuels or of fossil fuels, it could solve both the warming problem and the depletion of non-renewable fuels and organic feed-stocks. Ash and other inorganic residues would be recycled to the forest floor.

Such calculations combine a number of measurements with large error bars. The proposed model assumes that 'truth' falls within the approximations of these calculations.

The case for Australia is similar, but the comparable 'desert' has an area about 60% of that of the Sahara.

The Sahara and Australian Outback present tremendous infrastructural challenges. Installation of roads and aqueducts, in some areas might be prohibitive. But

to "end" global warming, only sequestration of something like 7.2 GtC/yr is 'required', if deforestation and land abuse end; otherwise about 8.8 GtC/yr. Therefore, a more selective, culturally-compatible, restricted planting of the forests within the deserts may be possible, avoiding mountains and saline, toxic or other particularly infertile or inaccessible areas. Sufficient area might still remain for even further drawdown of atmospheric $CO_2$, if desired.

But from where will the 500 mm/yr irrigation water come, ($\approx 4.9 \times 10^{12}$ m$^3$/yr for the Sahara, as defined)?  What will it cost? Over and above the global control of atmospheric $CO_2$ buildup and global warming, what will be the climatological consequences of such extensive terraforming: for example, on rainfall within the Sahara; on rainfall in the rest of the world; on Atlantic hurricanes; on the loss of the 'Sahara dust fertilization' of the Atlantic, Amazon and Caribbean; on Atlantic upwellings and the fisheries they support; and on the climate of surrounding countries?

Support for answers to these questions will be sought with simple calculations, with modeling of global climate with such irrigated forests 'installed' (Figure 1a), using the GISS ModelE GCM (Schmidt et al. 2006; Friend and Kiang 2005) and with speculations about other testable models.

2.1    Water and its Cost

Fresh water resources are rare in deserts. Precipitation over much of the Sahara ranges from 0 to only 40 mm per year; and 50 to 300 mm per year over much of the driest part of the Australian Outback.
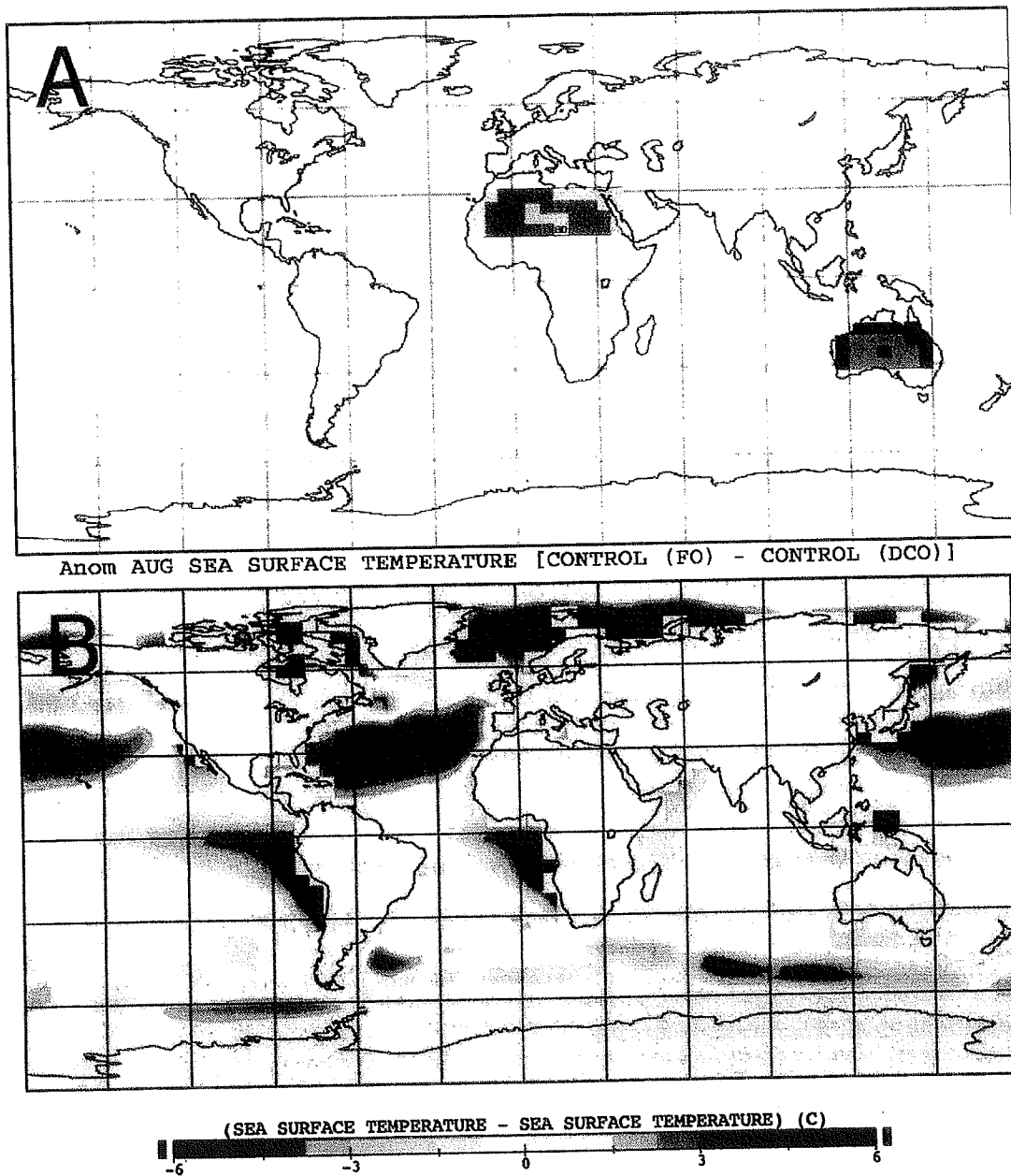
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**AFFORESTATION AREAS**



Anom AUG SEA SURFACE TEMPERATURE [CONTROL (FO) — CONTROL (DCO)]

(SEA SURFACE TEMPERATURE — SEA SURFACE TEMPERATURE) (C)

**Fig. 1** (a) Illustrates which 4° x 5° cells were modified with irrigation and Rain Forest (RF) for GCM runs: Yellow plus orange represent Sahara-Forest only runs [SRF fixed ocean (FO) and SRF dynamic coupled ocean (DCO)]. Red plus magenta represent Australian-Forest only runs [AuRF (FO) and AuRF (DCO)]. Orange plus magenta represent combined Sahara- and Australian-Forest runs [SRF/AuRF (FO) and SRF/AuRF (DCO)]. (b) The difference (anomaly) between the 10-year averages of August sea surface

temperatures (SSTs) of the fixed-ocean-control and the dynamic-ocean-control (both without desert afforestation and irrigation).

Perhaps surprisingly, the world's largest, ground-water aquifers reside beneath the Sahara.

"In the Sahara Desert, the major water resources are the Nubian Sandstone and the North Western Sahara nonrenewable aquifer systems, which extend from Egypt to Mauritania. The Nubian Sandstone Aquifer is a non-rechargeable reserve that was filled up during the humid periods of the pluvial age 8,000 years BC and before. The aquifer is shared by four countries: Egypt, Libya, Sudan, and Chad. Its area covers 2,350,000 km², and it has a maximum reservoir capacity of 150,000 km³ ($1.5 \times 10^{14}$ m3). Geologically, this reservoir is made up of continental sand stones of Mesozoic and Cambro-Ordovician which extends all through the Sahara Desert and the Arab Peninsula (from the Atlantic Ocean to the Arabian Gulf)" (Abu-Zeid et al. 2004)."

The Nubian and other large fossil aquifers are illustrated in Figure 2a (from CEOS TIGER-Workshop 2004). The Iullemeden Aquifer System is shared by Mali, Niger and Nigeria. Some of these were laid down during the Holocene, others 40k and 75k years ago and some during the previous interglacial, about 125k years ago (Zuppi and Sacchi 2004; Beyerle et al. 2003). They are nonrenewable and, at best, could only supply forest irrigation for a few years, to 'prime' a possibly sustainable, biogeophysical-feedback pump (to be discussed).

The only substantial, renewable water-resource in the Sahara is the Nile River. It has an average flow rate of about 2,830 m³/s ($\approx 10^{11}$ m³/yr) (Wikipedia 2007), only a little more than 2% of that required for irrigation of the Sahara Forest, as proposed above.
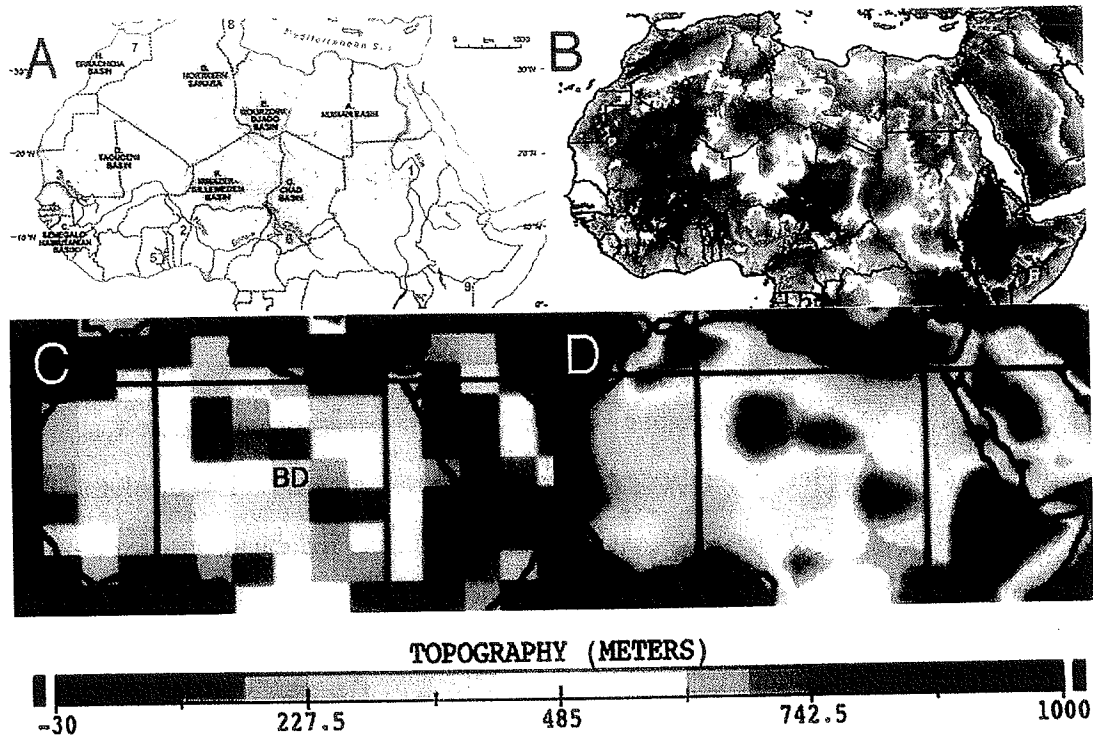
Fig. 2 (a) The distribution of fossil aquifers in northern Africa (Zuppi and Sacchi 2004). (b) A topographic map of northern Africa for comparison with c and d. (c) Raw 4° x 5° representation of the topography, as used by GISS ModelE GCM. The cell which represents the Bodélé Depression is indicated as "BD". (d) The same data as in c, but interpolated to give a better sense of how this level of model resolution represents 'truth'; i.e., b.

By comparison, both the ground- and surface-water-resources of Australia are more limited (e.g., its Great Artesian Basin contains about 8.7 x $10^{12}$ m$^3$ of water (Malkovic 2007)).

In the early 1980s, (Ornstein, Rind, Russell, Stone and Hansen, unpublished)[2], used GISS Model II GCM, with 8° x 10° resolution (Hansen et al. 1983), to model an irrigated, forested Sahara, with low albedo and increased surface roughness to explore the

use of the Saharan fossil aquifers to prime a pump for Charney's biogeophysical positive feedback (Charney et al. 1975). If sufficient, biogeophysically-induced precipitation were distributed relatively uniformly during the year, irrigation might only be required during the early establishment of the forest. Having 'primed the pump', further irrigation (with unrenewable, fossil water) might no longer be required. But if the induced precipitation were seasonal, some irrigation would be needed 'forever'.

As only recently appreciated, 'irrigation' was poorly simulated by the computer code employed in that 1980's experiment; it added irrigation water only at the first time-step. That quickly dissipated, and resulting annual, weak increase in precipitation stimulated north of the Sahel, resulted only from albedo and roughness changes, and was insufficient to maintain the 'pump' – and no 'unlimited' supply of water was in the offing and the experiment was abandoned.

However, the cost of desalination of sea water, using reverse osmosis (RO), has very recently dropped to about $0.53/m$^3$ of fresh water produced, (pumping/pressurizing, 1.58 kWh/m$^3$, reported as half of the cost, and the rest for amortization and maintenance (Service 2006)). Construction of power stations in proximity to, or integrated with, desalination plants provides opportunities for delivery and production savings. And 'waste' heat might be used to separate sodium chloride and most magnesium and calcium sulfate ($\approx$90% of the desalination 'waste') to recover remaining marketable inorganics – some for selective addition back into the irrigation supply, as nutrients.

Powered by sunlight, Eucalyptus trees can sequester about 2 kg of Carbon from about 7.33 kg of atmospheric $CO_2$ for each m3 of water transpired (Stape et al. 2004). Associated with such a broadleaf, evergreen tree, planted and irrigated on a sub-tropical desert, there are four major 'maintenance costs' and one 'one-time' construction cost to

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be considered:

    a. The 'CO$_2$ footprint cost' is about equal to the CO$_2$ footprint of the power

sources used to desalinate and distribute the irrigation water needed to support it.

