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Impact of Forests on Mesoscale Meteorology [and Discussion]

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Impact of forests on mesoscale meteorology

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The effect of forests on local meteorological circulations is discussed with particular regard to the consequence of their lower albedo, enhanced roughness and larger minimal stomatal resistance when compared with agricultural crops. The effect of these is determined by numerical simulation using two different mesoscale atmospheric models. Emphasis is given to the surface energy budget because this is the driving mechanism behind atmospheric circulation at the mesoscale. Experimental measurements taken during the 'HAPEX-MOBILHY' programme are shown to be consistent with the conclusions drawn from this numerical simulation.

1. Introduction

Over the past decade it has been recognized that land-surface processes affect atmospheric circulations at all temporal and spatial scales, ranging from multi-annual, climatic scales (Charney 1975; Shukla & Mintz 1982), through global intra-annual scales (Yeh *et al.* 1984) to local mesoscale circulation (Anthes 1984). The purpose of the present paper is to present further evidence on the impact of land-surface processes, and in particular of forest-driven surface fluxes, on atmospheric circulations at the meso-β-scale (Orlanski 1975).

There are, indeed, several aspects that are significantly affected by the presence of a forest. One can mention the modification of the surface energy budget induced by the forest's lower albedo compared with agricultural crops; the influence of its comparatively higher stomatal resistance on the partition of the energy available at the surface; the change in the surface fluxes of momentum and heat resulting from higher aerodynamic roughness, and the possible enhancement of local precipitation from increased evaporation as a result of the interception of more rainfall.

2. Methodology

The impact of forests on mesoscale meteorology is addressed here from numerical experiments with three-dimensional models. Atmospheric mesoscale models have improved significantly over the past decade (see, for example, Pielke (1984) for a review) and now provide adequately realistic simulations. Experiments are made with the two meso-β-scale hydrostatic models developed by Nickerson *et al.* (1986) and Bret & Bougeault (1988).

The one-dimensional schemes used to describe land-surface processes and the turbulent and radiative fluxes into the atmosphere implemented in these three-dimensional models have been carefully tested and validated against experimental data. They have been described in more detail by Pinty & Mascart (1988) for the Nickerson *et al.* (1986) model (used in §3) and by Noilhan & Planton (1989) for the Bret & Bougeault (1988) model (used in §4 and §5). The Pinty & Mascart (1988) transfer scheme solves the diffusion equations for heat and moisture at 13 levels distributed through the top 1 m layer of soil, and energy budgets for both the soil surface and the vegetation layer, as in Deardorff (1978). On the other hand, in Noilhan & Planton's (1989) scheme, the soil is represented with two reservoirs for heat and moisture, and there is only one energy budget equation to describe the surface, which may or may not be completely covered by vegetation.

Both one-dimensional schemes appear to behave well and are able to reproduce the daily variation of latent and sensible heat fluxes over various canopies accurately, together with longer-term change associated with either ground-moisture depletion or the growth and maturity of agricultural canopies. Pinty & Mascart (1988) give more detail of the validation of their scheme. Here we show only two results, taken from Noilhan & Planton (1989), which demonstrate that such schemes can indeed reproduce the observed variation in surface heat fluxes. Figure 1*a*, *b* compares modelled and measured heat fluxes for young corn growing on sandy soil. These experimental data were taken on 16 June 1986 during the HAPEX-MOBILHY experiment (André *et al.* 1986, 1988). It can be seen that this corn crop, which covered about 80% of the soil surface and was in full growth, evaporated at a substantial rate. In comparison, figure 2*a*, *b* shows that on this same day the 'Landes' pine forest, which is located

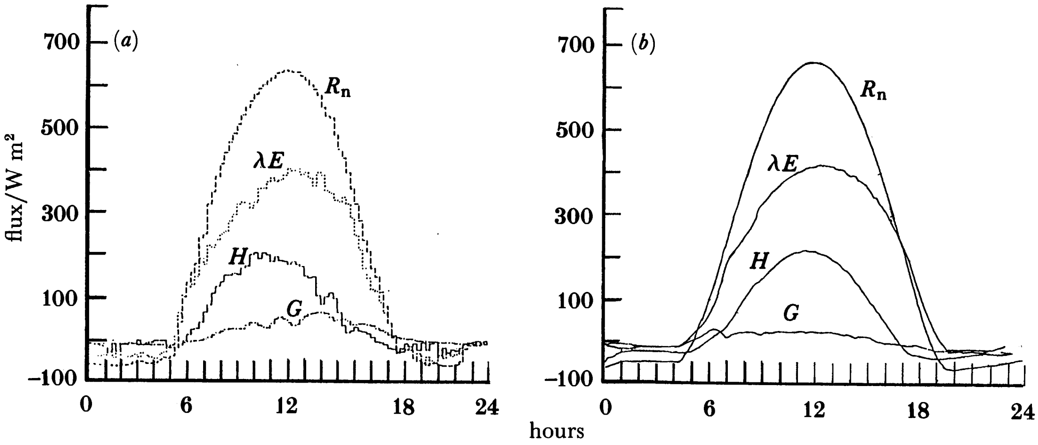
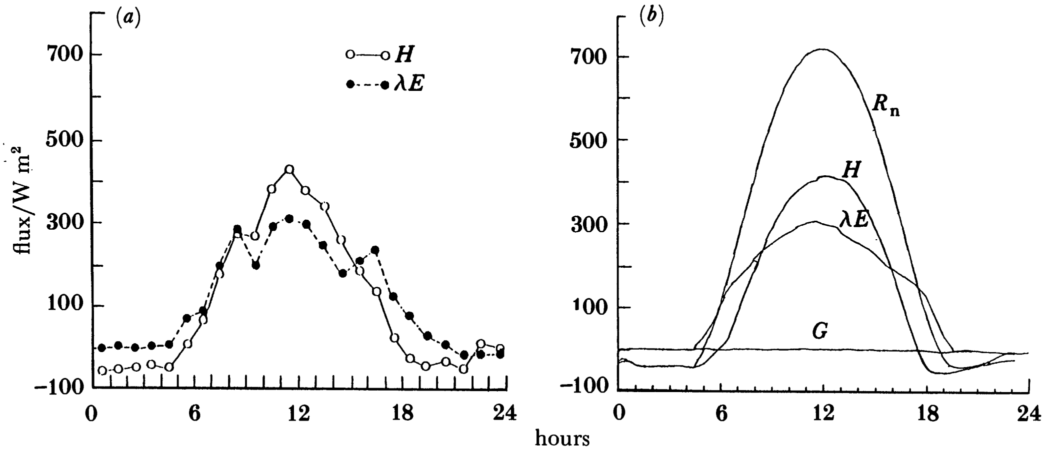


FIGURE 1. Diurnal variation of surface-energy budget and net radiation (R_n), sensible (H), latent (λE) and ground (G) heat fluxes over corn growing on sandy soil: (*a*) observed; (*b*) modelled. This case corresponds to 16 June 1986, over southwest France.



IGURE 2. Same as figure 1, but for the 'Landes' pine forest.

nearby, transpired at a significantly reduced rate, despite the fact that the soil was close to saturation (see Gash *et al.* (1988) for more detail). This feature is reproduced fairly well by the numerical scheme, with the forest's stomatal resistance (100 s m^{-1}) much higher than that of the corn (40 s m^{-1}).

