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Advancing understanding of land–atmosphere interactions by breaking discipline and scale barriers

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Abstract

Vegetation and atmosphere processes are coupled through a myriad of interactions linking plant transpiration, carbon dioxide assimilation, turbulent transport of moisture, heat and atmospheric constituents, aerosol formation, moist convection, and precipitation. Advances in our understanding are hampered by discipline barriers and challenges in understanding the role of small spatiotemporal scales. In this perspective, we propose to study the atmosphere–ecosystem interaction as a continuum by integrating leaf to regional scales (multiscale) and integrating biochemical and physical processes (multiprocesses). The challenges ahead are (1) How do clouds and canopies affect the transferring and in-canopy penetration of radiation, thereby impacting photosynthesis and biogenic chemical transformations? (2) How is the radiative energy spatially distributed and converted into turbulent fluxes of heat, moisture, carbon, and reactive compounds? (3) How do local (leaf-canopy-clouds, 1 m to kilometers) biochemical and physical processes interact with regional meteorology and atmospheric composition (kilometers to 100 km)? (4) How can we integrate the feedbacks between cloud radiative effects and plant physiology to reduce uncertainties in our climate projections driven by regional warming and enhanced carbon dioxide levels? Our methodology integrates fine-scale explicit simulations with new observational techniques to determine the role of unresolved small-scale spatiotemporal processes in weather and climate models.

KEYWORDS
clouds, land–atmosphere interactions, leaf to regional, photosynthesis

INTRODUCTION

Ecosystems are undergoing large transformations due to anthropogenic activities that have led to drastic changes in the land,[1] weather,[2] climate,[3] and atmospheric composition.[4] The changes are having dramatic effects on sensitive regions, such as the Amazonia basin.[5] Climate modifications are specifically inducing changes in the hydrological cycle,[6,7] in which the coupling between vegetation, evapotranspiration, and clouds plays a prominent role.[8] Owing to the many stabilizing feedbacks between vegetation, evapotranspiration, and clouds, ongoing changes in the climate and land surface may lead to unexpected and transformative changes. These changes could have a profound impact on clouds and atmospheric circulation[9] and the role of ecosystems as sources and sinks of greenhouse gases.[1]

Currently, these effects are difficult to quantify specifically because observations and models do not reflect the relevant processes in enough details to capture all potential feedbacks. In this article, we will focus on two interrelated phenomena that are poorly understood and hard to quantify: the coupling across scales (leaf-canopy) between transpiration and photosynthesis occurring under various ecosystem conditions[10] and the relationships to cloud variations on space and time[11] . For both phenomena, the atmosphere integrates biochemical and physical processes occurring at a wide range of spatiotemporal scales and we must interrelate knowledge from the disciplines of atmospheric and plant sciences to fully unravel all potential feedbacks in the coupled vegetation-atmosphere system. Until now, the separation between disciplines has hampered the interconnection between the vegetation dynamics regulating CO_2 and transpiration on the one hand and the influence of atmospheric dynamics (including cloud feedback) on these vegetation dynamics on the other hand.

The current generation of weather and climate models does include many process representations and feedbacks between the vegetation, hydrological cycle, and atmosphere.[12] However, their spatiotemporal resolution as well as process description, for instance, the diurnal cycle of state meteorological and atmospheric composition variables, are insufficient to fully capture the detailed feedbacks between vegetation and clouds that drive meteorological processes.[2,8,12] Therefore, we believe that special attention needs to be placed on how the local dynamic interactions between leaf, canopy, and clouds lead to a large temporal and spatial variability in the photosynthesis rate.[13] As a result, the regional partitioning and properties of the surface turbulent fluxes will result in changes that yield modifications in the cycling and organization of clouds. Advancing understanding and improving on the parameterizations could lead to a reduction in the large uncertainties in the projections of cloud feedback and terrestrial CO_2 uptake under climate modification conditions.[8] Therefore, we argue that by integrating all these small spatiotemporal processes, including the combined effects of the impact of clouds and CO_2 assimilation at the regional level, we could assess how the atmosphere-ecosystem is modified by current and future climates.