The energy to pump water from sea level, to an elevation of about 450 m (the

average elevation of the Sahara), with 50% hydraulic and electrical efficiency, is

2.46 kWh/m$^3$. Our above estimate for the power consumed for RO desalination

(1.58 kWh/m$^3$) plus this additional amount for pumping for distribution totals

4.04 kWh/m$^3$. The CO$_2$ footprints of coal and natural gas (*without* Carbon

Capture and Sequestration, CCS) and nuclear power are respectively about 0.7

kgCO$_2$/kWh, 0.4 kgCO$_2$/kWh and 0.0033 kgCO$_2$/kWh (Wikipedia, 2009c).

Thus, the total mitigation provided by irrigated afforestation might be diminished

by CO$_2$ footprints of about 38% with coal power, 22% with gas and 1.8% with

nuclear power.

    b. The cost of electricity, at the power plant, varies from about $0.005/kWh to

$1.60/kWh, (more typically $0.02/kWh to $0.06/kWh) depending upon the kind

of power used (Wikipedia 2009d). This includes interest and amortization.

Therefore, the 4.04 kWh/m$^3$ (for sequestering 7.33 kg CO$_2$ in irrigated trees)

varies from about $0.02 to $6.50 ($2.73/tonne of CO$_2$ to $890/tonne of CO$_2$).

*The value of the potentially-marketable carbon, sequestered by the trees, could*

*reduce the net cost substantially.*

    c. The costs of maintenance, interest and amortization of the desalination plants

(about equal to the power costs), and of the aqueducts and irrigation systems (to

be determined, but probably a small percentage of the power costs) must be

added.

    d. The intangible costs of risks of possible leakage of stored CCS-CO$_2$; leakage

of radioactive wastes; of nuclear proliferation; of air pollution; of accelerated deforestation; etc. must be considered.

e. A one-time, $CO_2$ footprint for construction of power plants, RO plants and aqueducts also must be taken into account, 'amortized' over the *very long life* of such structures.

To provide substantial mitigation, it will be desirable to power RO plants and pumping stations with low, or 'negative', $CO_2$-footprint, electrical power plants: nuclear; coal-fired with CCS; sustainably-harvested wood-fired (e.g., Ornstein 2009), with or without CCS; hydropower; solar; wind; tidal; geothermal; etc. Which few types might entail the lowest dollar cost and lowest risks, at various locations along the coasts of North Africa and Australia, remains to be determined.

*But generally, the larger the average biogeophysically-induced rainfall, the smaller will be all five costs – particularly the power costs.*

The $CO_2$ from the burning of most oil, gas and gasoline enters the atmosphere from widely distributed, point emitters, incompatible with local capture. The price of a gallon of gasoline is a useful frame of reference for the current cost of energy. Because the supplies of oil are being depleted rapidly, that price now usually is increasing. A gallon of gasoline contains about 2.3 kg of Carbon. Therefore, forest sequestration of the $CO_2$, produced by the burning of a gallon of "gas", could cost as little as $0.61 in desalination costs. With electric power at about $0.10/kWh, delivered, that raises the combined steady-state desalination and distribution pumping costs to about $0.87 per gallon of "gas". ($0.10/kWhr is generous, if desalination plants and their power sources are built in proximity, as suggested above, since *delivered* costs for nuclear- and coal-

generated electricity run between about \$0.04 and \$0.06/kWh (Wikipedia 2007b),) (Another way to look at it, using energy costs rather than 'dollar' costs: to produce and deliver 1 $m^3$ of irrigation water to the Sahara therefore requires something like $14 \times 10^6$ Joules.) Such an amount might be viewed as a new "tax" to be tacked on, at the pump, as the cost to recapture the $CO_2$ produced as exhaust. (Note: since the energy to lift water increases almost linearly with elevation, the cost of pumping ground water exceeds that for desalination, as the depth of aquifers approaches 1,000 meters.) An undetermined small amount, per $m^3$ of water delivered, also must be added (at subsidized – as is often the case for 'agricultural' water-supply systems – or free-market prices). This would cover interest, amortization and maintenance costs for aqueduct and irrigation, distribution and pumping hardware, (with high conveyance and irrigation efficiencies (Howell 2003)).

To provide a somewhat different, economic perspective, we will examine costs from the frame of reference of the familiar 'barrel of crude'. A barrel of crude oil contains about 110 kg of carbon (0.11 tC/bl). The current cost of capturing approximately 90% of the $CO_2$ from flue gas of yet-to-be-built, coal-fired, electric power plants, and pumping it underground, or under the ocean, (CCS), is between \$100 and \$300/tC, (estimated by the Congressional Research Service; Folger 2007) ($\approx$ \$10/bl to \$30/bl). This raises the effective cost of burning coal towards about half the 'present' price of oil. British estimates of CCS costs run about twice as high (Gough and Shackley 2005). On the other hand, forest sequestration of the carbon, produced by the burning of a barrel of crude oil, could cost as little as \$30/bl in desalination costs. Adding distribution pumping costs, that increases to about \$43/bl. But CCS $CO_2$ is (hopefully) buried 'forever', and represents a total economic loss, whereas that captured by trees is mostly safe and useful, reduced carbon; a valuable product 'in the bank'. Effectively, this doubles the savings for photosynthetic sequestration relative to CCS; and it could capture an amount equal to

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100% of all the $CO_2$ currently released. This makes sub-tropical afforestation a more attractive 'solution' to warming. It adds a "tax" per unit $CO_2$, comparable to, but probably less than the added CCS cost per unit $CO_2$ from coal. And large-scale, RO-desalination and irrigation involve relatively mature technologies, whereas those of CCS are only beginning to be designed.

*If the total volume of water required for irrigation can be reduced substantially, through biogeophysical-feedback-induced precipitation* (Charney et al. 1975), the afforestation of subtropical deserts will gain *additional* economic advantage over CCS. Such possibilities will be explored next.

## 3      Modeling Biogeophysical Feedback

We now appreciated that we needed better irrigation code than we used in the 1980's.

We use the GISS GCM ModelE,[6] which provides 4° latitude by 5° longitude resolution (Schmidt et al. 2006). In the first of these irrigated rain forest experiments we replaced parts of the Sahara (yellow and orange areas in Figure 1a) with an evergreen, tropical-rain-forest, vegetation type and also changed the corresponding desert soil to a composition typical for rain forests. [Figures 2c and 2d illustrate the actual resolution of the model's topography and its interpolated representation (for a comparison Figures 2b shows "real world" topography). Note: all model computations use the equivalent of the 2c representation – uninterpolated.] The 'land properties' were changed. Surface albedo was decreased to that of evergreen, tropical-rain-forest vegetation with prescribed seasonal variation according to this vegetation type. Among other things, this defines the rate of evapotranspiration. The surface roughness was increased to match that of tropical rain forest; and the desert soil type was 'replaced' with the soil type for a rain forest

'cell'. ModelE employs a photosynthetic model as described by Friend and Kiang (2005), which allows us to compute gross primary productivity (GPP). At the start of the experiment the wetness of the "desert rain forest" soil was set to the value typical for a rain forest, close to saturation. At each time step (1/2 hour) the soil water content was checked, and if lower than this initial value, irrigation water was added under the trees to bring it back to a "rain forest" level (this is an equivalent to a "very high-efficiency irrigation" regime).

Typically, the program is run for 20 years; 10 for spin-up, and 10 for data collection. Most run-outputs were for the decade, 1991-2000. 10-year monthly- or 10-year-annual averages are illustrated. Raw output data are usually graphically interpolated[7].

Two separate models of the oceans are utilized:

1.                                    A Fixed Ocean (FO), which uses interpolated, 10-year (1991-2000), monthly averages of the known sea surface temperatures (SSTs) and sea ice distribution – the same set, repeated each year. The FO model was run with fixed, pre-industrial (1880) atmospheric, trace-gas forcings (the same each year). (With fixed, realistic SSTs, model results are not very sensitive to the known differences in atmospheric, trace-gas forcings from 1880 to 2000.)

2.                                    Russell's Dynamic Coupled Ocean model (DCO) (Russell et al. 1995), that includes atmosphere-to-ocean interactions which may locally or globally increase or decrease effects seen with the FO. The DCO model was run with historical atmospheric forcings (i.e., different each

year).

The 1990s were characterized by four El Niño events; 1991 (strong), 1992 (moderate), 1994 (moderate), and 1997 (very strong) and one La Niña event, 1998 (strong); and this decade was also characterized as a 'warm phase' of the North Atlantic Oscillation during which the subtropical and tropical northern Atlantic averaged about 0.5° C warmer than average (Rodwell and Folland 2003; Kerr 2000; Null 2004).

So otherwise identical runs made with FO and DCO can be expected to show some differences which mainly relate both to atmosphere-to-ocean, interaction biases associated with the differences in their ocean representations and any inadequacies related to the nature of the approximations built into their designs. Figure 1b, illustrates the SST anomaly, when ten-year, annual averages of control DCO (computed 1991-2000 atmosphere and ocean) are subtracted from control FO (with fixed atmosphere and a fixed ocean with interpolated monthly SSTs, averaged from historical, 1991-2000 measurements). Despite the fact that the DCO is 'representing' years with especially strong El Niños, the anomaly records especially cool SSTs off the coast of Peru, (a 'ghost' of the El Niños in the 10-year FO-average of the historical record). [The DCO model produces a realistic thermohaline circulation, but yields unrealistically weak, El Niño-like, tropical variability as a result of its coarse resolution (see Fig. 17c, Hansen et al. 2005). But it can produce a semi-permanent El Niño as well as warmer-than-realistic temperatures in the northeastern Atlantic.] The northern, subtropical Atlantic also shows a pronounced warm anomaly (up to 4°C); that is, DCO gives cooler SSTs there, than FO (the historical record). Therefore, simulated north African climate may show a significant positive bias with FO, relative to DCO, if SST in this Atlantic region plays a significant role in precipitation over northern Africa. These possible 'limitations' will enter in to the interpretation of the results that will now be reviewed.

## 3.1     First Results

Figures 3a (FO) and 3b (DCO) illustrate annual precipitation anomalies over the irrigated Sahara (SRF) (differences from their respective 'normal' Sahara controls). Both show very substantial stimulation of precipitation over the Sahara; in FO, a minimum of about 700 mm/yr, and well over 1,200 mm/yr for about 1/2 the Sahara; and for DCO, over 1,000 mm/yr for about 1/2 of the Sahara. The eastern irrigated Sahara receives considerably more precipitation in FO than DCO. The effects of afforestation and irrigation are decidedly local; and except for a desirable increase in rainfall over the Sahel to the south, there is very little modification of rainfall, over land, outside of the Sahara. The amount of precipitation is substantial, relative to the 'requirement' of something like 1,000 mm/yr rain for vigorous *Eucalyptus* growth. QuickTime files, SRF(FO).mov and SRF(DCO).mov (Ornstein et al. 2008) provide 12 month animations of the FO and DCO precipitation anomalies. The rainfall is shown, in both cases, to be highly seasonal; beginning in April, and ending in November, with a time and intensity profile very similar to that of a typical West African Monsoon (WAM) (Lebel et al. 2005). Figures 3c and 3d show the annual required irrigation with FO and DCO; automatically compensating for the available rainwater. In FO, the required irrigation for the western and southern Sahara has been reduced to the order of 300 mm/yr, with substantial gains (over DCO) in the southeastern Sahara. The 'arc' of mountains, the Ahaggar, Tibetsi, Ennedi and Jabal Marrah (captured in ModelE's topography, Figures 2c and 2d) play a role, in the WAM mechanism (Drobinkski 2005), and apparently in the distribution of the induced precipitation. Figure 3e shows the difference, in required irrigation, between FO and DCO. Since the induced precipitation is all seasonal rain, an additional run was performed with irrigation applied only during the months from May to October.

