Land–Atmosphere Interaction in a Semiarid Region: The Bunny Fence Experiment

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Abstract

Southwestern Australia, with a semiarid Mediterranean climate, has been extensively cleared of native vegetation for winter-growing agricultural species. The resultant reduction in evapotranspiration has increased land salinisation. Through detailed meteorological and vegetation measurements over both agricultural and native vegetation, the bunny fence experiment is addressing the impact on the climate of replacing native perennial vegetation with winter-growing annual species. Such measurements will give a better understanding of the interaction between the land surface and the atmosphere and are important for improved parameterization of the boundary layer in climate models.

1. Introduction

General circulation models (GCMs) reproduce large-scale meteorological fields (Tiedtke et al. 1988) but cannot account for small-scale detail. In particular, the parameterization of the atmospheric boundary layer concentrates on the correct parameterization of the vertical fluxes of momentum, heat, and water vapor as they affect the upper atmosphere rather than the development of the boundary layer itself (Reiff et al. 1986). Thus, although GCMs have highlighted the role of surface variations on climate, in showing that the fluxes of energy and moisture between the surface and the atmosphere are influential even for short-term weather systems and become increasingly dominant on larger time scales, the prediction of local effects is difficult because land-surface parameterization schemes are inadequate (Dickinson and Henderson-Sellers 1988).

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For example, changes in soil moisture affect the albedo and thermal diffusivity of the soil as well as the Bowen ratio in the surface boundary layer. As moist soil dries out, a larger fraction of the absorbed energy is used to heat the air—heat flow into soil increases at first, then decreases as soil becomes very dry (Rose 1966). Drought begets drought. Kunkel (1989) noted a marked decrease in evapotranspiration during the 1988 drought in America, and suggested that this may have played a role in the persistence of the drought by reducing the atmospheric water vapor supply and increasing the flux of sensible heat to the atmosphere. This is in accord with simulations of the African drought (Rowntree et al. 1985).

Neglect of latent heat in condensation and precipitation as well as sensible and latent heat exchanges at the surface produces significant bias in numerical mesoscale forecasts over periods of 0–3 days (Anthes et al. 1989). Kalma et al. (1991) concluded that the main hope for extending the time horizon of our models and their spatial resolution lies in a more realistic simulation of surface boundary conditions.

Mahfouf et al. (1987) incorporated soil texture in their numerical model as it modifies the soil moisture availability of surface evaporation and the uptake of soil moisture by plants. However, Wetzel and Chang (1987) found that within each soil textural class, typical variations in soil properties are larger than the differences between classes. Thus, appropriate scale modeling of surface heterogeneity is essential (McCumber and Pielke 1981; Wetzel and Chang 1987) to adequately represent the initial surface regime and apply appropriate forcing to the model.

As surface heterogeneities are invariably unrelated to numerical grid resolutions, adequate simulation of surface conditions requires averaging across the numerical grid. Wetzel and Chang (1988) examined the response of the averaging process to soil moisture content and found that the variability of soil water content will increase the area average evapotranspiration in the case of bare soil and decrease it for a fully vegetated surface compared to an area mean soil moisture content. Mahrt (1987) found that the net effect of heterogeneity on the area-averaged fluxes was less important in the unstable cases compared to the stable case, at least for gradual surface variations. Jacquemin and Noilhan (1990) also highlighted the sensitivity of the latent heat flux to changes in both soil and canopy parameters. Pielke et al. (1991) have shown, in the absence of a larger-scale wind flow, that mesoscale circulations induced by spatial landscape variability make an important contribution to the domain averaged total vertical heat flux.