To illustrate how processes interact across scales, Figure 1 shows a common transition from ocean to land whereby cloud formation and intensification predominantly occurs over the vegetated land surface. This clear-to-cloud transition is shown for climate-sensitive forest ecosystems in (sub)tropical, temperate, and boreal climates.[14] Although the transitions are visually similar among these forest ecosystems, there are significant differences in terms of species and plant type as well as the magnitude and seasonality of the energy input and available soil water. Also, the synoptic and mesoscale atmospheric patterns differ largely as a function of latitude and seasonality. As illustrated in Figure 1, cloud properties are continuously modified and shaped due to ongoing interactions with vegetation when developing over land. These interactions depend on the surface exchange fluxes and partitioning of water and energy as well as on boundary layer dynamics connected to radiation perturbation by clouds and on canopy roughness via its effects on wind shear and turbulence.[15] In all these ecosystems, horizontal gradients and vertical contrasts between the land, canopy, atmosphere, and clouds play a key role in controlling precipitation[16] and carbon dioxide uptake by vegetation at regional scales.[4] With this in mind, we offer a way to integrate these processes at the meteorologically relevant spatiotemporal scales using current

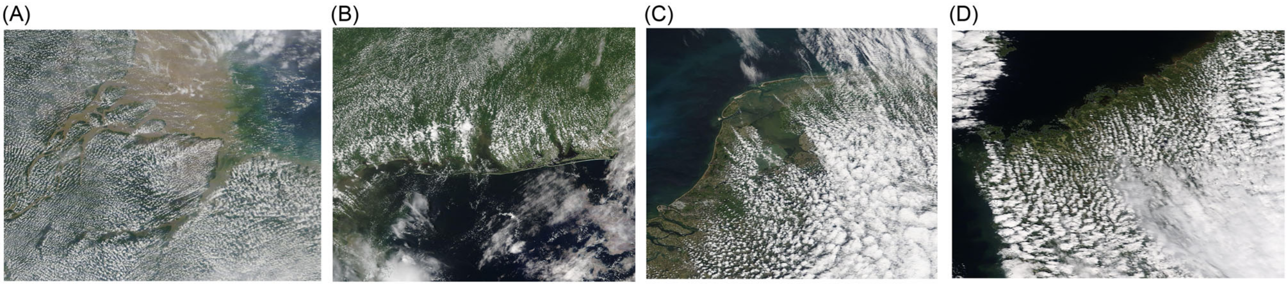

FIGURE 1 (A) Rainforest (Amazonian basin), (B) subtropical (Southeast USA), (C) temperate (The Netherlands), and (D) boreal (Finland) ecosystems interacting with shallow cumulus cloud fields in transit to deep convection. Wind is blowing perpendicular to the coast and the scale of the transition from shallow to deep convection is $\sim$ 100 km.

advances in observations and simulation techniques. We introduce this by presenting four challenges:

1. How are photosynthesis and photolysis influenced by the disturbances of radiation due to the presence of clouds and due to the transference inside the canopy?
2. How is atmospheric composition (greenhouse gases and reactive species) impacted by turbulent transport, mixing, convection, weather variables (temperature, moisture, and wind), and reactivity?
3. How do physical, chemical, and biological processes interact between local and regional scales, and at different time scales?
4. How does climate change, in terms of enhancement of carbon dioxide and warming, lead to changes in cloud and plant physiology feedback?

