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Numerical Estimation for Greening Effect over the Desert in Saudi Arabia

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Synopsis

Greening effect over the desert in Saudi Arabia was estimated by a meteorological numerical model (MM5) with sophisticated land surface model (LSM). It is pointed out that the regional climate after greening by grassland vegetation changes rainfall amount increased by +65%. However, latent heat flux, LHF, largely increases in arid season, and increases a little in wet season. Evergreen needle tree was found to suppress LHF by 50% ~74% compared with grassland greening. As a result with estimation for the net rainfall, greening only around a mountainous area with needle tree can keep positive net rainfall even in arid season.

Keywords: greening desert, land surface model, net rainfall

1. Introduction

Desertification over the world is one of the most problems in the global climate, and especially in water resource, because population explosion predicted in the future may cause water shortage. Greening desert is a challenging way to improve the water shortage. This technique of greening desert, arid, or semiarid region has been applied to several regions, but the improvement by this technique seems to be difficult not only due to technical measure for greening, but also the complex feedback among a regional climate, surface condition, and underground aspect. The project of greening coastal desert over the western coast of Saudi Arabia commenced, that was supported by MEXT. This area is divided to the hot desert climate by the Köppen classification, and covered by large scale anticyclone or large scale subsidence mainly in summer (Taha et al., 1981; Subyani, 2004). Rainfall over southwest Saudi Arabia in summer is maintained mainly by the southwesterly wet flow, well known as the Indian monsoon, and rainfall over northwest is almost only identified in winter due to northwest flow or disturbance. Fig. 1 shows the mean profile of temperature and relative humidity, RH, for 22 years at Jeddah, and shows seasonal characteristics in summer (Fig.1 (a)) and winter (Fig. 1(b)). The thick layer that consists of large scale subsidence and dry westerly flow from North Africa are represented as dry warm region above 500hPa. On the other hand, the south-eastern wet flow from the Indian Ocean reaches Jeddah in the limit below 850hPa. Distributions of moisture and wind are represented by Fig. 2. In winter season, however, cold and moisture flow from the Mediterranean prevails over the Red Sea that is touch with Jeddah, and bring about an extent of moisture to inland. the target area of greening was set to the north region of Asir that is mountainous region along the west coast includes Jeddah (coastal city), Mecca (sacred city), and Taif (mountainous city). Climate of this region is categorized as arid or semiarid, and rainfall pattern varies with space and time. North Asir seems to be classified to have wet season in winter same as other arid or semiarid region in western Asia except for south region in Arabian Peninsula that is affected by the Indian monsoon. Additionally, mountainous area in Asir secures an extent of rainfall because wet flows produce condensation due to lifting up along the slope of the mountain. So rainfall in north Asir including mountainous area seems to be occurred by the wet flow mainly in winter.

Since long ago, response by modification of landuse with extensive scale with mainly as deforestation has been reported, namely cutting forests cause cloud formation and rainfall decrease, and also erosion and runoff increase, such as the destruction of nature. As for greening with regional scale less than about several hundred kilometers square, effects of landuse modification on rainfall are discussed in several studies and areas (Anthes, 1984; Perlin and Alpert, 2001). Anthes (1984) summarized the changes in physical properties and processes by greening soil land greater than about 100km^2 with vegetation, and many properties or processes receive various change, such as evapotranspiration increasing, moisture retention increasing, roughness increasing, and also infrared emission decreasing, maximum temperature decreasing, and Bowen ratio decreasing. However, greening effect on rainfall and cloud is identified as uncertainty response because of the including complicated process and interaction among large scale phenomena, micro scale phenomena and processes around the ground. Numerical simulation not only with considering large scale atmospheric processes but also with solving surface processes is one of the appropriate tool to describe the physical processes that is changed by greening landuse. Perlin and Alpert (2001) discussed the effects of landuse modification with plantation and irrigating nearly 10,000km^2 area from the shrubs and non-irrigated agriculture on the dynamic processes of regional scale convection with planetary boundary layer (PBL) height, and convective available potential energy (CAPE) over the coastal region along the Mediterranean with using numerical model, MM5, and they showed that rainfall increased the PBL height when the disturbance moving from the Mediterranean because the maximum height of PBL kept longer than the control run, PBL contained more moisture, and finally CAPE keeps higher value before rainfall event. So greening seems to change directly the moisture amount and the radiation balance on the surface.