The resulting precipitation (not illustrated) was virtually identical to that for the full-year irrigation, with much heavier irrigation required in May to refill the dried-out, soil profiles, but with slightly reduced total required annual irrigation.
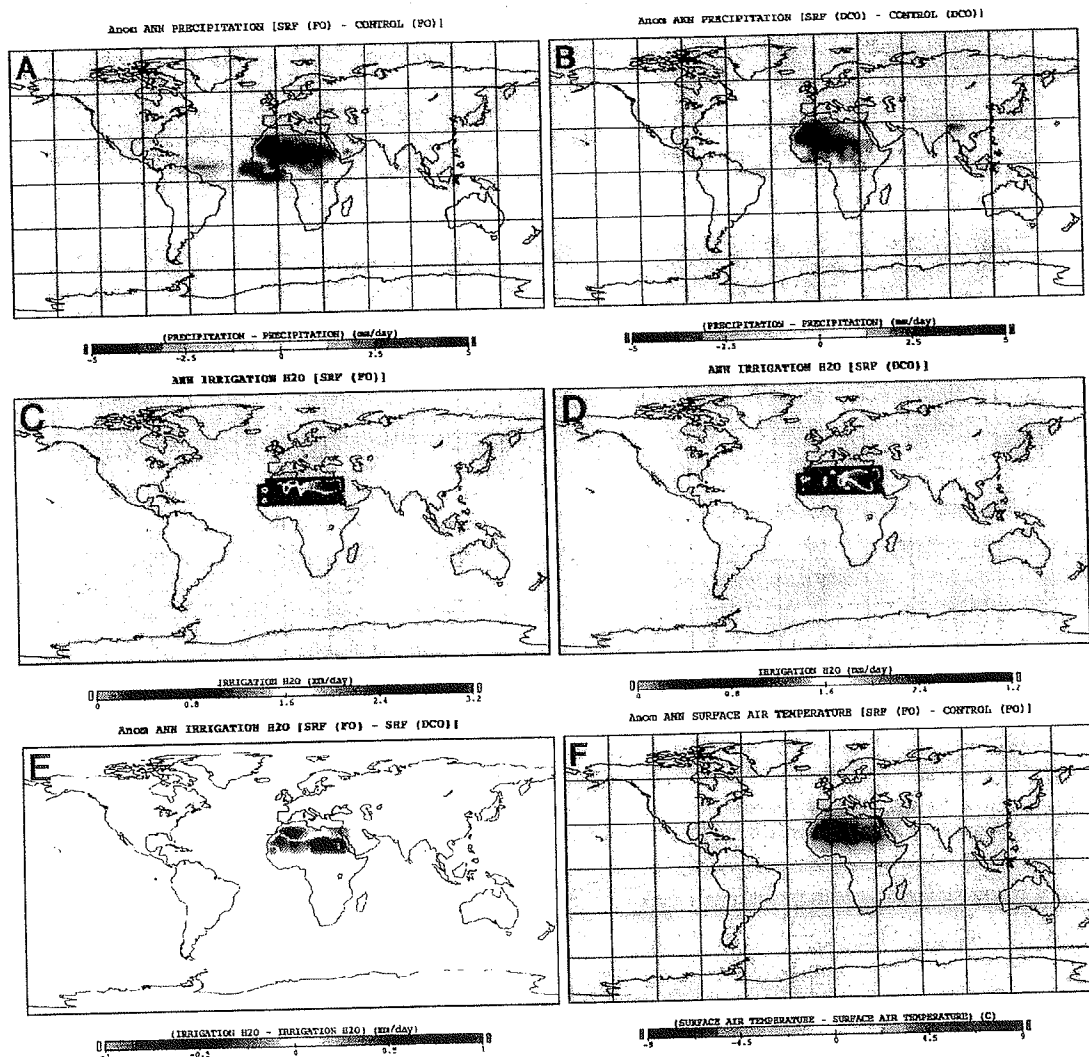


**Fig. 3** All 10-year annual averages (ANN). (a, b, e, and f) Differences between of SRF and CONTROL . (a and b) Precipitation, in mm/day; (a) fixed ocean; (b) dynamic couple ocean. (c and d) Annual SRF irrigation, in mm/day; (c) fixed ocean; (d) dynamic coupled ocean. (e) Difference between c and d. (f) Difference in surface air temperatures, in °C, for fixed ocean.

So an irrigated Sahara forest may be climatologically possible; the induced precipitation may be substantial and thus reduce irrigation costs favorably, compared to



10° W

630 mb

wind speed (m/sec)

Hurricane Tracks
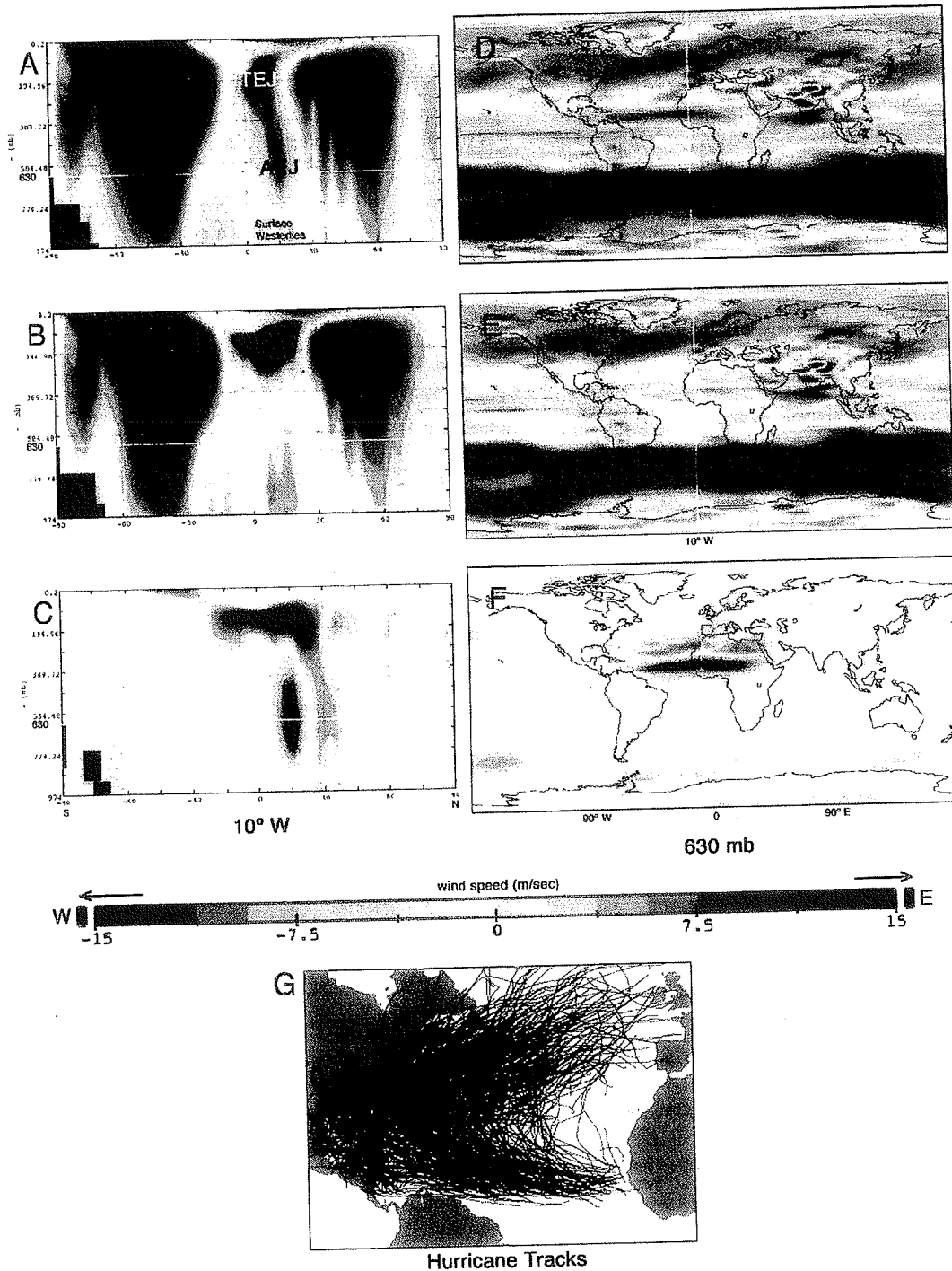
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**Fig. 4** (a–f) 10-year August averages of SRF East-West component of wind speeds, in m/sec; fixed ocean (FO). (a through c) Air pressure, in mb ('elevation'), versus latitude at 10° W longitude; indicated by a vertical white line in d through f. (d through f) Latitude versus longitude, at 630 mb pressure; indicated by horizontal white lines in a and b. (a and d) Control winds. (b and f) Winds with irrigated Sahara forest (SRF). (c) Difference between a and b. (f) Difference between d and e. (g) Historic Atlantic hurricane tracks (Hall and Jewson 2005). Note that many of these tracks overlap the location, in d and f, of the AEJ.

CCS costs. In addition to sequestering $CO_2$, the irrigated forest also causes pronounced local decrease in surface temperature over the Sahara (e.g., Figures 3f and 5e). Evapotranspiration converts large amounts of sensible heat into latent heat. Although, from a global, net energy point of view, the conversion of sensible to latent heat is a 'wash', induced cloudiness over the forest (e.g., Figure 8a) keeps planetary albedo high (not illustrated) and further reduces surface heating. As a result no additional global warming was observed in our simulations, in contrast to what might be expected of afforestation at higher latitudes (Bala et al. 2007).

Can the irrigation requirements (fixed capital investment and/or operating costs) be further reduced without significantly reducing feedback rainfall?

Our ability to answer that question may depend on our understanding of the climatic mechanisms that have produced this initial result.

3.2    Local Mechanisms Associated With Saharan Rainfall

Perhaps the most valuable clue is the similarity of the induced precipitation event to the ordinary WAM. Important parameters in the highly variable northward penetration of the WAM have been noted (Gu and Adler 2004; Matthews 2004). In the summer months,

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surface westerlies develop over the Atlantic, near the western and southwestern coasts of
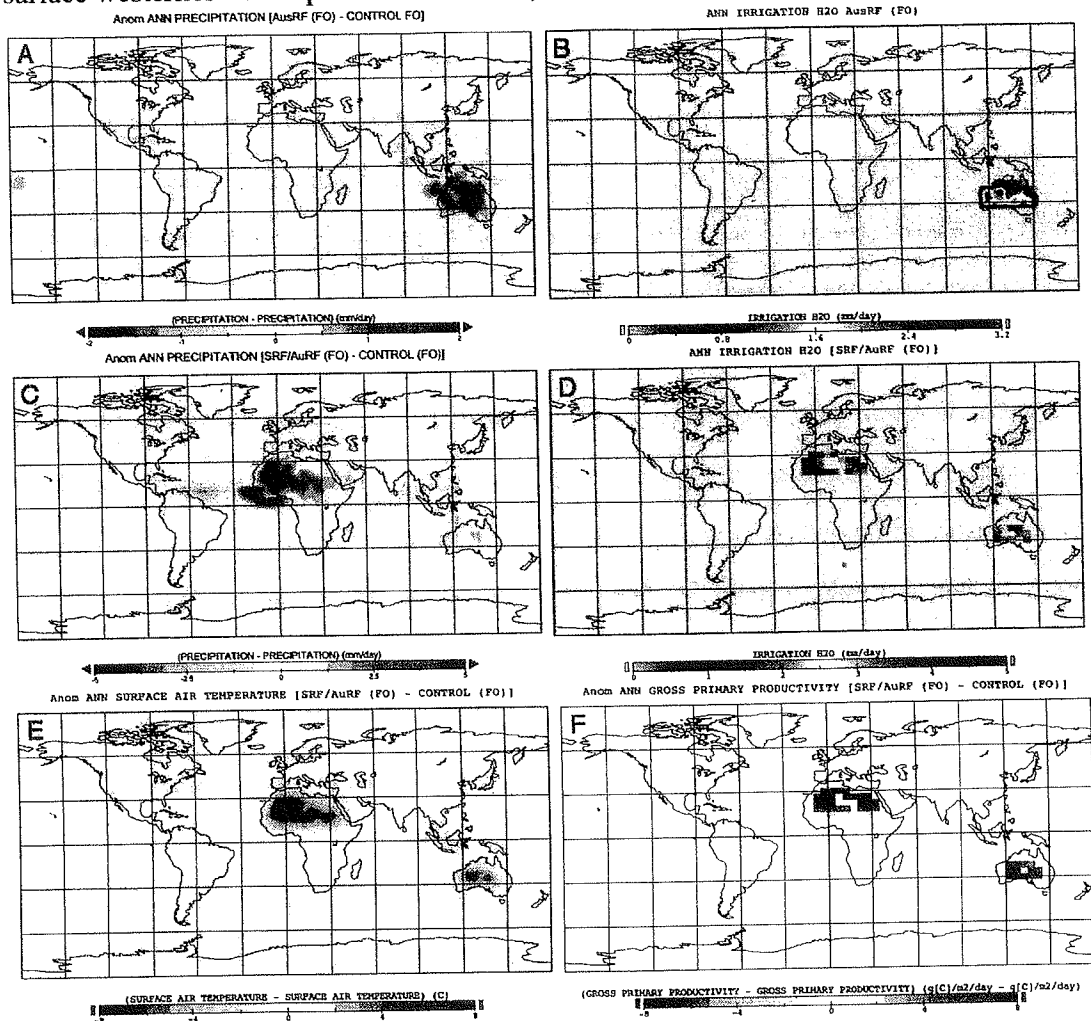


**Fig. 5** All 10-year annual averages. (a and b) Australian Rain Forest runs with fixed ocean AuRF (FO). (c

through f) Combined reduced Sahara and reduced Australian Rain Forest runs with fixed ocean SRF/AuRF

(FO). (a) Difference in precipitation, in mm/day, between AuRF (FO) and CONTROL (FO). (Note: the

scale here is -2 to +2, rather than -5 to +5, as in 5c, 5e, 3a and 3b, to emphasize the weaker induced

precipitation.) (c) Differences in precipitation, in mm/day, between SRF/AuRF (FO) and CONTROL (FO).

(Also see S7 for details over Australia.) (b) Irrigation, in mm/day, with AuRF (FO). (d) Irrigation, in

mm/day, with SRF/AuRF (FO); raw data. (e) Difference in surface air temperatures, in °C, [SRF/AuRF

(FO) minus CONTROL (FO)]. (f) Difference in Gross Primary Productivity (GPP), in g/m²/day,[SRF/Aurf

(FO) minus CONTROL (FO)].

northwest Africa, picking up moisture from the warm, northern, equatorial and subtropical Atlantic, and advecting it in over the coast. During the summer, the African Easterly Jet (AEJ) develops at a latitude of about 15°N, at about 600 mb, tending to steer the northward penetrating WAM back towards the Atlantic. The Tropical Easterly Jet (TEJ) is found centered at about 170 mb. The strengths and locations of these winds seem to be important to the WAM (Nicholson 1981; Nicholson 2006). Kerry Cook (1999) established that the AEJ arises because of the strong contrast between the hot, dry, summer low over the Sahara and the cooler, moist, equatorial, air mass to its south. With a meso-scale climate model, she demonstrated that if the Sahara soil is kept moist during the summer, the AEJ fails to form. Figures 4a and 4d illustrate that the surface westerlies, the AEJ and the TEJ are well simulated in August (the peak of the WAM) in an FO, control-model run (normal Sahara). Figures 4b and 4e show that with irrigation and forest, the AEJ has disappeared and the TEJ has strengthened and its northern edge has moved from about 15°N to about 22°N. Figures 4c and 4f show the differences between the FO run with, and without, irrigated forest. 'Blue' differences show clearly that virtually the only large, global change in E-W winds at 630 mb is that the AEJ has been 'wiped out' by the irrigated forest. The story is almost identical for the DCO runs (not illustrated).