The first challenge focuses on radiation as a primary source of energy, where clouds[17–19] and canopies[20,21] modify the transfer of incoming shortwave radiation, and therefore, the distribution between the direct and diffuse radiation. Small-scale and short-term variability in the partitioning between direct and diffuse radiation leads to large fluctuations in the photosynthesis rate and stomatal aperture that cannot be captured without considering these processes at high spatiotemporal resolution. Clouds also modulate the temperature and the water vapor pressure deficit (VPD) in and above the canopy.[22] This results in relationships between radiation, temperature, and moisture[23] that regulate photosynthesis and transpiration of plants, which, in turn, governs the surface energy distribution over land.[24] These relationships continuously change over time and space, and are regionally dependent. Considering atmospheric factors driven by weather and a changing climate, current efforts focus on developing consistent and reliable theories to calculate photosynthesis and plant hydraulics[25] that will need to be integrated and evaluated in weather and climate models.

The second challenge focuses on connecting atmospheric turbulence to biochemistry processes at the surface. The former is governed by wind and thermodynamic instabilities driving transport and mixing. The latter, biochemistry, governs the exchange and transformation in atmospheric composition. Vegetation properties, such as canopy structure, leaf area index (LAI), and leaf color, determine how much energy is absorbed and regulates the skin temperature and the near leaf VPD.[15] Within the entire canopy, this absorption and partly reflected radiation strongly influences vertical profiles in skin temperature and VPD. Therefore, this radiative energy drives the turbulent-canopy fluxes of energy and moisture,[26] which return to the atmosphere in the form of momentum, heat, and moisture. This resulting energy–water–carbon partitioning and redistribution over land governs atmospheric turbulence and cloud formation.[27] As a result, there are two direct effects on cloud dynamics and microphysical-chemical processes. The first effect involves the relationship between the energy and moisture fluxes at the vegetated land surface and how this drives the vertical transport of heat and moisture to higher atmospheric levels where condensation occurs.[28,29] The second effect concerns the key role played by plants in regulating the exchange of biogenic volatile organic compounds.[30,31] These highly reactive compounds act as precursors of aerosols and new particle formation as well as bio-aerosols, prior to the formation of cloud condensation nuclei.[32] A key aspect of these processes is how the aerosol composition becomes a mixture originating from natural and anthropogenic sources. Aerosols characterized by different compositions (sea, rural, and urban) could lead to changes in the cloud microphysics with subsequent influence on the formation, maturity, precipitation, and dissipation of clouds.[33]

The third challenge focuses on the interactions and feedbacks between regional-scale weather and climate phenomena with the local processes described above. These cross-scale interactions can lead to large regional variations in the thermodynamic state variables and the composition of greenhouse gases and chemically active species. In particular, the variations in land properties exert a large influence on the organization of the atmospheric flow. This can be either dynamically driven by, for instance, the shading of clouds,[34,35] or by more static or gradual variations of land properties, such as albedo, roughness, and soil moisture,[36] for example. Figure 2 shows the relationships between surface heterogeneities and flow organization. Three length scales are relevant: the patch (X_P; defined as the length scale in which surface properties are disturbed), the length scale of the surface heterogeneity (X_H), and the most representative length scale of the land–atmosphere interaction, represented by the turbulence length scale (L).[37] In brief,