3. Atmospheric response to a two-dimensional transition between forest and agricultural crop

Before proceeding to a more realistic case, it is of interest to study an idealized situation in which the atmosphere's mesoscale circulation develops in response to the thermal and hydric contrasts between a forest and an adjacent agricultural canopy. This study was done with the two-dimensional version of the Nickerson *et al.* (1986) model, in which the left and right parts of the soil surface were covered, respectively, by a typical cereal crop and a typical pine forest. The soil was assumed to be sandy and close to saturation, corresponding to the HAPEX-MOBILHY observations of 16 June 1986 reported in the preceding section. Table 1 shows the values of the most relevant surface parameters used in this numerical simulation. The effects of ambient wind and Coriolis force were not taken into account because the aim was merely to assess if such a simple contrast in surface conditions could lead to a significant atmospheric response at the mesoscale.

Table 1. Canopy parameters for the cereal (left part of the domain) and the forest (right part of the domain) in the two-dimensional simulation using the Nickerson *et al.* (1986) model with the Pinty & Mascart (1988) transfer scheme

	cereal	forest
fraction of covered surface	0.8	0.85
dry-leaf area index	0.2	0.7
green leaf area index	1.5	3.5
height	0.7 m	15 m
minimal stomatal resistance	50 s m^{-1}	350 s m^{-1}
albedo	0.25	0.10
emissivity	0.96	0.98

Figure 3*a* shows variations of the surface fluxes of sensible and latent heat. Because of the reduced albedo (see table 1) and a smaller heat flux into the ground, the available surface energy is larger over the forest than it is over the cereal field, leading to a larger total heat flux ($H+\lambda E$). In addition, the relatively large stomatal resistance of the forest means the Bowen ratio remains close to one, so that the sensible heat release there is larger than for the adjacent cereal crop. As a result (see figure 3*b*), a 'forest breeze' circulation develops, with horizontal winds of about 4 m s^{-1} blowing from the cereal field to a depth of approximately 1 km, and a return flow aloft of the order of 2 m s^{-1}. It should be mentioned that the intensity of this forest breeze circulation is approximately one third of that observed during a typical 'sea breeze' episode. This type of breeze circulation is further illustrated in figure 3*c*, where it can be seen that the vertical velocity is of the order of 4 cm s^{-1} over the forest, with a weaker subsiding flow of the order of 2 cm s^{-1} over the cereal crop. The depth of the planetary boundary layer does, of course, respond to the differential heating, as can be seen from figure 3*d*, which shows the

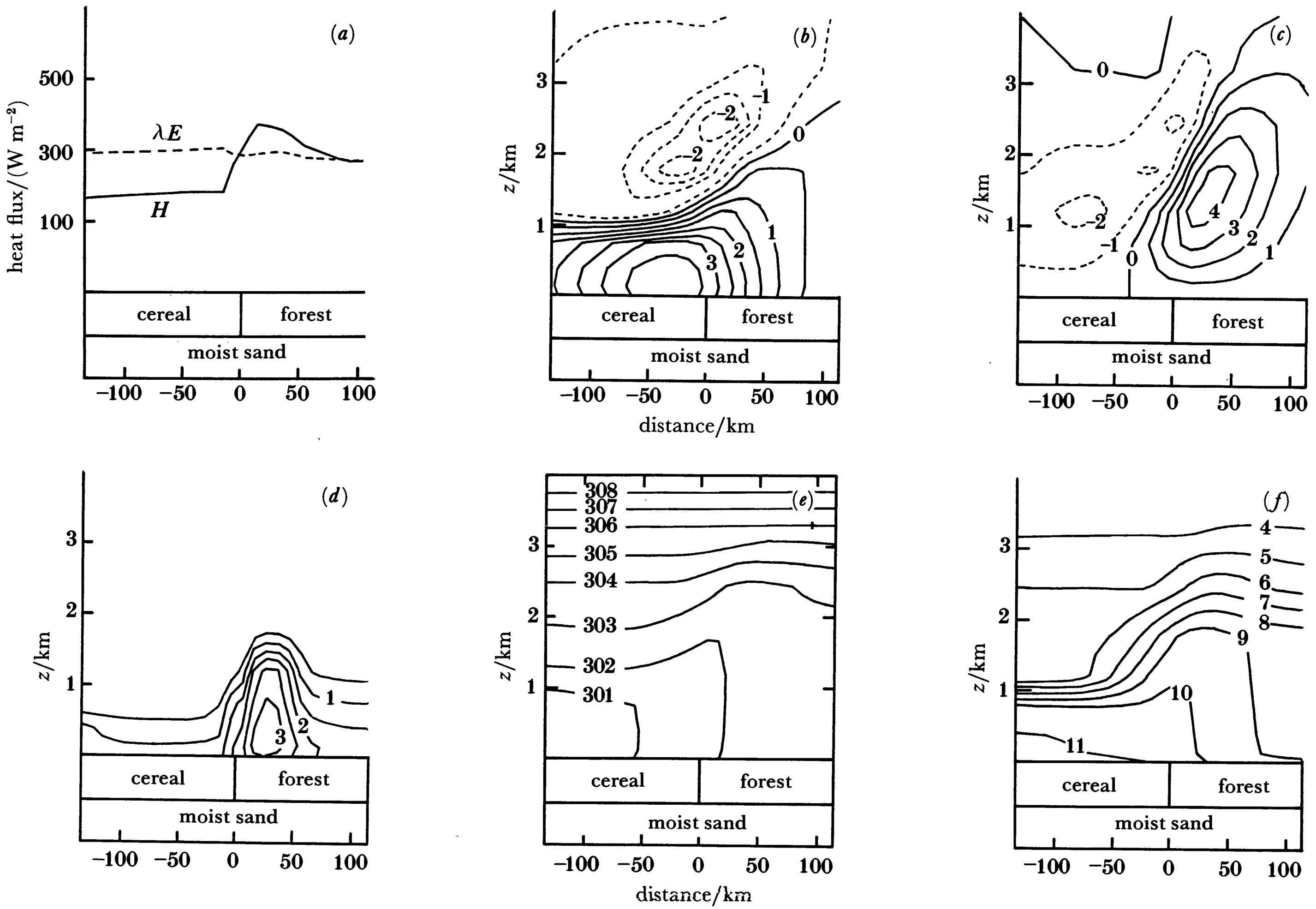


FIGURE 3. Two-dimensional transition between a cereal crop (left part of the domain) and a forest (right part of the domain) growing over sandy soil close to saturation: (*a*) sensible (H) and latent (λE) heat fluxes; (*b*) cross section of horizontal wind velocity (isolines, labelled in metres per second represent wind blowing from either the left (solid lines) or the right (broken lines)); (*c*) cross section of vertical velocity (isolines, labelled in centimetres per second represent either ascending (solid lines) or descending (broken lines) velocities); (*d*) cross section of eddy kinetic energy, with isolines labelled in square metres per square second; (*e*) cross section of potential temperature, with isoline labelled in Kelvins; (*f*) cross section of water-vapour mixing ratio, with isolines labelled in grams per kilogram.

eddy kinetic energy distribution. The rougher forest, which is also transferring a larger amount of sensible heat into the atmosphere, gives rise to a thicker and more turbulent boundary layer. The depth of the boundary layer is close to 1 km over the forest, but it is only 500 m over the cereal field. The temperature distribution (see figure 3*e*) indicates that air is warmer over the forest, a result of increased surface sensible heat flux, but the forest boundary layer is somewhat drier (see figure 3*f*); although the same amount of moisture is injected into the atmosphere (figure 3*a*), this is distributed over a deeper layer. Finally, the transition zone between the cereal and the forest exhibits increased turbulence (figure 3*d*) related to increased wind shear (figure 3*b*), and leading to relatively enhanced moist convection (figure 3*f*). We return to this point in the next section, because this mechanism may contribute to preferred cloud formation over the forest.

