JUNE 2011

WORKING DRAFT

Desert Cloud Forests:

Adapting a unique ecosystem to climate change

PROFOR

PROGRAM ON FORESTS

ACKNOWLEDGEMENT

This paper was prepared by Elfatih AB Eltahir, Professor of Environmental Engineering at the Massachusetts Institute of Technology (M.I.T.) for the World Bank Middle East and North Africa Region, as part of a larger knowledge activity on cloud forests in Oman and Yemen. This activity was prematurely closed in 2011 due to political instability in Yemen. The work was funded by the Program on Forests (PROFOR), a multi-donor partnership managed by a core team at the World Bank.

PROFOR finances forest-related analysis and processes that support the following goals: improving people's livelihoods through better management of forests and trees; enhancing forest law enforcement and governance; financing sustainable forest management; and coordinating forest policy across sectors. In 2011, PROFOR's donors included the European Commission, Finland, Germany, Italy, Japan, the Netherlands, Switzerland, the United Kingdom and the World Bank. Learn more at www.profor.info.

DISCLAIMER

Suggested citation: Eltahir, Elfatih AB. 2011. *Desert Cloud Forests: Adapting a unique ecosystem to climate change.* Working draft. Washington DC: Program on Forests (PROFOR).

Published in June 2011

For a full list of publications please contact:

Program on Forests (PROFOR)
1818 H Street, NW
Washington, DC 20433, USA
profor@worldbank.org
www.profor.info/knowledge

Profor is a multi-donor partnership supported by:

Table of Contents

Executive Summary

The Desert Cloud Forests in Oman (Dhofar region) and Yemen (Hawf region) are different from cloud forests in other relatively humid regions. Cloud forests in humid regions drive only a small fraction of their water input by intercepting cloud water. Hence, changes in cloud cover may only impact the type of forest or species composition however trees are likely to still dominate the ecosystem even if we assume disappearance of the clouds. In contrast, desert cloud forests would cease to exist as an ecosystem dominated by tree species without the clouds. The water intercepted by the trees from the clouds is crucial for the survival of trees in this environment. In considering the impact of climate change on the desert cloud forest ecosystem, the primary focus should be on how climate change may pose a threat for the health of the *Anogeissus dhofarica* trees that dominate the escarpment region of the mountains. Frankincense produced from the endemic tree, *Boswellia sacra,* is probably the most important non-timber commercial product from this ecosystem. The best quality Frankincense is produced from the desert region north of the mountains. Climate conditions in this region are rather stable and not as likely to be impacted by climate change as the escarpment region.

During the last few decades the region around the desert cloud forest has been experiencing significant change driven by large increases in human population and economic activity. This rapid change was accompanied by significant accumulation of wealth in traditional communities that value ownership of camel and other animals, especially in Dhofar. Hence, the population of animals in the desert cloud forest ecosystem increased significantly which added significant additional pressures on the natural ecosystem. Due to camel browsing on tree canopies, the desert cloud forest is gradually degrading to grassland in many locations. This change in land cover represents one of the main challenges to the survival of the desert cloud forest ecosystem.

The main hazard from climate change to the desert cloud forests of Oman and Yemen is the scenario of upward shift in cloud cover and fog. Since the upper boundary of the cloud forest in this region corresponds to the highest elevation of the escarpment, there is no room in this setting for the cloud cover and the cloud forest to migrate upward. Hence, any reduction in relative humidity, as a result of climate change, will result in reducing the width of the elevation band that can be covered by clouds, with the extreme scenario of complete disappearance of the cloud cover and the associated cloud forest. On the other hand, the region of Oman and Yemen is located next to the desert of Arabia, a region of large-scale atmospheric subsidence (downward movement of air). There are indications that over such regions, the desert cloud forests may actually experience denser or more frequent clouds. Different General Circulation Models (GCMs) disagree on the sign of their predictions of changes in cloud cover over this region. Hence, we conclude that although the worst case scenario of climate change over this region would result in complete disappearance of the cloud cover and the associated desert cloud forest, there is a great deal of uncertainty about the likelihood of such scenario, to the extent that we cannot rule out the possibility of increased clouds frequency over this region as a result of climate change. The models predictions regarding the impact of climate change on the desert cloud forests of Oman and Yemen remain quite uncertain.

1. Background and Context

(Based mainly on TOR)

A cloud forest is defined as an evergreen mountain moist forest characterized by frequent presence of low clouds at canopy level, supplementing rainfall in the satisfaction of plants water requirements. This ecosystem is common in many tropical and subtropical regions worldwide, along the Pacific costal line from Mexico to Bolivia, in Africa (DRC and Madagascar among others), in South-East Asia (from Malaysia to Papua New Guinea). If cloud forests are not an unusual phenomenon in high rainfall ecosystems, they are extremely rare to find in regions characterized by chronic dryness, like the Arabian Peninsula. The Desert Cloud Forests in Oman (Dhofar region) and Yemen (Hawf region) are unique yet fragile ecosystems, subject to human threats and climate change repercussions.

In Desert Cloud Forests, trees have preserved an ecological niche by exploiting a wispy-thin source of water that only occurs seasonally. The "water-limited seasonal cloud forest" is kept alive by extracting water droplets gathered from low-lying passing clouds. The water dribbles into the ground and sustains the trees later when the weather is dry. Studies conducted in Oman suggest the trees actually get more of their water through contact with clouds than via rainfall. The Desert Cloud Forests contribute greatly to ground water recharge, supporting the water cycle in a rain limited region. In the decades to come, temperature increase, precipitation variability, and change in air humidity can have negative effects on the ecosystem and consequently on the hydrological cycle. Understanding the Desert Cloud Forests could be important for counteracting implications of climate change, as part of a broader adaptation strategy that would be able to harness more water into the hydrology of these and associated landscapes.

The Desert Cloud Forest in Oman and Yemen represent a safety net integrating household income of local population, who rely on them for wood collection (construction and fuel) and as grazing land. However, development pressure in terms of deforestation and uncontrolled herding represents a serious risk. Camels' grazing is considered one of the main threats, inducing defoliation of these unique forests. The issue is deeply linked to local culture and traditions, with family prestige in the Arabian Peninsula being still linked to the number of camels owned, independently for the "concrete" needs of the household. While trees in wetter ecosystems would likely recover from limited over-grazing, this is unlike to happen in this vulnerable environment, where even small pressures can lead to irreparable impacts. Without the trees that sweep the extra water from clouds, the forest can unlikely regenerate, as grass, even if abundant, cannot collect enough moisture from the fog. Climate change could further undermine the regeneration process of the ecosystem.

The Desert Cloud Forests represents a living sign of the historical past of the Arabian Peninsula, as a remnant of a moist vegetation belt that once spread across the region when the climate was generally wetter. Because of the "superlative natural phenomena" and being the "natural habitats for in-situ conservation of biological diversity", the Dhofar and Hawf regions have been included as a whole in the UNESCO World Heritage Tentative List.

The present activity aims to propose climate-proofing strategies for the sustainable use and conservation of the Desert Cloud Forests in Oman and Yemen. Specifically, it aims to:

- undertake an assessment of the Desert Cloud Forests and define the potential risks of climate change on the ecosystem
- explore the full range of goods and services associated with the Desert Cloud Forests and their contribution to meet basic needs of poor communities, defining local population' practices within this fragile ecosystem, and identifying future challenges in relation to climate change
- derive best practices on how to manage, conserve, and promote the Desert Cloud Forests under future climate change

The desert cloud forests of Dhofar and Hawf are very similar in their settings and climates. The Dhofar forests are located in Oman along a 200 kilometers stretch of the coast of the Arabian Sea, while the Hawf forest stretches for only about 50 kilometers along the same coast on the Yemen side of the Oman/Yemen border (See the red enclosure in Figure 1). The Dhofar cloud forest has been studied and characterized much better than the Hawf cloud forest. Hence, in this report we use the Dhofar forest as an example for this ecosystem. Any lessons learned in Dhofar should be quite applicable to Hawf. We refer to the overall ecosystem including both areas as Desert Cloud Forest Ecosystem.

Figure 1: Map of the Area

In the following sections, we focus on (i) current understanding of desert cloud forests; (ii) local population and its practices; (iii) potential risks of climate change on the desert cloud forests; and (iv) design of a questionnaire on interaction between forest environment and human population activities.

2. Our Current Understanding of Desert Cloud Forests

This chapter is organized in three sections. One section is on cloud forests in general; the second section on desert cloud forests in particular; and the third section covers plants of the desert cloud forests.

2.1 Cloud Forests

Cloud forests are defined as forests that are frequently covered in cloud or mist. Cloud forests are in general wetter, cooler, and less seasonal than other forests that are not affected by flog and low level clouds.

Cloud forests exist in regions characterized by certain elevations, rainfall amounts, temperature, and distance from the coast. The United Nations Environment Program (UNEP) identified 477 cloud forest sites. Most of the sites are located at altitudes between 400 m and 2800 m above sea level, with an average altitude of about 1700 m. The majority of cloud forest sites occur in regions with 2000–2600 mm of annual rainfall, and annual mean temperatures of 14 –18°C. Cloud forests are confined to a zone within 350 kilometers from the coast (Jarvis and Mulligan (2011)).