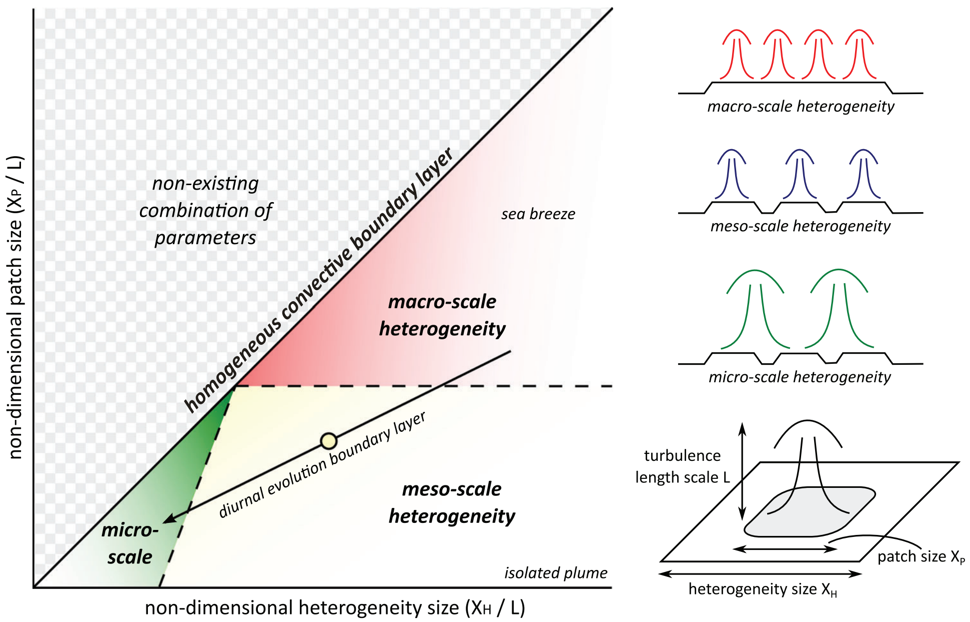

FIGURE 2 Nondimensional representation of the impact of surface heterogeneity, represented by the heterogeneity size (X_H) and the patch size (X_P) and the atmospheric flow organization represented by the length scale of turbulence (*L*). X_P is the size of the disturbed surface. The figure describes three regimes that are common in land–atmosphere interactions. From top to bottom: (1) the macro-scale heterogeneity in which the patch and surface heterogeneity are larger than the turbulent representative scale, that is, land or sea breeze. (2) The meso-scale heterogeneity in which patch and surface heterogeneity have a similar length scale as the turbulence and (3) micro-scale heterogeneity in which the length scale heterogeneity is smaller than the turbulence length scale. More information in how the length of the patch and the heterogeneity influence the atmospheric flow can be found at van Heerwaarden et al.[37]

in the case of macro-scale heterogeneity, the surface heterogeneity dominates turbulence which leads to the organization of flows characterized by larger length scales than turbulence, such as sea-breeze. Under the micro-scale heterogeneity regimen, the individual surface properties exert a relatively small influence on the flow, and turbulence is able to blend the small-scale heterogeneities, above a certain height. The most challenging case is represented by the meso-scale heterogeneity. Here, the length scale of turbulence is similar to the surface heterogeneity. Note that the relationship between these length scales varies during the day due to variation of radiation and turbulence that yields different conditions in the interaction between land and the atmosphere, that is, cloudy versus clear, and thermal stratification, that is, stable, unstable, and neutral.[38,39] The challenge relies on first understanding how these differences of surface heterogeneities influence the atmospheric flow and second how to represent this coupling between surface heterogeneity and flow organization in weather[40] and climate[12] models. In these models, processes related to land–atmosphere exchange and turbulence are represented in the form of parameterized expressions. As a result, surface heterogeneities are normally calculated as an aggregate of surface properties, which could lead to misrepresentations of turbulence.[40] These inaccurate calculations of the turbulent transport of momentum, heat, moisture, and aerosols could yield erroneous calculations of cloud dynamics and physics. Turbulent- and cloud-resolving models as presented and discussed in this article are able to simulate the most energetic parts of the coupling between land–atmosphere,[35,41] and therefore, simulate the three regimens presented in Figure 2 as a continuum of linked scales.[42]

With respect to the interactions between the local processes and regionally driven air masses, the recycling of moisture controlled by vegetation plays a key role.[43,44] Incoming air masses (for instance, the ones with oceanic origin at Figure 1), driven in synoptic and mesoscale patterns, are influenced by the local thermodynamic variables and atmospheric composition which leads to changes in the water budget (evaporation and precipitation). The coupling between the ecosystem and clouds, the identification of the sources and sinks of moisture, the capacity of locally recycling moisture,[43,44] and the vegetation/soil exchanges of CO_2[45] need to be properly quantified. By identifying the location and the monthly to yearly source regions of moisture or CO_2, one can understand if those air masses have a nonlocal origin over the ocean or if their origin is locally driven by evaporation recycled by ecophysiological and hydrological processes.[46]