Numerical simulations (not reported here) show that this forest breeze circulation is less marked for drier conditions when the amount of moisture available for cereal transpiration is reduced, leading to a different energy partition over the crop and reducing the thermal contrast with respect to the adjacent forest. Numerical simulations (not shown here) for such a case, confirm the above remark.

4. Three-dimensional atmospheric response to forest-induced surface flux variations, and sensitivity experiments with respect to roughness and stomatal resistance

We now present three-dimensional simulations using the Bret & Bougeault (1988) model, with initial conditions and surface sub-models taken from observations on 16 June 1986, made during the HAPEX-MOBILHY programme (André *et al.* 1988) (see also §2, figures 1 and 2). On this particular day the weather was fine but clouds were observed to develop over the 'Landes' forest, which covers a large part of the study area in southwest France.

The initial conditions are taken from the meteorological analysis specially done during the HAPEX-MOBILHY programme, which takes full advantage of the supplementary ground and upper-air observations (Mercusot *et al.* 1986). The surface cover is specified from a previous pedological survey of the simulated region and from NOAA-satellite observations of the normalized difference vegetation index (NDVI). This index was transformed into values of albedo, surface roughness, leaf area index, vegetation cover and minimal stomatal resistance by a prescribed correspondance table (see Phulpin *et al.* (1989) for more detail). The initial moisture content of the two ground reservoirs were assigned from neutron-soundings of the top 2 m of soil.

Figure 4*a*, *b* shows that the latent heat flux does not vary much over all the region north of the Pyrenees, whereas the sensible heat flux exhibits a significant increase over the forest in the northwest of the study area. This is in qualitative agreement with the results of the idealized two-dimensional simulation described in the preceding section, and confirms the importance of the increased minimal stomatal resistance of the forest. It is, moreover, in quantitative agreement with the air-borne measurements of the latent and sensible heat fluxes over this same area (shown in figure 5) which indicate that at solar noon (i.e. around 14h00 local time) the sensible heat flux may reach, or even exceed, 300 W m^{-2} over parts of the forest, but remains of the order of 200 W m^{-2} over nearby agricultural crops (see also figures 1–3*a*). The aircraft measurements also confirm that the latent heat flux does not change significantly between the forest and other vegetative canopies.

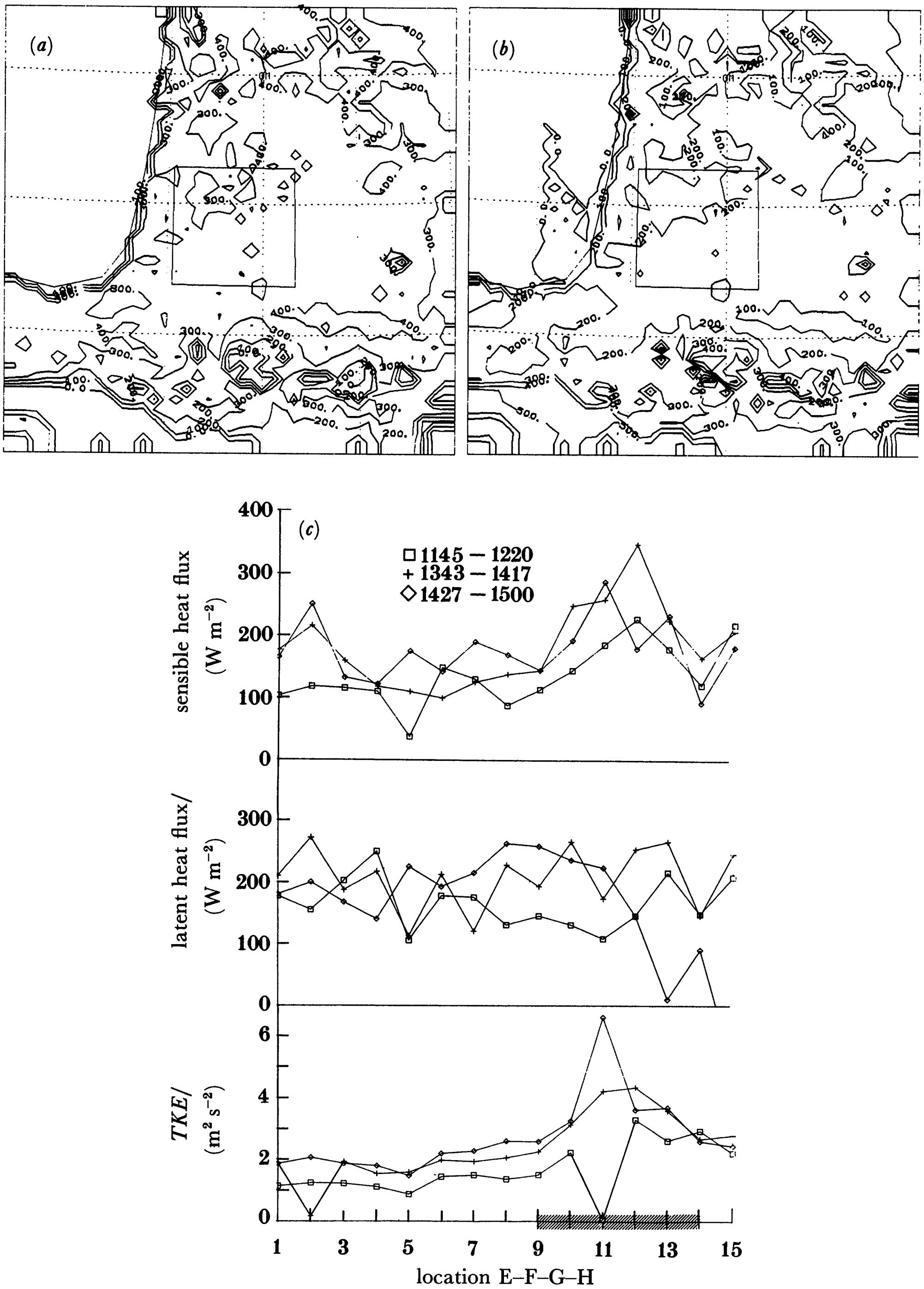


FIGURE 4. Horizontal variations of surface turbulent fluxes over southwestern France as modelled by the PERIDOT meso-β-scale model for 16 June 1986, at 15h00 Greenwich Mean Time (GMT). Isolines are labelled in watts per square metre. The square represents the experimental zone where the HAPEX-MOBILHY programme (André *et al.* 1986) was done: (*a*) latent heat flux; (*b*) sensible heat flux. (*c*) Aircraft measurements of sensible heat flux H, latent heat flux λE, and eddy-kinetic energy K, for 16 June 1986. Each measurement consists of the average over a 10 km segment. The hatched area between segments 9 and 14 corresponds to the location of the 'Landes' forest. (By courtesy of P. Hildebrand (see André *et al.* 1988).)

The larger sensible heat flux from the forest is consistent with enhanced, roughness-induced turbulent exchange, and corresponds to smaller atmospheric temperature gradient than for agricultural crops. The surface temperature is indeed 2 K cooler (see figure 5*a*) and the air near the ground 1 K warmer (see figure 5*b*), for the forest in the northwest of the study area than for the agricultural crops further east.