There have been numerous studies of variability and of modeled movements of the WAM, both recent (Vizy and Cook 2001; Nicholson 1993; Janicot 1992; Druyan 1991) and historic (e.g., during the Holocene wet period). The historical forcing is presumably solar (Milankovitch) precessional forcing, followed by glacial melting and accelerated by subsequent greenhouse gas release (Braconnot et al. 1999; Kutzbach and Liu 1997). During 8,500-5,300 B.C.E., the Sahel savannah and grasslands extended almost to 30°N, except over Egypt (Kuper and Kropelin 2006), and considerable amounts

of precipitation ended up in the Sahara aquifer basins (Figure 2a). Claussen (1997) examined a low-resolution climate model of the world, with deserts replaced with forests, and showed modest increase in precipitation over the Sahara. With a regional, meso-scale model, Cook et al. (2003), have simulated the Holocene climate of northern Africa with solar, albedo, surface roughness, soil moisture, $CO_2$ and SST forcings, alone, and in various combinations, and have 'induced' moderate increases in precipitation (Patricola and Cook 2007), comparable to that of the Holocene, but not as large, or as far west or north as that illustrated in Figures 3a and 3b. Near-surface, specific humidity is enhanced above an optimally irrigated forest, making our surface-moisture-forcing considerably stronger than theirs.

3.3     Australia

Irrigated afforestation of a realistic portion of the Australian desert would provide somewhat less than the required sink for the annual increase in anthropogenic $CO_2$. However, together with conservation practices, it could take us a long way. (And this would be true, even absent cost-reducing, induced rainfall.)

3.4     Modeling an Australian Outback Forest

The same treatment, as used with the Sahara, was applied to the combined red and magenta areas in Figure 1a, using FO.

Figure 5a shows that, on an annual basis, substantial rainfall was induced over the central desert region, but less than in the Sahara (note reduced scale in Figure 5a). However, since the Outback normally receives 50 - 300 mm/yr rainfall, the totals are not too different, and the required irrigation, Figure 5b, is similar. So costs would be reduced

in Australia, as well. World-wide, the annual effect seems to be largely local. But, 10-year, monthly averages (see QuickTime animation AuRF(FO).mov, Ornstein et al. 2008) show some weak teleconnections. And, small levels of anomalous rainfall occur over
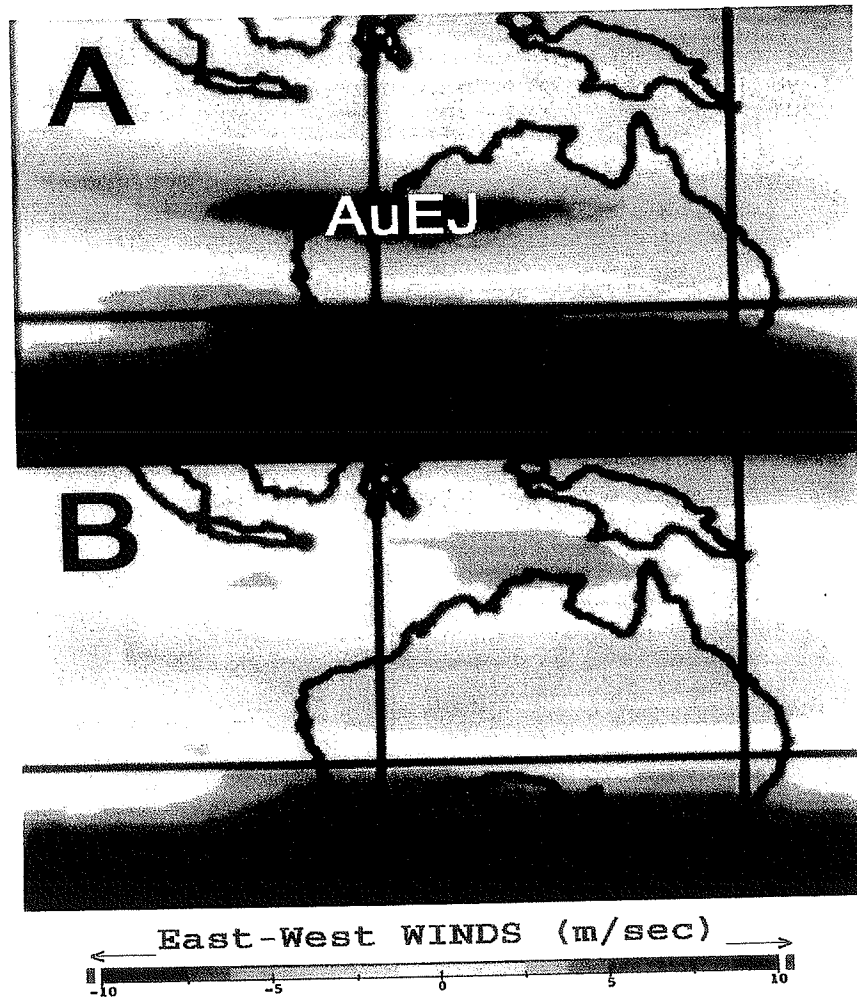


Fig. 6 The elimination of the "AusEJ." 10-year February averages of AuRF (FO) East-West component of wind speeds, in m/sec, at 630 mb; latitude versus longitude. (a) Control winds. (b) Winds with irrigated Australian forest.

different regions of the Outback all year. However, the predominant rainfall occurs

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during the austral summer, in parallel with the Indonesian-Australian Summer Monsoon
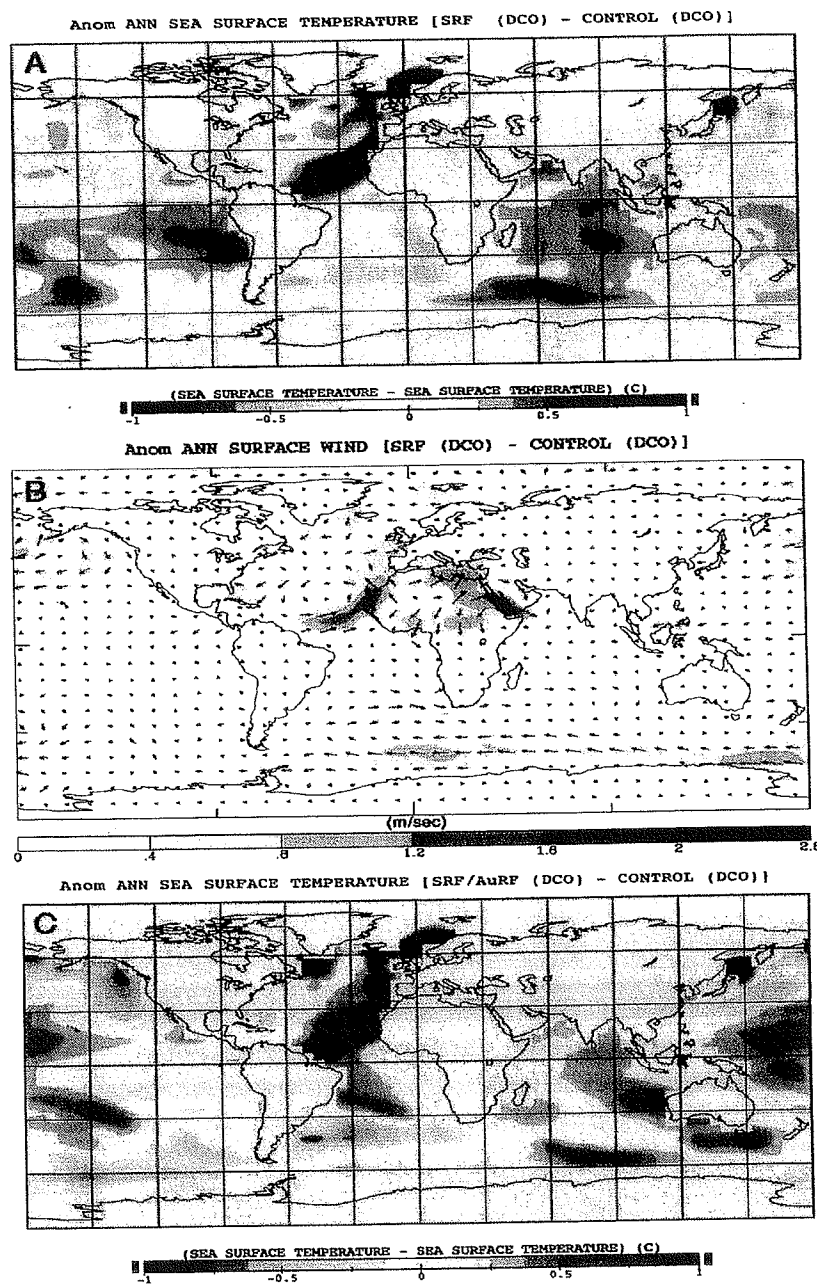


**Fig. 7** All 10-year annual averages differences with dynamic coupled ocean (DCO). (a) Difference, in °C,

in SSTs between (SRF and CONTROL). (b) Differences in surface wind speeds and directions, in m/sec,

between (SRF/AuRF and CONTROL). (c) Difference, in °C, in SSTs between (SRF/AuRF and

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CONTROL).

(I-ASM), and the austral, summer, control runs show an 'Australian Easterly Jet' (AusEJ), similar to, but less extensive than, the AEJ (see Figure 6a). The AusEJ is eliminated in the forested, irrigated run (see Figure 6b).


3.5     Loose Ends


In the original DCO runs, but not in fixed ocean runs (FO = fixed SSTs), the difference between the SSTs of the irrigated Sahara and its control, shows a small ($\approx 1°$ C), year-round increase, just adjacent to the western coast of northwest Africa (see Figure 7a). And this anomaly quickly developed during the first 6 months of spin-up. It was out of concern that a quirk in the DCO model might have been responsible for this warm spot and might have made an inordinate contribution to precipitation over the Sahara, that we then made FO runs. We concluded that, rather than anomalous transport of heat to the ocean, the rise in SSTs is probably due to an irrigated-forest-induced diminution of the component of the year-round, off-shore surface winds that blow steadily to the south (see Figure 7b (FO); almost identical in DCO runs, not illustrated). The northeast, trade winds, that Columbus and his successors depended upon to take them to the New World, blow quite steadily to the south along this coast. These winds normally induce steady, Ekman-pump upwelling that cools the surface, coastal waters and fertilizes a very prolific fishery (Santos et al. 2005). This supports, not only local Mauritanian fisherman, but international fleets of fishing, factory ships. The near-shore component of these winds are supposedly enhanced by the sharp contrast between the hot desert coast and the cooler Atlantic (somewhat like the mechanism for the AEJ), that the forest eliminated. Perhaps by excluding the irrigated forest from a strip of that coastal region, the usual coastal wind pattern, and the consequent upwelling, might be preserved?

A desert area in Chad, the Bodélé Depression (the BD-marked, 4° x 5° cell in Figure 2c), located northeast of Lake Chad (Figure 2b), is the almost exclusive source of iron-rich dust, from the residue of the Holocene 'Lake Mega Chad'. This dust is made airborne by the winter, Harmattan winds, that blow from the northeast over the Depression. And this dust ends up fertilizing the subtropical and tropical Atlantic, the Caribbean and the Amazon (Koren et al. 2006). Even if we avoided irrigating and afforestation of the BD cell, summer precipitation induced by the rest of the irrigated forest might wet this region sufficiently to terminate this mechanism. Perhaps we could test this hypothesis?

Therefore, we made two additional runs, with fixed ocean and dynamic coupled ocean, to try to resolve such loose ends. These used the orange and magenta regions, in Figure 1, to represent the Sahara and Australian Outback, respectively. The Saharan desert forest is reduced to about $5.7 \times 10^8$ ha (that can still sequester 3.5 to 7 GtC/yr). Both irrigated forests were 'installed' for each run. The possible upwelling- and BD-dust-preserving changes just discussed were implemented.

And, a) forest was not installed on other margins of the deserts, where competing uses might generate problems; b) a few prominent mountain regions (four cells in the Sahara and one in Australia) were excluded, because afforestation and irrigation of mountain ranges would be excessively expensive and therefore makes little sense; and c) forest was excluded from most of Egypt, which in our earlier irrigated runs, and during the Holocene wet period, received the least precipitation.

3.6    Supplementary Results

Figure 7c, with DCO, shows that even when the western coast is preserved as desert, the

local SST anomaly of Figure 7a is almost perfectly reproduced.

Apparently, the impact of an even somewhat reduced Saharan forest, through its still very large impact on its Hadley Cell circulation, also weakens the coastal northeast trade winds and impacts upwelling. (Figure 7c also shows some smaller SST-changes off the western and southern coasts of Australia.)

Figures 5 and 9 show that the unirrigated BD is nonetheless wet by about 500 mm/yr of induced precipitation.

Other results with FO and DCO were very similar. Only FO results are illustrated.

Figure 5b and QuickTime animation SRF/AuRf(FO).mov (Ornstein et al 2008) show that the reduction in the sizes of the two irrigated forests result in both diminished areas and magnitudes of the induced precipitation, and with a rather large, negative bias over Libya and Egypt. Figure 5e and 8a show that the latter bias is explained by the reduced cloudiness, and consequent increased surface temperatures over this part of the forest. The planetary albedo there drops almost to the value of the surface (forest) albedo (not illustrated). This results in increased evaporation (see Figure 8b) and resulting irrigation demands rise there to about 1,600 mm/yr (Figure 5d).