One of the most difficult problems of greening desert is that greening should be kept with wet canopy layer including soil layer. This maintenance condition seems to be greatly strict because of large amount of evapotranspiration from the vegetation of greening, so greening technique must be considered not only with rainfall increase but also with evapotranspiration increase, and namely with the net rainfall, rainfall subtracted by the evapotranspiration.

The purpose of this study is to estimate the net rainfall for a long time to maintain the desert greening with numerical experiment.

2. Model Description and Methodology

3-D meteorological model, MM5, was introduced in order to predict and estimate the greening effect over regional scale targeted area around north Asir.

2.1 Model description

MM5 had been developed by the Penn State University and National Center for Atmospheric Research (Dudhia, 1993, Dudhia, 1989), with nonhydrostatic primitive equations and sophisticated physical schemes for cumulus, radiation, boundary layer, and explicit moisture. As for the initial condition and boundary condition, NCEP final analysis data with 1 degree as horizontal and 24 layers from surface to 50hPa height as vertical resolutions and RTG SST data applied from satellite data with 0.5 degree resolution were adopted and landuse information by USGS was used.

Horizontal climate aspects were extracted from NCEP data for 6 years, monthly horizontal distributions of rainfall owed to satellite TRMM data, and surface and upper air observation data for about 20 years at some observation points were used to discuss regional climate around the target region.

2.2 Methodology

Fig.1 means map around the target area, and the target area that includes Jeddah, Mecca, and Taif is chosen as Fig. 1(b). Model domain is located at Middle Western coast of Saudi Arabia, with the grid as 85 x 130 points of 5km interval. Vertical grid is consists of 40 pressure sigma coordinate from surface to 50hPa, with lowest layer sigma as 0.001, nearly equivalent to 10m, on the other hand time step is fixed to 5s. Taif city is bedded on a mountain chain belonged to north Asir, and the height of mountain reaches more than 2000m, and this high mountain chain forms a steep slope from Mecca to Taif. The distance between Taif and Jeddah is about 150km. Mainly physical schemes are selected as follow,

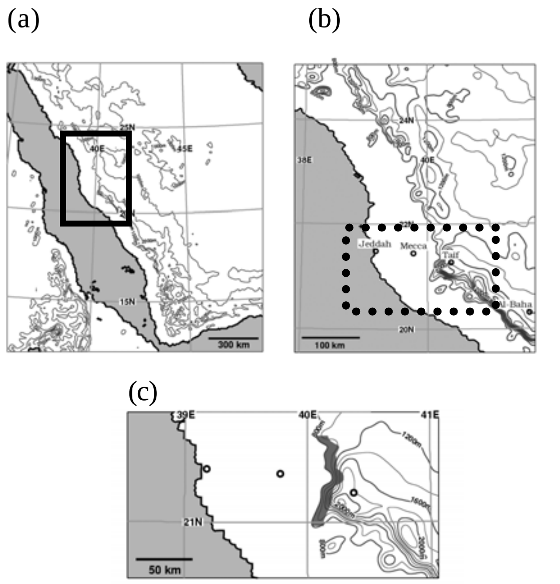

Fig.1 (a) Global map around Asir, and shading means water bodies. Thick square means (b) model domain including Jeddah, Mecca, Taif and Al-Baha, and square surrounded by dashed line means (c) greening area indicated by darker shading along the mountain slope.

Table 1 Parameters in the vegetation type

Parameter	Barren or sparsely vegetation	Grassland	Evergreen needle tree
Albedo (%)	**25**	**23**	**12**
Moisture Availability (%)	**5**	**30**	**60**
Emissivity (%)	**85**	**92**	**95**
Roughness (cm)	**10**	**10**	**50**
Surface heat capacity (10^6cal/m^3K)	**1.20**	**2.08**	**2.92**

CCM2 for radiation (Hack et al., 1993; Dudhia, 1989), MRF scheme for boundary layer (Hong and Pan, 1996), and Reisner graupel for explicit moisture, which is similar to the mixed phase scheme but with a little developed at the point of graupel and ice number concentration prediction (Reisner et al., 1998), and cumulus scheme is not used for this study. Boundary layer process includes the Noah land surface model, Noah-LSM, with 1 canopy layer, 4 soil layer, and interacting processes such as evapotranspiration, infiltration, and runoff (Chen and Dudhia, 2001).