An important distinguishing feature of cloud forests is the ability of trees within these forests to capture and intercept water droplets directly from the low level clouds, providing additional water source for trees. This added water source is sometimes referred to as horizontal precipitation and sometimes referred to as 'cloud-water' interception. Based on field measurements at several cloud forest sites, researchers estimate that annual 'cloud-water' interception varies widely between different locations ranging between 22mm and 1990 mm. Scientists have attempted to develop numerical models and representations of hydrologic processes within cloud forests. The simulations of 'cloud-water' interception by such models produce estimates that range from less than 5% of total precipitation in wet areas to more than 75% in low-rainfall areas. (Bruijnzeel et al. (2011))

For most cloud forests, the combination of rainfall and ‘cloud-water’ interception exceeds the loss of water through evapotranspiration, with the excess water contributing to streams and flowing rivers. However, under relatively dry conditions, such as those existing along desert borders; this excess water could be quite small. Under such conditions, the vital water needs of the plants are satisfied to a significant degree through ‘cloud-water’ interception. We describe this class of forests as Desert Cloud Forests. The desert cloud forests of Dhofar and Hawf represent a unique ecosystem. As shown in the satellite picture below, these forests occupy a small niche next to the coast of the Arabian Sea surrounded by the vast desert of Arabia.

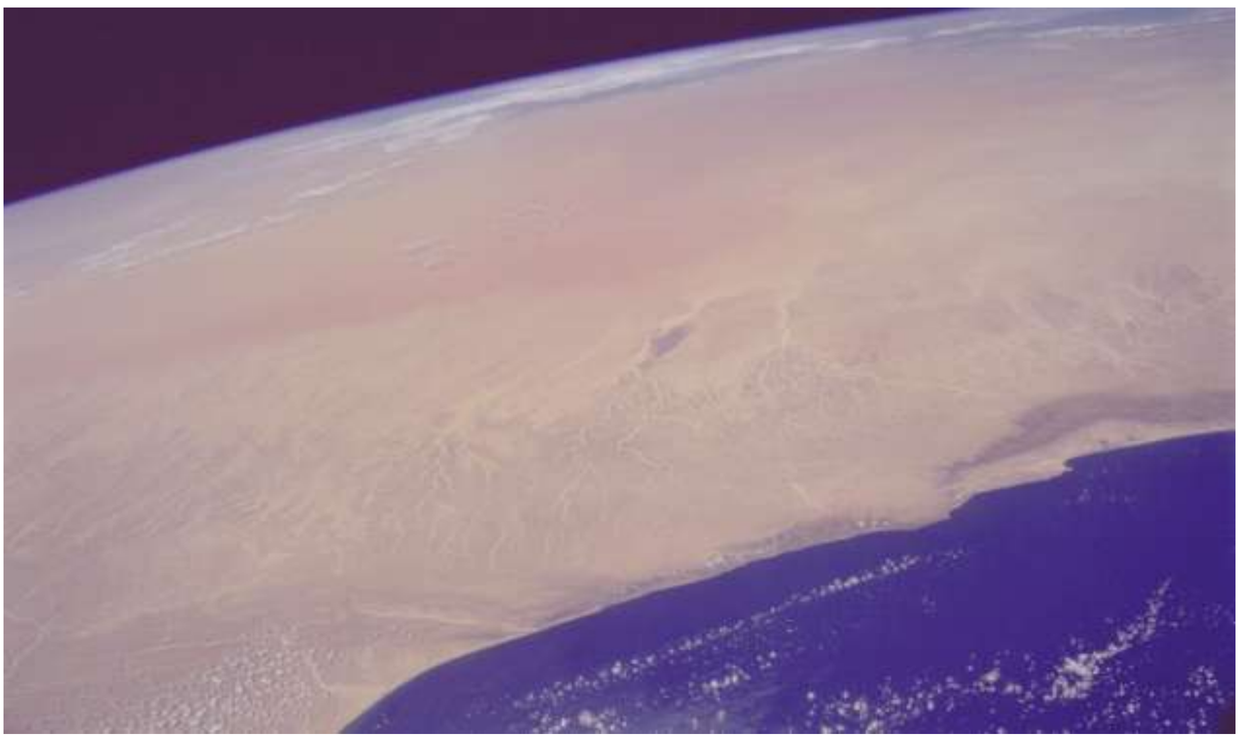

Figure 2: Desert Cloud Forest from Space: relatively dark areas to the right, next to the Arabian Sea

2.2 Desert Cloud Forests

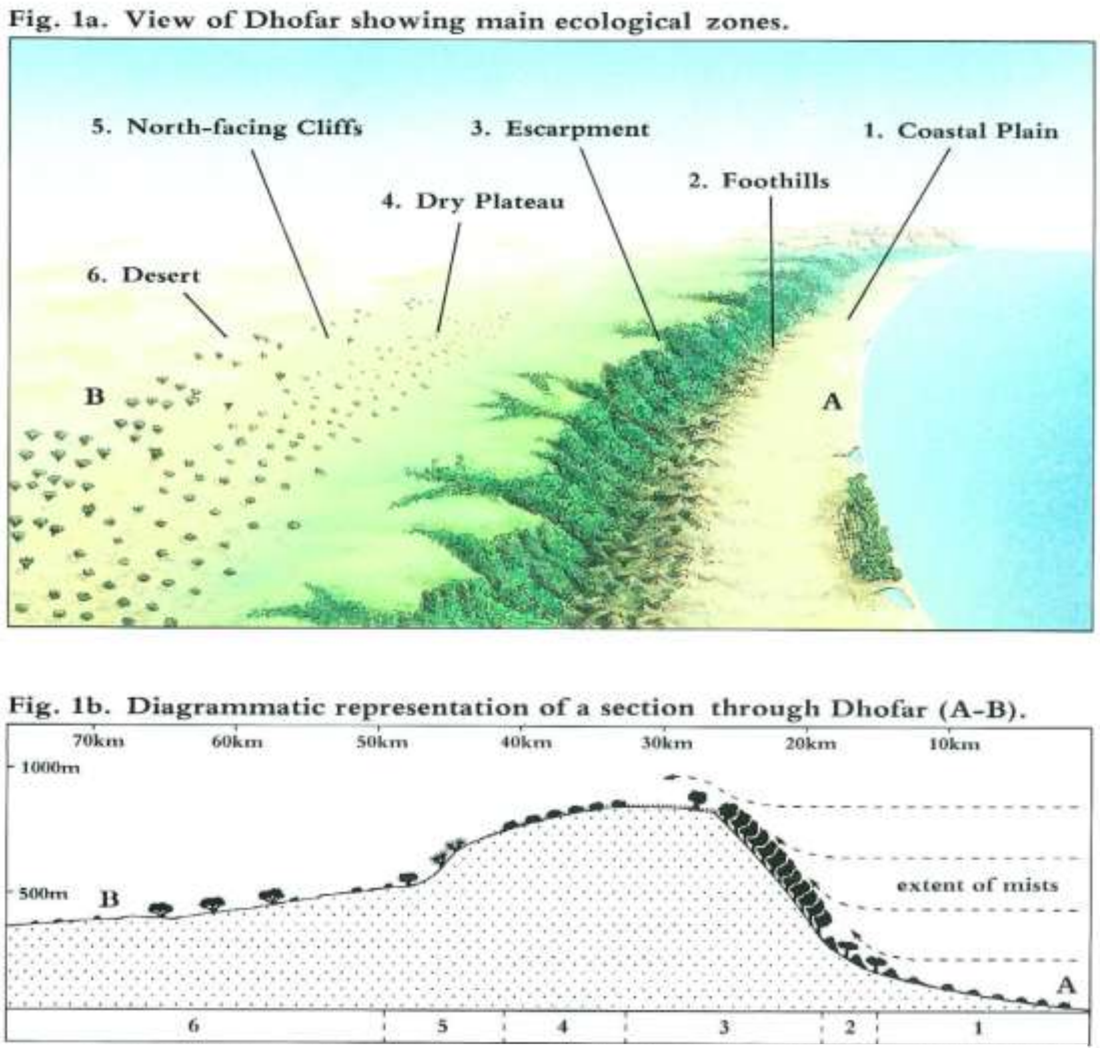

Figure 3: Dhofar Clouds Forests Ecosystem (Miller and Morris (1988))

The cloud forests of Dhofar and Hawf are classical examples for Desert Cloud Forests. As shown Figure 3, these cloud forests are located very close to the sea shore (~15 kilometers), occupying a relatively low altitude band between (300-700 meters). It is also important to point out the top boundary of the forests coincides with the maximum elevation of the mountains. Hence, there is no room for any upward migration of the cloud forest band.

