Climate Change Impacts in the Amazon:

Review of scientific literature[1]

The Amazon

The Amazon basin contains a staggering portion of the world's biodiversity, supports thousands of people through agriculture and silviculture, and provides the world with commodity and non-commodity products such as building supplies and medicine. The Amazon contains one of Earth's richest assortments of biodiversity with recent compilations indicating at least 40,000 plant species, 427 mammals, 1294 birds, 378 reptiles, 427 amphibians, 3,000 fishes, and likely over a million insect species. The Amazon River is the largest single source of freshwater runoff on Earth, representing some 15 to 20% of global river flow (Salati and Vose 1984). Subsequently, the Amazon's hydrological cycle is a key driver of global climate, and global climate is therefore sensitive to changes in the Amazon. Climate change threatens to substantially affect the Amazon region, which in turn is expected to alter global climate and increase the risk of biodiversity loss.

Observed Climatic Change and Variability

The climate in northwestern South America, including the Amazon region, has already changed over the last century. The monthly mean air temperature records show a warming of 0.5–0.8°C for the last decade of the 20th century (Pabón, 1995a; Pabón *et al.*, 1999; Quintana-Gomez, 1999). In the Amazon region specifically, a warming trend of +0.63°C per 100 years was detected by Victoria et al. (1998). Precipitation trends in the Amazon are not as clear, and multidecadal rainfall variations have shown opposite tendencies in the northern and southern portions of the basin (Marengo *et al.* 2000). The period 1950–1976 was regionally wet in northern Amazonia, and since 1977 the region has been drier (IPCC 2001), suggesting the affect of long-term climatic variability.

Recent studies have clarified the link between deforestation and precipitation in the Amazon. Chagnon and Bras (2005) found that current deforestation causes a dramatic change in climatological rainfall occurrence patterns; high-resolution satellite precipitation measurements show significantly more rainfall occurrence over deforested areas. They also found a long-term shift in the seasonality of precipitation that correlates with deforestation, suggesting the two are closely

---

[1] Prepared by Michael Case, Research Scientist, WWF Climate Change Programme

associated. Rainfall accumulations have decreased significantly at the end of the wet season, and have increased at the end of the dry season (Chagnon and Bras, 2005). These findings imply that current deforestation in the Amazon has already altered the regional climate and support previous findings of enhanced shallow cloudiness over deforested areas (Chagnon et al., 2004). However, earlier findings suggest more widespread changes; studies have shown a decadal intensification of precipitation over the entire Amazon (Chu et al., 1994; DeLiberty, 2000; Chen et al., 2002).

El Niño/Southern Oscillation (ENSO) seems to be a driver of much of the climatic variability in Latin America (IPCC 2001). For example, El Niño is associated with dry conditions in northeast Brazil, northern Amazonia, the Peruvian-Bolivian Altiplano, and Pacific coast of Central America. The most severe droughts in Mexico in recent decades have occurred during El Niño years, whereas southern Brazil and northwestern Peru have exhibited anomalously wet conditions at these times (Horel and Cornejo-Garrido, 1986). La Niña is associated with heavy precipitation and flooding in Colombia and drought in southern Brazil (Rao et al., 1986).

Predicted Climatic Change

General Circulation Models (GCM's) project a regional increase of 2–3°C by the year 2050 and a decrease in precipitation in the Amazon during dry months, leading to widespread drying (Mitchell et al., 1995; Kattenberg et al., 1996). Ecosystem models that use expected climatic changes show large declines in net primary productivity (NPP) and release of carbon as a result of Amazonian forest dieback (Friend et al., 1997). In fact, climate change effects may change the current status of Amazonian forests from a net sink of atmospheric CO_2 into a source, which will further contribute to dangerous levels of atmospheric CO_2 (IPCC 2001). GCM's also suggest that a globally warmer world may result in a permanent El Niño-like state (Wara et al., 2005), which if manifested by drought conditions, could have huge impacts on the Amazon.

Impacts

Empirical and modeled data suggest that the Amazon basin is at particular risk to climate change effects. Projected changes of warmer temperatures and decreased precipitation during already dry months could manifest in longer and perhaps, more severe droughts and substantial changes in seasonality. Coupled with land use changes, these changes could lead to devastating impacts, including; increased erosion, degradation of freshwater systems, loss of ecologically and agriculturally valuable soils, loss of biodiversity, decreased agricultural yields, increased insect infestation, and spread of infectious diseases.

Forests

Climate change effects pose a substantial threat to Amazonian forests and the biodiversity within them. Amazonian forests contain a large portion of the world's biodiversity; at least 12% of all flowering plant are found within the Amazon (Gentry 1982) therefore threats to Amazon forests translate into threats to biodiversity at large. In fact, climate modeling studies have projected a warming and drying effect, which when combined with a decrease in evapotranspiration from plants will likely lead to a substantial decrease in precipitation over much of the Amazon. These changes will likely lead to significant shifts in ecosystem types and loss of species in many parts of the Amazon (Miles et al., 2004; Markham 1998). Land-use change will also interact with climate through positive feedback processes that will accelerate the loss of Amazon forests (IPCC 2001).