Numerical experiments were executed for present situation (CTL Run) and greening situation that is shown in Fig.1(c) with greening area that is located above 800m height by 100km x 10km, and vegetation types were set to grassland with vegetation coverage of 60% (GRS Run) and evergreen needle tree with vegetation coverage

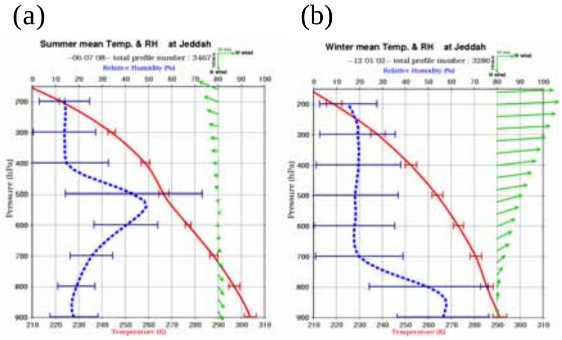

Fig. 2 Mean profile of temperature, RH, and wind in (a) summer and (b) winter at Jeddah.

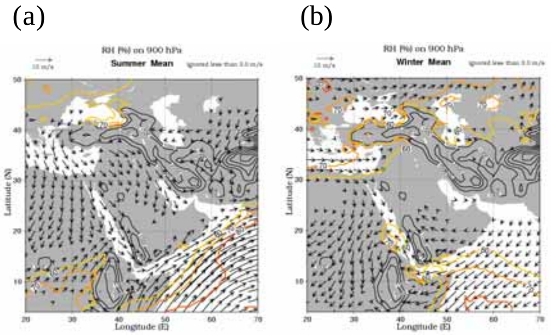

Fig. 3 Seasonal distribution of RH and wind in (a) summer and (b) winter on 900hPa.

of 20% (NDL Run), on the other hand present type is almost barren or sparsely vegetation in all the model domain except for the sea surface. Main parameters are shown in Table 1.

The period of model experiments is from 1st January to 1st March 2004, but 7 days period is prepared before the start time for analysis due to a numerical adjustment.

3. Seasonal Aspects

There is little rainfall over Arabian Peninsula due to large scale subsidence laying the subtropical zone, except for storm event coming from the Mediterranean (Taha et al., 1981), but seasonal variation in the atmosphere changes the arrangement of moisture under the subsidence layer. Fig. 2 shows the seasonal profiles for temperature and relative humidity at Jeddah. In summer, it is confirmed that a strong stability layer (or sometimes a capping inversion layer) lays nearly from 500hPa to 400hPa and the lower troposphere keeps dry (Fig. 2(a)), which means the convection continued from a lower height that can converge moistures has difficulty to go through this strong stability layer, so it is

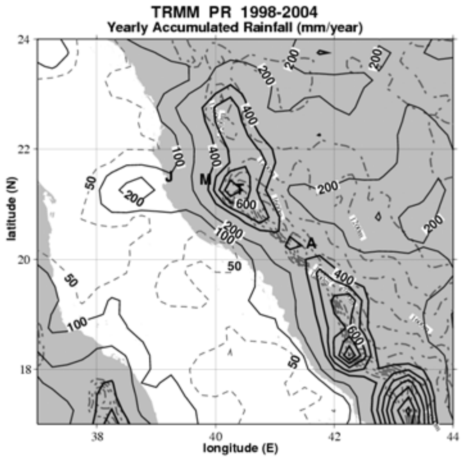

Fig.4 Yearly accumulated rainfall distribution detected by TRMM around north Asir. Characters of “J”, “M”, “T”, and “A” mean Jeddah, Mecca, Taif, and Al-Baha, respectively.