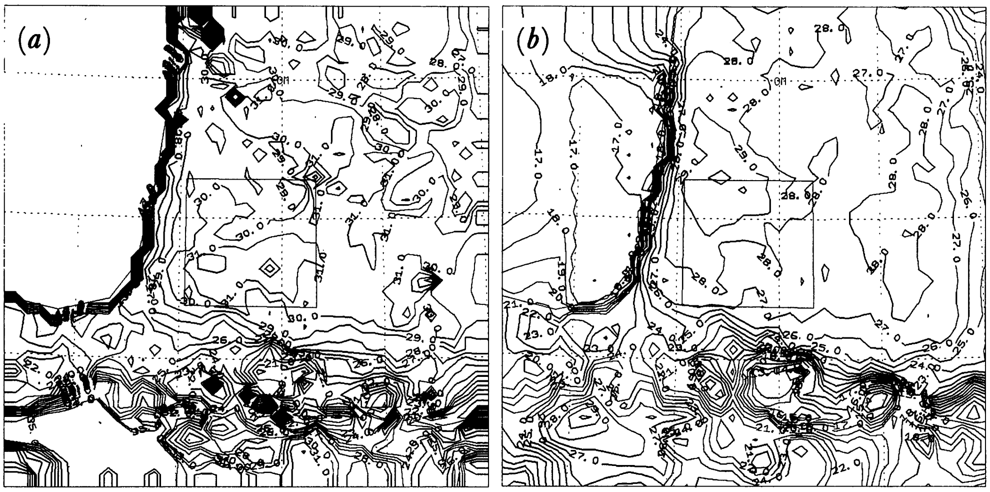


FIGURE 5. Horizontal variations of (*a*) surface and (*b*) air temperature over southwestern France, as modelled by the PERIDOT meso-β-scale model for 16 June 1986. Isolines are labelled in Kelvins.

The above features, which are related to particular properties of the forest canopy, were investigated further by performing numerical experiments in which the values of relevant forest parameters were changed. In the first experiment the roughness length of the forest was altered from 1 m to 15 cm while everything else remained unchanged. In the second experiment the minimal stomatal resistance of the forest was altered from 100 s m^{-1} to 40 s m^{-1}, with other parameters again unchanged. The decrease in the forest's surface roughness leads to a reduction in the turbulent activity near the surface and, consequently, to an increased surface temperature (figure 6*b*). This change is, however, too small to have significant impact on the

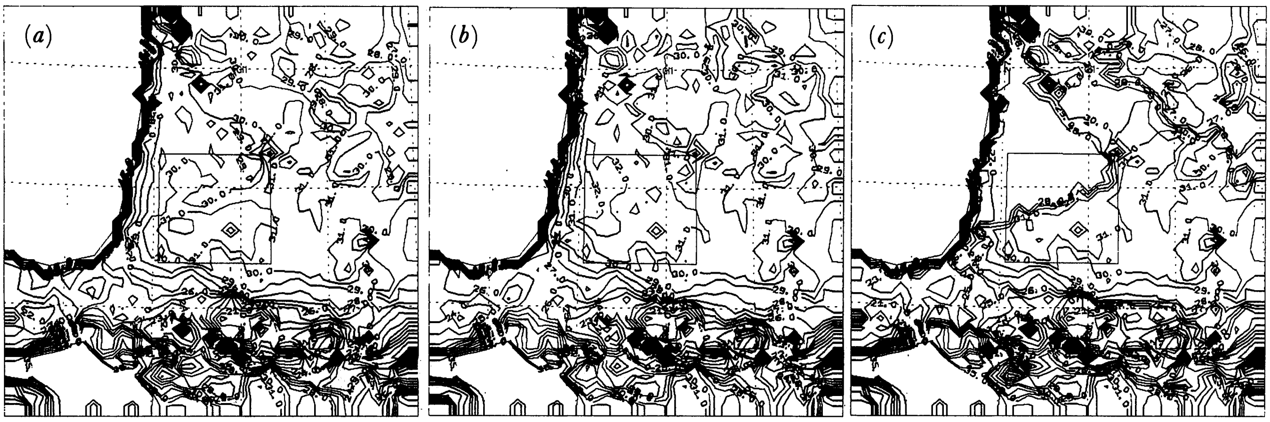


FIGURE 6. Modelled horizontal variations of surface temperature (isolines labelled in Kelvins): (*a*) control experiment, same as Figure 5*a*; (*b*) with reduced roughness length of the forest; (*c*) with decreased minimal stomatal resistance of the forest.

partition between sensible and latent heat fluxes (see figures 7*a* and 7*b*), on the development of the planetary boundary layer (figures 8*a* and 8*b*) or on the formation of clouds over the forest (see figures 9*a* and 9*b*). On the other hand, decreasing minimal stomatal resistance has almost no impact on surface temperature (figures 6*a* and 6*c*) but leads to a very significant change in the partition of available energy, with increased latent heat flux and decreased sensible heat flux (see figures 7*a* and 7*c*). This corresponds to reduced buoyant production of eddy kinetic energy and, consequently, leads to a decrease in planetary boundary layer depth (figures 8*a* and 8*c*). As a result, triggering of cumulus convection over the forest is much reduced, almost leading to dissipation of the convective clouds that otherwise develop here (figures 9*a* and 9*c*).

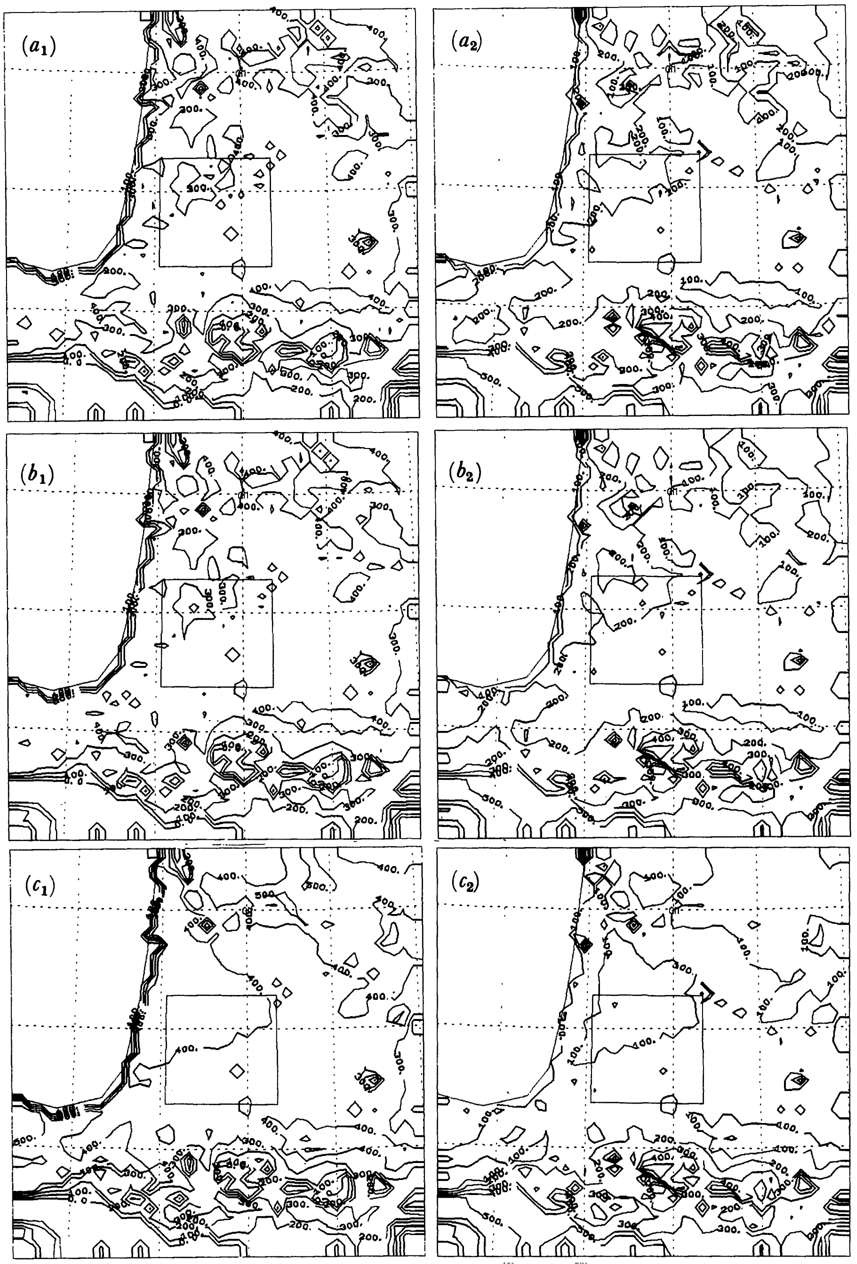


FIGURE 7. Same as figure 6, but for latent (left) and sensible (right) surface heat fluxes; isolines are labelled in watts per square metre; (*a*) is the same as figure 4*a*, *b*.