Thus, model responses to heterogeneity are very nonlinear, yet to properly model surface heterogeneities we need to synthesize a canopy from its constituent parts and a region from its constituent canopies to provide appropriate subgrid-scale parameterizations (Shaw et al. 1985). Andre et al. (1990) suggest that there are two types of nonhomogeneous landscapes: (i) the disorganized land surfaces, for which the characteristic horizontal scale is smaller than about 10 km, so that no apparent coherent response can be traced in the atmosphere since boundary-layer turbulence averages everything out; and (ii) the organized land surfaces, for which the characteristic length is greater than 10 km, so that the atmosphere develops a coherent response at the mesoscale.

Field studies in the semiarid region of Western Australia (Fig. 1) are particularly suited to addressing the impact of land-surface changes on the atmosphere as the state is characterized by large homogeneous areas with characteristic length scales well in excess of 10 km, as well as marked surface changes, particularly along the vermin-proof fence and the western and eastern edges of the wheat belt. Under drying soil conditions typical of these regions, evapotranspiration is limited by the supply of soil moisture, and the sensible heat flux dominates. The vermin-proof fence provides an area of marked contrast between grazed farmland and native vegetation that is clearly distinguishable on satellite pictures, and is well removed from coastal influences and major topographic features.

Thus, the bunny fence experiment (buFex) is geared to (i) obtain detailed measurements of surface fluxes over homogeneous areas of native and agricultural vegetation on either side of the vermin-proof fence of Western Australia using surface, aircraft, and satellite sensors; (ii) use surface and aircraft data to provide an in situ calibration of the satellite estimates of surface temperature and vegetation; (iii) validate a numerical boundary-layer model for each of the homogeneous regions; (iv) extend the modeling to nonhomogeneous areas and particularly locations with sharp gradients in land use; and (v) combine both observations and numerical modeling to obtain estimates of the spatial variation of fluxes over nonhomogeneous terrain as the basis for improved land-surface parameterization in a mesoscale climate model. This paper presents an overview of the experiment as well as some of the preliminary results.

2. Lake King region

The buFex experimental site is located at Lake King (Fig. 1) in the Lakes District of the Great Southern Region of Western Australia. The climate of this region is characteristically Mediterranean with hot, dry summers and mild, wet winters. It is dominated by the subtropical ridge (Gentilli 1971). During summer, heat troughs form along the western coast of Western Australia and move inland in accordance with a regular progression of anticyclones (Watson 1980). Winter rainfall comes with the northward movement of the ridge and incursions of midlatitude cyclones and cold fronts. Rainfall decreases toward the east and inland from the coast.

Native vegetation of the region is characteristically a woodland called mallee with *Eucalyptus eremophila* the most consistent species. Patches of *Eucalypt* woodland occur on lower ground, and scrub heath and *Casuarina* thickets are found on residual plateau soils. The topography is gently undulating country of low relief with duplex mallee soils, that is, sand overlying clay (Beard 1979). The vermin-proof fence marks the eastern extremity of agricultural lands.

Since the beginning of this century, approximately 13 million hectares of native perennial vegetation to

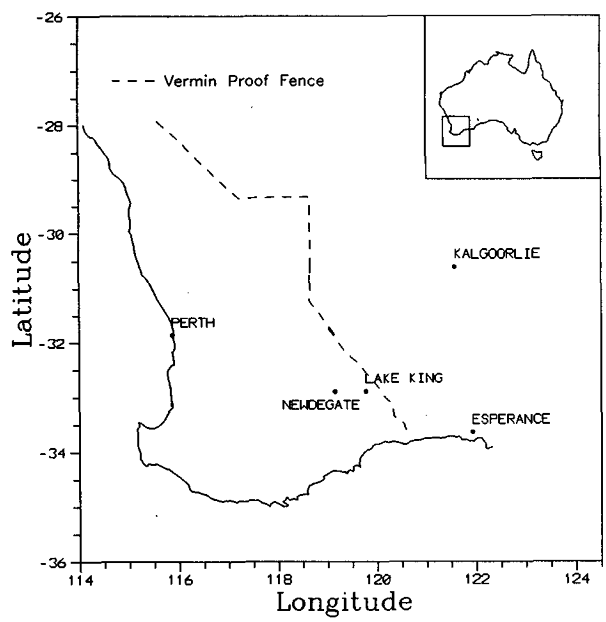

FIG. 1. Location of the study area—Lake King, Western Australia.

