Sensing the forest: a micro-meteorological study

by Fred Bosveld

Introduction • Entering a forest is always a special experience for a meteorologist. Forests form one of the few canopies of which the interior can be entered and experienced without special instruments. Wind speeds and radiation levels are lower than in the open field. And, when listening carefully, the development of wind gusts into the forest canopy can be followed by ear. Geiger was one of the pioneering forest meteorologists [1]. He showed that the actual microclimate depends on the density of a forest. In general the air in the interior of the forest is cooler and more humid than aloft during daytime. This effect is more pronounced for a dense forest. Although the large size of trees compared to other vegetation types is not a principle difference, the influence of forest on atmospheric and hydrological processes differs substantially from the influence of low vegetation. Most notable forest characteristics are a low albedo, a large rainfall interception reservoir and high aerodynamic roughness [2].

As an example, Figure 1 shows typical measurements of the components of the energy balance for a grassland site (Cabauw, the Netherlands) and a Douglas fir forest (Garderen, the Netherlands) for the same clear day (May 21, 1989). The figure shows that for the same short wave downward radiation (SWD), higher net radiation (QN) occurs at the forest site. This is related to the difference in albedo, 0.11 for the forest and 0.23 for the grassland site. But also, daytime surface temperatures (not shown here) are much lower for the forest site, due to the high roughness of the forest, leading to a smaller upward long wave radiation as compared to the grassland site. Transpiration rates (LHF) are very different. At the grassland site transpiration is so high that the afternoon change of sign of the sensible heat flux (SHF) occurs 3 hours earlier than at the forest site. The diurnal variation of the storage heat flux (G) is much larger at the forest site due to the significant amount of standing biomass. The large difference in sensible heat flux between the sites suggests that the atmospheric boundary-layer height will be higher over forest than over low vegetation.

Air-pollution and the Dutch forests • Concern for the hazardous effect of air-pollution on natural ecosystems in industrialised countries has initiated much research over the last decades. In the Netherlands this concern resulted, among others, in the Dutch Priority Program on Acidification. As part of this program the ACIFORN project (Acidification research on Douglas fir Forest in the Netherlands) aimed at assessing the impact of air pollution on tree vitality. The experimental part of this project culminated in a co-ordinated experimental effort in 1989 by a number of Dutch institutes at the Speulderbos research location, near the village of Garderen, the Netherlands. The experimental site was a Douglas-fir stand *(Pseudotsuga menziesii)* situated in an extended forested area. The co-operating institutes were the Agricultural University of Wageningen (air-pollution concentration, root density), the Research Institute for Forestry and Urban Ecology, Wageningen (bio-geometry), University of Amsterdam, Environmental Sciences (hydrology), University of Leiden, State Herbarium (bio-geometry), TNO Delft (Ammonia concentrations), KEMA Arnhem (tree sapflow) and KNMI De Bilt (micro-meteorology). After this period more experiments have been performed on this location. Among others the Speulderbos site has been one of the two landsurface stations for the KNMI Tropospheric Energy Budget Experiment (TEBEX). Since the beginning of the 1990's the site is managed by the Netherlands Institute for Public Health and the Environment (RIVM) and is part of their air-pollution monitoring network.

To study the impact of air pollution on tree vitality one has to estimate the amount of air pollution that is deposited onto the forest. For many air pollution components no direct flux measurement methods are available since these require fast response concentration measurements to apply the so-called eddy-covariance method. However, vertical concentration differences can be measured for many species with high accuracy. To apply this type of measurements the relation between the vertical concentration difference and the vertical flux close to the forest has to be known. For low vegetation well established relations for the turbulent transport resistance exists which hold well away from the surface. Theoretical and experimental studies suggest that by taking the low vegetation relations as a reference, a decreased resistance occurs in the air layer just above forests (typically lower then a few times the vegetation height). By lack of a good theory about the relation between forest geometrical parameters and this decreased resistance it appeared to be necessary to determine the turbulent transport resistance over the Douglas fir forest experimentally. To this end the transport properties for heat were derived on the basis of direct turbulent flux measurements and accurate temperature