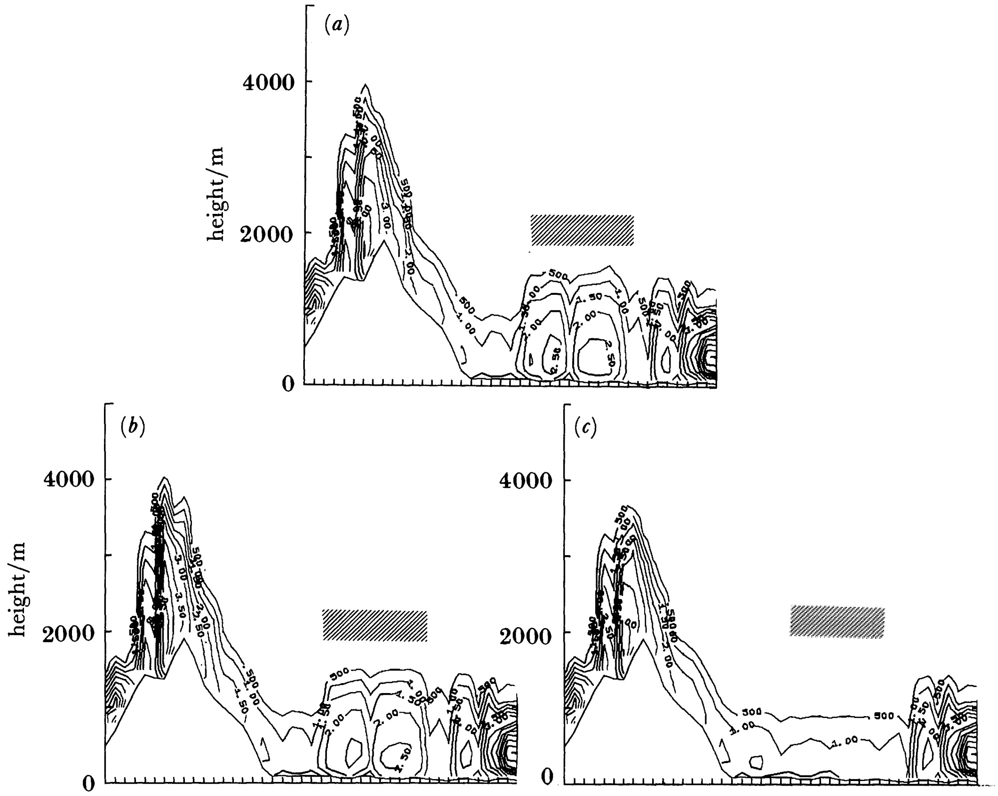


FIGURE 8. Same as figure 6, but for north–south cross section of eddy kinetic energy. Isolines are labelled in square metres per square second. The Pyrenees can be seen to the left, the location of the 'Landes' forest is shown by hatching.

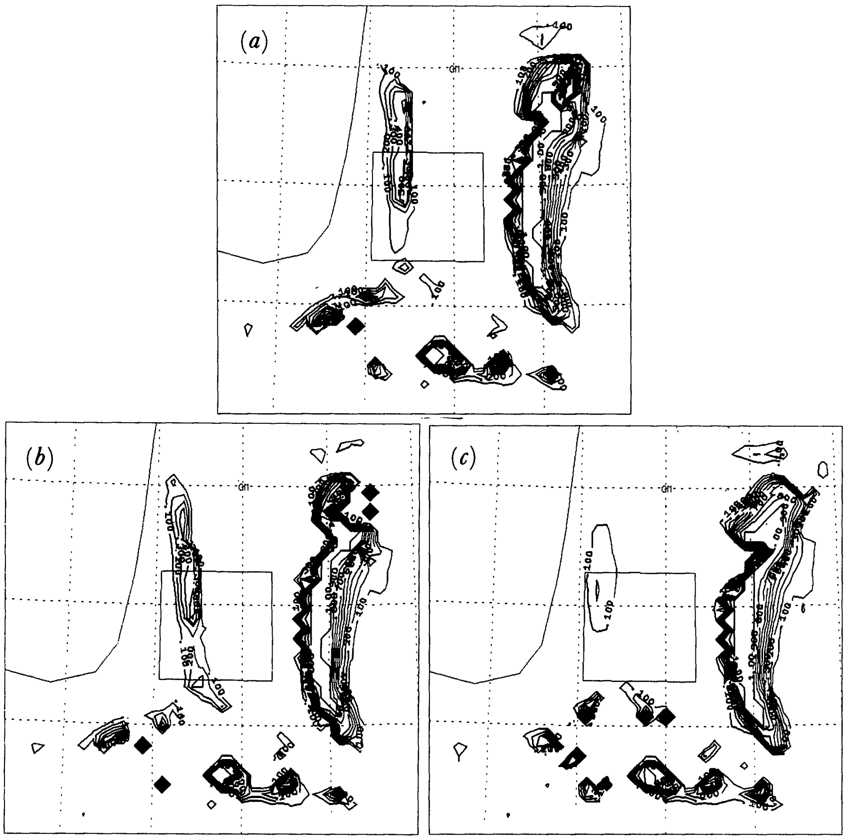


FIGURE 9. Same as figure 6, but for cloudiness.

5. Interception of rain by a forest, and resulting impact on downstream precipitation patterns

Bret & Bougeault's (1988) model is able to describe the cloud and rain formation, albeit rather crudely. Furthermore, Noilhan & Planton's (1989) vertical transfer scheme describes the interception of precipitation by canopy leaves, which is often significantly larger for forest than it is for agricultural crops. In the simulation experiments reported below, the interception reservoir depth was taken from Dickinson (1984) as $0.2 \times V \times L$ (in millimetres), where V is the fraction of soil surface covered by vegetation and L is the leaf area index. For the 'Landes' forest this corresponds to an interception store of 0.6 mm ($V \approx 1$ and $L \approx 3$), whereas it corresponds to 30% only of this value or less for nearby cereal crops ($V \approx 0.7$ and $L \approx 2$).