the west of the fence have been cleared for agriculture based on winter-growing annual species. Analysis of long-term rainfall data indicates that following the extensive clearing between 1950 and 1980 of the native vegetation, which transpires year round, and its replacement with annual vegetation, which only transpires during the winter, winter rainfall has declined by about 20% (Pittock 1983; Williams 1991). Pittock (1983) and Allan and Haylock (1993) have ascribed this decrease to large-scale circulation changes, but such a process of desertification initiated by deforestation is also in accord with observational and numerical studies (Anthes 1984; Segal et al. 1988; Otterman 1974; Shukla and Mintz 1982; Charney 1975) and highlights the need to gain a greater insight into the climatic impact of the large-scale clearing of native perennial vegetation and its replacement by winter-growing annual species. Such a change is known to cause a significant reduction in evapotranspiration, as evidenced by rising water tables and increased salinity (Greenwood et al. 1985). Its climatic impact is relevant to proposed plans to replant trees and clear further land for agriculture.

The buFex is thus using surface observations made using a portable field spectrometer and infrared thermometer to calibrate the airborne observations, which in turn can be compared to the satellite measurements.

3. The buFex experimental plan

The buFex experimental phase is running over the period 1991–1993 utilizing satellite, aircraft, and conventional meteorological sensors. Satellite-borne sensors provide, in combination with conventional meteorological data, large-scale spatial estimates of the surface fluxes, subject to atmospheric corrections, whereas aircraft observations provide direct measurements at specific times and surface observations provide site specific measurements as well as their temporal variation. An integration of data from these different measurement platforms will thus allow us to address the regional variation in surface fluxes and provide in situ calibration.

Because of sensor drift and atmospheric effects, satellite measurements of reflectance in the visible and near-infrared wavebands and radiant surface temperatures need to be calibrated with ground-based measures. The buFex is thus using surface observations made using a portable field spectrometer and infrared thermometer to calibrate the airborne observations, which in turn can be compared to the satellite measurements. The National Oceanic and Atmospheric Administration Advanced Very High Resolution Radar (NOAA AVHRR) satellite has a footprint of about 1 km; therefore, in a situation of sparse vegetation, the line profile of the airborne sensor gives estimates at a scale comparable to the satellite.

Hacker et al. (1988), Kerschgens and Hacker (1985), and Hacker (1988) have used an instrumented aircraft to determine the convective and sensible heat fluxes over a variety of surfaces. These results highlight significant differences in energy budgets, including the divergences of the turbulent heat fluxes, depending on surface conditions. For example, under strong insolation, convection is greater over bushland than agricultural areas and it is tempting to ascribe this to differences in surface temperatures. However, it is difficult to determine an integrated surface temperature for the vegetation canopy during overflight because the sensing radiometer "sees" not only the dark leaves, but the dark, shaded areas on the ground below. Thus, simultaneous surface infrared thermometry combined with the aircraft observations is essential to determine the relative enhancement of convection by canopy elements as well as the possible separation of the air above the canopy with that below.

Low-altitude radiometer measurements of reflectance in the visible and near-infrared wave bands will enable calculation of the fractional green vegetation cover measured by the Normalized Difference Vegetation Index (NDVI) and the establishment of the relationship between NDVI, fractional green vegetation cover, surface roughness, and surface albedo for the two contrasting vegetation types. NDVI most directly represents the absorption of photosynthetically active radiation and hence is physiologically a measure of the photosynthetic capacity of the canopy and bulk stomatal or canopy resistance to water vapor transfer (Tucker and Sellers 1986). The NDVI can then be used to determine the spatial heterogeneity of the vegetation from both airborne and satellite measures. Sellers et al. (1990) have questioned the use of NDVI in sparsely vegetated areas and a comparison between satellite, aircraft, and ground-based observations will assist in clarifying this empirical formulation. Estimates of NDVI also provide a convenient means to estimate the fluxes assuming a ground heat flux as a proportion of net radiance modified by NDVI (Daughtry et al. 1990).