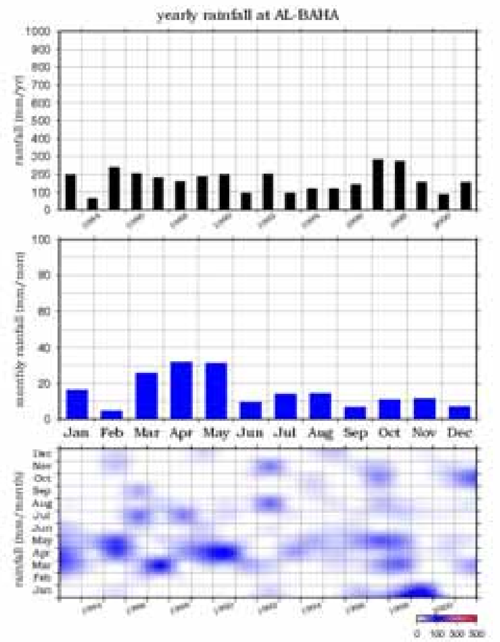

Fig.5 Rainfall characteristics summarized by (upper) each year, (middle) each month, and (lower) year-month at Al-Baha, which is shown in Fig.1(b).

usual situation that rainfall due to convective seems hardly to occur. In winter (Fig.2(b)), however, wet layer covers over the surface without the strong stability layer. Fig.3 depicts moisture and wind distributions in (a)summer and (b)winter. Northwesterly wind, which is not so wet, blows over the western coast of the Arabian Peninsula in summer. However in winter, large scale southeasterly wet flow comes into the Red Sea and the Mediterranean wet flow also blows on this ocean, and these flows converge around north Asir. These climate aspects show convective rainfalls in winter have possibility to occur easier than in summer. Yearly

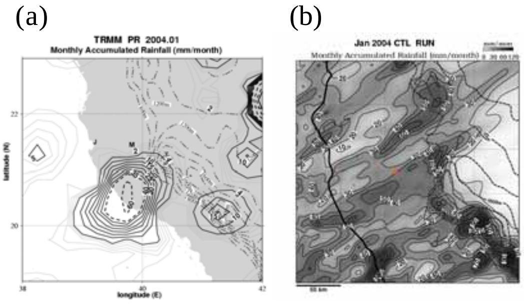

Fig.6 Rainfall distribution in January 2004 by (a) TRMM and (b) model result.

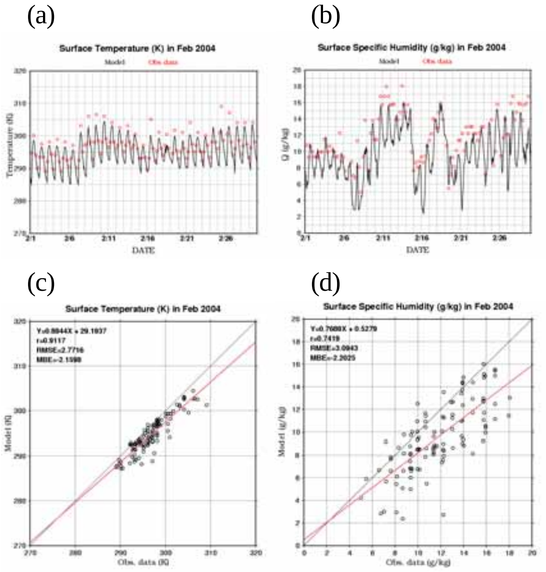

Fig.7 Model comparison with observation data in February 2004 at Jeddah. Upper panels mean time series for (a) temperature and (b) specific humidity at 2m height on the ground; solid lines mean model results and circles show observation data, and lower panels represent correlations for (c) temperature and (d) specific humidity, with regression lines.

accumulated rainfall distribution detected by TRMM is represented by Fig.4. Western coast including Jeddah and Mecca shows little rainfall of nearly 100mm/year, on the other hand, area near the top of mountain including Taif has an extent of rainfall of nearly 600mm/year, and other region over mountainous chain including Al-Baha shows nearly 300mm/year.

Fig.5 shows one example of climate aspects of rainfall at Al-Baha, which is shown in Fig.1(b) and is away from Taif by 150km and located on the mountainous region. Yearly series rainfall variation indicates that rainfall amount varies with age; the minimum peak is less than 100mm/yr and the maximum peak is near 300mm/yr. Seasonal aspect

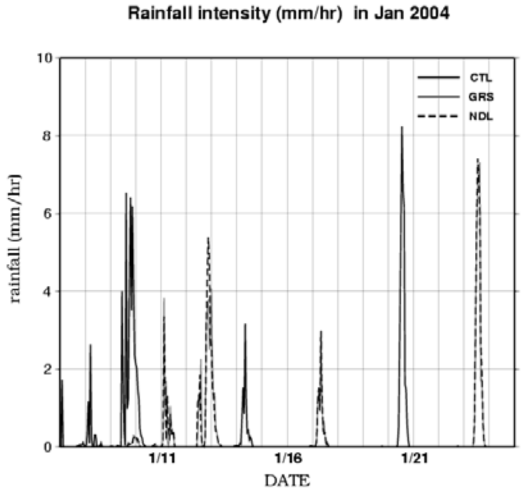

Fig.8 Rainfall time series in the period of some events, for CTL, GRS, and NDL Run over the greening area.