The reference simulation was done for 5 June 1986 and used, as above, initial and surface boundary conditions taken directly from the measurements and observations of the HAPEX-MOBILHY programme. On this day a cold front passed through the study area. This can be seen from figure 10 where the simulated rainfall pattern progresses from northwest to southeast, with a maximum precipitation intensity of about 4 mm h^{-1}, and the cooling of the air associated with this frontal passage was of the order of 1–2 K. The interception reservoirs of both the forest and adjacent agricultural canopies are filled to saturation (see figure 11 *a*) when

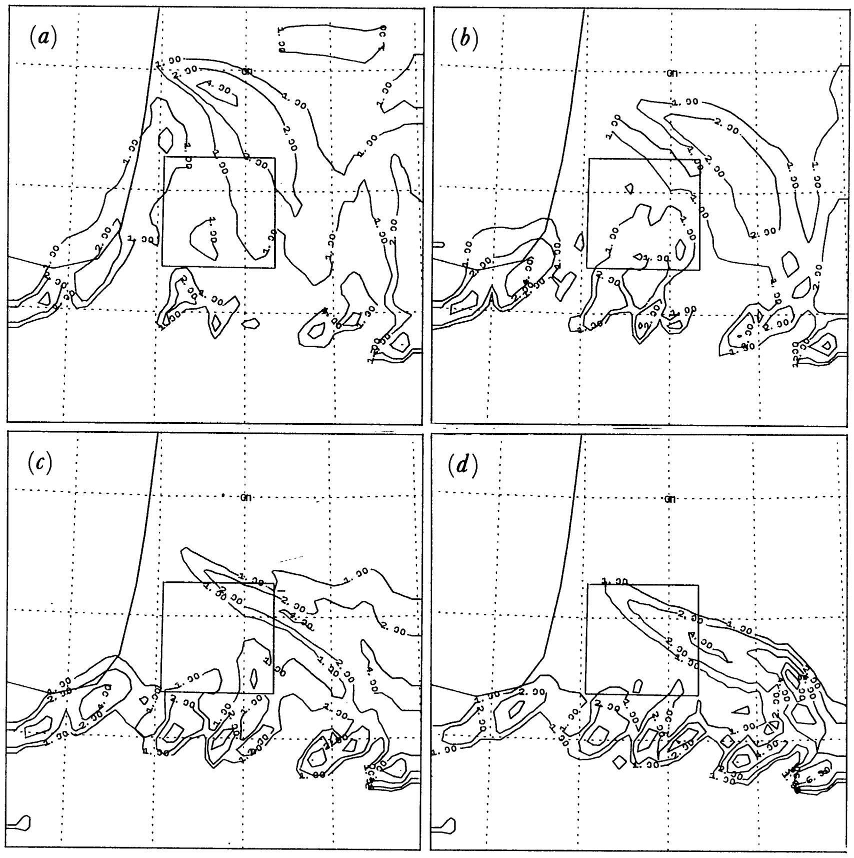


Figure 10. Modelled horizontal variations of precipitation intensity (isolines in millimetres per hour) for 5 June 1986, over southwest France: (*a*) 12h00 GMT; (*b*) 14h00 GMT; (*c*) 16h00 GMT; (*d*) 18h00 GMT.

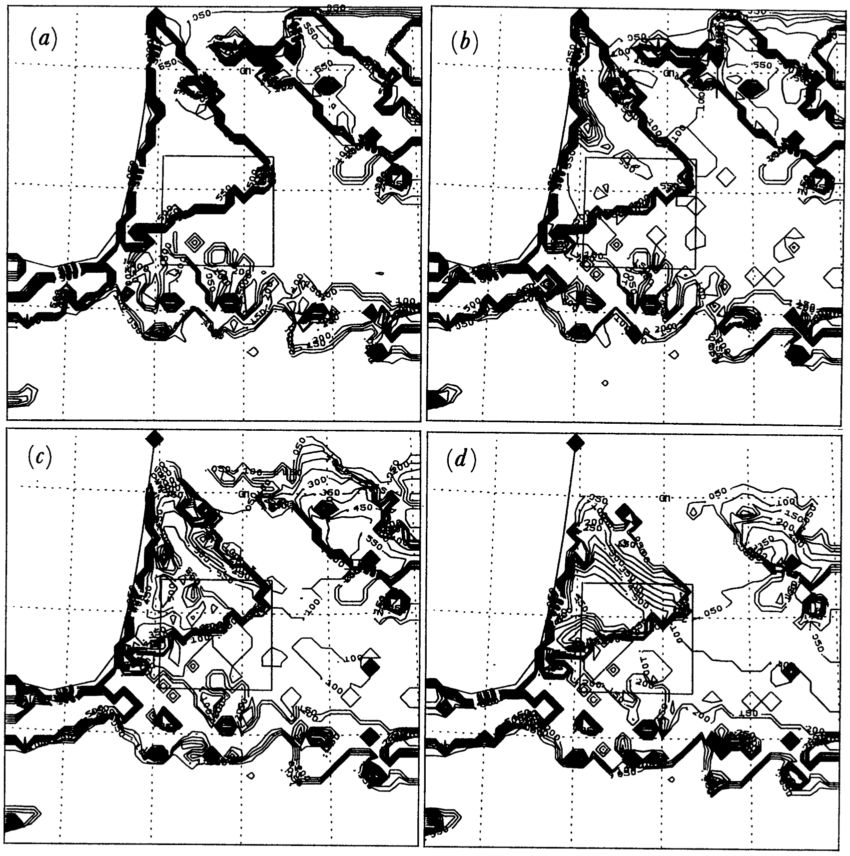


FIGURE 11. Same as figure 10 but for the amount of water intercepted by the canopy (isolines are labelled in millimetres).

the front passes, but the intercepted water rapidly re-evaporates as soon as clearings develop in the cold air-mass behind the front (see figure 11*b*–*d*). This leads to an enhanced latent heat flux over the forest (larger than 100 W m^{-2}) immediately behind the front (see figure 12*a*, *b*).

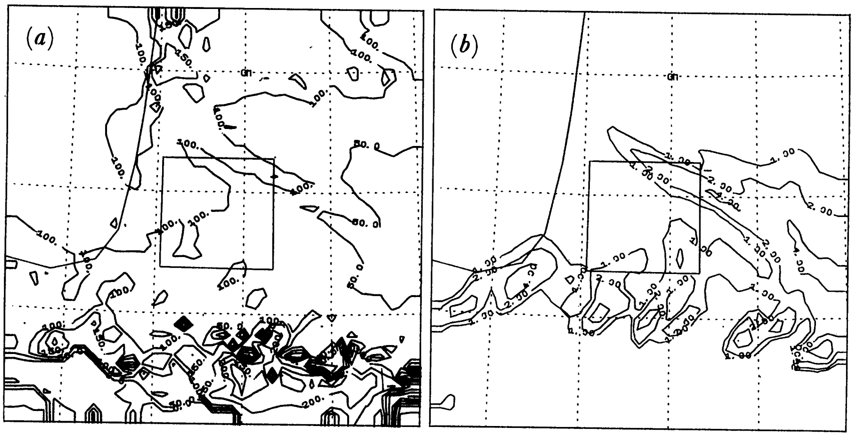


FIGURE 12. Modelled horizontal variations of (*a*) latent heat flux and (*b*) precipitation intensity for 5 June 1986, taking into account interception by vegetation; isolines are labelled in watts per square metre and millimetres per hour, respectively; (*b*) is the same as figure 10*c*.

Figure 13*a*, *b* shows, for the same day, the results of a sensitivity experiment in which no canopy interception of rain was allowed, but all other conditions and parameters remained unchanged. It can be clearly seen that the latent heat flux is significantly reduced, particularly over the forest. It can further be seen that the amount of precipitation falling behind the cold front is also noticeably decreased just downstream of the forest. This indicates that a significant part of the water that evaporates at one location is rapidly transformed into local precipitation at another. More rainfall interception by forests, therefore, leads then to enhanced downstream precipitation.