The intensive field studies involve traverses over

Table 1. BuFex experiments.

Experiment	Date	Observations
buFex1	August 1991	Aircraft (turbulent fluxes); satellite
buFex2	April 1992	Aircraft (turbulent fluxes, short- and longwave radiation, air chemistry); satellite; turbulent fluxes and continuous standard surface observations and solar radiation over both surfaces; selected surface infrared thermometry
buFex3	September 1992	Aircraft (turbulent fluxes, short- and longwave radiation, air chemistry); satellite; turbulent fluxes and continuous standard surface observations and solar radiation over both surfaces; selected surface infrared thermometry
buFex4	Proposed October 1993	Proposed aircraft (turbulent fluxes, short- and longwave radiation, air chemistry); satellite; turbulent fluxes and continuous standard surface observations and solar radiation over both surfaces
buFex5	Proposed January/February 1994	Proposed Aircraft (turbulent fluxes, short- and longwave radiation, air chemistry); satellite; turbulent fluxes and continuous standard surface observations and solar radiation over both surfaces

homogeneous areas with the Flinders research aircraft, which is capable of measuring all the components of the surface energy budget (Hacker and Schwerdtfeger 1988). These measurements are supplemented by simultaneous continuous surface observations of the turbulent fluxes as well as standard meteorological parameters and infrared thermometry (see Table 1). During the field experiments, data from the daytime overpasses of the NOAA AVHRR satellite sensor will be collected from the routine collection and archive of the Western Australian Remote Sensing Application Centre. Relationships derived from the field and airborne measurements will be used to analyze the satellite data to characterize the larger-scale variation in surface temperature, albedo, and surface roughness. This will be used with local meteorological data to estimate the differences in latent and sensible heat fluxes between native and agricultural vegetation.

As the fluxes of heat and moisture to the atmosphere are heavily dependent on surface conditions, the initial experiments are being conducted over homogeneous terrain beyond the vermin-proof fence on selected clear-sky days. The Lake King area has large homogeneous regions (both cultivated farmland and uncultivated land) in close proximity and experiments can be conducted in association with the Western Australian Department of Agriculture's climate monitoring program as well as the long-term observations from the Newdegate Agricultural Research Station.

Intensive experiments are being conducted in both the austral summer/autumn and winter/spring to account for seasonal variations in evapotranspiration rates and the difference in transpiration between the native and agricultural vegetation during the summer, when native vegetation continues to transpire while the annual agricultural vegetation has zero transpiration. Simultaneous measurements on either side of the vermin-proof fence will enable the impact of sharp gradients in surface conditions provided by short (<1 m) agricultural vegetation of annual species that are senescent during the summer months and medium height (1–6 m) native perennial woodland vegetation that is green year-round to be addressed. These will provide the necessary field data to extend the modeling to nonhomogeneous areas and allow us to address the more complex question of incorporating improved surface parameterization for nonhomogeneous regions in mesoscale climate models.

4. Preliminary results

An initial pilot field experiment using aircraft and satellite sensors was carried out at Lake King in August 1991 during the middle of the agricultural growing season when crops and pastures were approaching full canopy cover. Detailed aircraft observations were taken at selected intervals throughout the day along the flight track shown in Fig. 2. The aircraft flew at a true airspeed of approximately 40 m s^{-1} with a data sampling rate of 10.4 Hz, thereby implying a spatial resolution of approximately 12 m. These data were subjected to a high-pass Lanczos filter with a cutoff frequency of 0.4 Hz to obtain estimates of the fluxes, which were then averaged over 10 km.