The fourth challenge is related to how large-scale climate changes[47] influence key meteorological and ecophysiological processes at regional and global scales.[3,8] As shown in Figure 3, weather, atmospheric composition, and climate modifications drive the dynamics of ecosystem and clouds. These dynamics are strongly influenced by modifications of the atmospheric thermodynamic structure (stabilization) disturbed by more frequent weather extremes. The figure is far from complete, but it attempts to show that as part of the research challenge, some processes offset each other. In short, we have divided the interaction of these processes in two groups. The first group includes ecosystem processes affected by climate change that leads to modifications in plant assimilation and transpiration, and

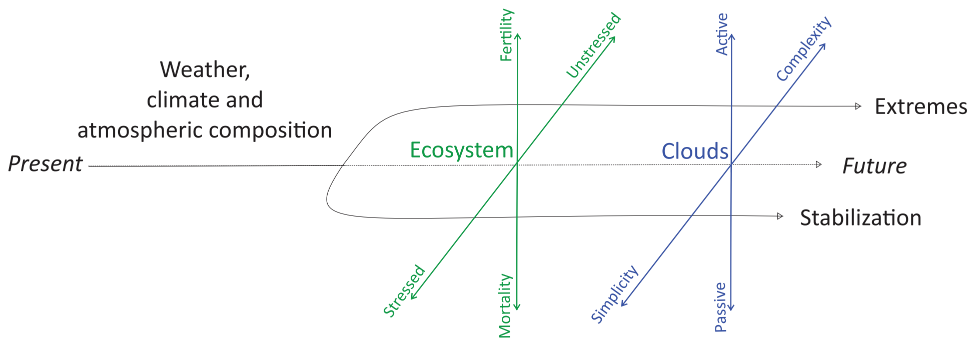

FIGURE 3 Weather, climate, and atmospheric composition are changing due to the transitions between present and future climate conditions. Ecosystem (green) and cloud processes (blue) are influenced by opposite effects which, in turn, influence the dynamics of ecosystems and clouds. These opposite effects depend on thermal *stabilization* of the atmosphere under current climate predictions, but also on higher frequency of *extreme weather* events, such as drought, heatwaves, and flooding that are expected to occur. Both thermal stabilization and extreme weather effects can become dominant for longer periods and are region-specific.

consequently, the distribution of the land exchange fluxes of energy, water, and carbon. For example, the fertilization and increased growth of plants due to the enhancement of leaf-level CO_2 can be counteracted by large vegetation mortality rates due to more frequent droughts.[48] Similarly, the closure of the stomata under elevated CO_2 reduces leaf-level transpiration, although this may be offset by increases in total leaf area.[49] Both interactive processes influence how the available radiation is partitioned between evaporation and sensible heat flux. To the right in Figure 3, at the second group, the light perturbed by clouds and intercepted by canopies drives photosynthesis, and influences leaf-level transpiration via changes in leaf energy balance and stomatal conductance. Here, under future climate scenarios, the two opposite effects are the following: clouds could become less frequent and less active due to the increase in thermal stabilization of the atmosphere. However, clouds could become more dynamically active and vigorous due to larger evapotranspiration rates driven by regional warming that enhance the capacity of the atmosphere to hold water vapor. It is within this context that the organization of clouds in terms of complexity[50] can play a key role in regulating the radiation reaching the surface.

Scientific communities in the fields of ecology, ecophysiology, and atmospheric science have implemented initiatives to further develop and integrate land surface and atmospheric processes.[28,29,51,52] Harrison et al. (2021) presented clear guidelines to improve land-surface representations. This included developing more coherent theories, clarifying hypotheses, thoroughly testing individual components of the vegetation, and re-evaluating original formulations.[53] van Diepen et al. (2022) addressed this latter aspect when examining and comparing the formulation and performance of widely used leaf photosynthesis models. In the atmospheric science community,[54] Emanuel (2020) stressed the need to maintain a balance between observations, theoretical concepts, and supportive and integrative numerical experiments.[23] To accomplish this, we need to first determine the relevance of each individual process on the representative scale and any subsequent interactive effects occurring when the individual processes are interconnected.