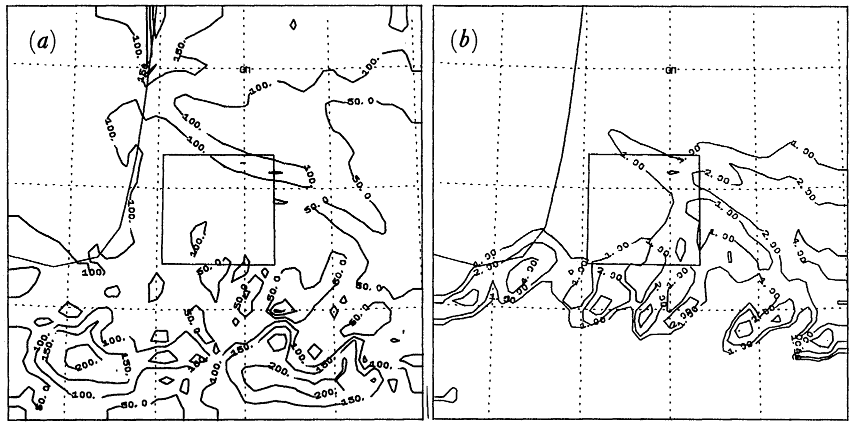


FIGURE 13. Same as figure 12, but when neglecting interception of precipitation by vegetation.

6. CONCLUSIONS

It has been shown, both from observations taken during the HAPEX-MOBILHY experiment and from numerical simulations using two different, meso-β-scale, three-dimensional models, that the impact of forest on mesoscale atmospheric circulation and local meteorology may be important.

Firstly, it is possible to observe the development of 'breeze' circulation over a forest whenever conditions are favourable, i.e. when there is enough available moisture in and around the forest, so that the evaporation rate from adjacent bare soil or agricultural crops or both is higher because of their lower minimal surface resistance. The forest canopy then transfers more sensible heat into the atmosphere than its surroundings, possibly leading to heat-island effects or breeze development or both at its edge if it covers a large enough area. This also has an impact on the development of cumulus convection, with a marked triggering of cloud convection over a forest during clear days.

It is also very likely that forests influence local precipitation patterns because their larger capacity for intercepting precipitation leads to more re-evaporation immediately after the passage of a cold front. Such effects can be detected at the mesoscale, but they are of more importance at global climate scales, as they provide a positive feedback mechanism for the interaction between the water cycle and the growth of vegetative canopies.

References

André, J. C., Goutorbe, J. P. & Perrier, A. 1986 HAPEX-MOBILHY: a hydrologic atmospheric experiment for the study of water budget and evaporation flux at the climatic scale. *Bull. Am. met. Soc.* **67**, 138–144.

André, J. C., Goutorbe, J. P., Perrier, A., Becker, F., Bessemoulin, P., Bougeault, P., Brunet, Y., Brutsaert, W., Carlson, T., Cuenca, R., Gash, J., Gelpe, J., Hildebrand, P., Lagouarde, J. P., Lloyd, C., Mahrt, L., Mascart, P., Mazaudier, C., Noilhan, J., Ottlé, C., Payen, M., Phulpin, T., Stull, R., Shuttleworth, J., Schmugge, T., Taconet, O., Tarrieu, C., Thépenier, R. M., Valencogne, C., Vidal-Madjar, D. & Weill, A. 1988 Evaporation over land-surfaces: first results from HAPEX-MOBILHY special observing period. *Annls Geophysicae* **6**, 477–492.

Anthes, R. A. 1984 Enhancement of convective precipitation by mesoscale variations in vegetative covering in semiarid regions. *J. Climate appl. Met.* **23**, 541–554.

Bret, B. & Bougeault, P. 1988 Simulation de quatre journées MOBILHY à l'aide du modèle PERIDOT. *Note travail EERM.* **211**, 1–90.

Charney, J. G. 1975 Dynamics of desert and drought in the Sahel. *Q. Jl R. met. Soc.* **101**, 193–202.

Deardorff, J. W. 1978 Efficient prediction of ground temperatures and moisture with inclusion of a layer of vegetation. *J. geophys. Res.* **83**, 1889–1903.

Dickinson, R. E. 1984 Modeling evapotranspiration for three-dimensional global climate models. In *Climate processes and climate sensitivity* (*Geophys. Monogr.* **29**) (ed. J. E. Hansen & T. Takahashi), pp. 58–72. Washington, D.C.: American Geophysical Union.

Gash, J., Shuttleworth, W. J., Lloyd, C. R., André, J. C., Goutorbe, J. P. & Gelpe, J. P. 1989 Micrometeorological measurements in Les Landes forest during HAPEX-MOBILHY. *Agric. Forest Met.* **44**, (In the press.).

Mercusot, C., Bougeault, P. & Durand, Y. 1986 Programme HAPEX-MOBILHY, atlas des données PERIDOT. Toulouse: Centre National de Recherches Météorologiques (internal report).

Nickerson, E. C., Richard, E., Rosset, R. & Smith, D. R. 1986 The numerical simulation of clouds, rain, and airflow over the Vosges and Black Forest mountains: a meso-β model with parameterized microphysics. *Mon. Weath. Rev.* **114**, 398–414.

Noilhan, J. & Planton, S. 1989 A simple parameterization of land-surface processes for meteorological models. *Mon. Weath. Rev.* **117**, (In the press.).

Orlanski, I. 1975 A rational subdivision of scales for atmospheric processes. *Bull. Am. met. Soc.* **56**, 527–530.

Phulpin, T., Jullien, J. P. & Lasselin, D. 1989 AVHRR data processing to study the surface canopies in temperate regions, first results of HAPEX. *Int. J. Remote Sens.* **10**, (In the press.).

Pielke, R. A. 1984 *Mesoscale meteorology modelling*. London: Academic Press.

Pinty, J. P. & Mascart, P. 1988 Evaluation d'un modèle d'interface sol/végétation/atmosphère à l'aide de données SAMER et Hydra de la campagne HAPEX-MOBILHY 1986. *Note OPGC* **96**.

Shukla, J. & Mintz, Y. 1982 Influence of land-surface evapotranspiration on the earth's climate. *Science, Wash.* **215**, 1498–1500.

Yeh, T. C., Wetherhald, R. T. & Manabe, S. 1984 The effect of soil-moisture on the short-term climate and hydrology change. A numerical experiment. *Mon. Weath. Rev.* **112**, 474–490.

Discussion

A. Henderson-Sellers (*Department of Geography, University of Liverpool, U.K.*). I have two questions about space and time scales. What was the spatial resolution of the three-dimensional model which Dr André used and has he considered undertaking integrations with coarser resolution versions? Also, how did he determine T_{air} and T_{surface} from satellite data, and from which satellite? Has he tried looking at the time evolution of these temperatures or the day-night temperature differences or both?

J.-C. André. The two atmospheric, three-dimensional models that have been used in this study have an horizontal grid size of 10 km. We have not yet done any simulation with coarser grids, although this would be of much interest.

Air temperature has been determined from a network of automatic weather stations, whereas surface temperature has been estimated from NOAA-AVHRR and METOEOSAT data. We have not yet looked at the relation between the time evolution of these temperatures and the partitioning of available energy into sensible and latent heat fluxes, depending upon moisture availability and canopy properties. This will be done in the near future, as it may indeed lead to a method for remotely sensing ground moisture from space.

P. G. Jarvis (*Department of Forestry and Natural Resources, University of Edinburgh, U.K.*). I would like to know a little bit about the forest at 'Les Landes'. I refer to Dr André's sensitivity experiment in which he reduced the stomatal resistance from 100 s m^{-1} to 40 s m^{-1}. The latter figure is quite typical as a minimum value for much unstressed forest in the U.K., although 100 s m^{-1} is more appropriate for Thetford. Is 'Les Landes' like Thetford? What is it like? What are the species, stocking rate age, height structure, etc.? Without some knowledge about this, it is difficult to judge whether 40 or 100 s m^{-1} is the more appropriate figure.