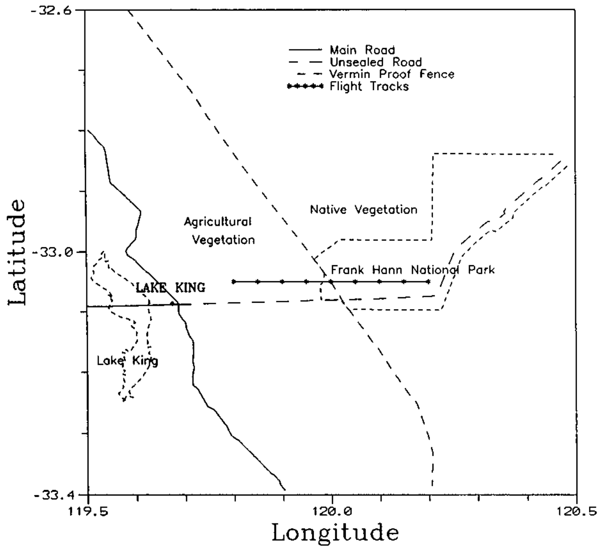

FIG. 2. Aircraft flight track over agricultural farmland and the native vegetation of the Frank Hann National Park.

Figure 3 shows satellite measurements of NDVI uncorrected for atmospheric effects, at a resolution of approximately 1 km, corresponding to the aircraft flight track. They illustrate the large relatively homogeneous tracts on either side of the vermin-proof fence and the marked discontinuity at the fence. Similar features are evident in the sensible and latent heat fluxes (Fig. 4). Under wet soil conditions and complete canopy cover of agricultural vegetation pertaining at the time, Fig. 4 illustrates a dominance of the sensible heat flux over the native vegetation compared to a strong latent flux over the agricultural area. The strong latent flux was undoubtably associated with transpiration from the dense crops of wheat and pastures whereas the dominance of the sensible flux is likely to be associated with reduced albedo, increased surface roughness, and surface resistance. Novak (1990) suggests that the sum of daily average sensible and latent heat flux densities decreases as the surface resistance and albedo increase, and the surface roughness decreases. For a dry surface, daytime atmospheric heating decreases with vegetation removal because albedo and soil admittance increase and atmospheric admittance decreases. Such effects are not apparent in this dataset but may be more clearly defined in data collected in the summer/autumn before the crop emerges.

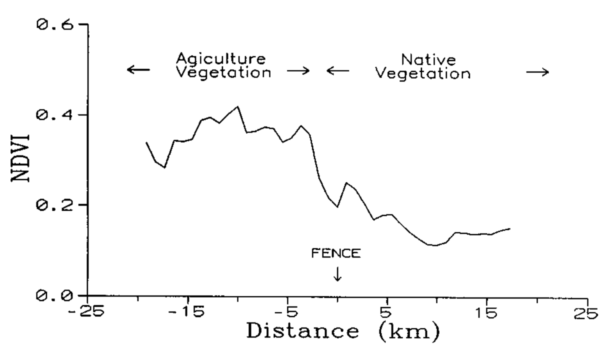

FIG. 3. Satellite measurements of NDVI corresponding to the flight track.

Surface temperature, NDVI, and red and near-infrared reflectance from the NOAA AVHRR sensor were used to estimate average albedo and surface resistance as input into a boundary-layer model with interactive soil and plant canopy (Ek and Mahrt 1989) to simulate the exchange of heat and moisture fluxes between the surface and the atmosphere. The model was modified to treat the land surface as one layer but to distinguish between the surface temperature and latent heat flux from the canopy and soil. In particular, the surface temperature for a partially vegetated area is a weighted average of soil and canopy temperatures (Xinmei and Lyons 1993).