Discovering the forest

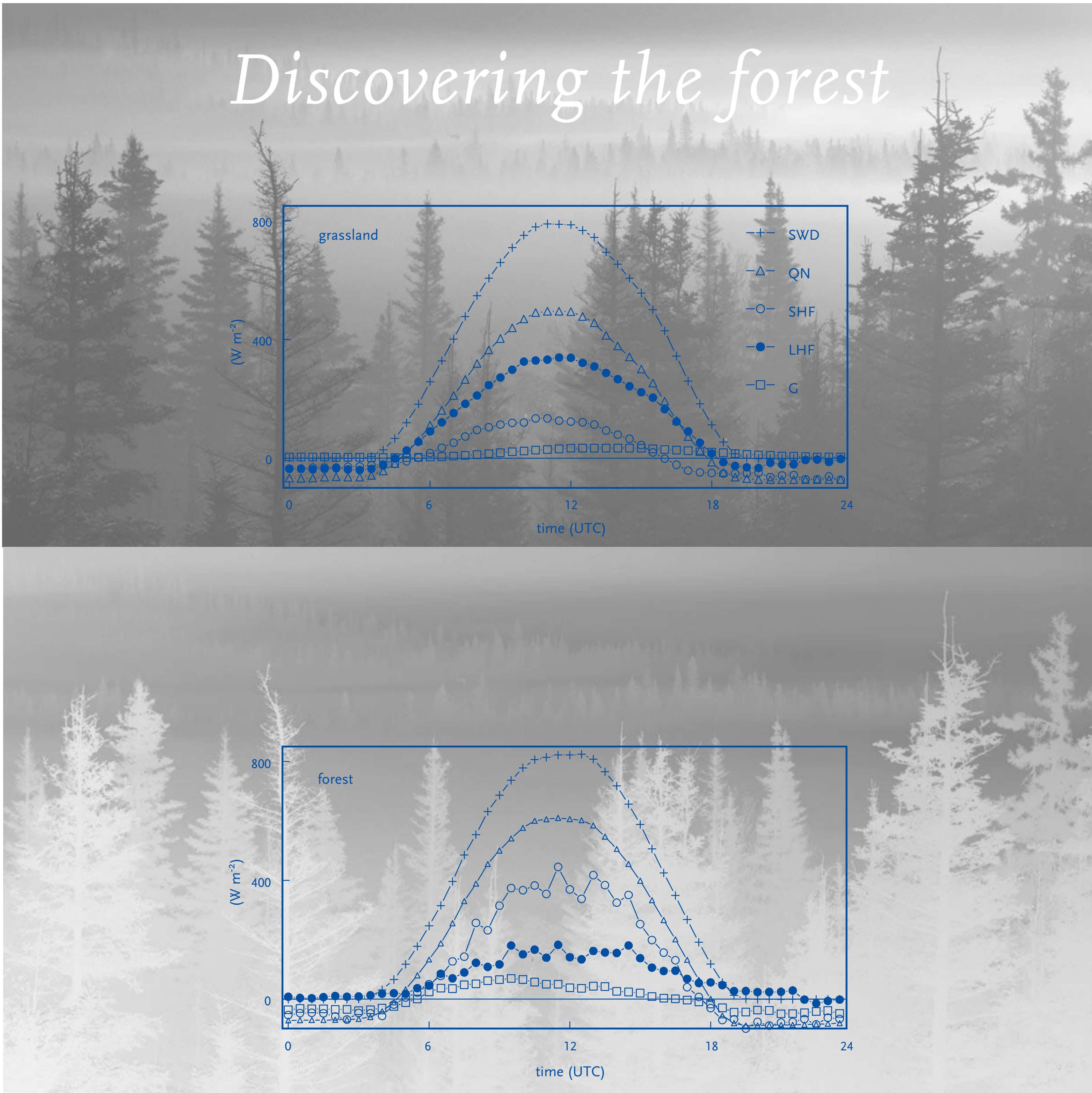

Figure 1. Surface fluxes of short wave incoming radiation (SWD), net radiation (QN), sensible heat flux (SHF), latent heat flux (LHF) and storage heat flux (G) for a forest and a grassland site for the same day.

difference measurements [3]. Figure 2 shows the decreased transport resistance (again relative to the low vegetation value) as function of height (scaled on the vegetation height) for the Douglas-fir forest (full circles). Also shown are the results for a number of other forest studies. In general the transport resistance approaches the low vegetation value above approximately two times the forest height and decreases when going down to the forest. However, the differences between forests are large, partly related to the density and other geometrical characteristics of the forests. Having established the site specific exchange coefficients the observed air pollution concentration gradients could be interpreted in terms of deposition fluxes. The results of the deposition estimates produced within the ACIFORN project has played an important role in the national debate about air-pollution reduction measures.