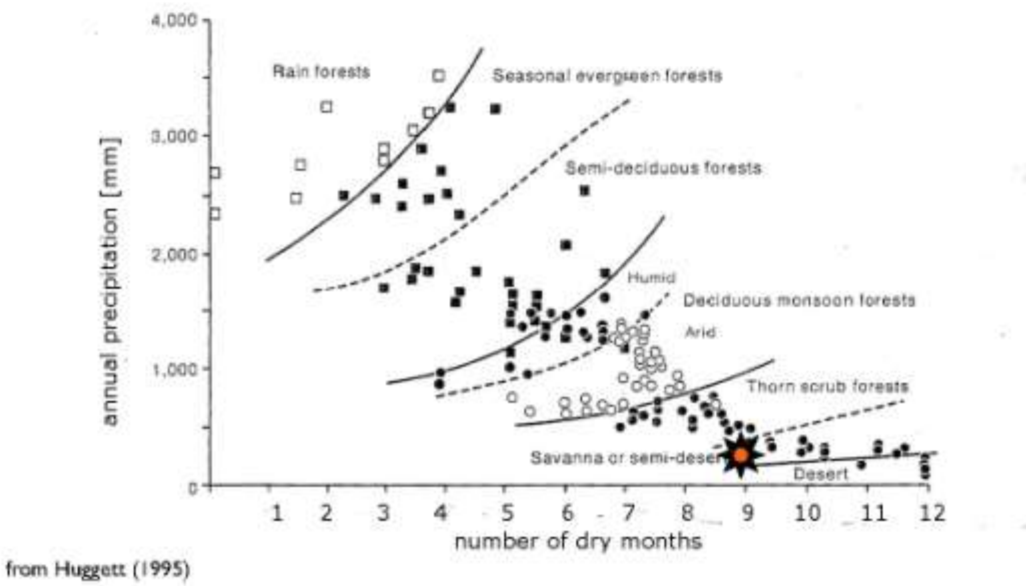

Figure 4: Ecosystems Distribution in Relation to Precipitation and Length of Dry Season

The climate conditions of the desert clouds forest are quite different from those typical of cloud forest sites in other regions, the annual temperature is about 21°C compared to a range of (14°C - 18°C) for other sites, and the annual rainfall is about 250 mm compared to a range of (2000-2600 mm) for other sites. Hence, desert cloud forests survive under conditions that are significantly warmer and significantly dryer compared to other cloud forest sites.

The ecosystem of Desert cloud forest is a unique semiarid broadleaf deciduous forest. The forest is surrounded by desert and is confined to a coastal area, where the summer wet season is characterized by a persistent dense cloud immersion. Field observations show how clouds shape an ecosystem that uses water quite efficiently and therefore creates a niche for a moist forest biome in a semiarid area in three ways. First, horizontal precipitation (collection of cloud droplets on tree canopies) adds valuable water, such that twice as much water is received below the canopy (net precipitation) compared to above (rainfall). Second, the high stemflow (flow of water over the stem of the tress) rate, which accounts for about 30% of net precipitation, concentrates additional water input around the stems. Third, transpiration is suppressed during the cloudy summer season, which allows for storage of the soil water to be used after the end of the wet season. The stored water lasts for the following 3 months, which roughly doubles the length of the growing season. By supplying more water, and at the same time helping to make the growing season longer, clouds push the desert cloud forest ecosystem within the domain of Figure 4 upward and to the left, from "desert" to "Arid deciduous monsoon forest". This aspect of desert cloud forest is different from cloud forests in other areas, where the impact of the clouds may shape the forest ecosystem to a significant degree, however even in absence of the cloud cover the ecosystem is likely to survive as a forest of some type. (Hildebrandt and Eltahir (2007a))

The hydrology of the desert cloud forest is described in Figure 5 based on field measurements of throughfall, sap flow (surrogate for transpiration), soil saturation, and estimates of potential evaporation. Throughfall refers to the rainfall collected beneath the canopy. Potential evaporation is a measure of the atmospheric demand for evaporation. Three seasons are identified: a wet season (phase I) from June to September, a dry season (phase III) after November, and a transition season (phase II) between September and November. During Phase I, which is known locally as "khareef", the forest is immersed in a persistent layer of clouds (fog). Trees intercept cloud droplets and drain that water to the surface, which supplements significantly the low precipitation amounts, and enhances the input of water to the soil. At the same time, the cloud layer reflects solar radiation back to the atmosphere, and limits the solar radiation reaching the surface. As a result potential evaporation rate is reduced significantly during this phase which limits the loss of water from the soil to the atmosphere. Hence, the net effect due to persistent cloudiness is to enhance the input of water to the soil and to reduce the loss of soil water through evaporation.

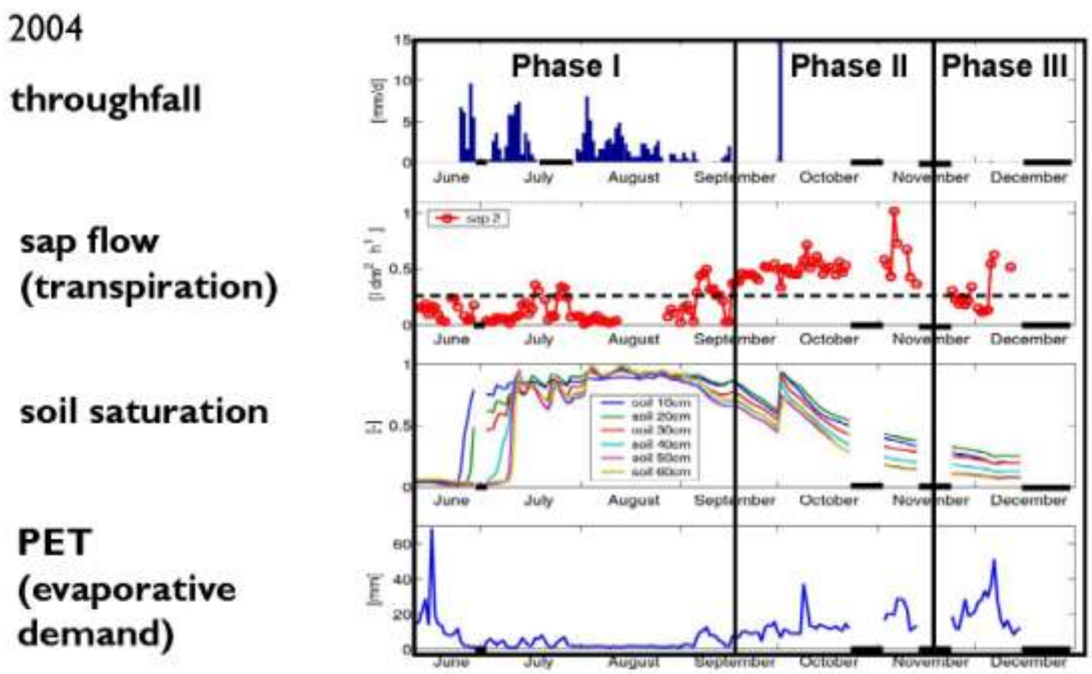

Figure 5: Hydrological Cycle of Desert Cloud Forest (Hildebrandt and Eltahir (2007a))

Because of both of these effects, the soil storage gets filled quickly and remains filled during phase I. By the end of the "khareef" season (phase I), the wind pattern shifts and the clouds layer disappears. During this transition season all conditions are ripe to support high rates of evaporation, photosynthesis, and greening of the ecosystem. First, in absence of clouds plenty of solar radiation reaches the surface to fuel a high evaporation demand. Second, the soil storage is rather full which insures that the roots of the plants can easily extract the soil water in support of a healthy transpiration rate. This is evident in the measured rates of sap flow during this transition season. In absence of a sustained input of water during this season, the soil water storage declines in response to the high transpiration rates. These processes continue until the low soil water storage becomes limiting to the rate of transpiration. At that point, trees start to shed their leaves to limit transpiration and the ecosystem moves into the long dry season. The latter is characterized by lack of water input to the soil, and low rates of transpiration constrained by the limited amount of soil water.

In addition to field investigations described above, dynamic ecosystem models are used to study the role of summer cloud immersion in the ecohydrology of desert cloud forests. Ecosystem models are numerical representations of the physical and biological processes that are important in functioning of ecosystems and in determining which ecosystem dominates a certain environment. The desert cloud forest ecosystem occupies a semiarid region where vegetation is immersed in dense cloud during the 3-month-long monsoon season (khareef). The equilibrium vegetation simulated by the ecosystem model in this region depends strongly on cloud cover during the wet season, with trees predicted when assuming cloudy conditions and grasses dominate when assuming a cloud-free monsoon. By varying soil type and rooting depth, the results of modeling studies identify a rooting depth at which tree performance is optimal. This is the depth at which transpiration is maximized and the sum of all other fluxes from the soil is minimized. The conclusions of this study show that cloud cover over this region plays an important role by creating a pattern of seasonality that is crucial for favoring trees over grass. This is achieved by (1) prolonging the growing season from 3 months to 6 months and (2) allowing deeper infiltration, which favors trees in an otherwise too dry environment. (Hildebrandt and Eltahir (2007b))

As discussed earlier, 'cloud-water' interception by tree canopies (horizontal precipitation) constitutes a substantial fraction of available water for Desert cloud forests. The study of Hildebrandt and Eltahir (2008) investigated the following question: can tree removal (deforestation) reduce cloud interception to the extent that natural reestablishment of trees is inhibited? They investigated the feedback between vegetation height and 'cloud-water' interception in the desert cloud forest. A model describing turbulent cloud droplet deposition is developed and added as a module into a dynamic vegetation model. The model allows for estimation of cloud water deposition based on cloud properties and dynamically changing vegetation structure. When the model is applied to this region, Hildebrandt and Eltahir (2008) found that equilibrium vegetation simulated by the model depended on the initial vegetation condition. For most of the range of assumed cloud properties, equilibrium vegetation tended toward grassland, when the initial condition was grassland, and to forest, when the model was initialized with forest. However, the difference between the equilibrium vegetation conditions emerging from different initial vegetation types depended to some degree on the assumed cloud properties. According to these modeling results, land degradation or climate change in this semiarid cloud forest might lead to irreversible destruction of the forest biome. The results can also be interpreted as suggesting a significant sensitivity of vegetation conditions to the properties of the cloud layer, which could change as a result of climate change.