Table 2 Rainfall, Latent heat flux, and net rainfall value over the greening area in January and February 2004.

	Rainfall (mm/mon)	Latent Heat Flux (mm/mon)	Net Rainfall (mm/mon)
Jan CTL	61.4	11.6	+55.6
Jan GRS	89.6	29.5	+60.1
Jan NDL	87.2	21.8	+65.4
Feb CTL	0.46	6.6	-6.1
Feb GRS	0.80	65.2	-64.4
Feb NDL	0.72	33.0	-32.2

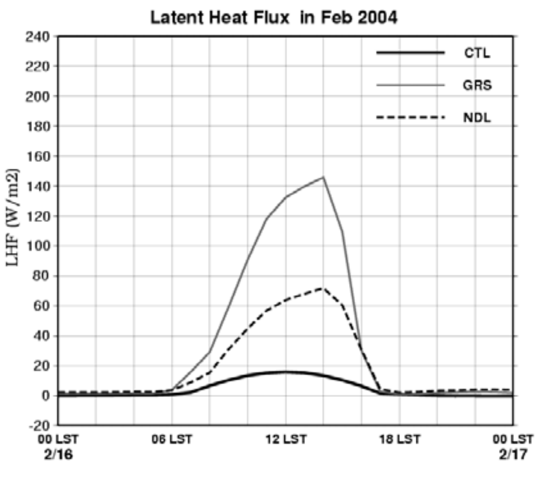

Fig.9 LHF daily series for a sunny day in 16th Feb, for CTL, GRS, and NDL Run.

shows more rainfall not only in winter but also in spring that is transition season, and it is difficult to categorize rainfall aspects with season, mainly because rainfall occurs by intermittently disturbances in additional to seasonal situation. Since next chapter effect of greening desert in typical rainy month and dry month and discuss the alternation of the net rainfall amount.

4. Model Validation

Fig.6 displays monthly rainfall in January 2004 as rainy season. TRMM data (Fig.6(a)) shows some spotty events near mountain chain, but model result represents these spots with hazy. This reason seems to owe to the difference of the way to detect rainfall between TRMM that catch only along a thin line and numerical calculation that follows rain generations at each grid points. It is confirmed, however, that the amount and coarse distribution of rainfall from the model calculation are similar to that from TRMM, so this simulation still is worthy of analyzing to discuss physical processes concerned with moisture distribution. In February 2004, there was hardly rainfall, so other parameters were compared to the observation data substitute for rainfall.

5. Greening Effect

5.1 Effect on rainfall

In order to estimate the greening effect over the desert in wet season and dry season, the period to simulate was fixed as 2 month, January and February 2004. It is not satisfied to understand completely the aspect of greening effect for the long ages as some decades, including the variation of ENSO, or IOD, but it is satisfied to estimate the local scale, or mesoscale dynamical effect on the region for some months that includes rainy season and dry season. As for this view, Jan 2004 is categorized as rainy season and Feb 2004 is as dry season. Especially the period from 7th to 24th January has some rain events, as shown by Fig.8. This figure shows the change of rainfall intensities among the landuse modification for each rainy event, but the change seems to be small.

5.2 Effect on LHF and net rainfall

Table 2 represents total value of rainfall, latent heat flux, and the net rainfall over the greening areal mean in Jan 2004. Rainfall intensity enhances due to greening, by +28.2mm/mon with grassland, and by +25.8mm/mon with evergreen needle tree, compared to the natural value of 61.4mm/mon, so enhancement ratios become +46%, and +42%, respectively. The values of accumulated LHF are converted to the values that are easier to compare with rainfall value (mm/mon). LHF also increases after greening, by the ratio of +154%, and +88%, respectively, and the LHF after grassland greening has greater value than the LHF after needle tree greening by 7.7mm/mon. As a result, the net rainfall values both increase compared to CTL Run by +8%, and +18%, respectively. However in February, greening causes a little terrible and negative effect, to become drier by –58.3mm/mon compared to CTL Run. This is due to the huge increase of LHF after greening, especially grassland greening, mainly because of dryness climate and large value of evapotranspiration.