CHALLENGE 1: RADIATION AND PHOTOSYNTHESIS

The transfer of shortwave and longwave radiation throughout the atmosphere is a crucial component of the interactions of the land–atmosphere system as they represent the energy input into the ecosystem. Although routine measurements of the upward and downward/short- and longwave radiation components to obtain the radiative budget, and therefore, the net available radiation energy are regularly carried out,[39] new observational techniques are required to quantify its complex behavior in space and time and unravel any missing features. As an illustration of the nonlinear high space and time variability in the radiative transfer, Figure 4 shows the vertical profile of global horizontal irradiance inside the canopy[55] measured at the Loobos temperate forest station (52°10 N 5°44 E),[56] which is characterized by a canopy of 20 meters. These measurements are carried out at a 10 Hz sampling rate across the shortwave spectrum to measure at 18 bands of the spectra, making them novel and unique (see for more information, https://chiel.ghost.io/slocs/). These observations were selected because they show the simultaneous impact of the passage of clouds, characterized by the decrease in global horizontal radiation between 09:45 and 10:00 UTC, and the disturbances due to the canopy structure. This latter feature can be seen in the larger values of the global irradiance at the canopy top as compared to the measurements taken 6 m above ground level during the period from 10:15 to 10:30. The reason for this vertical distribution depends strongly on the solar angle and the canopy structure as well as the wind that governs the radiative transfer and the partitioning of direct and diffuse radiation. Although more targeted experiments address these radiation transitions in time and vertical direction, several key research questions remain open: what is the partitioning of direct and diffuse shortwave radiation and the time evolution of the partitioning,[57] what is the impact on photosynthesis,[21] how is the variability of the net ecosystem exchange (NEE) or latent heat flux under clear or cloudy conditions affected,[18,23] and what is the subsequent effect on surface turbulent fluxes and boundary-layer dynamics?[58] To answer these questions, we need to determine how the variations at the leaf level

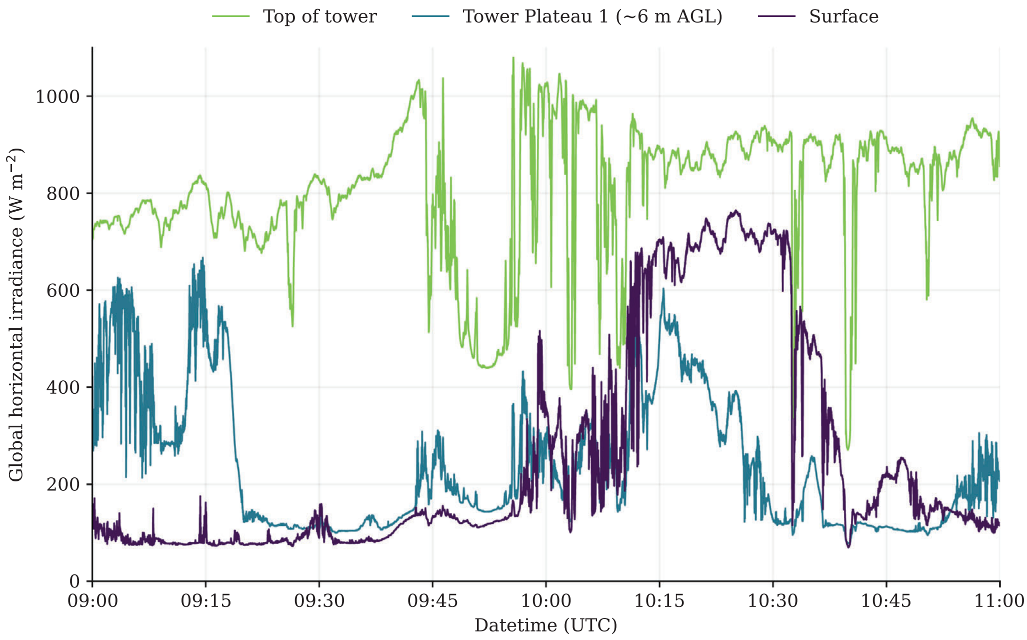

FIGURE 4 High-frequency global horizontal irradiance measurements (10 Hz) taken at the Loobos station tower above and below the forest canopy during the 18th of May 2022 between 11 and 13 LT (9-11 UTC).

influence the fluxes of heat, moisture, and carbon dioxide at the canopy level and the feedback with the clouds.