Forests in weather and climate • The Earth's surface forms the lower boundary condition of the atmosphere. As such it strongly modulates the internal dynamics of the atmosphere. The distribution of land and sea and the location of mountain ridges are of importance for the large-scale variations in weather and climate, as is the distribution of sea surface temperature. But also land surface types and their variation over the globe have an important impact on global and regional climates. Forests form one of the important ecosystems of the Earth's land surface.

Predicted climates are sensitive to the model treatment of surface albedo, soil water availability, surface roughness and stomatal control [4]. Feedbacks on the diurnal scale occur through the coupling between evapotranspiration on one hand and boundary-layer development and boundary-layer cloud formation on the other hand [5]. On the seasonal scale the coupling of soil water availability with atmospheric precipitation is important [6]. At still longer time scales, changes in vegetation cover are to be considered. For weather prediction in the short range (3 days) the impact of land-surface cover is less important due to the process of continuous assimilation of observations. However, a correct representation of surface processes is still of great importance for the translation of large-scale weather characteristics to phenomena close to the surface, where most human activities takes place.

Comprehensive observational data sets of surface fluxes of precipitation, radiation, sensible and latent heat and momentum covering at least one hydrological year, can contribute significantly to the evaluation of climate and weather models. But also process studies can shed light on deficiencies in the model formulation. For the Speulderbos a data set is available which can be used to evaluate land surface models. The time series are made continuous with an intelligent time gap-filling procedure [7]. As an example of a process study we discuss the results on evaporation and transpiration and their interaction for the Speulderbos site.

Transpiration is the loss of water through the stomata of the tree leaves. For dry days this is the dominating process of water loss from the

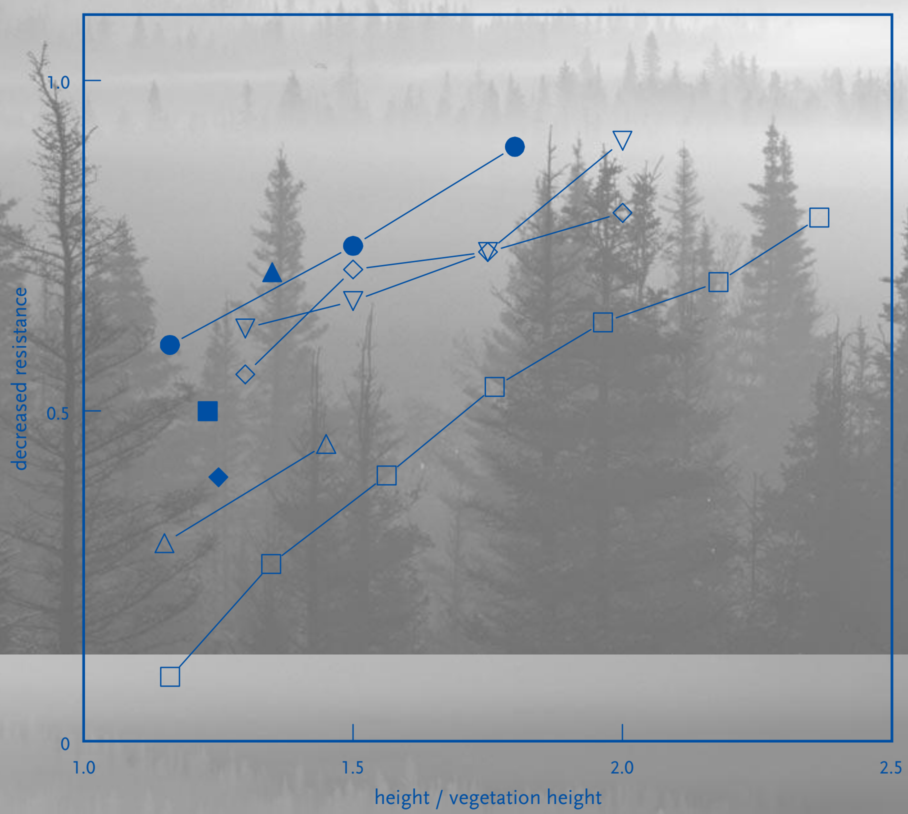

Figure 2. Decreased transport resistance for Speulderbos (full circles) and various other forests as function of height scaled on vegetation height.