5.3 Landuse effect on LHF

Fig.9 shows an example of the variation of LHF in sunny day in 16th February, 2 days after short rain event. The each maximum value of LHF show drastic change by landuse type, from $18W/m^2$ as CTL Run to $146W/m^2$ as GRS Run, on the other hand, LHF of NDL Run is suppressed compared with GRS Run as $72W/m^2$. The net rainfall value after needle tree greening surpasses that after grassland greening by 5.3mm/mon, and this is caused by the suppression of LHF as transpiration release with sparsely needle tree that has larger roughness length than grassland in Table 1.

6. Estimate the Net Rainfall for A Year

Table 2 shows the net rainfall in January as rainy season and February as dry season, and rainfall value in January is not so much compared to other rainy season with considering Fig.4 and Fig.5. Rainfall aspects of Fig.5 is at the location that has nearly 300mm/year, and Taif that is near the top of mountain keeps nearly 600mm/year, so it seems to be the twice values of Fig.5 at Taif, namely monthly rainfall as 60mm/month is expected usually. Under this consideration, and the consideration that Al-Baha has totally 4 rainy months and 8 dry months in a year, Taif seems to receive such climate as 4 rainy and 8 dry months. With this assumption it is estimated that how is the change of rainfall value after greening at Taif, with the net rainfall value of 65.4mm/mon and –32.2mm/mon. The result of this estimate becomes +4mm/year after needle greening. This value means the climate around north Asir can accept a kind of landuse change as greening without dryness due to evapotranspiration, and also the surface over the greening area keeps getting amount of moisture or water in every years. The net rainfall value of +4mm/year on the greening area with $1,000km^2$ means $+4x10^6$ton/year.

7. Conclusions

Greening effect over the desert in Saudi Arabia that contains dry climate especially in summer was estimated by a meteorological numerical model (MM5) with sophisticated land surface model (LSM). Rainfall variance is difficult to be fixed with categorized as seasonal characteristics, so it is decided to estimate in typical rainy and dry season, namely in January 2004 and February 2004 in order to estimate the greening effect on the net rainfall through a year. Greening area was selected on the slope of the mountainous chain over the north Asir, with 100km x 10km above 800m height, and vegetation types for greening was set to grassland and evergreen needle tree with the vegetation coverage as 60%, and 20%, respectively.

It is pointed out that the regional climate after greening by grassland vegetation changes rainfall amount increased by +65%. However, latent heat flux, LHF, largely increases in arid season, and increases a little in wet season. Evergreen needle tree was found to suppress LHF by 50% ~74% compared to grassland greening. As a result, estimated net rainfall values in selected months are 65.4mm/mon in rainy season and –32.2mm/mon in dry season. Roughly estimate for the net rainfall through a year showed a little positive value with the assumption for the rainfall climatology at Taif by +4mm/year that equals to $4x10^6$ton/year over the greening area, and this means that greening only around a mountainous area with sparsely needle tree can keep neutral or positive net rainfall even in arid area.

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数値シミュレーションによる海洋性砂漠緑化の影響評価

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要旨

サウジアラビア西海岸における海洋性砂漠緑化が水収支に与える影響を，気象モデルおよび洗練された陸面モデルを用いて評価した．山岳地域に施した緑化による気候場変化により，降水量は約65%増加した．しかしながら特に乾燥期には蒸発散量も大幅に増加することが判明したため，常緑針葉樹を緑化に適用した結果，蒸発散量を50%～74%抑え，正味降水量を見積もったところ，年間を通した正味降水量が正になる可能性があることが判明した．

キーワード:砂漠緑化，陸面モデル，正味降水量

数値シミュレーションによる海洋性砂漠緑地化の影響評価

○穂積 祐・植田 洋匡

１．はじめに

地球温暖化と砂漠拡大との関連が指摘される中，砂漠緑化の試みは生活空間や飲料水，農業水の確保のみならず，地球温暖化に対する一つの対策となる．これら砂漠緑化の必要性があるにもかかわらず，緑化対策はあまり進んでいないのが現状である．文部科学省 RR2002 の「人・自然・地球共生プロジェクト」にて砂漠緑化対策への取り組みが行なわれており，本研究では海洋性砂漠の緑地化が環境場に及ぼす影響を，特に水収支に着目し，緑化維持について議論をする．