At the biome level, GCMs of potential future climates project that evergreen forests are succeeded by mixed forest, savanna and grassland in eastern Amazonia and savanna expand into parts of western Amazonia (Cramer et al., 2001; Cramer et al. 2004). Other modeling experiments project an expansion of savanna, grasslands and desert ecosystems into north-eastern Amazonia (White et al. 1999). Large-scale modeling shows widespread forest loss over most of the Amazon, accelerated by positive feedback between warming, forest dieback, and emissions of carbon from soil and vegetation (White et al., 1999; Cox et al., 2000; Jones et al., 2003; Cox et al., 2004). In fact, the Brazilian government has released figures suggesting that deforestation has exceeded 520,000 square km since 1978, with the second worst year of forest loss occurring in 2004 (National Institute for Space Research, 2005). Species specific modeling suggests that 43% sampled Amazon plant species may become non-viable by the year 2095 because their potential distributions will have changed due to climatic shifts (Miles et al. 2004). In order for species affected by these changes to reach appropriate new bioclimatic zones, dispersal or migration would have to occur over hundreds of kilometers (Hare, 2003).

Many of the aforementioned modeling experiments have not considered non-climate influences such as land use, deforestation, water availability, pests and diseases, and fire, all of which may limit the migration and dispersal of tropical forest species. The IPCC suggests that the combination of forces driving deforestation makes it unlikely that tropical forests will be permitted to expand into climatically suitable habitats that are created by climate change.

Amazon forests are also threatened by secondary effects of climate change, such as a potential increase in the frequency and perhaps in intensity of fires. It is suggested that fire poses the greatest threat to Amazon forests and numerous studies have shown a well established link between forest fires, habitat fragmentation, climate change, and extreme El Niño events in the Amazon (Nepstad et al., 2001; Laurance and Williamson, 2001; Laurance et al., 2001; Nepstad et al., 2001; Cochrane and Laurance, 2002).

As mentioned previously climate models predict that a globally warmer world may result in a permanent El Niño-like state (Wara et al., 2005) with dramatic effects such as; droughts, fires, and increased release of carbon to the atmosphere. El Niño events (the positive phase of the El Niño/Southern Oscillation (ENSO)) tend to dry affected areas and lead to large, intense droughts and fires. Severe droughts can also stress and potentially kill sensitive plant species, resulting in a replacement of tropical moist forests with drought-tolerant plant species (Shukla et al., 1990). It has also been shown that there are substantial releases of carbon from the Amazon during El Niño years (Tian et al., 1998). Strong El Niño years bring hot, dry weather to much of the Amazon region and the ecosystems act as a source of carbon to the atmosphere instead of a sink as during non-El Niño years (Tian et al., 1998).

There are a number of positive feedback loops that drive the expansion of fires in the Amazon: 1) Forest fires release substantial amounts of smoke into the atmosphere which can reduce rainfall and thus promote more drought and more fires (Rosenfeld, 1999); 2) Fire-assisted conversion of forests to agriculture and pastures also promotes drought by decreasing water vapor flux (evapotranspiration) to the atmosphere, further inhibiting rainfall (Nepstad et al., 2001); and 3) Fire increases the susceptibility of forests to recurrent burning by killing trees, thereby allowing sunlight to penetrate and dry the forest interior, and increasing the fuel load on the forest floor (Nepstad et al., 2001).

Human activities such as deforestation, logging, and settlement obviously work in tandem with climate change and increase the drying effect that leads to forest fires. For example, mortality of trees, which increases the fuel load for fire, has been observed to increase under dry conditions that prevail near newly formed edges in Amazonian forests from land clearing and harvesting (IPCC 2001). Edges, which affect an increasingly large portion of the forest with the advance of deforestation, are especially susceptible to the effects of reduced rainfall and are increasingly susceptible to fire.

Freshwater

The Amazon river, with more than 1000 tributaries, discharges into the Atlantic Ocean some 209,000 cubic meters of water per second (about 60 times the rate of the Nile), which represents more than 15% of all the fresh water entering the oceans each day. The average rainfall in the Amazon basin is about 2,300 mm per year and the Amazon River plays an important role in the water cycle and water balance of much of South America. Changes in water regime such as the quantity, quality, and timing can affect the habitats and behavior of many plant and animal species (Hare, 2003), in addition to extremes caused by climatic perturbations in water cycling. Changes in total precipitation, extreme rainfall events, and seasonality will affect the amount, timing, and variability of flow. Changes in total volume or timing of runoff may result in increased or decreased intermittency, while altered volume, variability, and extremes of runoff may affect timing, frequency and severity of flash flooding (Carpenter et al., 1992). Such changes in magnitude and temporal distribution of extreme events may disrupt ecosystems more than changes in mean conditions.