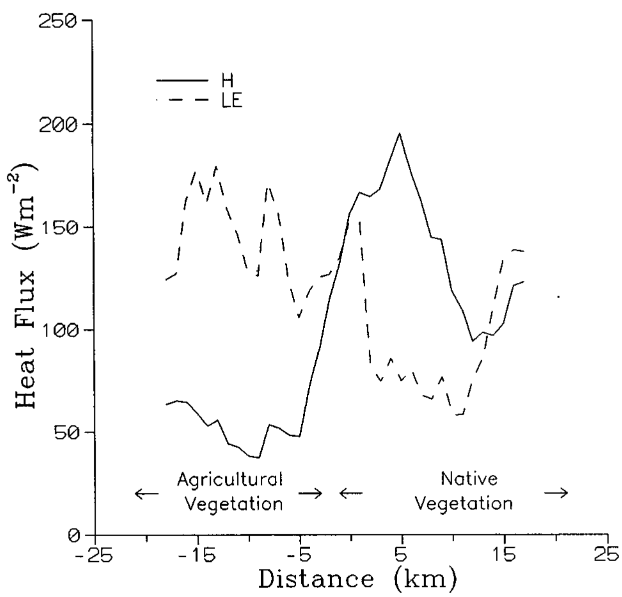

FIG. 4. Averaged latent (LE) and sensible (H) heat fluxes measured by the aircraft along the flight path, at an average height of 170 m.

Model estimates of sensible and latent heat were compared to the aircraft observations and illustrated encouraging agreement (Xinmei et al. 1993). The model simulations also suggest that these differences lead to greater mixing over the native vegetation (Fig. 5). Subsequent aircraft observations during buFex2 confirmed the difference in height of the convective boundary layer over the two surfaces. Such effects are in accord with the work of Otterman (1989) and Otterman et al. (1990), who have argued that increases

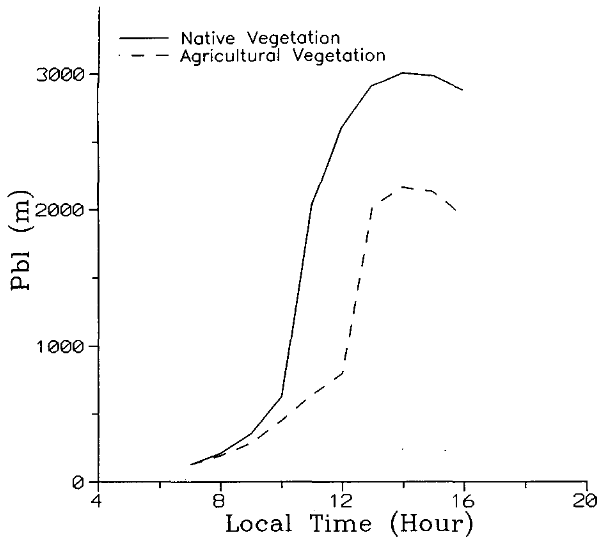

FIG. 5. Estimated evolution of the height of the planetary boundary layer over native and agricultural land.

in precipitation resulting from land use changes are attributable to intensification of the dynamical processes of convection and advection resulting from plant-induced enhancement of the daytime sensible heat flux from the generally dry surface. They suggest that enhancement results both from the reduced surface albedo and the reduced soil heat flux. Rabin et al. (1990) also suggested that clouds form earliest over regions characterized by high sensible heat flux and are suppressed over regions characterized by high latent heat flux during relatively dry atmospheric conditions.

Further evidence in support of this mechanism is seen in a visible satellite picture of the region taken several weeks after the experiment (Fig. 6), in which convective cumulus clouds are associated with the native vegetation (shown as dark green) and not with the agricultural region (shown as light green). One could speculate that the extensive mixing over the