forest. The magnitude of transpiration is determined by the atmospheric conditions (available energy, temperature, humidity and wind speed) and by the control of the trees on the stomatal aperture. This control itself is a feedback on atmospheric conditions and on the soil water conditions. In the 1960's a concept was developed to separate the atmospheric influence from the vegetation influence by the introduction of the surface conductance for water vapour. From this concept the so-called Penman-Monteith equation was derived [8)]. This concept was applied to the Speulderbos forest observations [9)]. Figure 3 shows the observed surface conductance (based on eddy covariance transpiration rates) for water vapour as a function of specific water vapour deficit (a measure for the dryness of the air). There is a dramatic decrease of conductance with increasing dryness. For this forest the control is so strong that it fully counteracts the atmospheric influence of increased drying power of dryer air. The figure also shows that with increasing short wave downward radiation (SWD) the conductance increases. This is a well known effect that is related to the need of a plant to take up more carbon-dioxide through the stomata when assimilation potential is high at high irradiation levels.

The forest control fully counteracts the atmospheric influence of dryer air

During rainy episodes the crown layer of the forest intercepts part of the precipitation. This intercepted water is then evaporated back into the atmosphere. Trees have no control over this process; it is almost fully regulated by the atmospheric conditions. Interception amounts are especially high in maritime climates where the yearly rain amounts fall with relatively low intensities spread over the whole year. The other determining factor for interception loss is the evaporation rate itself. This determines how quick the canopy dries out and how precipitation is partitioned between drainage and the evaporation of intercepted water. By using a novel technique based on microwave attenuation, Bouten from the University of Amsterdam was able to measure the interception process in great detail [10)]. Due to the energy consumption by the evaporation process and due to the blocking of stomata by free liquid water on the needles the transpiration rate is suppressed. With the so-called heat pulse velocity technique long time series of the sapflow velocity in the trunks of trees were obtained. This sapflow velocity is a measure for the transpiration rate. However, due to storage of sap in the tissue between the trunk and the crown of the tree the two may differ in timing. The combination of measurements enabled us to distinguish transpiration from evaporation during wet conditions [9)]. The Penman-Monteith equation was extended to describe both processes and their interaction. Figure 4 shows for one day observed evaporation (microwave attenuation) and transpiration rates (sapflow),

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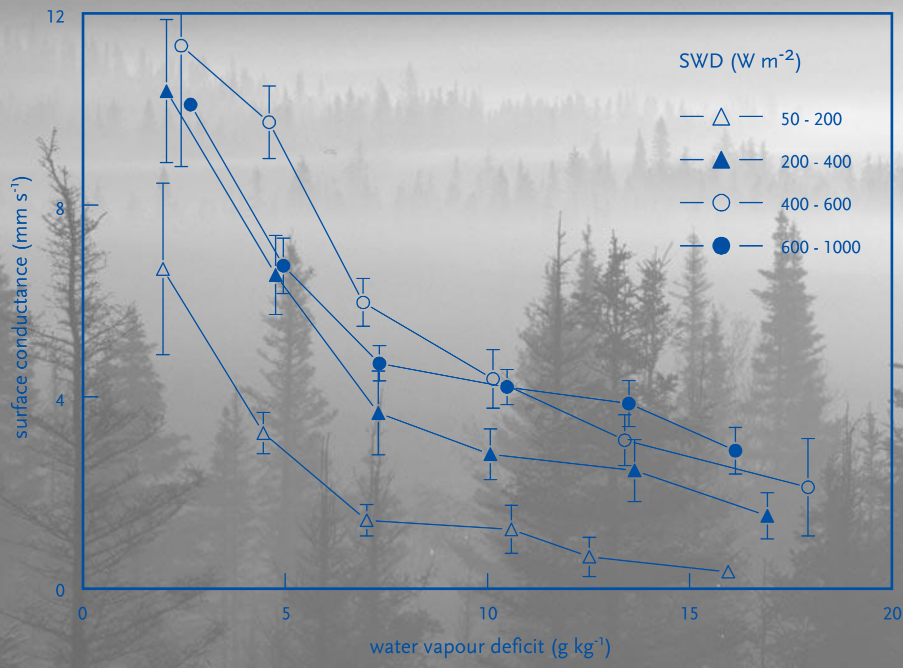

Figure 3. Observed forest surface conductance as a function of water vapour deficit, stratified into classes of short wave downward radiation (SWD).