These more advanced measurements of radiation should be accompanied by an improvement in the radiative transfer calculations, in particular, the study of the radiative transfer in three dimensions and how this transfer is perturbed by the presence of clouds and the penetration within the canopy. Our reasoning is that despite the fact that radiation is a primary variable, our calculations still remain inaccurate when combining clouds and canopy effects, which has an impact on key processes related to photosynthesis and the surface energy balance. Figure 5 shows the differences in the global shortwave radiation and sensible and latent heat fluxes calculated by solving the radiative transfer either by one- (top panel) or three-dimensional radiative (bottom panel) transfer models.[19] These numerical experiments were performed using a fully coupled soil-plant-turbulent-cloud model, that is, using a large-eddy simulation technique (LES). LES numerical experiments calculate clouds explicitly[18,59] and the ecophysiology and soil processes with evaluated mechanistic representations.[23] As discussed by Veerman et al. (2020)[19] for the one-dimensional radiative transfer, the reduction in direct radiation below clouds is partially compensated by an increase in diffuse radiation, but it leads to an overall reduction in the sensible and latent heat fluxes. This decrease happens in the source region where the thermal plumes originate. This leads to a weakening of the turbulent transport of heat and moisture and a flow situation characterized by less cloud cover and smaller volume clouds.[59] In turn, the displaced cloud shadows with three-dimensional radiative transfer are responsible for decoupling the system between surface properties and clouds, which leads to the formation of atmospheric circulations.[60] The level of coupling between land and atmosphere exchanges also depends on the background wind[61] and the thickness of the clouds. Cloud thickness regulates the redistribution of direct and diffuse radiation reaching the surface. Therefore it influences the partition of the available radiative energy in sensible or latent heat fluxes[18]

In moving from one- to three-radiative transfer calculations, we expect to improve the calculations of the perturbations and the partitioning between the direct and diffuse global irradiance that has a direct impact on plant photosynthesis. This impact has been shown in observational studies[62,63] based on the FLUXNET network (https://fluxnet.org/). Disturbances in this partitioning are driven by the presence of clouds and the in-canopy penetration of radiation. Clouds organize on scales ranging from few meters to hundreds of kilometers, affecting plant photosynthesis by increasing the fraction of diffuse solar radiation that arrives at the top of the canopy.[64] The isotropic property of diffuse solar radiation enables the radiation to spread more equally over all the leaves and thereby increases the light-use efficiency of a canopy.[65,66] Following pioneering work by Freedman et al.,[67] and as shown in the observations in Figure 10 from Vilà-Guerau de Arellano et al.,[23] cloud radiation perturbations have opposite effects on the net primary production (enhancing) and latent heat (diminishing), which is still not well understood nor well represented in our weather and carbon-climate models. Our explanation for this more effective behavior under diffuse light is the following. Under these conditions, and even when the available radiation is lower at the top of the canopy, the much larger marginal increase of the net primary production, with increasing radiation in low light conditions, results in a significant gain in net primary production as compared to situations of near light-saturation.