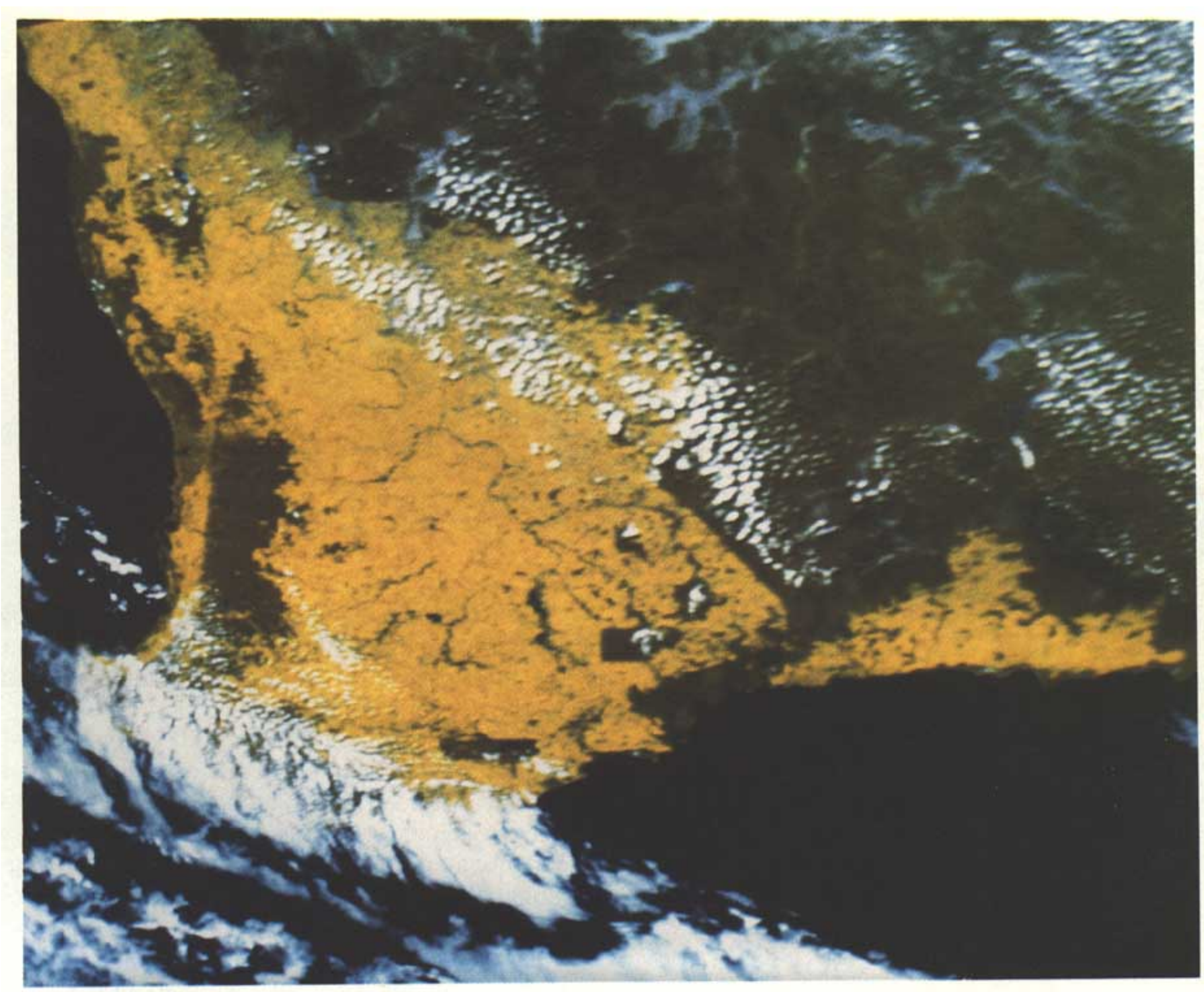

FIG. 6. Satellite photograph of the region showing the formation of convective clouds over native vegetation.

native vegetation is sufficient to reach the lifting condensation level, whereas although the agricultural area is supplying more moisture, insufficient mixing is occurring to allow condensation. These mechanisms should become more clear as the experimental data from the next phase of buFex becomes available.

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