Water and aquatic resources provide many essential services to the people of the Amazon. The region’s native fisheries provide a large proportion of animal protein consumed by inhabitants. Fish are also a valuable source of income to fishermen. River and lake water satisfies nearly all of the water supply needs of Amazonian peoples, including drinking, cooking, bathing, and waste removal. While little water is used for irrigation, river channels and lakes are important avenues of transportation and shipping and provide opportunities for recreation (McClain, 2001).

Climate change threatens the Amazon’s water regime and freshwater ecosystems because warming temperatures will result in greater evaporation from water surfaces and greater transpiration by plants, which will result in a more vigorous water cycle (Allen et al. 2005). If projected declines in precipitation during dry months occur, climate change impacts to the Amazonian water regime may be exacerbated (Nijssen et al., 2001). Climate change threats to Amazonian freshwater ecosystems are varied, but include:

1) **Warming water temperatures** because of global warming will impact temperature dependent species. Temperature tolerances often govern both the local and biogeographic distribution limits of freshwater fishes (Carpenter et al., 1992). Distributions of aquatic species will likely change as some species invade more high altitude habitats or disappear from the low altitudinal limits of their distribution. Elevated temperatures may also result in reduced water dissolved oxygen concentrations, which may have immediate adverse effects on eggs and larvae, which rely on dissolved oxygen for survival (Carpenter et al., 1992). Increased water temperatures and reduced precipitation may also reduce suitable habitat during dry, warm summer months and potentially lead to increased exotic species. Exotic fish species often out-compete native species for habitat and food resources and lead to declines in native populations and decreased species diversity (Latini and Petrere Jr, 2004).

2) **Decreased precipitation during dry months** will affect many Amazonian streams and freshwater systems. Small, shallow habitats (ponds, headwater streams, marshes, and small lakes) will likely experience the first effects of reduced precipitation (Carpenter et al., 1992). While prospects for successful relocation of spawning activities for fishes exist, some may be thwarted by the strong imprinting and homing behavior present in many species.

3) **Changes in nutrient input** into streams and rivers because of altered forest productivity can greatly affect aquatic organisms. Forested streams are highly dependent upon inputs of terrestrial organic matter, especially leaf fall, because of their nutrient supply. Shifts in terrestrial vegetation and changes in leaf chemistry will impact stream biota and ecosystems. In fact, several climate modeling studies and field experiments show that about 50% of the rainfall in the Amazon region originates as water recycled in the forest.

4) Climate models project a future that has a **more variable climate and more extreme events** (IPCC 2001b), and local fish populations will more often experience extreme events such as those that produce lethal conditions for short periods of time. Such disturbances can

deplete stocks of adult fish and other biota, disrupt ecological processes, and redistribute resources (Lake et al. 2000). Even short-lived stresses such as temporary climatic extremes can cascade throughout the trophic network for extended periods. Fish adapted to cooler water temperatures are most vulnerable to climatic extremes such as warm water conditions because they rely on constant temperatures. Relatively modest changes in the weather can dramatically increase variability in recruitment (Cushing, 1982). A cascade of food web effects can follow from the removal or enhancement of fishes whose effects as predators cause variability in the trophic structure, productivity, and water quality of lakes (Carpenter, 1988; Carpenter et al., 1985). Recreational and commercial fisheries are particularly at risk of climate extremes and increased variability because fish populations are notoriously variable, and fisheries yields are often heavily dependent on the occasional strong year class (Pitcher and Hart, 1982). Survival during early life history stages is a key to recruitment success (Wooton, 1990), and the expected increase in climatic variability may lead to variable reproductive success in individual cohorts, which will have immediate social and economic effects (Carpenter et al. 1992). For example, fishermen in the River Tocantins have chosen capture strategies specific to seasonal variations in fish behavior and reproduction (Welcomme 1985) and changes in climatic spatio-temporal variability could cause these species to decline in numbers or become extinct. Changes in seasonal fluctuations may change the migratory pattern and ecology of fish species and lead to changes in fish catches (Cetra and Petrere Jr, 2001).

Agriculture

The IPCC (2001) suggests that projected warmer temperatures and changes in precipitation will undoubtedly impact the agricultural sector (including plantation forestry) in the Amazon. Particularly hard hit will be subsidence farming. In fact, agriculture is the basis of subsistence lifestyles and is the largest user of human capital rural communities that are situated within the Amazon. In these areas, agriculture is the main producing sector and it will be severely affected by climatic change and variability (Rosenzweig and Hillel, 1998). A reduction in rainfall during critical dry months may also lead to increased evapotranspiration and pest infestation, which will undoubtedly negatively impact agricultural yields (IPCC 2001). Climatic change would subsequently require larger areas of land to meet the current levels of demand. In fact, Fearnside

(1999) predicts that the total plantation area will have to increase up to 4.5 times the 1991 area by 2050.