The bottom line: the combined GPP for the reduced-sized Sahara and Australian irrigated forests, as calculated by (the currently, rather simple vegetation module of) ModelE, is illustrated in Figure 5f. For a Eucalypt forest, this is multiplied by about 0.45 to get NPP (Stape et al. 2004). And this comes to about 8 GtC/yr; close to the required sequestration capacity to deal with global warming. And there is a bonus of a slight increase in GPP for the Sahel and northern tropical Africa from the up to 700mm/yr of

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extra rainfall (Figures 5c and 9).

Anom ANN TOTAL CLOUD COVER [SRF/AuRF (FO) – CONTROL (FO)]



(TOTAL CLOUD COVER – TOTAL CLOUD COVER) (%)

Anom ANN EVAPORATION [SRF/AuRF (FO) – CONTROL]



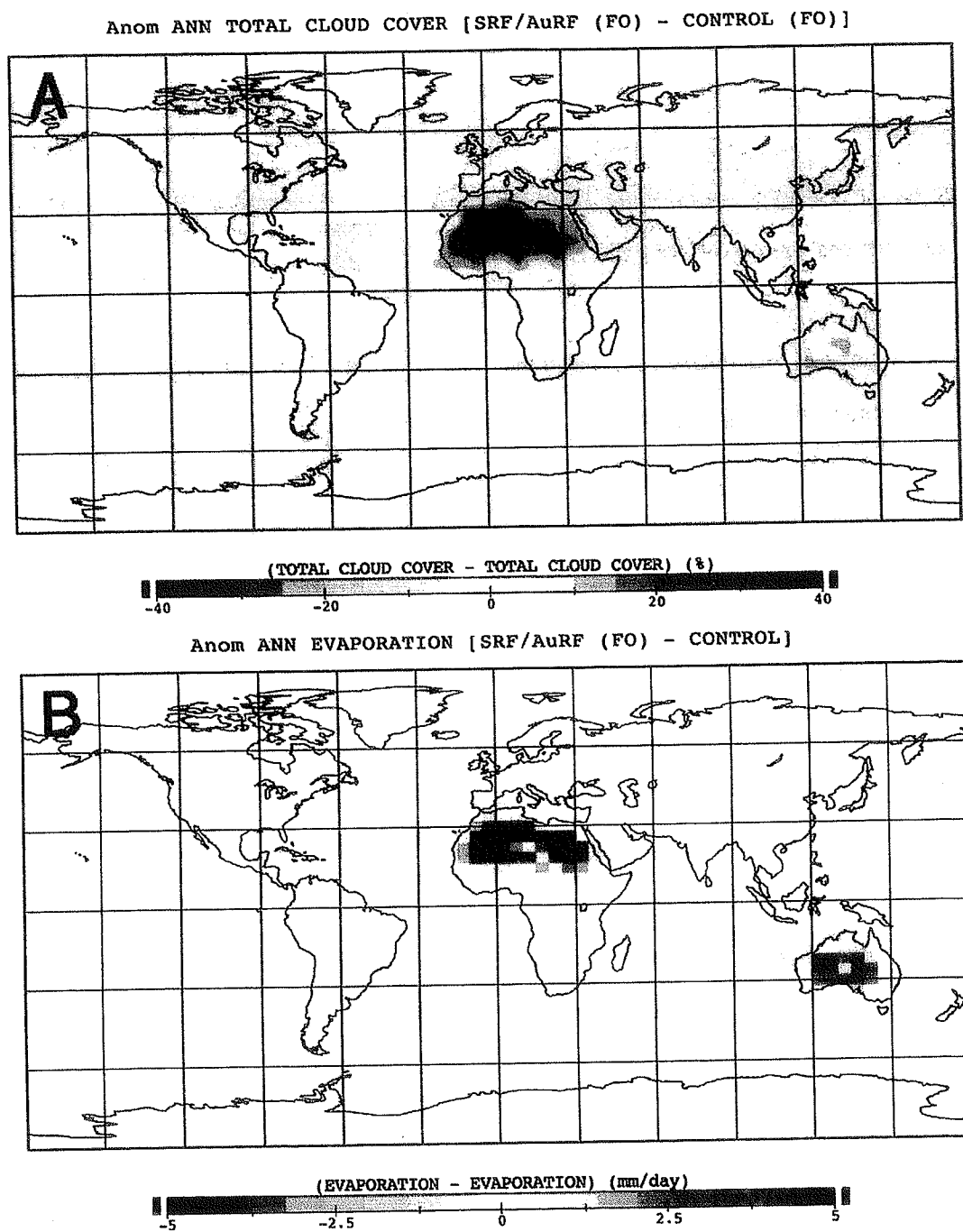(EVAPORATION – EVAPORATION) (mm/day)

Fig. 8 Cloud cover and evaporation in SRF/AuRF. 10-year annual averages of SRF/AuRF (FO)

differences from CONTROL (FO). (a) Total cloud cover, in percent. (b) Evaporation, in mm/day; raw

output.

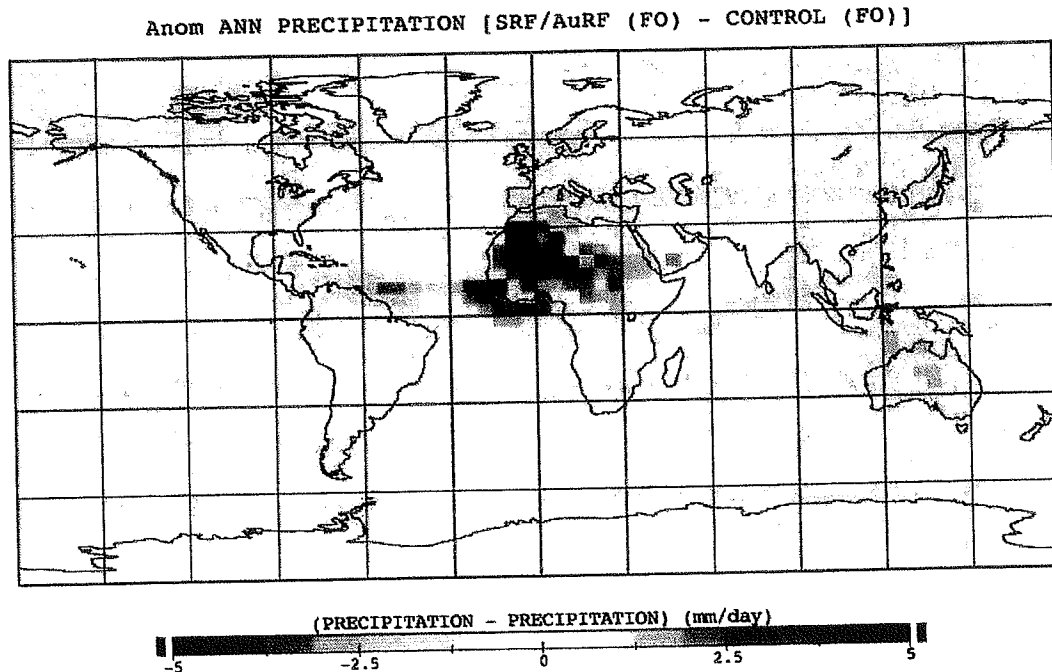**Anom ANN PRECIPITATION [SRF/AuRF (FO) - CONTROL (FO)]**



**Fig. 9** Rainfall over the Bodélé Depression. 10-year annual average of SRF/AuRF (FO) difference in precipitation, in mm/day, from CONTROL (FO); raw output. The cell which represents the Bodélé Depression is outlined in white and exhibits over 450 mm/yr precipitation.

## 4 Mechanisms Common to Impacts of Both Saharan and Australian Afforestation/Irrigation

In Saharan and Australian runs, irrigated forests provide enough extra humidity to that advected in from the oceans by warm, moist winds, to induce deep convection and resulting local precipitation. Since Australia is surrounded by oceans, there are more occasions during the year when various winds may advect near-dew-point masses of air in over its deserts. Additionally, elimination of the AEJ and AusEJ, and the northern

displacement of the TEJ, may increase the coverage of the WAM and I-ASM monsoons by presently poorly understood mechanisms; permitting deeper northern penetration of such oceanic, moist-air masses in Africa, and deeper south, in Australia. The larger the local area irrigated and forested, the more extensive the induced precipitation. And the induced cloud-cover and surface cooling probably play a significant role in lowering the level of required irrigation somewhat independently of, and in addition to, the level of induced precipitation.

These mechanisms do not hint at any manipulations that might produce further substantial reductions in the costs of irrigation. It would appear that larger, rather than smaller areas of irrigated afforestation favor reduced operating costs per ha, but of course, increased capital costs.

## 5    The Australian Opportunity

Australians are in a unique position. They have a democratic form of government, are well-educated and have a thriving economy. They will easily appreciate the unique opportunity they have to help control warming. With 1/3 of the Carbon taxes collected from the rest of the developed world (2/3 might be set aside to cover conversion of the Sahara), and with support of the capital markets, they should be able to start construction of the necessary infrastructure and then begin planting and irrigating an Outback Forest with relative dispatch.

The required capacity in desalination and power infrastructure, that would normally be under-used during parts of the year, provide opportunities for substantial creative agricultural and industrial use, outside of the forest.

A working Australian example may help convince the populations and governments of Mauritania, Mali, Niger, Chad, Sudan, Algeria, Tunisia, and (Libya and Egypt?) that similar cooperation in controlling global warming is also in their own self interests. If such creative opportunities were seized by these African nations, it could permit accelerated transition from their status from "developing" to "developed", with rapid increase in standards of living. On a smaller scale, similar opportunities may be available through irrigated afforestation of parts of the Arabian peninsula and the Kalahari desert.

## 6      What might we find in this Terraforming Pandora's Box?

Even though the main climatological sequelae seem quite 'local', in the examined scenarios, some obvious (and not so obvious) possible results need to be closely examined.

Global warming is an unanticipated, Malthusean consequence of "tampering with mother nature". We may anticipate other consequences that might follow from planting such enormous irrigated forests. In the spirit of the medical admonition, "First, do no harm," we review possible negative outcomes:

Extraordinary volumes of highly saline 'waste' water, from the desalination plants, will have to be diluted and safely diverted back to the ocean in ways which ensure that thermohaline circulations are not disturbed, and that hyper-saline, anoxic 'dead zones' are not created in ocean basins.

Capping warming should cap the world-wide, increasing intensity of tropical cyclones that is expected to be otherwise induced by rising SSTs (Willoughby 2007; Kerr

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2006; Gopalakrishnan 2002). But many Atlantic hurricanes originate in a region that matches the western portion of the AEJ (see Figure 4g, (from Hall and Jewson 2005)), and the AEJ is selectively 'wiped out' by irrigation of the Sahara (see Figures 4a–f). The AEJ

" ... forms and blows essentially through the monsoon season, and it is disturbances on that jet that move into the Atlantic... Perhaps half of the major hurricanes that hit the United States have their origin in those disturbances" (Zipser 2006; also see Cifelli et al. 2007).

Will the Caribbean, Gulf of Mexico and US be better off, or worse off, after the forest is installed on the Sahara? Also, it has been suggested that summer, Saharan dust suppresses hurricanes (see Kerr 2007). Most summer, Saharan sources of dust will definitely be eliminated. Can that consequence be tolerated?

In connection with an Australian forest, teleconnections, and the 'wiping out' of the AusEJ, in a region so sensitive to, and intimately connected to the western end of the ENSO (El Niño Southern Oscillation) (Lau and Bua 2004; Lau and Yang 1996; Allen 1983), need to be explored with care. In Figure 7a, the Pacific looks like its in an El Niño state; in 7c, more like a La Niña state, suggesting a significant impact on ENSO.

During the cool, nearly precipitation-free third of the year, the Sahara forest would be quite dry, even with irrigation (see SRF(FO).mov, SRF(DCO).mov and SRF/AuRF(FO).mov, Ornstein et al. 2008). It may be important to select drought-resistant clones of Eucalypts with low nighttime and winter transpiration rates (Benyo 1999), especially if irrigation is to be reduced during the winter. Ground litter will be very dry. Whether planted with broadleaf evergreens, like Eucalypt species, or with deciduous, water conserving trees, like Baobabs, or mixtures of appropriate species (to

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avoid the hazards of monoculture (Cannell 1999; Powers 1999)), such forests will be at considerable winter risk of destruction by fire. They will have to be planted with strategically located firebreaks and fire stations to protect these enormous investments and climate engines.

It may be possible to optimize locations and schedules for irrigation to provide the most stable control of the nonlinear AEJ. However, since the WAM is notoriously fickle, 'bad years' must be anticipated due to other, uncontrolled variables. And it may be necessary to overdesign the irrigation system capacity to enable intervention during exceptional dry spells. Otherwise, substantial parts of a forest might die during such droughts, and turn off the biological, $CO_2$ 'sequestration-pump'. Historically, such droughts (and fire) are presumed to have led to the demise of forests that previously occupied extensive parts of the present deserts of Africa and of Australia (Bradstock et al. 2002).

Africa, from Mauritania to Egypt, has been the home of the plague locust. Swarms are often stimulated by increases in precipitation. This may require a new level of 'insecticidal' preparedness.

Desert sands and soils are depleted of soluble nitrogen. As a result, it will probably be necessary to preplant, or interplant with nitrogen-fixing legumes (Forrester 2006), such as fast-growing *Acacia* species. In order to learn how to transition local, arid micro-environments into moist, evergreen tropical-forest macro-environments, it may be necessary to conduct some preliminary field-trials of various mixes of tree species and of 'establishment strategies' on a variety of desert 'soils'[3] (using fossil aquifers and perhaps wind or solar power to pump the irrigation water). Some analysis with dynamic vegetation GCMs (e.g., Kiang et al. 2007) may be helpful in this connection. This might

delay the date at which the forest reaches a break-even state, perhaps past a "tipping point," a point beyond which some very high costs of runaway, positive feedback can not be controlled immediately (Lindsay and Zhang 2005).