In summary, the desert cloud forests of Oman and Yemen are different from cloud forests in other regions. Cloud forests in humid regions drive only a small fraction of their water input by intercepting cloud water. Hence, changes in cloud cover are likely to impact the type of forest and species composition however trees are likely to still dominate the ecosystem even if we assume disappearance of the clouds. In contrast, desert cloud forests would cease to exist as an ecosystem dominated by tree species without the clouds. The water intercepted by the trees from the clouds is crucial for the survival of trees in this environment. This is the reason why disappearance of clouds would lead to disappearance of the trees, especially on the escarpment region of the mountains.

2.2.1 Plants of Desert Cloud Ecosystem

The desert cloud forest ecosystem is a rich ecosystem with many endemic species. Here, we describe in Table I the most dominant plant species, their physical characteristics, their locations within the ecosystem, and their traditional and medicinal uses (Please see Appendix for pictures of plants). The most important species of the Dhofar cloud forest is *Anogeissus dhofarica* which is an endemic tree, dominant in the escarpment region of the Dhofar Mountains. This is a tall tree, with physical height of up to 12 meters. *Anogeissus dhofarica,* which is known locally as miset, is the main tree responsible for intercepting cloud droplets, and for this reason *Anogeissus dhofarica* plays a significant role in supplying this ecosystem with an additional water input.

This tree is quite valuable to the local population with many uses most notably as the favored browse for their camels, as a source of wood for building, and as source of leaves that are processed for medicinal purposes.

Name	**Genus and Species**	**Characteristics**	**Location**	**Uses**
simer	***Boscia arabica***	**Evergreen Tree, 5 meters**	**Foothills**	**(1) wood (building); (2) medicinal**
miset	***Anogeissus dhofarica***	**Deciduous Tree, 12 meters**	**Escarpment**	**(1) browse; (2) wood (building); (3) medicinal**
tikedoha	***Euophorbia balsamifera***	**Shrub, 1.5 meters**	**Dry plateau**	**(1) cosmetics; (2) adhesives**
samra	***Acacia etbaica***	**Tree, 4 meters**	**North-facing cliffs**	**(1) browse; (2) firewood; (3) medicinal**
luban	***Boswellia sacra***	**Tree, 5 meters**	**Desert**	**(1) Frankincense**

Table I: Dominant Plants of Dhofar

Boscia Arabica is the most characteristic tree of the foothills. It is endemic to Arabia. It has dense, umbrella-like canopies which provide a welcome-shade in all seasons of the year. The leaves are good popular fodder for the livestock, especially for camels. The fruits are not liked, and the wood is not used for firewood since it generates a lot of smoke. The female version of this tree (*Maerura crassifolia*) is known locally for strong wood that is used for building purposes. The leaves of this tree have several medicinal uses in the Middle East, including the use to treat intestinal ailments, fever, headaches, and wounds.

Anogeissus dhofarica is probably the most important tree in desert cloud forests ecosystem. It is endemic to Dhofar. This tree is deciduous. It loses its leaves during the dry season and the new leaves appear just before the monsoon. The leaves are bluish green. The flowers are short-lived, and the fruits form cone-like balls persisting well into the summer. This tree is of major significance as a browse for camels, believed by the locals to help them put on weight and improve milk yield. The wood from this tree is an important local building material. The dead wood is an excellent charcoal material. The leaves are used as a dye to color cotton cloth and clay utensils. Medicinally, extracts from the leaves are used by women for their personal hygiene and washing, believed by locals to be purifying, antiseptic, and invigorating stimulant. Dried leaves are crushed into a powder that is used to treat wounds and sensitive skin.

Euophorbia balsamifera is a shrub that dominates the dry plateau at the edge of the monsoon zone. It forms dome-shaped bushes, and produces white latex when cut. The latex is put in clay pots, and together with added water is heated, poured out and left to dry. The resulting product is used by women as a cosmetic. The leaves and the fruits are edible. The latex is also made into an excellent adhesive.

Acacia etbaica is a bush or a small tree that dominates the north facing cliffs. It had great economic value in earlier times. It provided the best tanning agent of leather used for many purposes such as waterskins and milkskins. The tanning agent is produced by traditional processing of the branches of this tree. This tree is also important for firewood, and for medicinal use.

Frankincense produced from the endemic tree, ***Boswellia sacra**,* is probably the most important non-timber commercial product from the desert cloud forest ecosystem. This product has been of great value to many of the world cultures, from Southern Europe, to Arabia, and India. Production and trade in Frankincense has been carried for many generations in this region. This product has many uses as a fragrant, and for medicinal purposes.   The best quality Frankincense is produced from the desert region north of the Dhofar Mountains. Climate conditions in this region are rather stable and not as likely to be impacted by climate change as the escarpment region.

In considering the impact of climate change on the Dhofar ecosystem, the primary consideration should be on how climate change may pose any threat for the health of the ***Anogeissus dhofarica*** trees that dominate the escarpment region of the Dhofar Mountains.

3. Local Population and its Practices

The region surrounding the desert cloud forests is sparsely populated. The only exception is the city of Salalah which has a population of more than 150,000 inhabitants. Table II describes the distribution of the population of Dhofar. More than 75% of the population lives in Salalah. The remainder of the population is scattered in about 7 districts. On the Yemen side of the border the population size is relatively small. The Hawf District of Yemen belongs to Al Mahrah Governorate, Yemen. As of 2003, the district had a population of only 5143 inhabitants. ("Districts of Yemen". Statoids. http://www.statoids.com/yye.html)

Willayat	No. of Houses	No. of Families	No. of People						
			Omani			Non-Omani			Total
			Male	Female	Total	Male	Female	Total	
Salalah	28,340	20,532	53184	50914	104089	39485	13004	52489	156,587
Thumrayt	1,185	798	2363	2292	4655	2166	369	2535	7,190
Taqah	2,411	1,919	7747	7629	15376	1518	376	1894	17,270
Mirbat	1,996	1,536	6521	3671	12892	1623	375	1998	14,890
Sadah	679	563	2163	2075	4238	1004	177	1181	5,419
Rakhyut	734	510	2004	1866	3870	510	67	577	4,447
Dalkut	577	351	1329	1210	2539	286	59	345	2,884
Muqshin	118	93	198	161	359	140	36	176	535
Shaleem and The Hallanitat Island	728	546	1562	1205	2767	2252	90	2342	5,109
Total	36,758	26,848	77071	73723	150794	48984	14553	63537	214,331

Table II: Population Count for different Districts (Willayat) of Dhofar Governorate (2003)

In the first half of the twentieth century the population in this region was much smaller than the current population. This population depended on services of the desert cloud forest ecosystem for many purposes. The main uses included: (1) browse and feed for camels and goats; (2) firewood as a source of energy; (3) wood as a building material; (4) extracts from leaves, fruits, and branches are used for medicinal, cosmetic, tanning, and adhesive purposes; (5) production of

Frankincense as a cash crop that was used locally and traded with other regions. The size of the population and the scale of ecosystem utilization were relatively small. Hence, human interactions with this fragile ecosystem were somewhat sustainable.

During the last few decades the region around desert cloud forests has been experiencing significant change driven by large increases in human population and economic activity. The annual population growth rate is 2.6% in Yemen, and the corresponding rate is 2% in Oman. This compares to a global population growth rate of about 1.1%. Hence, the region surrounding the desert cloud forest is experiencing a rapid population growth. The same has been experiencing rapid economic growth too. Oil export started in Oman during the second half of the twentieth century which resulted in fast economic growth and significant improvement in living standards. This rapid change was accompanied by significant accumulation of wealth in traditional communities that value ownership of camel and other animals. Hence, the population of animals in the desert cloud forest ecosystem increased significantly. Though these animals depend to a significant degree on feed that is imported from outside the region, their owners choose to show them off, and to raise them in traditional ways that rely on the natural ecosystem. As a result, the increase in animal population resulted in significant additional pressures on the natural ecosystem. Due to camel browsing on tree canopies, the desert cloud forest is gradually degrading to grassland in many locations. This change in land cover represents one of the main challenges to the survival of the desert cloud forest ecosystem.