Climate change effects on agricultural yields vary by region and by crop. Under certain conditions, the positive physiological effects of CO_2 enrichment could be countered by temperature increases—leading to shortening of the growth season and changes in precipitation, with consequent reductions in crop yields (IPCC 2001). In fact, reduced availability of water and warmer temperatures are expected to have negative effects on wheat, maize, and potentially soybean production in Brazil (de Siqueira et al., 1994). However, it should be noted that there are relatively few agricultural climate change impact studies have been done in South America, especially the Amazon.

Subsistence farming in the Amazon is particularly threatened by potential consequences of climate change. In fact, Rosenzweig et al. (1993) identifies northeastern Brazil as suffering yield impacts that are among the most severe in the world (also see Reilly et al., 1996; Canziani et al., 1998; Rosenzweig and Hillel, 1998). In addition, northeastern Brazil is home to more than 45 million people and is prone to periodic droughts and famines even in the absence of expected climate changes, and any changes in this region would have major consequences for human populations.

Plantation farming, or silviculture, will be greatly impacted by the potential decrease in precipitation caused by climate change in Amazonia. Because water often limits tree growth during the dry season, a decrease in rainfall will have negative impacts on growth and yield. To quantify this effect, Ferraz (1993) has developed a regression equation to approximate the effects of precipitation changes on plantation yields. General circulation climate modeling using the UKMO model (Gates et al., 1992) indicates that annual rainfall changes for regions of Brazil would cause silvicultural yields to decrease by 6% in Amazonia and 8% in southern Brazil. During the June – July – August rainfall period, yields would decrease by 12% in Amazonia, 14% in southern Brazil, and 21% in the northeast (Fearnside, 1999). However, the climate modeling effects on yield are likely to underestimate the true effect of climate change because other secondary climate factors may reduce yield substantially more (i.e., pest and diseases infestation) (Cammell and Knight, 1992). Reduced rainfall may also lead to increased fire risk in plantations, also affecting yield. For example, Eucalyptus is particularly fire-prone because of the high content of volatile oils in the leaves and bark.

CO_2 enrichment may be beneficial for plantations because higher atmospheric concentrations of CO_2 increase the water-use efficiency of some species (i.e., Eucalyptus). While the photosynthetic and nitrogen fixation rates increase (thus lowering the fertilizer demands of plantations) in some Eucalyptus species increased when exposed to high concentrations of CO_2 (Hall et al., 1992), other factors such as reduced water availability, insect, disease, and fire effects are typically not considered and may result in a net negative response to climate change.

Larger areas of plantations (at a higher cost) will likely be needed to meet current levels of demand in a globally warmer world. Fearnside (1999) modeled rainfall reductions of 5, 10, 25, and 50% (all possible climate change scenarios), and calculated the required plantation area would need to increase as much as 38% to meet demands.

Climate models predict that a globally warmer world may result in a permanent El Niño-like state (Wara et al., 2005) and this would have substantial effects on agriculture. Because El Niño events tend to dry impacted areas and lead to large, intense droughts and fires, crops will likely be impacted.

Health

Climate change will threaten human health in the Amazon. However, health impacts will vary in magnitude due to the size, density, location, and wealth of the population and are not uniform (WHO 1998). Human death and mortality rates (injuries, infectious diseases, social problems, and damage to sanitary infrastructure), due to heatwaves, droughts, fires, and floods increased for most of the climate change scenarios that have been modeled from baseline climate conditions in Latin America. However, most modeling has examined urban populations, which because of the poor housing conditions (crowded and poorly ventilated) they are particularly vulnerable to temperature extremes (Kilbourne, 1989; Martens, 1998). Furthermore, the effects of extreme temperature may be significantly different for rural populations (Martens, 1998).

In addition to the already established relationship between extreme temperatures and increased death rates (McMichael et al., 1996), other climate change impacts such as increased occurrence of extreme weather events (e.g., floods, droughts, fire, heatwaves). It has been found that some extreme weather events, such as floods, may be responsible for outbreaks of vector-borne diseases such as malaria and dengue (Moreira, 1986; PAHO, 1998a,b) and for outbreaks of infectious diseases such as cholera and meningitis (Patz, 1998). El Niño and La Niña can also cause changes in disease - vector populations and the incidence of water-borne diseases (Epstein et al., 1998). During droughts, the risk of wildfires increases and the direct effects on human health occur from burns and smoke inhalation (Kovats et al., 1999), in addition to indirect effects from air pollution, primarily from smoke and suspended particles, which can lead to loss of forests, property, livestock, and human life (OPS, 1998). Typically not lethal, increased temperature may lead to an increase in the distribution and growth of allergenic plants. In fact, higher temperatures and lower rainfall at the time of pollen dispersal are likely to result in higher concentrations of airborne pollen during the peak season (Emberlin, 1994; Rosas et al., 1989). Consequently, people who are already sensitive to pollen could be substantially impacted by increased temperature and potential drying of the Amazon and others may developed allergies due to the increased concentrations.