The capital costs of the forests will exceed the revenues from any reasonable carbon tax and traded carbon credits. And in the Sahara, the necessary foreign capital-windfall would be spread across 8–9 underdeveloped nations. The political distribution will be difficult. Even for an Australian forest, the conflicts between concerned interests (indigenous residents, ranchers, farmers, conservationists, foreign investors, etc.) may be substantial.

## 7      Conclusion

Such multi-trillion-dollar projects provide lots of motivation for scientifically-creative entrepreneurs – as well as for swindlers. International mechanisms for monitoring and managing (without mangling or strangling) such projects will be essential. This may be the most difficult hurdle.

Our DCO model showed a cool bias in the Atlantic (Figure 1 b). It would be helpful to confirm these studies with other GCMs that do credible jobs at simulating both coupled oceans as well as monsoons (e.g., Cook and Vizy 2006), and particularly with higher resolution meso-scale models. The latter may better simulate the squalls that are typical of WAM precipitation (Druyan et al. 2004), and therefore should yield more confident estimates of stimulated rainfall and its distribution. However, GISS Model E underestimates both Amazonian precipitation (Schmidt et al. 2006) and the strength of monsoons (Rind et al., 2007). We have some concern that this may stem from the uncertain vertical convective parameterizations, shared by all GCMs. This could result in

overestimation of the temperatures in the upper tropical troposphere, and as a consequence, an underestimate of deep convection and precipitation by most other GCMs, as well.[8] As already noted, increased confidence in estimates of induced precipitation would be especially helpful, because the larger the induced rainfall, the smaller will be both the final average carbon footprint and the cost of maintenance of such afforestation projects.

Anthes (1984) demonstrated "Enhancement of convective precipitation by meso-scale variations in vegetative covering in semiarid regions". A patterned planting of the forests could be explored, at mesoscale, to determine whether precipitation might be further enhanced; perhaps during the winter dry seasons, ultimately making the forests sustainable, without irrigation. Meso-scale modeling also would permit restriction of irrigated afforestation fairly precisely (and more realistically) to elevations less than about 800m.

Many of the threatening scenarios, just reviewed, should be subject to extensive analysis.

And with refined calculations, costs may be lower – or higher.

Bias against consideration of afforestation, even as a possible solution, will be strong because of the common "scientific reticence" and "behavioral discounting" with respect to delayed bonuses. Such discounting tends to dominate analyses of risks and rewards that are perceived to be far off (Hansen 2007; Hariri 2006; Axtell and McRae 2006). At the very least, such reticence must be repressed sufficiently to permit a balanced evaluation of the full spectrum of cures for the Earth's, anthropogenically-induced and mounting fever.

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We must bite the bullet. Global warming will not go away by itself. A rapid approach towards zero-population-growth is required (Ornstein 1967; Anthes 1993). Existing forests must be conserved. Incremental increases in energy-use efficiencies are a *sine qua non* for improvement. However it is unlikely that energy conservation can provide the complete solution.

A replacement of present fossil-fuel, electric-power-generation plants with nuclear power generation, (with much stricter control of fissionable isotopes and radioactive waste) and/or with coal-fired plants with CCS, also can be managed incrementally, but at very large capital costs (and additional operating costs, for CCS). Solar, geothermal and wind power can make modest contributions. All of these are other parts of a fix. But the quicker a forest can be grown, the more time will be available to choose among, and to implement such adjustments – and perhaps to develop more attractive substitutes (e.g., working fusion power plants).

Our observations have slightly simplified the problem. Afforestation of subtropical deserts can reduce increases in atmospheric $CO_2$, incrementally, and enormously. However, it can begin to show an operating-cost bonus (over CCS operating costs) of biogeophysically-induced rainfall, only after monumental capital investment in a major portion of the required desalination, power and irrigation infrastructure.

These capital costs of mitigation will be borne mainly by the citizens of the developed world. They must be weighed, not only against those of CCS, but as a kind of preemptive disaster relief – or repair of the 'commons' – to avoid the future, and as yet not easily estimated costs of vast coastal inundations, desertification of crop- and range-lands, drying up of water supplies; more intense tropical storms; the acidification of the oceans and loss of biodiversity. The integrated costs of coping with such changes could

approach those of recovery following an asteroid impact or a nuclear war.

These are ecumenical, ethical, altruistic issues. How we deal with them depends upon how much value ordinary people (not economists or politicians) place on the welfare of their descendants; self versus children, grand-children, etc. The results of economic and policy calculations are meaningless unless we agree upon the magnitude to assign to this value (Hopkins 2007; Nordhaus 2007; Stern and Taylor 2007). Future generations ought not be 'discounted'.

Conservation, through increased efficiency, contributes to a "win-win" situation; reducing $CO_2$ emissions and producing economic savings (e.g.,"more miles per gallon of gas"). If automobile manufactures delivered a CAFE[9] increase from the present standard of 27.5 miles per gallon to a value of 35 miles per gallon by 2020, as called for in the 2007 Energy Act H.R.6, passed on December 18, 2007[10], an "afforestation tax" of about 1/3 of the pump price of gasoline, would just be 'canceled'. There would be little pain, for an average driver, especially if technology more innovative than vehicle-weight reduction is used (Thompson 2007). Adjusted for inflation, about the same *price per mile* would be payed for gasoline, as today. (This is calculated without including additional savings resulting from biogeophysically-induced rainfall or from the marketing of renewable forest biomass.) And energy conservation of other kinds also reduce the size, and therefore capital costs of the 'required' subtropical, irrigated forests, and consequently can result in a still "lower tax per gallon of gas."

Notes

1     1 GtC/yr $=10^{15}$ gmC/yr $=0.47$ ppm $CO_2$ added to the atmosphere/yr.

2     In a published address to the Electrophoresis Society, Ornstein (1986) discussed the paths to and from the invention, in 1959, of polyacrylamide gel electrophoresis (PAGE). He explained how his subsequent invention of the Irristat, a small, moisture-sensitive, self-regulating, irrigation valve (Ornstein 1980), that uses very slightly cross-linked polyacrylamide gel, as both a moisture sensor and valve actuator, led him, in 1980, to climatological speculations and then collaboration with Jim Hansen of GISS and Peter Stone of MIT.

"When musing on its possibilities for agriculture in arid lands[3], I tried to imagine the consequences of covering the Sahara Desert with a forest irrigated with the extensive fossil aquifers that lie beneath it. Unless the forest induced sufficient increase in natural rainfall by positive feedback [117][4], such a plan would eventually fail as the aquifers dried out. This has involved me with global weather modeling at the Goddard Institute for Space Studies in New York City [118][5]" (Page 10, Ornstein 1986).

3     **The keys to initiating forest growth on desert soils**

With present insolation, the poleward, then descending, atmospheric circulation of Hadley-cells desiccate the Sahara, the Australian Outback and subtropical deserts in general. Low levels of rainfall are responsible for their striking failure to support plant growth. There is no evidence that Sahara or Australian Outback mineralogy, with respect to average composition, is different than that of Amazonia or the Congo Basin, which support lush old-growth forests.

The textures of desert soils range from that of coarse sand to the very fine structure of deposits of clay. The water-holding capacity of sand is very low; only the narrowest capillary spaces between grains of sand oppose gravitational forces, as water rapidly percolates downward. On the other hand, a much larger proportion of the volume of clay is made up of microscopic capillary spaces, providing substantial water-holding capacity. Counterbalancing this advantage, water rapidly applied to a clay surface, tends to run off the surface much faster than it penetrates because viscous flow into small capillary spaces is slow. Water rapidly applied to a coarse sand surface usually penetrates quickly, down to roots – and then below. This summarizes two of the most important dimensions of soil variability that impact a soil's suitability for sustaining plant growth in natural, variable, nearly-chaotic, rainfall regimes. No desert-wide, mineral deficiencies of potassium, phosphate and trace-elements, differentiate deserts from other regions which support lush growth.

Therefore, when high-efficiency irrigation is used to apply water to root zones at slow rates that just replace losses due to local evapotranspiration, the suitability of a very wide range of soils is both equalized and maximized.

Accumulation of above-ground litterfall and root litter, and conversion, by soil microorganisms, fungi and invertebrates, into fibrous, hydrophilic humus, also improves, and tends to further increase and equalize, water-holding capacity and more rapid water-penetration of most types of soils. In addition to plants with symbiotic, nitrogen-fixing, root nodules (e.g., legumes), some non-symbiotic microorganisms provide nitrogen-fixation (Murder 1975). Those microorganisms, and traces of nitrate in rainfall, are the source of most forest, nutrient nitrogen. And mycorrhiza somewhat increase accessibility of inorganic nutrients, particularly phosphates.

Therefore, afforestation of most of a desert should require 'little more than' carefully-controlled irrigation – although in the forest's first years, until ecologically stable rhizospheres begin to form in the tree root zones, some auxilliary fertilization and microbial seeding should help. An irrigation system that can deliver 500 mm per year can be used to maintain a high relative humidity, with fogger/mister dripline emitters and/or seedling shelters around 'seedlings' (which themselves initially have very small photosynthetic transpiration demands). Preplanting and/or interplanting with tree species better adapted to the initial aridity than *Eucalyptus grandis*, may also help to transition and shelter from the arid environment, dominated by evaporation, to a humid macro-environment, dominated by transpiration. In a few years, that transition also benefits from the positive-biogeophysical-feedback precipitation of the enhanced WAM that we demonstrate in this study.

[4]    [117]=(Charney et al. 1975)

[5]    [118]=(Hansen et al. 1981).

[6]    For our experiments, we employ the Goddard Institute for Space Studies (GISS) ModelE General Circulation Model (GCM) which was documented in (Schmidt et al. 2006) and had its sensitivity studied in (Schmidt et al. 2006; Hansen et al. 2005). Its atmospheric part is a 20-layer version with model top at 0.1 hPa and 4° x 5° horizontal resolution. The land surface part employs a 6-layer ground hydrology model (Rosenzweig and Abramopoulos 1997), a 3-layer Snow model (Lynch-Stieglitz 1994) and Friend-Kiang canopy conductance model (Friend and Kiang 2005). The Friend-Kiang model is physiology-based, and can compute Gross Primary Productivity (GPP) (which is of particular interest for our studies). GISS ModelE can run either with prescribed ocean (i.e. driven by observations), or it can be coupled to a dynamic ocean

model. In the coupled version we employ the Russell et. al. (1995) ocean model.

The land surface has a prescribed vegetation cover. The model distinguishes between 8 types of vegetation and bare soil. For each vegetation type, its height and root distribution are fixed, while its albedo and leaf area index follow a prescribed seasonal cycle. The soil is a prescribed composition of five different soil textures.

The horizontal resolution of the model is rather coarse, but use of second-order moments for numerical differencing improves the effective resolution for the transport of tracers. For a convenience of representation most results of simulations shown in this paper are interpolated[7].

[7]    Most of the output of ModelE GCM has been processed with R. B. Schmunk's NASA Goddard Institute for Space Studies graphical output software, Panoply 2.2.1; http://www.giss.nasa.gov/tools/panoply/.

[8]    Figures 9.1c and 9.1f of Chapter 9 of the report to the IPCC's AR-4, a study of GCM hindcasts (Hegerl et al. 2007), illustrate a rather uniform warming of about $1°$ C in the upper tropical troposphere (400 to 150 hPa, 30°N to 30°S) for the 20th century, but only about 0.5° C/century increase at the surface. They state, "The major features shown in Figure 9.1 are robust to using different climate models". Figure 6 in (Santer et al. 2008) also shows a mean of 19 different GCMs (including ModelE), supporting an upper tropical troposphere warming of about 1° C/century, and about 0.5° C/century at the surface.

Whether the tropical upper troposphere has warmed about twice as much as the surface, should be resolvable by examining historical measurements. Satellite measurements lack sufficient vertical resolution in the troposphere to settle this issue.

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Radiosonde environmental lapse-rate measurements have adequate vertical resolution and might provide a useful test. Radiosonde data (also in Figure 6, Santer et al. 2008) seem to falsify these GCM hindcasts, but the geographical radiosonde samplings in the tropics are few and far between and a bias of direct solar-heating of sensors may also be involved.

The warmer upper tropical troposphere of the GCMs implies convective stability that is somewhat greater, compared to that expected from the (limited) radiosonde data. Therefore until the question is resolved, of whether the modeling of the dynamics of tropical vertical heat transfer by GCMs is faulty, or alternatively that the sparse radiosonde data is unrepresentative or in error (Titchner et al. 2009), there will be concern that most GCMs, even if they confirm our results, may also tend to underestimate the precipitation induced by irrigated afforestation of Hadley Cell deserts.

[9]     CAFE (Corporate Average Fuel Economy): National Highway Traffic Safety Administration. US Dept. Transp. (2006),

http://www.nhtsa.dot.gov/portal/site/nhtsa/menuitem.d0b5a45b55bfbe582f57529cdba046a0/

[10]     2007 Energy Act H.R. 6,

http://www.govtrack.us/data/us/bills.text/110/h/h6.pdf

[11]     **Legend for Online QuickTime Animations**

Animations of 10-year average precipitation anomalies.

SRF(FO).mov is for SRF (FO). SRF(DCO).mov is for SRF (DCO). AuRF(FO).mov is for AuRF (FO). SRF/AuRF(FO).mov is for SRT/AuRF (FO).

In all cases, the first frame is a 10-year annual average, corresponding to Figures 3a, 3b, and (5c and Figure 9), respectively, of the main text. The next 12 frames are 10-

year monthly averages, January through December. Color scales are 'nonlinear', and may be of differing magnitude in some frames (the scale used is indicated within each frame) to emphasize both small teleconnections and other small anomalies (and unfortunately 'noise') as well as the large differences. The lower, right-hand corner displays the magnitudes of the minimum and maximum values of the precipitation anomalies for each frame. (DCO = Dynamical Coupled Ocean. FO = Fixed Ocean, with the same set of local 10-year averaged observed monthly SSTs, reused for each of the 10 years.)