4. Potential Risks of Climate Change on the Desert Cloud Forests

The process of climate change is caused by evident changes in the chemical composition of the global atmosphere. In particular direct field observations indicate a significant increasing trend in the concentration of carbon dioxide during the last 50 years. This radiatively active constituent of the atmosphere is well mixed with nearly uniform distribution everywhere. Similar trends were observed in other radiatively active gases (known as green house gases), namely nitrous oxide, methane, and chlorofluorocarbons. All these gases trap the radiation emitted by the earth surface and remit it back to the surface creating a tendency for surface warming. This initial warming increases the capacity of the atmosphere to hold water vapor, and hence increases the actual water vapor concentration. The latter is the most significant radiatively active constituent of the atmosphere. Hence, the initial warming is exacerbated by this water vapor feedback. This set of processes which are dominated by atmospheric radiation trigger a complex set of feedbacks and processes involving atmospheric convection, atmospheric dynamics, clouds microphysics, and rainfall formation processes. The exact nature of how these processes and feedbacks should be represented in climate models is not unique and hence their representations vary from one climate model to another. As a result, the response to the increase in concentrations of carbon dioxide and other greenhouse gases may vary from one climate model to another.

In the following, we present the impact of climate change on Oman and Yemen, followed by a section on the potential impacts of climate change on desert cloud forests.

4.1 Impact of Climate Change on Oman and Yemen

The IPCC 4th Assessment Report (AR4) 2007 does not present any significant trends in observed climate of Yemen or Oman. Several trends have been reported for other Asian countries. The observation that no trends have been reported in AR4 for Yemen or Oman does not imply that no trends exist in the actual climate system, but rather indicative of the fact that no such trends have been documented.

Sea Surface Temperature (SST) is an important climate variable since SST impacts many other variables such as surface temperature, rainfall and clouds. Figure 6 shows the seasonal variability in observed sea surface temperature at several Asian cities on the Arabian Sea. In particular, we focus on SST in Muscat and Salalah. The SST off the coast of both cities shows remarkably different seasonality. The SST off Salalah dips in August, when the SST in Salalah is about 7 deg C colder than Muscat. This cooling is restricted to a small area off the coast of Salalah where the deep ocean water up wells to the surface bringing cold water to the surface. The occurrence of this upwelling phenomenon, off the coast of Salalah, is a critical ingredient for the formation of the cloud layer associated with the desert cloud forests. The air next to the ocean surface is at equilibrium with the SST and flows from the south to the north, from the Arabian Sea towards the desert of Arabia, as part of the global monsoon circulation. When this air flows over this small upwelling area characterized by cold SST, the relative humidity of the air increases significantly which sets the conditions for the occurrence of clouds over Salalah and the surrounding region.

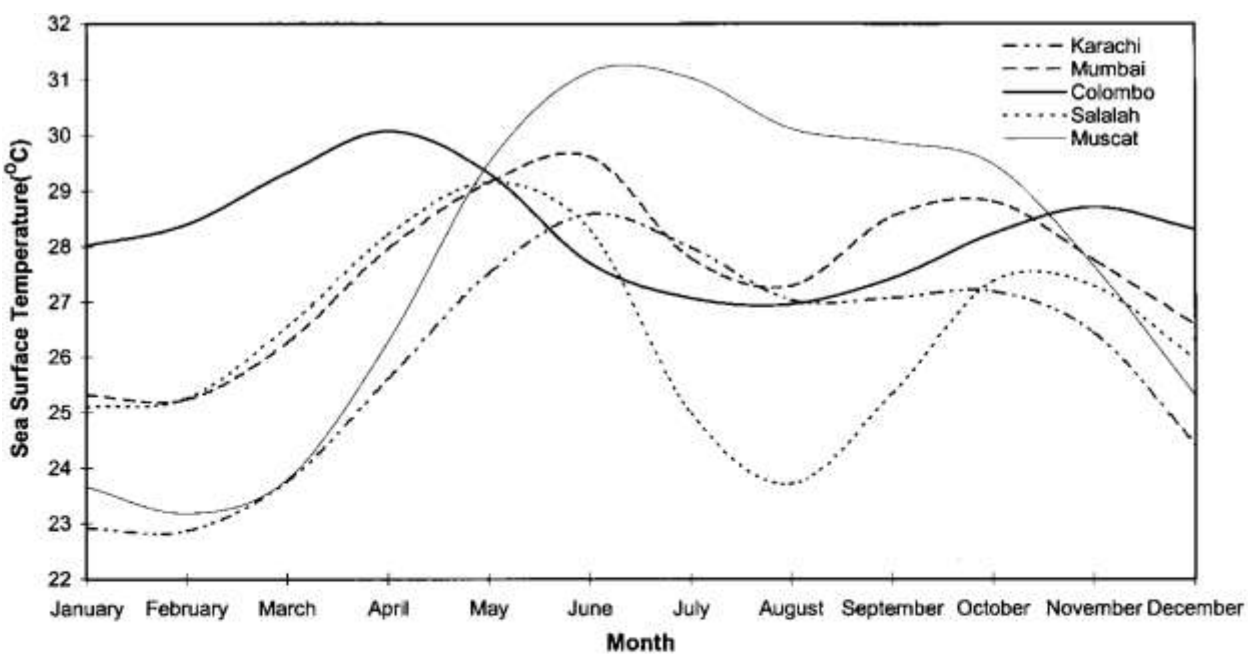

Figure 6: Seasonality of Sea Surface Temperature near Asian Cities on the Arabian Sea. (from Khani et al., 2004)

Sea Surface Temperature variability is a good indicator of variability in the climate system. Figure 7 shows observed trends in SST near several Asian cities on the Arabian Sea. Significant trends are recorded near Muscat and Salalah during the last two decades of the twentieth century. The magnitudes of these trends are 0.6 deg C per decade for Muscat, and 0.5 deg C per decade for Salalah. Both are statistically significant trends. In general, if such trends continue into the future they would have significant implications for the climate of the region.

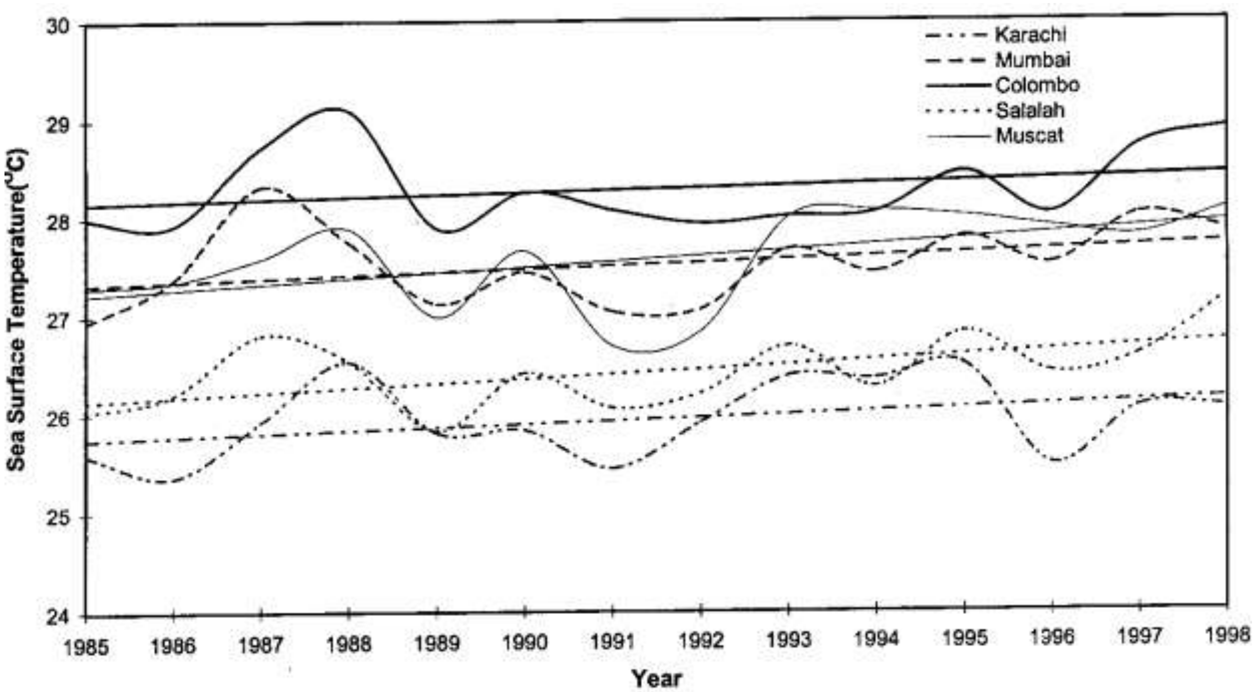

Figure 7: Observed Trends in Sea Surface Temperature near Asian Cities on the Arabian Sea. (from Khani et al., 2004)

Climate models are the primary tools from making predictions about future climate change. IPCC AR4 provides model predictions of the regional climate of West Asia, for the next 90 years, based on assuming two scenarios for emissions representing the highest and lowest future emissions trajectories. The region of West Asia is defined as (12N-42N; 27E-63E) and hence includes Yemen and Oman. These predictions are summarized in Table III.