この緑化対象地域であるサウジアラビア西海岸は，年間降水量が **100mm～200mm**，被植率はほぼ **0%**の領域が広がり海洋性砂漠を形成している．緑化研究では緑化の維持がひとつの大きな課題となっているため，まずは緑化維持にはどのような環境である必要か，環境場は緑化によってどのように変わるのか，を評価する必要がある．

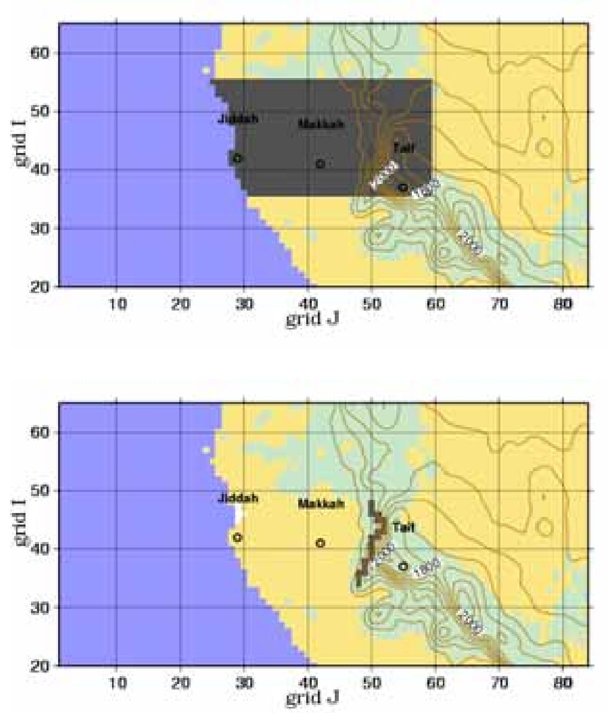

図 1：数値モデル中での緑化領域（灰色）．(a)はジェッダ，メッカ，タイフを含む 100km×150km，(b)は山岳地域の 100km×10km．

２．領域気象モデル

数値モデルは **3** 次元非静力学領域モデル **MM5 ver.3.6** であり，降水過程の再現が可能である．水平格子はランベルト，間隔は **5km**，鉛直は静水圧を基にした地形準拠座標で地表直上では約 **10m** の間隔である．インプットデータは **NCEPfnl**，**RTG-SST** データであり，植生，土壌データはこれらのデータおよび **AVHRR**，**USGS**（米国地質調査院）等のデータを用い，緑化時にはこれらを編集して用いた．環境場の再現期間は **2004** 年の **1** ヶ月間である．なお，海岸都市ジェッダにおける気象観測と計算結果との比較では，再現された温度場の相関係数は **0.92**，水蒸気場の相関係数は **0.74** であった．

３．緑化による正味降水量の変化

2004 年 2 月におけるコントロール計算および図１(a)の領域に緑化を施した後の計算における緑化領域での積算降水量を表 1 に示す．降水量は緑化により約 0.3mm/month 増加しているが，地表からの蒸発散による潜熱フラックスが急激に増大し正味の降水量は負値になっている．次に，2 月および 1 月におけるコントロール計算および図１の緑化領域における値（表１）から，針葉樹を緑化することで蒸発散量が抑えられること，および 1 月は典型的な雨季であり，正味降水量は緑化により増大することがわかる．

なお本研究は文部科学省 RR2002「人・自然・地球共生プロジェクト」の援助を受けています．

	降水量 R (mm/mon)	蒸発散量 LHF (mm/mon)	R－LHF (mm/mon)
2 月 Ctl	0.46	6.6	-6.1
2 月草地 a	0.76	67.6	-66.8
2 月草地 b	0.80	65.2	-64.4
2 月針葉樹 b	0.72	33.0	-32.2
1 月 Ctl	61.4	11.6	+55.6
1 月草地 a	67.3	47.6	+19.7
1 月草地 b	89.6	29.5	+60.1
1 月針葉樹 b	87.2	21.8	+65.4

表 1：コントロール計算および図１の緑化領域における積算降水量，蒸発散量，およびそれらの差．