**Note**: With QuickTime animations, you may select the 'slider' to move backwards or forwards to view individual frames.

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# Replacing coal with wood: sustainable, eco-neutral, conservation harvest of natural tree-fall in old-growth forests: an editorial essay

Leonard Ornstein

## 1 Introduction

The beginnings of the industrial revolution and global warming coincide with the replacement of wood by coal. Is it time to reverse this process, as a way of implementing "Biosphere carbon stock management" (Read 2008)?

The construction of new, coal-burning plants, utilizing carbon capture and sequestration (CCS), is now favored as a likely avenue to control global warming. However, modifying existing coal-burning plants, where the bulk of coal will continue to be burned for some time, is considered to be uneconomical (Gough and Shakley 2005). Modifications to allow the fueling of existing plants with clean-burning, renewable 'wood-chips' and charcoal[1], in place of coal, is a different proposition – technologically, economically (Bergman and Zerbe 2008, Marland and Schlamadindger 1997) and with respect to global warming. But it is not obvious where enough wood, that could be harvested sustainably, might be found to begin to replace coal.

Deforestation and degradative land abuse inject about 1.6 gigatonnes of carbon per year (GtC/yr)[2] into the atmosphere as $CO_2$, a greenhouse gas (GHG), (Alley et al. 2007 ). Halting deforestation is the principal forest-management tactic proposed to mitigate this contribution to global warming. The position of groups like the World Wildlife Fund, Sierra Club, and the Rainforest Action Network is, 'Don't mess with the remaining old-growth forests!'

Below is an outline of a biologically-motivated conservation strategy for the management of such climax forests that might yield

> a large, sustainable supply of wood,
> further motivation for the cessation of deforestation and
> up to as much as 4.6 GtC/yr in drawdown of $CO_2$, with very minimal ecological impact:

## 2 The Core of the Model

Enormous numbers of trees fall 'naturally' each year in the world's remaining old-growth forests. In moist tropical forests, these decay, on average, within a few ($d$) years, and release their minerals to the soil and their carbon to the atmosphere, as $CO_2$. If most of these trunks were carefully harvested, shortly after they fell, they could be stored 'permanently' preventing decay and conversion to $CO_2$; e.g., anoxic storage in sealed 'containers'; dry, under oxygen-free-$N_2$ and/or -$CO_2$, or wet, under oxygen-free, slightly acidic water. Anaerobic storage prevents the growth of fungi, which are the initiators of the attack on wood and bark. Such storage is much cheaper and safer than the proposed CCS storing of captured, pressurized $CO_2$ at great depths underground or under the ocean.

Alternatively, they could be stored conventionally for use as a sustainable replacement for fossil

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[1] Charcoal is an attractive storage alternative to wood. It is compact and burns very cleanly. Like all bio-char (Lehmann et al. 2006), it is uniquely resistant to degradation by organisms. The only threat, during storage in air, is its susceptibility to destruction by accidental fire.

[2] tC = metric tonne carbon = megagrams carbon = $10^6$ grams carbon; GtC = gigatonne carbon = $10^9$ tC; ha = $10^4$ $m^2$.

Leonard Ornstein, Emeritus Professor of Pathology (Biology)
Mount Sinai School of Medicine, NYC
5 Biltom Road
White Plains, NY 10607
e-mail: lenornst@pipeline.com

fuel.

If stored but not burned, the harvest would contribute to a drawdown of atmospheric $CO_2$ starting at (harvest tC)/$d$/ha/yr, and leveling off at the rate of (harvest tC)/ha/yr, beyond the first $d$ years. Within a given area, net primary productivity (NPP) is defined as the difference between the carbon sequestered through photosynthesis and the carbon released as $CO_2$ due to respiration. Thus, when decay of the fallen trees is prevented, the harvest itself represents an increase in NPP.

On the other hand, if burned to replace fossil fuel, in existing[4] plants, the just 'computed' drawdown of atmospheric $CO_2$ would hardly be diminished, because the burning of equal masses of fossil-fuel-carbon or dry wood-carbon produce the same amounts of $CO_2$ and very nearly the same amounts of energy (Bergman and Zerb 2008). Therefore, burning, in lieu of coal or heavy fuel oil, and to a lesser extent natural gas and lighter burning oils, and long-term safe storage are 'substitutes' that 'equally' reduce the atmospheric load of $CO_2$. Of course, storage costs are minimized if most of the harvest is consumed as fuel. Much 'storage function' is served – and saved – by leaving the fossil fuel in the ground.

In either case, removal of the wood also removes the mineral content of the harvested trunks from the local forest biome. Applying the 'wood-ash-equivalent' of each tree-trunk, representing approximately 1% of dry mass, to each harvest site would cancel that recycling deficit and should make the harvest 'indefinitely' sustainable. That ash-equivalent 'fertilizer' may come from previously burnt organic waste or wood or from mineral sources. Such harvest would then be 'eco-neutral' in its impact (see Section 5).

I call this a sustainable, eco-neutral, conservation harvest (SENCH). SENCH was accidentally 'discovered' during preliminary analysis of somewhat different strategies of how best to manage very large tree-harvests in a sustainable way. These harvests involve about $8.8 \times 10^8$ ha of proposed, irrigated tree-plantations on the Sahara and Australian Outback deserts (Ornstein et al. 2008). An eco-friendly, uneven-aged, harvest strategy, similar to that developed for northern hardwood old-growth forests (Keeton 2006), may be an attractive alternative approach with similar yields.

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[3] It seems there is considerable confusion, at least among public policy makers and the general public, regarding under what conditions, and by what amounts, crops and forests and/or fuels derived from them, might contribute to drawdown in the amount of $CO_2$ injected into the atmosphere.

> When land is cleared and a new crop is established, the old-cover carbon is usually released, through decay or burning, as $CO_2$, as a 'one-time-event' ($cl_1$ tC/ha). In addition, there will be a one-time releases of $CO_2$ ($cl_2$ tC/ha) from the energy expended to clear the land. The continuing previous NPP of the old cover ($npp_o$ tC/ha/yr) is eliminated. The new crop has a different continuing NPP ($npp_n$ tC/ha/yr). If $npp_n$ is less than $npp_o$, there is already a net, permanent increase in annual release of $CO_2$ into the atmosphere, as is typical of deforestation. The maintenance of the crop (cultivation, irrigation, fertilization, harvest, transportation, and so on) contribute an additional ($m$ tC/ha/yr). The total impact ($CO_2$-footprint) is approximately $[(npp_o+m-npp_n)$ tC/ha/yr]$+[(cl_1+cl_2)$ tC/ha] .
>
> When a 'natural' cover (prairie, savanna, forest, etc.) is itself harvested sustainably, the total will be about ($m-npp_o$ fraction harvested) tC/ha/yr.
>
> When a previously barren area ($npp_o = 0$, $cl_1 = 0$, $cl_2 = 0$) is afforested or put into sustainable agricultural production, the total $CO_2$-footprint will be about ($m-npp_n$) tC/ha/yr, because all net production is above the barren baseline. So long as $m$ is small, this is a substantial improvement.

$cl_1$, is very large when forest is cleared, whereas $cl_2$ usually is *relatively* small. For crops like corn, $m$ is often a substantial *proportion* of $npp_o$, but for forests, it is usually a very small fraction.

---

[4] Fossil fuel contributes to its $CO_2$-footprint in proportion to $p$ tC. Extracting and transporting it adds a small $q$ tC/t$_{fuel}$ for most coal, gas and oil, but larger for oil tars and much larger for shale. Permanently replacing fossil fuel with biofuel often means that the annual new $CO_2$-footprint of an *existing* power plant depends upon the relationship of ($npp_o+m-npp_n$) to a $f(p+q)$. When $npp_n$ is smaller than ($npp_o+m$), the $CO_2$-footprint often is not reduced when biofuel substitutes for fossil fuel.

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## 3 How Much Carbon is involved?

The areas of old-growth, broad-leaf, evergreen, rain forests of the Amazon and Equatorial Africa, harboring some of the ecologically richest biomes on Earth, coincidentally also total about $8.8 \times 10^8$ ha (Lewis 2006). The above ground biomass (AGB) of such forests averages about 200 to 350 t/ha (Mahli et al. 2006) (equal to about 100 to 175 tC/ha), of which about 2/3 is in tree-trunks. Tree mortality rates in those forests run about 1.5% of biomass/yr (Carey et al. 1994; Philips and Gentry 1994). The harvest of fallen trunks could yield something like 1.0 to 1.75 tC/ha/yr. This is equal to a local increase of NPP of about 1 to 1.75 tC/$d$/ha/yr. A continuing total harvest, beyond $d$ years, just from these two geographic regions, would *reduce* released $CO_2$ by about 0.88 to 1.54 GtC/yr – whether stored or burned in existing plants in place of fossil fuel.

Compared to the present increment of about 8.8 GtC/yr injected into the atmosphere as $CO_2$ from the combined world-wide burning of fossil fuels, deforestation and land abuse (Alley et al. 2007), the 0.88 to 1.54 GtC/yr is significant. This could begin to provide substantial mitigation of warming, especially if combined with an end to deforestation and with the application of other conservation practices such as the maximizing of industrial-, transportation- and home-energy-use-efficiencies. Also, it might be amplified two or three times, as discussed below under Section 6.

## 4 Economic And Additional Ecological Costs and Risks of SENCH

Extraction of high-value wood is one of the motives that contributes to ongoing tropical deforestation. I have not assessed the amounts in those forests. But non-fuel uses for the most valuable wood among the fallen trees can reduce the net cost of SENCH. Counteracting this are increased costs of transportation of logs and the much smaller amount of 'ash', over global distances, rather than the transportation of coal, usually over shorter distances. These transportation differences will often contribute to the largest cost-disparity between wood and coal for countries – like the US – with ample domestic coal and far from the Amazon or Congo. The burning of fuel for any extra transportation of wood and ash will generate some additional $CO_2$ that also will offset the net $CO_2$-savings of 'renewable wood' by up to a few per cent. And the greater the care in removal of trees, the greater the economic cost, but the lower the ecological cost.

The following are some eco-friendly harvesting options:

- Reduced impact logging (RIL) uses narrower logging-roads and narrow skid trails for removing trunks (Asner et al. 2004).
- Skyline yarding, that might be employed for an advanced form of RIL, uses above-canopy, mobile towers and cables, requires fewer skid trails and permits more widely-spaced logging-roads. But it requires higher capital and operating costs and better-trained manpower.
- The most ecologically benign approach, uses satellite location of new canopy gaps (Clark et al. 2003), and aerial transfer of logs to yards beside roads or rivers, using lighter-than-air ships (e.g., see Boeing SkyHook 2008) or helicopters. This permits removing the harvest by the use of only very widely-spaced logging-roads or, instead, rivers. Though it may be the most expensive strategy, it minimizes access for illicit harvesting or damage and may therefore significantly reduce policing costs.

A portion of the sum of RIL costs, policing costs, storage costs, transportation costs and 'chipping' and drying costs may need to be 'subsidized' with fossil-carbon-taxes to make wood cost-competitive with fossil fuels – particularly with coal. These considerations also apply, although unequally, whether the harvest is 'permanently' stored, or used in place of fossil fuel.

## 5 Eco-Neutrality?

If an old-growth forest were truly at steady-state, by definition its yearly NPP would average zero. A fallen-trunk-only harvest strategy therefore would be expected to have a positive effect on NPP but a very minimal impact on biodiversity. Harvesting standing dead trees ("snags") should be intentionally avoided, because these survive decay a good deal longer than fallen trees. And snags are host to numerous unique and often rare species that should be conserved. On the other hand, in moist tropical forests the fallen trunks are rapidly degraded by the same organisms that degrade the branches, intentionally left behind as litter by SENCH. Therefore, only small shifts in the frequencies of the ubiquitous species that participate in

these degradative processes should result as a consequence of SENCH.

In a truly steady-state forest, the ecological impact, if any, of such a harvest could be monitored in a straightforward manner. But all recent evidence (e.g., Zhao et al. 2007) indicates that most old-growth forests are , in fact, exhibiting substantial net growth for whatever reasons. The tropical rain forests have NPPs of $800 - 1200$ $gC/m^2/yr \approx 10$ tC/ha/yr (see Figure). That means their ecologies are in flux. Therefore, biological impacts of a presumed eco-neutral harvest might be more difficult to measure.



MEAN NPP (2000–2005) $gC/m^2/yr$

From Zhao et al. 2007
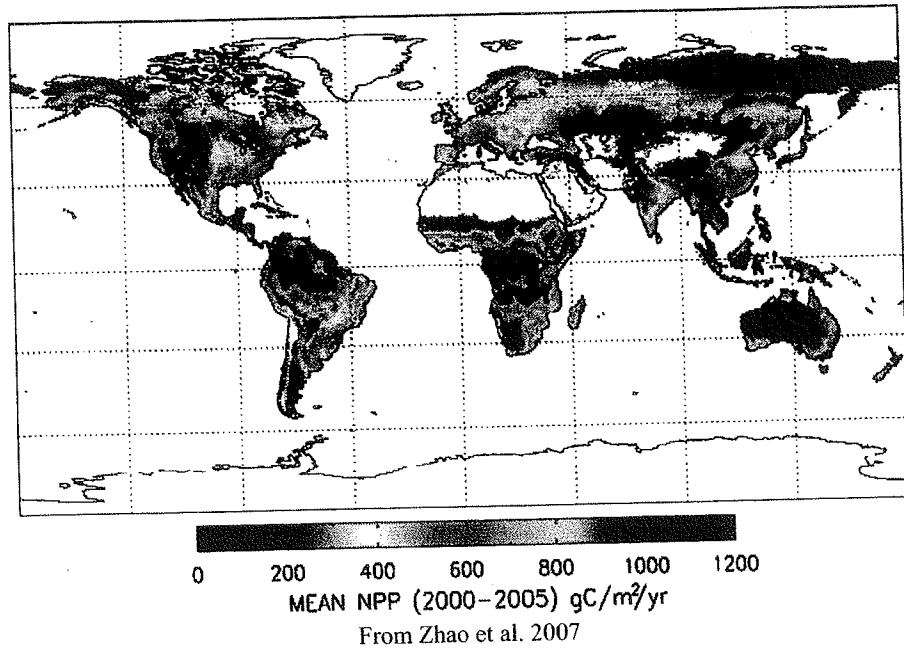
## 6 Further Opportunities and Risks to be Explored

Harvest only of fallen trees can be almost ecologically neutral and can drawdown atmospheric $CO_2$ while providing a large, sustainable supply of wood to substitute for fossil fuels.