Based on the predictions summarized in Table III, the climate of Yemen and Oman is likely to get warmer in the coming decades in all seasons. The magnitude of this warming increases with time from less than 2 deg C in the (2010-2040) period to possibly more than 6 deg C in summer during the period (2070-2100). These predictions are consistent with warming trends projected for other regions.

Season	2010-2039 Temp (C)	2010-2039 Precip (%)	2040-2069 Temp (C)	2040-2069 Precip (%)	2070-2099 Temp (C)	2070-2099 Precip (%)
DJF	1.3 1.1	-3 -4	3.1 2.0	-3 -5	5.1 2.8	-11 -4
MAM	1.3 1.2	-2 -8	3.2 2.2	-8 -9	5.6 3.0	-25 -11
JJA	1.6 1.5	13 5	3.7 2.5	13 20	6.3 2.7	32 13
SON	1.5 1.4	18 13	3.6 2.2	27 29	5.7 3.2	52 25

Table III: Predicted Climate Change over West Asia (12N-42N; 27E-63E) including Oman and Yemen (the range is based on assuming the highest/lowest future emission trajectories) (IPCC 4th Assessment Report 2007)

The predicted change of precipitation is less consistent across seasons. The models predict a decrease for spring and winter precipitation and an increase in summer and fall precipitation. The corresponding magnitudes range from a few percent reduction in winter precipitation during the decades of (2010-2040), to more than 50% increase in fall precipitation during the decades of (2070-2099). Among all these predictions what is particularly important for desert cloud forests are the projected warming and increase in precipitation during summer. Both factors are important in shaping the ecohydrology of desert cloud forests.

The models predictions of future summer precipitation over Yemen and Oman are quite uncertain. About half of the model simulations used in the IPCC AR4 indicate an increase in precipitation, while the other half suggest a decrease in precipitation (Please see Figure 11.9 of the IPCC report). The disagreement between different models highlights the high degree of uncertainty about future climate projections concerning hydrologic fluxes over Yemen and Oman.

4.2 Potential Risks of Climate Change on the Desert Cloud Forests

The most important hazard to desert cloud forests from climate change is the potential change in clouds and fog at cloud forest sites. A decline in cloudiness over these forests would not only reduce the additional water input captured by the trees from the clouds directly, but also increase the rate of evapotranspiration, leading to significant changes in the forest hydrology.

The leading scientific theory in describing the impact of climate change on cloud forests is the Lifting-Cloud-Base (LCB) Hypothesis. This hypothesis is described in Figure 8. In one of the early studies on this topic, scientists simulated the impact of climate change on tropical montane cloud forests (TMCF) (Still et al. (1999)). (TMCF are cloud forests associated with relatively wet and humid conditions) They used a general circulation model to estimate the shift in elevation of the atmospheric relative humidity surface that corresponds to the altitudes of existing cloud forests, as a result of doubling the concentration of carbon dioxide.

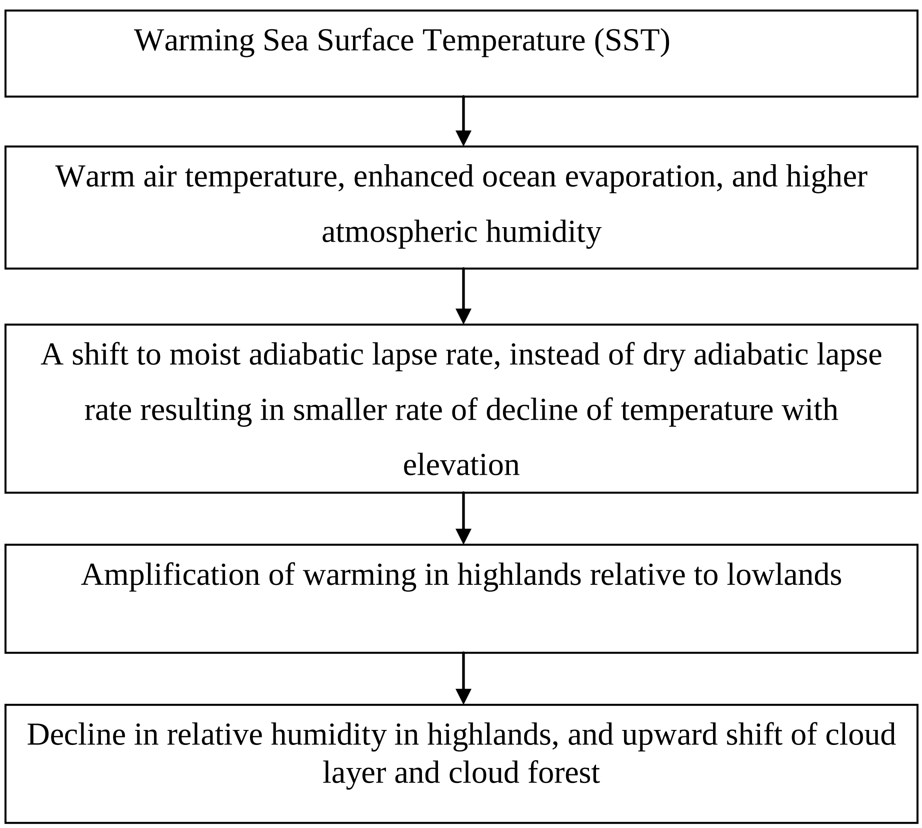

Figure 8: Lifting-Cloud-Base Hypothesis

As predicted by the LCB hypothesis, the model simulated an upward shift of the relative humidity surface by hundreds of meters, implying fewer clouds during the relatively dry winter season when TMCF rely most on moisture intercepted from the clouds. The same study predicted an increase in evapotranspiration. Less moisture from clouds and increased loss of water to transpiration would indicate significantly less surface runoff and less aquifer recharge from cloud forest sites.

In a similar study that was published around the same time as the study cited above, scientists provide observational evidence for the impact of climate change on TMCF in the highlands forests of Montverde, Costa Rica (Pounds et al. (1999)). They investigate whether recent warming has triggered the observed biological response, characterized by changes in species distribution and abundance. They suggest that this response has been associated with patterns of dry season mist frequency that has declined dramatically since the 1970s. The warming has raised the average altitude of the base of the cloud layer as predicted by the LCB hypothesis.

General Circulation models (GCMs) are mathematical representations (computer codes) of atmospheric and oceanic properties and processes. These models attempt to describe earth's climate system. Developed in 1960s, they have become the primary tools in analyzing effects of climate change.

The potential negative impacts of global climate change on cloud forests has been discussed by scientists based on the application of GCMs. They have analyzed the results of simulations by four GCMs: ECHAM, HAD, CCC, and CCSR which are leading German, UK, Canadian, and Japanese climate models, respectively (Foster (2001)). The focus of this study is on comparing surface relative humidity, used as an indicator of low level clouds, between current climate and a future climate scenario characterized by doubling of CO_2 concentration. The results are shown in Figure 9. For all the models, significant drying is simulated over most of the domain. The only exception is a small region over the Middle East where two of the models (ECHAM and CCSR) show a relatively large increase in relative humidity while the (HAD and CCC) show a decrease in relative humidity. This increase in surface relative humidity is consistent with the results of previous scientific studies which predicted a cloudiness increase over areas of large scale atmospheric subsidence as a result of warming in sea surface temperature (Schneider et al. (1978)).