Sea level rise

The IPCC suggests that flooding associated with sea-level rise will have substantial impact in lowland areas such as the Amazon River delta. In fact, according the IPCC (2001), the rate of sea-level rise over the last 100 years in has been 1.0-2.5 mm a year and this rate could now rise to 5 mm per year. Increased temperature, changes in precipitation and runoff, and sea-level rise will have significant impacts on the present habitats of mangroves and create new tidally inundated. Sea-level rise would eliminate mangrove habitat at an approximate rate of 1% yr^{-1}. This effect will cause species composition shifts and will likely affect the region's fisheries that depend on mangrove habitat as nurseries and refuge. For example, commercial shellfish and finfish use mangroves for nurseries and refuge, and a direct relationship of mangrove decline and fisheries decline has been identified in these systems (Martínez et al., 1995; Ewel and Twilley, 1998). The potential disappearance of some mangrove forests could undermine the livelihoods of local fishing communities. Coastal inundation stemming from sea-level rise will also affect water availability (i.e., saltwater intrusion could affect estuaries and freshwater sources) and agricultural land suitability, therefore exacerbating the socioeconomic and health problems in sensitive areas (IPCC 2001).

References:

Allan, J. D., M.A. Palmer and N.L. Poff. 2005. Climate change and freshwater ecosystems. Pp. 272-290. *In* T.E. Lovejoy and L. Hannah (*eds*.), Climate Change and Biodiversity. Yale University Press, New Haven CT., USA.

Cammell , M.E. and J.D. Knight. 1992. Effects of climatic change on the population dynamics of crop pests. Advances in Ecological Research 22: 117–162.

Canziani, O.F., S. Díaz, E. Calvo, M. Campos, R. Carcavallo, C.C. Cerri, C. Gay-García, L.J. Mata, A. Saizar, P. Aceituno, R. Andressen, V. Barros, M. Cabido, H. Fuenzalida-Ponce, G. Funes, C. Galvão, A.R. Moreno, W.M. Vargas, E.F.Viglizao, and M. de Zuviría. 1998. Latin America. *In*: The Regional Impacts of Climate Change: An Assessment of Vulnerability. Special Report of IPCC Working Group II [Watson, R.T., M.C. Zinyowera, and R.H. Moss (*eds*.)]. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 187–230.

Carpenter, S. R., (ed.) 1988. Complex Interactions in Lake Communities. New York: Springer-Verlag. 283 pp.

Carpenter, S. R., Kitchell, J. F., Hodgson, J. R. 1985. Cascading trophic interactions and lake productivity. Bio-Science 35:634-39.

Carpenter, S.R. Fisher, S.G., Grimm, N.B., and Kitchell, J.F. 1992. Global change and freshwater ecosystems. Annual Reviews Ecology and Systematics 23: 119-139.

Cetra, M. and Petrere Jr, M. 2001. Small-scale fisheries in the middle River Tocantins, Imperatriz (MA), Brazil Fisheries Management and Ecology 8(2): 153-162.

Chagnon, F. J. F., and R. L. Bras. 2005. Contemporary climate change in the Amazon. Geophysical Research Letters 32: L13703, doi:10.1029/2005GL022722.

Chagnon, F. J. F., R. L. Bras, and J. Wang. 2004. Climatic shift in patterns of shallow clouds over the Amazon, Geophysical Research Letters 31: L24212, doi:10.1029/2004GL021188.

Chen, J., B. E. Carlson, and A. D. Del Genio. 2002. Evidence for strengthening of the tropical general circulation in the 1990s. Science 295: 838–841.

Chu, P.-S., Z.-P. Yu, and S. Hastenrath. 1994. Detecting climate change concurrent with deforestation in the Amazon basin: Which way has it gone? Bulletin of the American Meteorology Society 75: 579–583.

Cochrane, M. A., and W. F. Laurance. 2002. Fire as a large-scale edge effect in Amazonian forests. Journal of Tropical Ecology 18: 311-325.

Conde, C., D. Liverman, M. Flores, R. Ferrer, R. Araujo, E. Betancourt, G. Villareal, and C. Gay, 1997. Vulnerability of rainfed maize crops in Mexico to climate change. Climate Research 9: 17–23.

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408: 184 – 187.