But even well-managed harvest of live trees in old-growth forests could be the beginning of deforestation with its well-known disadvantages; increasing atmospheric $CO_2$ leading to global warming, the destruction of ecological networks and potential extinctions.

Is there any strategy for limited, near-eco-neutral harvest of live trees? Such harvest should at least not *increase* atmospheric $CO_2$, but sustainably further increase the supply of wood to substitute for fossil fuel or, in the case of valuable timber species, perhaps substitute for logging operations elsewhere.

Suppose, along with the fallen trees, numbers of live trees were harvested, selected to both match the species and the size/age frequencies of fallen trees. Then the site-of-harvest would simultaneously be selected to widen those gaps in the canopy created by the recently fallen trees. This would increase illumination of the already exposed understory to further stimulate rapid regrowth. If the NPP of those stimulated and ash-fertilized understory trees quickly rises to at least equal that of the harvested live trees, drawdown of $CO_2$ would not diminish and such increased harvest will be sustainable from year to year. Again, as with SENCH, it can be stored or used to replace coal, with about the same reduction in global warming. But the larger the harvest, the larger the ecological disturbance.

An incremental harvest of live trunks of about twice the mass of fallen trunks would leave a total mass of branches, as litter, that would be about equal to that of the total mass of the fallen trees in the untouched old-growth forest. This means the natural ecology of the above-ground detritus biome would be only marginally perturbed. However, the area of canopy gaps would increase to about three times that created by natural tree-fall. In the first year, the canopy biome would still be about 95% of the size of the original and barely perturbed. But the gap biome would be enlarged by 200% .

Harvest of such magnitude may be sufficiently 'eco-neutral' to be encompassed under SENCH.

Careful modeling (e.g., like in Marland and Schlamadindger 1997) might be used to establish some confidence in the magnitudes of projected yields and sustainabilities of various very-restricted dead-tree+live-tree SENCH scenarios. The fallen-tree-only SENCH strategy is likely to maintain the well-known skewed distribution of old-growth forests, with respect to species, age and biomass, where a few old and massive emergents represent a very large proportion of the biomass, and the average age and size are biased to high values. Over centuries or millennia, regularly harvesting even a few live trees would almost certainly lower those average values and modify the ecology, hopefully only slightly.

Such 'conservation' efforts unfortunately run the risk of failing catastrophically. If the market for wood is strong, some will be motivated to cheat and over-harvest. Effective enforcement, and perhaps costly policing, would be required to prevent such illegal 'poaching'. Failing enforcement, this could lead to the rapid destruction of remaining forests and to runaway global warming. However, satellite observation is cheap and it can detect features the size of forest clearings. Communication to enforcement agencies could be quick, and policing effective, if the political will is there.

Of course, the planet is already running such risk without SENCH. Deforestation is a problem that is being faced quite widely (see the Forest Now Declaration 2007) under the rubric of REDD (Reduced Emissions from Deforestation and Degradation). However, I believe that political and economic mechanisms previously proposed in such contexts are not especially promising.

## 7 Comparisons and Politics

Compared to the expensive replacement of most operating coal-fired power plants with CCS power plants and/or nuclear fission plants (two "Faustian Bargains" that risk uncertainties in the natural, long-term containment of 'dangerous wastes'; Spreng et al. 2007), the technology to implement SENCH already exists, is cheap and is direct – but it depends on effective policing. It could be exploited in forests much sooner than vast CCS replacement. Therefore, it could begin to reduce the rate of increase of atmospheric $CO_2$ sooner. This is because the maximum rate of reduction of atmospheric $CO_2$ follows the first 'harvest-rescue' by $d$ years, and is almost the same, whether the harvest is stored, while the politics of if and when to burn wood in place of coal is debated, or whether such policy is promptly instituted and the harvest is routinely used as fuel.

The politics of CCS and of old-growth-forest SENCH are quite different. Each presents its own set of difficulties. The risks, uncertainties and costs of the respective storage problems may create quite different levels of political resistance. And renewable resources, like forests, must be managed prudently and vigorously to remain sustainable, representing quite a different problem from managing power plants and burying pressurized $CO_2$.

However, the SENCH strategy also could create significant employment and corporate opportunities in Amazonia and equatorial Africa, from:

logging and lumber production;
manufacture of charcoal, syngas, methyl alcohol and 'biodiesel', using anoxic pyrolysis;
safe storage of wood or charcoal;
manufacture of flexible fuel vehicles;
the export of these commodities;
'wood'-burning power plants;
forest management;
others.

These could provide competing economic incentives to replace those currently responsible for the world's largest deforestations in these same two regions; "killing two birds with one stone".

With appropriate taxes on fossil fuels, and with wood and/or charcoal substituting for coal, a substantial shrinkage of the world-wide coal industry would probably follow. Those taxes may also stimulate the more efficient production from wood, beyond classic anoxic pyrolysis, of 'new' renewable liquid and gaseous hydrocarbon fuels (e.g., Carlson et al. 2008; Ryan et al. 2008) and of feedstocks for organic syntheses. I believe such must ultimately serve as the main sustainable substitutes for the non-renewable GHG-generating supplies of fossil oil and natural gas that all agree are being depleted rapidly.

In summary, the SENCH strategy not only can lower atmospheric $CO_2$, as does CCS, but

simultaneously provides an alternative supply of renewable reduced carbon at low cost, probably with smaller risks, and at the same time, may further motivate forest conservation.

## 8 Conclusions

A SENCH strategy, combined with increasing energy-use efficiencies, might provide a breathing spell for the further development of other attractive 'solutions' to global warming; e.g., $CO_2$-free sources of energy, such as cheaper 'solar' with cheap energy-storage and/or, best of all, controlled fusion and a more rapid approach towards zero population growth.

$CO_2$-free energy sources may fail to contribute quickly enough to allow all nations, and particularly China and India, to wean themselves from fossil fuels. Wide-spread use of CCS and expansion of the nuclear fission industry, both with risks and high costs, may then need to be instituted. (Note: CCS power plants fueled with SENCH wood almost double their effective carbon sequestration; they emit very little $CO_2$, and through the increase in effective NPP of SENCH, can contribute twice the negative carbon footprint per watt of a standard CSS plant that replaces an existing coal burning plant; and half that, for a plant that adds to net power output.)

Alternatively, another SENCH-related solution that we have proposed, "Irrigated Afforestation of the Sahara and Australian Outback to End Global Warming" (Ornstein et al, 2008) could be initiated to renewably sequester about 8 *additional* GtC/yr. We had recommended CCS or nuclear-fission to power the sea-water desalination plants and pumps needed to supply fresh irrigation water to the 'desert forests'. To avoid the associated Faustian Bargain (Spreng et al. 2007) and to reduce capital costs, such coal-fueled, power plants might instead be fueled with SENCH wood, without CCS or with CCS, to further lever the effectiveness of the overall system in removing carbon from the atmosphere.

However, if SENCH wood is to replace coal, effective policing and taxing of high-$CO_2$-footprint biofuels and *excessive* harvest and use of other wood, both tropical and non-tropical, that is *neither* eco-neutral *nor* forest-preserving, may become very difficult.

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*Land surface:* While extensive snow and ice cover represent natural examples of the cooling influence of bright surfaces, the potential for geoengineered approaches to counter greenhouse gas induced warming by increasing surface reflectivity is quite limited. Not only do clouds and atmospheric absorption reduce the amount of solar radiation that reaches the surface by ~50% as compared to the top of the atmosphere, but only ~30% of that amount falls onto land areas. In addition, the land areas with a low albedo that could be significantly enhanced are generally committed to purposes such as agriculture or forests.

To avoid covering land needed for other purposes, Gaskill and Reece (2003) proposed increasing the reflectivity of large areas of desert. They estimated that it would require covering ~70,000 km$^2$ of land each year with a Mylar film to counter the effects of each year's addition of greenhouse gases. Although covering a bright desert area would limit the increase in the albedo per unit area that could be achieved, choosing such regions would, assuming the weather remains unchanged, benefit from having clear skies. A critical research question is whether such large-scale modification of the surface albedo would alter the regional weather and climate, and, if so, the environmental and societal consequences of such changes. In addition, there would be the practical problem of maintaining the effectiveness of the reflective surface over time.

Rather than increase the albedo of large, unused areas, another alternative would be to increase the albedo of existing uses of the land by, for example, whitening the roofs of structures and transportation corridors (Akbari et al., 2008). Although the fraction of the Earth's surface that could be affected is relatively small unless a means (e.g., genetic engineering) is developed to increase the average reflectivity of trees and grasslands, the basic problem with geoengineering the land surface as a means of achieving a global result is getting enough of a change over a large enough area. An additional problem is that regional changes in the weather seem likely to result, as has been evident in studies that, for example, investigate the potential effects of deforesting the Amazon (e.g., Dickinson and Kennedy, 1992). Smaller scale efforts would, however, seem likely to have a favorable result in the local area as well as reducing the heat load on the particular structure, and if such changes were done worldwide, there might well even be a noticeable large-scale effect (Akbari et al., 2008).

*Ocean surface:* Because the ocean's albedo is low, raising it could lead to a very large change in surface reflectivity. Were this to be done by floating a reflective structure, its size would need to be roughly the size of a continent in order to raise the global albedo by 1%. Such an extensive covering would have significant impacts, particularly by reducing both the amount of energy absorbed and the evaporation. In addition, there would be impacts on the weather and ocean currents, perhaps reducing the overall effectiveness of the approach. Russell Seitz (2008, personal communication) has proposed an interesting alternative to covering the ocean surface with a reflector. His approach would augment the formation of tiny bubbles by natural wave-breaking processes. Injected a few meters below the surface, for example by existing ships as part of a process to reduce their drag (e.g., Graham-Rowe, 2008) or by the type of special ships proposed by Salter et al. (2008), the lifetime of very small bubbles might be as long as a few days, and, over this time, the albedo of the ship wake would be increased by several percent.

Finally, efforts to maintain or increase the formation of sea ice might be possible. If a way could be found to transfer heat from the water below sea ice to the surface so that it could be radiated

upward during the polar night when the insulating effect of sea ice limits upward flow of heat from the ocean, sea ice could be made thicker and therefore longer lasting, thus making it more capable of reflecting solar radiation away during the polar summer. With the Arctic being the source of the very cold air that spreads south into mid-latitudes, creating violent weather when such air masses undercut warm, moist air, increasing the extent and persistence of sea ice could exert an important cooling influence on the climate that would become manifest through its effects on the weather.

When the sea ice is thin, an approach to thickening the ice that has been suggested is to break up the new ice using icebreakers, which would allow heat to escape more easily in the disrupted regions; the disadvantage, of course, is that doing so would likely be quite expensive. An alternative approach would be construct a fleet of floating devices that would augment wintertime heat flow through the sea ice while enhancing surface albedo in the summer. Possible approaches would include floats that provide a high thermal conductivity path from below to above the sea ice, and distributed snow-making machines that would shoot sea water up from below the sea ice, perhaps powered by the thermal gradient that exists from below to atop the ice. While theoretically imaginable, engineering such devices and assuring an adequate capability seem likely to be problematic.

**Counter-acting Specific Impacts or Effects in Specific Regions**

Using geoengineering to counterbalance specific consequences of global warming or effects in specific regions has also been proposed. While adaptation and increasing resilience to impacts are approaches to moderate the adverse consequences of climate change, they focus on how human activities might be adjusted to avoid or limit the specific adverse consequences. By contrast, geoengineering approaches would seek to reduce the intensity of the factor or process leading to a particular impact or set of impacts. Several proposals likely merit more detailed consideration than has been given to date.

*Moderating the intensity of hurricanes and typhoons:* The projected increase in the intensity and rain production of tropical cyclones (i.e., typhoons, hurricanes, etc.) threatens to cause greatly increased damage to the increasing number of people living in potentially vulnerable coastal regions. Initial studies to seed near-eyewall clouds in hurricanes in order to modify their track started roughly 50 years ago, but were generally unsuccessful for both observational and theoretical reasons. With the new, very high-resolution models, theoretical studies are starting to receive a bit more attention, but problems remain in determining ways to alter such large and intense weather systems once they form. What would be most useful is some sort of environmentally friendly, easily dispersed, inexpensive, and controllable surfactant that would slow evaporation of the seawater that ultimately powers these storms, but none has yet been developed (Kerry Emanuel, personal communication, 2001).

Alternatively, finding a way to limit solar absorption by the ocean or to increase ocean mixing might be used to cool ocean waters in areas where tropical cyclones intensify, thus limiting the energy available to power these storms. For example, increasing the reflectivity of low-level marine stratus clouds as proposed by Salter and Latham (2006) could be used to limit ocean warming in the regions where tropical cyclones tend to form or intensify (e.g., in the Caribbean