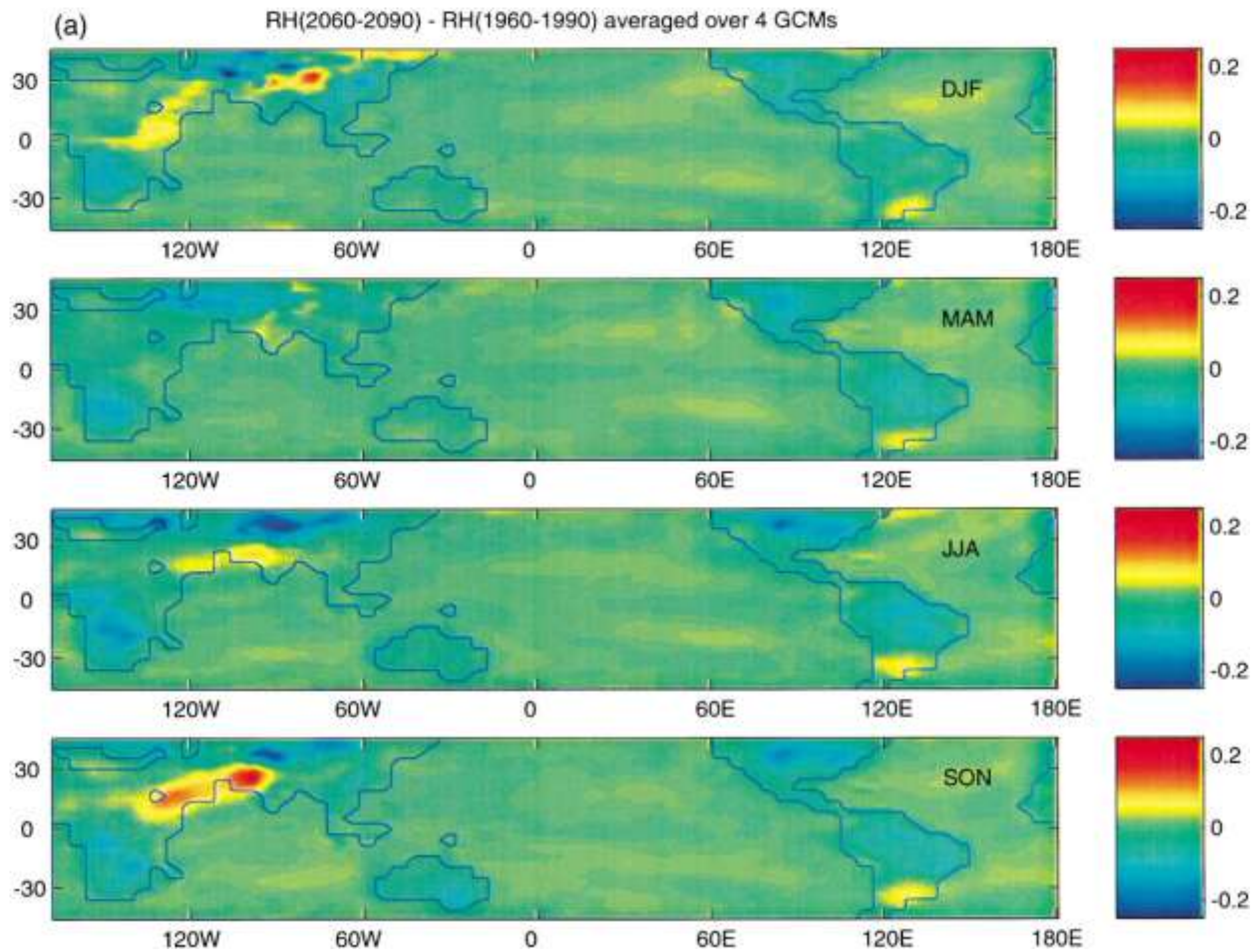

Figure 9: Changes in the surface relative humidity field from 1960–1990 to 2060–2090 as modeled in four GCMs. The results of four GCM simulations for today and 2XCO2 concentrations are compared and shown for the four seasons. The relative humidity change is given as a fraction from 0.20 to -0.20 or 20% to -20%.. Most of the tropical land area shows a decrease in RH of 5–10%. This could imply decreases in low-level cloudiness and consequent damage to the cloud forest. (from Foster, 2001)

The Middle East is one of large atmospheric subsidence regions. The rising air over the Tibetan Plateau associated with the Indian monsoon eventually descends over Arabia causing the large scale subsidence that is responsible for limiting rainfall amounts and creating desert conditions. The descending air feeds the observed divergence of air away from Arabia at mid atmospheric levels. Figure 10 shows the wind around Dhofar Mountains in summer. The divergent wind from Arabia is responsible for the northerly wind at mid atmospheric levels which caps the cloud layer and prevents it from developing deeper into the atmosphere. The LCB theory described above is not valid over regions of large scale subsidence. This factor may prove to be critical in shaping how the desert cloud forests may respond to climate change.

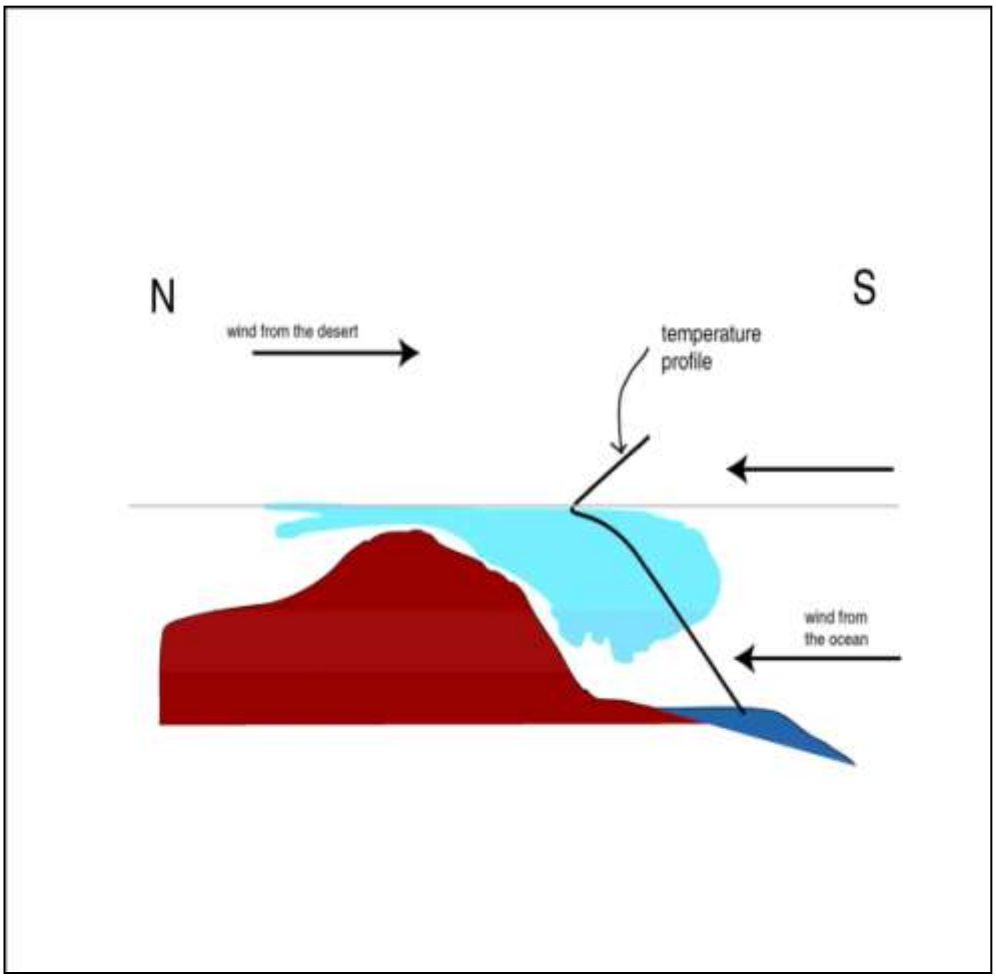

Figure 10: Wind Pattern Around Dhofar in "Khareef" (summer), Hildebrandt and Eltahir (2007a)

The average change in cloud cover from all GCM simulations described in Figure 9 would suggest an increase in surface relative humidity over a small region in the Middle East implying an increase in low level clouds as a result of climate change. Interestingly enough, this small region of possible increase in low level clouds over the Middle East includes the desert clouds forests of Dhofar and Hawf. However, we should emphasize that not all GCMs agree on the sign of the predicted change over this region with two of them suggesting an increase in cloudiness and two suggesting a decrease in cloudiness!

Recently scientists are acknowledging that GCM predictions of climatic drying due to increase in concentration in greenhouse gases are likely to have profound effect on functioning of cloud forest, but they also note that different GCMs are likely to produce different and sometimes opposing results (Bruijnzeel et al (2011)). Based on the results of all these scientific studies, we conclude that there are significant differences between the different climate models predictions regarding the extent and even the sign of future change in low level of clouds over our region of interest. The models predictions regarding the impact of climate change on low level clouds over desert cloud forests remain quite uncertain!

One main reason for this uncertainty is the coarse horizontal resolution (size of the numerical grid used in describing physical climate processes) of a typical GCM (hundreds of kilometers). With such coarse resolutions, climate models would not be able to represent realistically the sharp elevation gradients associated with cloud forests. Since the earliest study on the topic of the impact of climate change on cloud forests, it became evident that in order to make credible predictions regarding the impact of climate change on low level clouds, we need to use regional models with high spatial resolution (Still et al. (1999)). In their pioneering research paper, Still et al. (1999) suggested that ”More realistic analyses at each of our “cloud forest” sites will require transient GCM simulations ….coupled to mesoscale regional models that better resolve the steep topographic conditions and local land use changes at most cloud forest sites”. Despite of this early recognition for the need to develop and use high resolution models, we cannot find any published study that has taken such approach. One research paper refers to a submitted manuscript that describes a regional modeling study (Foster (2001)). However, by consulting records of published literature, we concluded that this manuscript did not survive the peer review process.

Most of the studies reviewed in this section are based on climate models simulations. In a recent study scientists used satellite observations of clouds from archived cloud climatology data for the years (1979-2001), to assess changes in cloud frequency in the tropics (Mulligan and Burke (2005)). They calculated changes in the frequency of clear sky conditions over known cloud forest sites. They report a decrease in the number of clear days (i.e. increased cloudiness) for cloud forest sites next to the equator and the reverse for cloud forest sites located between 10 and 20 degrees (both north and south of the Equator). Cloud frequency declined over Southeast Asia; however both decreases and increases are reported for Latin America. Again the signal from observational studies is not clear regarding the sign of the change in future cloudiness.