Figure 4. Evaporation (Evap) and transpiration (Trans) both observed (obs) and modelled (mod) for one day with a drying episode. Also shown is the reference transpiration for dry days (Trans(ref)). The sapflow (Trans(obs)) deviates at night.

the forest

together with the modelled values based on the observed meteorological conditions. The transpiration reference line shows the model transpiration that would occur with the same atmospheric conditions when the canopy would have been dry. In the morning a clear transpiration reduction is observed. The deviation in the late afternoon is related to the difference in timing between sapflow and transpiration

Forests and satellite based remote sensing • With the advent of satellite based observational systems, global observations of the Earth's surface become available. Characterisations of various parameters related to land surface type can be obtained on a global scale by using radiance observations. Although still hampered by various problems, (atmospheric transmission, cloud detection, linking observed parameters to canopy parameters) satellite based observations seems to be the way forward to improve on describing the lower boundary condition of the atmosphere quantitatively on a global scale. Ground-based observations are essential to interpret these remote sensing data.

The surface radiation-temperature plays an important role in the surface energy budget and it is one of the important surface parameters that can be observed from satellite-based observational systems. The temperature difference between the surface and the atmosphere is related to the partitioning of the available energy into its components. Various methods to estimate the evapo-transpiration from observations of infrared radiation temperature are investigated [11)]. For a good interpretation of these observations, we need a thorough understanding of the various processes that determine the surface temperature.

During daytime the surface radiation temperature for the Speulderbos forest appeared to behave in a predictable way. Given the atmospheric conditions and the forest geometrical characteristics the surface radiation temperature could be predicted by extrapolating the atmospheric temperature profile to the forest crown layer [12)]. However, when turning to night-time conditions, at times unexpected behaviour was found. Deviation from theory occurred during low wind and clear sky conditions [13)]. These are

Deviation from theory occurred during low wind and clear sky conditions

typical conditions for canopy convection to occur as already described by Geiger in the 1930's. Figure 5 shows for two nights potential temperature differences relative to the temperature at 24 m height. The temperatures indices are (i) interior of the forest (4 m) and (c) crown radiation. The left panel is a high wind speed case and it is observed that the interior temperature is close to the air temperature aloft, whereas the crown radiation temperature is somewhat lower due to long-wave cooling of the crowns. The right panel is a low wind