J.-C. André. The 'Landes' forest and its micrometeorological and hydrological characteristics have been quite extensively studied by J. Shuttleworth and his group at the NERC Institute of Hydrology, U.K. The value of 100 s m^{-1} taken here for the minimal stomatal resistance is consistent with their measurements. The 'Landes' forest is otherwise an artificial forest, planted approximately one century ago with pine trees over sandy, poorly drained, soil. The particular stand under study here has trees of about 20 m tall, with approximately 430 stems per hectare (*Pinus pinaster* Aiton), and an understorey of bracken (*Pteridium aquilinum*(L.) Kuhn).

P. G. Jarvis. In the two-dimensional model simulation early in Dr André's talk, he showed changes at a vegetation boundary at distances of ±50 and 100 km. Over these distances, steady conditions did not result. Forests in Europe are generally not more than about 10 km across. If steady conditions are not obtained over 50 km, how useful is his approach with respect to forests 10 km across?

J.-C. André. The main outcome of the idealized numerical study Professor Jarvis is referring to, is simply to show that atmospheric mesoscale circulations respond to land-surface variations with horizontal scales of at least 10 km. This, of course, does not mean that the atmospheric response is always stationary. It simply indicates, on the contrary, the horizontal variations in land-surface properties at scales smaller than *ca.* 10 km do not contribute to mesoscale flow variations, but only to the determination of area-averaged surface heat fluxes.

W. Kohsiek (*Koninklijk Nederlands Meteorologisch Instituut, De Bilt, The Nederlands*). How are net radiation and precipitation calculated in the model?

J.-C. André. Net radiation is computed numerically from a transfer model for both solar and infrared radiation, using predicted humidity and temperature profiles as well as modelled cloudiness.

Precipitation is computed by the usual method, i.e. transferring downward liquid water whenever the water vapour mixing ratio exceeds its saturation value at a given level, and re-evaporating it or transferring it further downwards according to the temperature and relative humidity at the next lower level.

J. R. Milford (*Department of Meteorology, University of Reading, U.K.*). Dr André showed that the 'forest breeze' effect produces a mean ascent of warm air over some tens of kilometres, and the sensible heat transfer by this mechanism may be tens of watts per square metre: is this a significant effect within the model? Also, in the presence of a mean wind a similar transfer by mean flow is found in the region of convergence because of increased roughness: does this produce a detectable effect near the leading edge of a large forest?

J.-C. **André**. The ascending velocity cell, which develops over the transition region between the forest and nearby agricultural crops, does indeed contribute significantly to the vertical transfer of heat. Furthermore, additional production of eddy kinetic energy by the shear associated with the development of the forest-breeze circulation notably enhances convection over the transition region. This last effect appears to be much more significant for convection triggering than convergence associated with variations in surface roughness, at least for the particular case we considered here.

J. I. L. **Morison** (*Department of Meteorology, University of Reading, U.K.*). Dr André suggested that for the three-dimensional model a mosaic of six land types was used. Presumably, each of these has to be assigned characteristic values of canopy or surface resistance. Surely the practical problem is in estimating these values over the whole regions involved?

J.-C. **André**. Dr Morison is right: we had to rely on some pre-prescribed correspondence between vegetation type, as estimated from the normalized difference vegetation index (NDVI), and properties such as roughness length and minimal stomatal resistance. This is, of course, not an unambiguous way to proceed.

P. **Rowntree** (*Meteorological Office, Bracknell, U.K.*). Analysis of the Penman–Monteith equation shows that the sensitivity of the partitioning of the available energy between evaporation and sensible heat flux to r_A (the atmospheric resistance) depends, to a considerable extent, on the surface resistance, the available energy, the temperature, and the vapour-pressure deficit. Even the sign of the variation with r_A can change with variations in these quantities, and conditions exist in which there is no dependence on r_A. Is it possible that the modification of r_A in the experiment was for such conditions of relatively little or no sensitivity?

J.-C. **André**. The results that are shown here correspond to a given set of surface parameters, and in this case there is a clear effect upon partitioning of energy available at the surface. We have not explored all the parameter-space, and there are other values of surface parameters that would lead to different conclusions.

D. A. **Warrilow** (*Meteorological Office, Bracknell, U.K.*). 1. Did Dr André observe a significant modification in the low-level wind flow in his three-dimensional model experiments?

2. Is there any evidence of spatial variations in, say, rainfall statistics because of the land surface variations?

J.-C. **André**. 1. There is, of course, some modification of the low-level wind pattern associated with variations in surface roughness when passing from agricultural crops to the forested area. For the few cases we have studied up to now, such modifications were, however, of much less importance than the ones associated with the observed synoptic variability.

2. Although there may be some influence of land-surface variations upon spatial patterns of rainfall, the statistical studies we have done show only the importance of three factors: proximity of the Pyrenees mountains to the south, proximity of the Atlantic ocean to the west, and of the type of synoptic situation. The first two factors are, of course, specific to the particular region under study, i.e. southwestern France.

W. J. **Shuttleworth** (*NERC Institute of Hydrology, Wallingford, U.K.*). I should like to comment on the relevance of length scale in the organization of variability in surface vegetation, and its influence on the mesoscale meteorological processes described by both Dr André and Dr de Bruin.

I think something of considerable significance may well have been learned in the course of HAPEX, which could be important to our understanding of how to aggregate the surface hydrology of variable land surface cover to the area scale of interest in climate models. It can be noticed that the forest breeze effect, described by Dr André, requires change from agricultural land to forest organized at the scale of tens of kilometres. At scales less than this, the planetary boundary layer is not able to respond to changes in surface vegetation cover in an organized way and, in effect, acts as an efficient averaging mechanism. At larger scales an organized response can occur which may well be such as to modify, usually mitigate, the consequences of surface variations. In the case studied, the forest preferentially generates cloud, which acts to reduce the enhanced radiation capture that, in part, created it.

Recently, Shuttleworth (1988) suggested that it may prove useful to classify land surfaces according to the organization in their surface cover see figure d 1. Type A surfaces correspond to land cover that is disorganized at scales of 10 km or less; these are most common and probably require the simpler aggregation procedure, perhaps a simple weighted average. Type B surfaces are more complex and in this case it will, I think, be necessary to use mesoscale meteorological models to investigate the numerical significance of the mitigation given by the organized mesoscale response in the turbulent boundary layer.

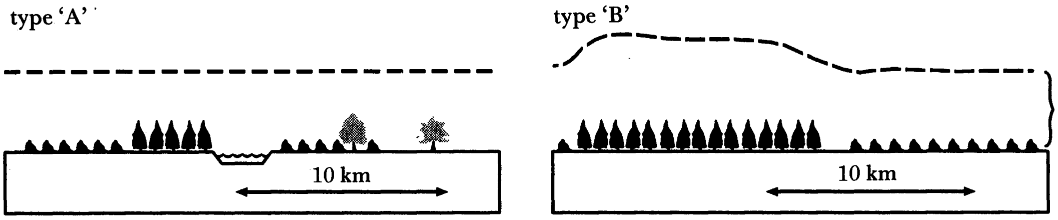


Figure d 1. Types of land surface classified according to the organization in the variability of their surface cover. Type 'A' land surfaces are disorganized at length scales of 10 km or less and give no apparent organized response in the planetary boundary layer: type 'B' are organized at scales larger than 10 km and may give an organized response such as to moderate the effective variability in surface parameters.

Reference

Shuttleworth, W. J. 1988 Macrohydrology: the new challenge for process hydrology. *J. Hydrol.* **100**, 31–56.