Cox, . M.P., R. A. Betts, M. Collins, P. P. Harris, C. Huntingford, and C. D. Jones. 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. Theoretical and Applied Climatology 78: 137–156.

Cramer W., A. Bondeau, S. Schaphoff, W. Lucht, B. Smith, S. Sitch. 2004. Tropical forests and the global carbon cycle: impacts of atmospheric carbon dioxide, climate change and rate of deforestation. Philosophical Transactions: Biological Sciences 359 (1443): 331 – 343.

Cramer, W., Bondeau, A., Woodward, F.I., Prentice, I.C., Betts, R.A., Brovkin, V., Cox, J., Fisher, V., Foley, J.A., Friend, A.D., Kucharik, C., Lomas, M.R., Ramankutty, N., Sitch, S., Smith, B., White, A. & Young-Molling, C. 2001. Global response of terrestrial ecosystem structure and function to CO2 and climate change: results from six dynamic global vegetation models. Global Change Biology 7: 357–373.

Cushing, D.H. 1982. Climate and Fishcries. London: Academic.

DeLiberty, T. L. 2000. A regional scale investigation of climatological tropical convection and precipitation in the Amazon basin. Professional geographer 52: 258–271.

de Siqueira, O.J.F., J.R.B. Farías, and L.M.A. Sans, 1994. Potential effects of global climate change for Brazilian agriculture: applied simulation studies for wheat, maize and soybeans. *In*: Implications of Climate Change for International Agriculture: Crop Modeling Study [Rosenzweig, C. and A. Iglesias (*eds*.)]. EPA 230-B-94-003, U.S. Environmental Protection Agency, Washington, DC, USA.

Emberlin, J., 1994. The effects of patterns in climate and pollen abundance on allergy. Allergy 49: 15–20.

Epstein, P.R., H.F. Díaz, S. Elias, G. Grabherr, N.E. Graham, W.J.M. Martens, E. Mosley-Thompson, and J. Susskind. 1998. Biological and physical signs of climate change: focus on mosquito-borne diseases. Bulletin of the American Meteorological Society 79(3): 409–417.

Ewell, K.C. and R.R. Twilley, 1998. Different kinds of mangrove forests provide different goods and services. Global Ecology and Biogeography Letters 7(1): 83–94.

Fearnside, P.M., 1999. Plantation forestry in Brazil: the potential impacts of climatic change. *Biomass and Bioenergy* 16(2): 91–102.

Ferraz, E.S.B. 1993. Influência da precipitação na produção de matéria seca de eucalipto. IPEF Piracicaba 46: 32–42 (in Portuguese).

Friend, A.D., A.K. Stevens, R.G. Knox, and M.G.R. Cannell, 1997: A process based, terrestrial biosphere model of ecosystem dynamics (hybrid v. 3.0). *Ecological Modelling*, 95, 249–287.

Gates,W.L., J.F.B. Mitchell, G.J. Boer, U. Cubasch, and V.P. Meleshko. 1992. Climate modelling, climate prediction and model validation. *In*: Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment [Houghton, J.T., B.A. Callander, and S.K. Varney (*eds*.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 97–134.

Gentry, A.H. 1982. Neotropical floristic diversity. Annals of the Missouri Botanical Garden. 69: 557–593.

Hall, D.O., R. Rosillo-Calle, R.H. Williams, and J. Woods, 1992. Biomass for energy: supply prospects. *In*: Renewable Energy: Sources for Fuels and Electricity [Johansson, T.B., H. Kelly, A.K.N. Reddy, and R.H. Williams (**eds**.)]. Island Press, Covelo, CA, USA, pp. 593–651.

Hare, W. 2003. Assessment of Knowledge on Impacts of Climate Change – Contribution to the Specification of Art. 2 of the UNFCCC. WBGU Potsdam, Berlin.

Horel, J. D. and Cornejo-Garrido, A. G. 1986. Convection along the Coast of Northern Peru, during 1983: Spatial and temporal variations of clouds and rainfall. Monitor. Weather Rev. 114: 2091–2105.

IPCC, 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK,1032p.

IPCC, 2001b. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 881p.

Jones, C. D., P. M. Cox, R. L. H. Essery, D. L. Roberts, and M. J. Woodage. 2003. Strong carbon cycle feedbacks in a climate model with interactive CO2 and sulphate aerosols. Geophysical Research Letters 30(9): 1479.

Kattenberg, A., F. Giorgi, H. Grassl, G.A. Meehl, J.F.B. Mitchell, R.J. Stouffer, T. Tokioka, A.J. Weaver, and T.M.L. Wigley, 1996: Climate models—projections of future climate. *In*: Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (*eds.*)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 289–357.

Kilbourne, E.M., 1989. Heatwaves. *In*: The Public Health Consequences of Disasters [Gregg, M.B. (*ed.*)]. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, Atlanta, GA, USA, pp. 51–61.