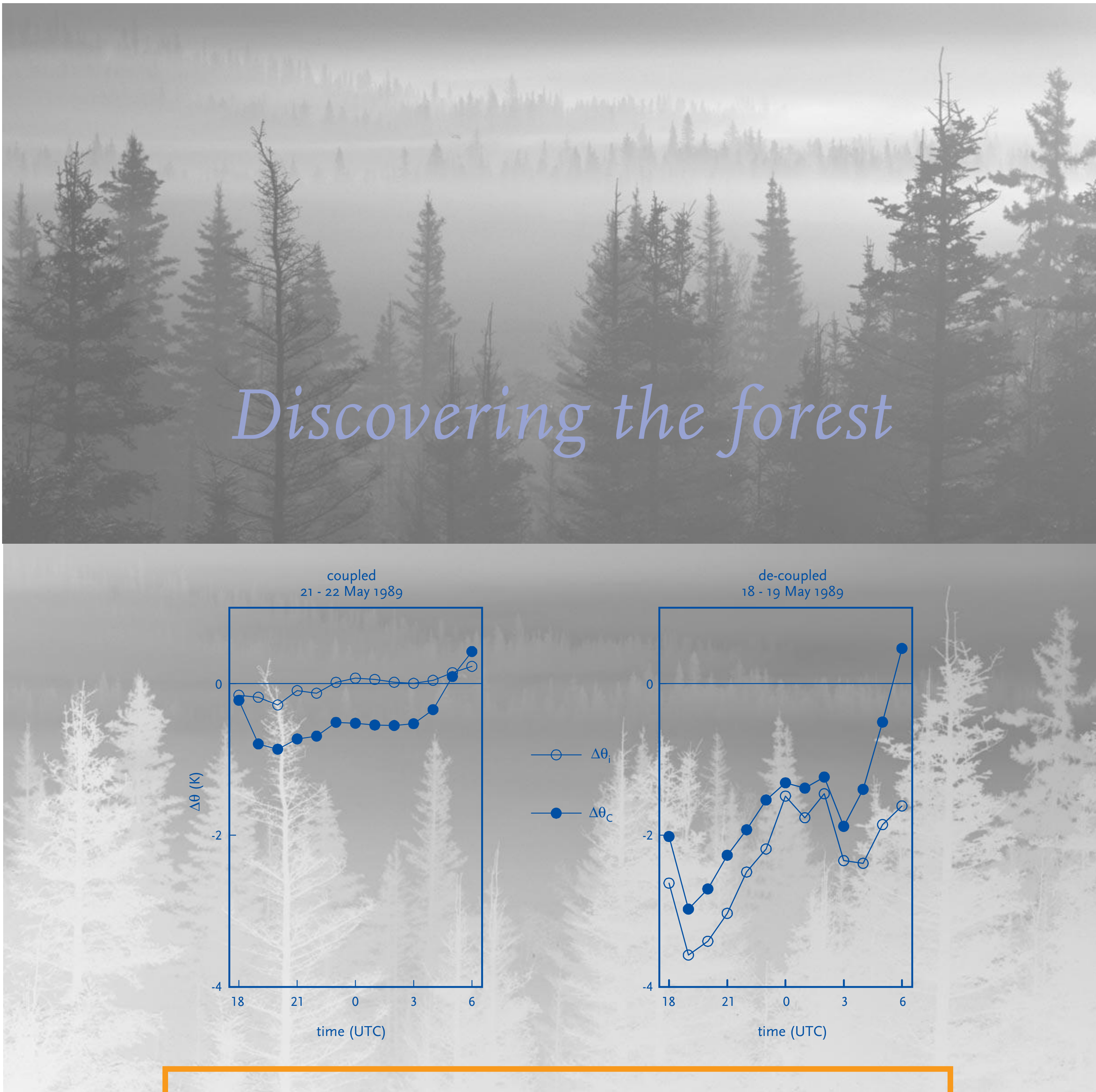

Figure 5. Observed potential temperature differences relative to the 24-m level, for two clear nights. Left panel - high wind speeds (coupled case). Right panel - low wind speeds (de-coupled case). (i) in forest interior and (C) crown radiation temperature.

speed case although later in the night wind speed increases. Here we see that the interior temperature follows the crown radiation temperature. This shows that at high wind speeds the interior temperature is coupled to the air temperature above the forest. At low wind speeds and clear sky conditions both the interior temperature and the crown radiation temperature are decoupled from the temperature above the forest. Due to long wave cooling, we would expect for the decoupled case the crown temperature to be lower than the interior temperature. In reality the crown radiation temperature is a mixture of temperatures along the depth of the crowns. In low wind conditions the temperature in this layer increases with height and the mean crown temperature is higher then the minimum temperature in the deeper layer. When correcting for this effect a well defined relation was found between the amount of storage heat transported through the air in the forest interior to the crown layer and the difference between the crown temperature and the forest interior temperature. This relation appeared to be of the same form as the relation between vertical temperature differences and transported heat in the convective atmospheric boundary-layer. These studies show that the interpretation of satellite-based infrared surface radiation observations of forests can be quite complex especially during night time.

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Probably, the Speulderbos forest site is the best investigated forest in the Netherlands. Thanks to the co-operation of many national institutes at one forest site many interdisciplinary studies could be performed related to forest growth, air pollution, hydrology and meteorology. The data sets and research results have found their way into both the scientific and the policy maker's communities. The estimates of air pollution loads have played an important role in the political debate on air-pollution regulations. Recently the data have been used, among other data sets, in the evaluation of the new land surface module of the model of the European Centre for Medium-Range Weather Forecasts (ECMWF). At the moment the data are used to evaluate a satellite-based method for deriving evapo-transpiration maps.

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