In summary, the main hazard from climate change to the desert cloud forest of Oman and Yemen is the scenario of upward shift in cloud cover and fog during summer according to the LCB hypothesis of Figure 8. Since the upper boundary of the cloud forest corresponds to the highest elevation of the escarpment (Figure 3), there is no room in this setting for the cloud cover and the associated cloud forest to migrate upward. Hence, any reduction in relative humidity will result in reducing the width of the elevation band that can be covered by clouds, with the extreme scenario of complete disappearance of the cloud cover and the associated cloud forest. On the other hand the region of Oman and Yemen is located next to the deserts of Arabia, a region of large-scale atmospheric subsidence (downward movement of air). There are indications that over such regions, the LCB hypothesis may not be valid and instead of drying and less clouds the desert cloud forests of Dhofar and Yemen may actually experience denser or more frequent clouds. Different GCMs disagree on the sign of their predictions of changes in cloud cover over this region. Hence, we conclude that although the worst case scenario of climate change over this region would result in complete disappearance of the cloud cover and the associated cloud forest, there is a great deal of uncertainty about the likelihood of such scenario, to the extent that we cannot rule out the possibility of increased clouds frequency over this region as a result of climate change. Hence, the models predictions regarding the impact of climate change over the cloud forests of Oman and Yemen remain quite uncertain!

5. Questionnaire on Interaction between Forest Environment and Human Population Activities

The proposed questionnaire will probe into the interaction between the forest environment and the human population activities at the local level. A cross section of the local community should be surveyed including elders of the community, youth, politicians, women groups, community activists, as well as the general public. The key challenge in any survey is how to identify a representative random sample of the population. Randomness of the sample is of critical importance since any bias in the sampling procedure would limit the value of the sample in representing the population at large. All statistical inference techniques are valid only for random samples. Random sampling requires that every member in the population should have equal chance of being picked as a respondent to the questionnaire. Another important criterion in designing this process is to keep the questionnaire simple and short, yet informative about the topic of interest. A lengthy and complex set of questions would not be attractive for the potential respondents. In the following we develop a methodology for the questionnaire, we then detail the information to be collected about the respondents, followed by a design of a specific set of questions.

5.1 Methodology

In the proposed methodology, the local population of the Desert Cloud Forest Community is stratified according to gender, nationality, age, profession, and geographic affiliation. The proposed methodology consists of the following steps:

(i) Collect official data on the following statistical distributions describing our target population:

  (a) Distribution of the population among the different age groups (e.g. 18-30; 31-43; 44-56; 57-59; 60-72; 73-);

  (b) Distribution of the population in different professions (homemakers, businessmen/women, government employees, students, farmers, ranchers, and others);

(c) Distribution of the population in the different official geographical districts (please see the appendix for the example of Dhofar).

In addition, data should be collected regarding the total population, population of men (women), and population of nationals/expatriates.

(ii) The first section of the questionnaire should ask respondents about their gender, age, nationality, profession, and geographic district. It should not ask them about their names or any other information that may reveal their identity.

(iii) In distributing the questionnaire forms to the population, as much as practically possible, the following conditions should be satisfied:

(a) Number of copies distributed to women and men should reflect their representation in the population;

(b) Number of copies distributed to nationals and expatriates should reflect their representation in the population;

(c) The number of copies distributed to different age groups should be roughly proportional to their relative distribution in the population. For example if the youth in (18-30 years) category represent 20% of the population, then 20% of the questionnaire forms should be distributed to this group;

(d) The number of copies distributed to individuals in different professions should roughly reflect their representation in the general population. This may be challenging to achieve since the information about profession may not be available before responding to the questionnaire;

(e) The number of copies distributed to different geographic districts should reflect the relative size of the population in that district.

(iv) After collecting the forms, adjustment should be made to balance the composition of the random sample. Before analyzing the results, some of the forms should be dropped from the survey in order to insure that the conditions satisfied roughly in (iii) above are accurately satisfied by the forms used in summarizing the results of the survey. For example if the youth in (18-30 years) category represent 20% of the population; however 22% of the questionnaire forms were filled by respondents from this group then 2% of those forms should be ignored.

(v) The total number of forms to be distributed should be about 2,500 (~1% of the total population)

5.2 Section I of the Questionnaire: Information about Respondent:

(i) Sex

(a) Female (b) Male

(ii) Nationality

(a) National (b) Expatriate

(iii) Age group

(a) 18-30 (b) 31-43 (c) 44-56 (d) 57-59 (e) 60-72

(f) 73 and older

(iv) Profession

(a) Homemaker (b) businessmen/women (c) government employee

(d) Students (e) farmers (f) ranchers (g) others

(v) Geographic Districts

For example, please see Appendix for the Dhofar Districts

5.3 Section II of the Questionnaire: Questions:

(i) The cloud forest ecosystem is the most important economic and social asset for your region and community.

(a) Strongly agree (b) agree (c) disagree

(ii) The economic livelihood of me and/or my family depends on services provided by the desert cloud forest ecosystem

(a) Directly (b) indirectly (c) remotely (d) not at all

(iii) Scientists predict that the global climate will change in the coming decades and centuries because of human activity (emissions from cars, power plants, and factories.) Are you aware of these predictions? Do you care?

(a) No, not aware (b) Aware, but do not care
(c) Aware and I care about global climate change

(iv) Are you concerned about the health and sustainability of the cloud forest ecosystem?

(a) Yes, definitely (b) Somewhat (c) Not at all

(v) If you are concerned about the ecosystem sustainability, what are the reasons for your concerns?

(a) Animal and human population pressures (b) Climate change (c) Both

(vi) Have you noticed any trend in the condition of the ecosystem?

(a) Yes, a lot of change (b) Yes, some change (c) No, not at all

(vii) What should be done, if anything, to insure sustainability of the cloud forest ecosystem for the long term?
(a) Limit number of animals (b) Create protected areas (c) Do nothing
(e) Brief suggestion:

(viii) Are there any traditional local practices that you support and should be adopted to achieve sustainability of the ecosystem?

(a) Yes, describe briefly:

(b) No, nothing comes to mind

(ix) Climate change may impact the cloud forest ecosystem in positive ways (increase clouds and enhance greenness) or negative ways (less clouds and less greenery) Are you aware of the potential for such impacts? Do you care?

(a) No, not aware

(b) Yes, I am worried about potential negative impacts, and I am hopeful for the potential positive impacts

(c) Yes, but I don’t care

6. References

Bruijnzeel LA, Mulligan M, Scatena FN. 2011. Hydrometeorology of tropical montane cloud forests: emerging patterns. *Hydrological Processes* **25**: 465–498. DOI: 10.1002/hyp.7974.

Foster P. 2001. The potential negative impacts of global climate change on tropical montane cloud forests. *Earth-Science Reviews* **55**: 73–106.

Jarvis A, Mulligan M. 2011. The climate of tropical montane cloud forests. *Hydrological Processes* **25**: 327–343. DOI: 10.1002/hyp.7847.

Khani TMA, DEWAN Abdulquadiri D, Murty T,Sarker MA, Seasonal and Interannual Sea Surface Temperature Variability in the Coastal Cities of Arabian Sea and Bay of Bengal, *Natural Hazards* **31:** 549–560, 2004

Pounds JA, Fogden MPL, Campbell JH. 1999. Biological response to climate change on a tropical mountain. *Nature* **398**: 611–615.

Schneider S H, W M Washington, and R M Chervin , 1978. Cloudiness as a Climatic Feedback Mechanism: Effects on Cloud Amounts of Prescribed Global and Regional Surface temperature Changes in the NCAR GCM, *Journal of the Atmospheric Sciences*, 35(12), 2207-2221.

Still C J, P N Foster, and S H Schneider, 1999. Simulating the effects of Climate Change on Tropical Montane Cloud Forests. *Nature*, 398, 608-610.

Hildebrandt, A, Eltahir EAB. 2006. Forest on the Edge: Seasonal Cloud Forest in Oman Creates Its Own Ecological Niche. GEOPHYSICAL RESEARCH LETTERS. Volume 33

Hildebrandt, A, Al Aufi M, Amerjeed M, Shammas M, Eltahir EAB. 2007a. Ecohydrology of a seasonal cloud forest in Dhofar: 1. Field experiment. WATER RESOURCES RESEARCH. Volume 43

Hildebrandt, A, Eltahir EAB. 2007b. Ecohydrology of a seasonal cloud forest in Dhofar: 2. Role of clouds, soil type, and rooting depth in tree-grass competition. WATER RESOURCES RESEARCH. Volume 43

Hildebrandt, A, Eltahir EAB. 2008. Using a Horizontal Precipitation Model to Investigate the Role of Turbulent Cloud Deposition in Survival of a seasonal Cloud Forest in Dhofar. JOURNAL OF GEOPHYSICAL RESEARCH-BIOGEOSCIENCES. Volume 113

Huggert, R. J., (1995). Geoecology. An Evolutionary Approach. New York ; USA, Routeledge.

Miller and Morris (1988) Plants of Dhofar, prepared and published by the Office of the Adviser for Conservation of the Environment, Diwan of Royal Court, Sultanate Oman, 361 pages.

Mulligan M, Burke SM. 2005. Global cloud forests and environmental change in a hydrological context. Final Report of DFID FRP Project ZF0216. http://www.ambiotek.com/cloud forests. [accessed: November 2010].