Kleidon, A., Heimann, M. 1999. Deep-rooted vegetation, Amazonian deforestation, and climate: results from a modelling study. Global Ecology and Biogeography 8: 397-405.

Kovats, R.S., M.J. Bouma, and A. Haines. 1999. El Niño and Health. WHO/SDE/PHE/99.4, World Health Organization, Geneva, Switzerland, 48 pp.

Lake, P.S. Palmer, M.A., Biro, P., Cole, J., Covich, A.P., Dahm, C., Gibert, J., Goedkoop, W., Martens, K., Verhoeven, J. 2000. Global change and the biodiversity of freshwater ecosystems: impacts on linkages between above-sediment and sediment biota. BioScience 50(12): 1099-1107.

Latini, A.O. and Petrere Jr, M. 2004. Reduction of a native fish fauna by alien species: an example from Brazilian freshwater tropical lakes. Fisheries Management and Ecology 11(2): 71-79.

Laurance, W.F., and G.B. Williamson. 2001. Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon. Conservation Biology 15 (6): 1529-1535.

Laurance, W.F., G.B. Williamson, P. Delamonica, A. Oliveira, T.E. Lovejoy, C. Gascon, and L. Pohl. 2001. Effects of a strong drought on Amazonian forest fragments and edges. Journal of Tropical Ecology 17: 771-785.

McClain, M.E. 2001. The Relevance of Biogeochemistry to Amazon Development and Conservation. In The biogeochemistry of the Amazon Basin. McClain, M.E., Victoria, R.L., and Richey, J.E. (eds.). London, Oxford University Press.

Marengo, J., U. Bhatt, and C. Cunningham, 2000: Decadal and multidecadal variability of climate in the Amazon basin. *International Journal of Climatolology*.

Marengo, J., Tomasella, J., and Uvo, C. R.: 1998. Trends in Streamflow and Rainfall in Tropical South America: Amazonia, Eastern Brazil, and Northwestern Peru. Journal of Geophysical Research 103: 1775–1783.

Markham, A. (*ed*). 1998. Potential impacts of climate change on tropical forest ecosystems. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Martens, W.J.M. 1998. Climate change, thermal stress and mortality changes. Social Science and Medicine, 46(3): 331–344.

Martínez, J.O., J.L. González, O.H. Pilkey, and W.J. Neal. 1995. Tropical barrier islands of Colombia Pacific coast: sixty-two barrier islands. Journal of Coastal Research 11(2): 432–453.

McMichael, A.J., M. Ando, R. Carcavallo, P. Epstein, A. Haines, G. Jendritzky, L. Kalkstein, R. Odongo, J. Patz, and W. Piver. 1996. Human population health. *In*: Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T. , MC. Zinyowera, and R.H. Moss (*eds.*)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 561–584.

Miles, L. A. Grainger, Phillips, O. 2004. The impact of global climate change on tropical biodiversity in Amazonia. Global Ecology and Biogeography 13: 553-565.

Mitchell, J.F.B., R.A. Davis, W.J. Ingram, and C.A. Senior, 1995. On surface temperature, greenhouse gases and aerosols: models and observations. Journal of Climate 10: 2364–2386.

Moreira, C.J.E. 1986. Rainfall and flooding in the Guayas river basin and its effects on the incidence of malaria 1982–1985. Disasters 10(2): 107 – 111.

National Institute for Space Research (INPE). 2005. Figures obtained from the National Institute for Space Research website, www.inpe.br, cited August 29, 2005.

Nepstad, D., G. Carvalho, A.C. Barros, A. Alencar, J.P. Capobianco, J. Bishop, P. Moutinho, P. Lefebvre, U. Lopes Silva Jr., E. Prins. 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. Forest Ecology and Management 154 (3): 395-407.

Nijssen , B. O'Donnell, G.M., Hamlet, A.F. and Lettenmaier, D.P. 2001. Hydrologic Sensitivity of Global Rivers to Climate Change. 50(1-2): 143 – 175.

OPS, 1998. Repercusiones Sanitarias de la Oscilación del Sur (El Niño). CE122/10, Organización Panamericana de la Salud, Washington, DC, USA, 22 pp. (in Spanish).

Pabón, J.D., 1995a. Búsqueda de series de referencia para el seguimiento de la señal regional del calentamiento global. *Cuadernos de Geografía*, **2,** 164–173 (in Spanish).

Pabón, J.D., G.E. León, E.S. Rangel, J.E. Montealegre, G. Hurtado, and J.A. Zea, 1999b. *El Cambio Climático en Colombia: Tendencias actuales y Proyecciones*. Nota Técnica del IDEAM, IDEAM/METEO/002-99, Santa Fe de Bogotá, Colombia, 20 pp. (in Spanish).

PAHO, 1998a. Report on the Epidemiological Situation in Central America. SC/XVII/40, Pan American Health Organization, Washington, DC, USA, 2 pp.

PAHO, 1998b. Infectious Diseases Posing in the Greatest Epidemiological Risk Following Hurricane Mitch in Central America, 1998.A Report of the Pan American Health Organization Emergency Task Force, Division of Disease Prevention and Control, Washington, DC, USA, 4 pp.

Patz, J.A., W.J.M. Martens, D.A. Focks, and T.H. Jetten, 1998. Dengue fever epidemic potential as projected by general circulation models of global climate change. Environmental Health Perspectives 106(3): 147–153.

Pitcher, T. J, Hart, P. J. B. 1982. Fisheries Ecology. London: Croom Helm.

Rao, V. B., Satyamurty, P., and Brito, J. I. B. 1986. On the 1983 drought in Northeast Brazil. Journal of Climate 6: 43–51.

Reilly, J., W. Baethgen, F.E. Chege, S.C. van de Geijn, L. Erda, A. Iglesias, G. Kenny, D. Patterson, J. Rogasik, R. Rotter, C. Rosenzweig, W. Sombroek, J. Westbrook, D. Bachelet, M. Brklacich, U. Dammgen, M. Howden, R.J.V. Joyce, P.D. Lingren, D. Schimmelpfennig, U. Singh, O. Sirotenko, and E. Wheaton. 1996. Agriculture in a changing climate: impacts and adaptation. *In*: Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T., M.C. Zinyowera, and R.H. Moss (*eds*.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 427–467.

Rosas, I., G. Roy-Ocotla, and P. Mosiño. 1989. Meteorological effects on variation of airborne algae in Mexico. International Journal of Biometeorology 33: 173–179.

Rosenfeld, D. 1999. TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. Geophysical Research Letters 26 (20): 3105-3108.

Rosenzweig, C. and D. Hillel, 1998. Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture. Oxford University Press, Oxford, United Kingdom, 324 pp.

Rosenzweig, C., M.L. Parry, G. Fischer, and K. Frohberg. 1993. Climate Change and World Food Supply. Research Report No. 3, Environmental Change Unit, Oxford University, Oxford, United Kingdom, 28 pp.

Salati, E., and P. B. Vose. 1984. Amazon basin: A system in equilibrium. Science 225: 129– 138.
Shukla, J., Nobre, C., and Sellers, P. 1990. Amazon deforestation and climate change. Science 247: 1322–1325.
Solomon, A.M., I.C. Prentice, R. Leemann, and W. P. Cramer. 1993. The interaction of climate and land use in future terrestrial carbon storage and release. Water, Air, and Soil Pollution 70: 595–614.
Tian, H.Q., J.M. Melillo, D.W. Kicklighter, A D. McGuire, J.V.K. Helfrich, B. Moore, and C.J. Vorosmarty. 1998. Effect of interannual climate variability on carbon storage in Amazonian ecosystems. Nature 396 (6712): 664-667.
Quintana - Gomez , R.A., 1999: Trends of maximum and minimum temperatures in northern South America. Journal of Climate, 12(7), 2104–2112.
Victoria, R., L. Matinelli, J. Moraes, M. Ballester, A. Krusche, G. Pellegrino, R. Almeida, and J. Richey, 1998: Surface air temperature variations in the Amazon region and its border during this century. Journal of Climate, 11, 1105–1110.
Wara, M.W., Ravelo, A.C., Delaney, M.L. 2005. Permanent El Niño-Like Conditions During the Pliocene Warm Period. Science, 309 (5735): 758-761.
Welcomme R.L. 1985. River fisheries. Food and Agriculture Organisation Fisheries Technical Paper 262, 330.
White, A., M.G.R. Cannel, and A.D. Friend. 1999. Climate change impacts on ecosystems and the terrestrial carbon sink: a new assessment. Global Environmental Change, 9, S 21–S 30.
World Meteorological Organisation WMO, 1998. Report on the Status of Observing Networks. Report submitted to CoP-4, World Meteorological Organisation, Geneva, Switzerland.
Wooton, R.J. 1990. Ecology of Teleost Fishes. New York: Chapman & Hall.
Zuidema, G., G.J. Van den Born, J. Alcamo, and G.J.J. Kreileman. 1994. Simulating changes in global land cover as affected by economic and climatic factors. Water, Air, and Soil Pollution 76 (1–2): 163–198.

Contact info:

Lara J. Hansen, Ph.D., Chief Scientist, WWF Climate Change Program
WWF-US, 1250 24th Street NW, Washington DC 20016 - USA
Lara.Hansen@wwfus.org - Tel +1 202 778-9619

Martin Hiller, Communications Manager, WWF Climate Change Programme
WWF International - Av du Mont Blanc - CH-1196 Gland - Switzerland
mhiller@wwfint.org - Tel +41 22 364 9226