By placing these examples of observations and simulations in perspective, and despite the fact that three-dimensional radiative transfer calculations are computationally expensive, we advocate for the use

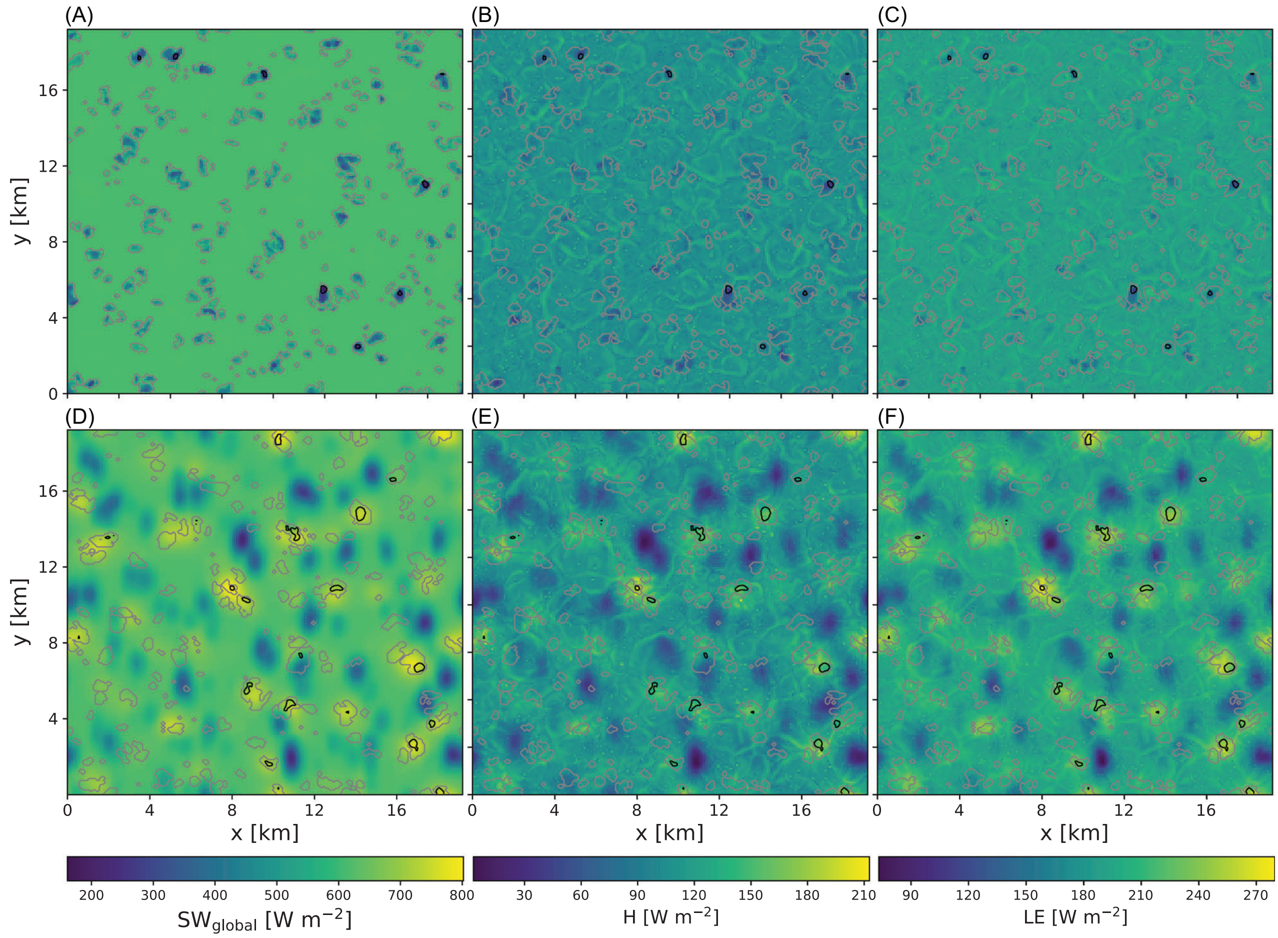

FIGURE 5 Spatial variability of the global shortwave irradiance (A and D), sensible heat flux (B and E), and latent heat flux (C and F). These variables are calculated using a fine-spatial resolution land–atmosphere model (numerical experiments using the large-eddy simulation technique with a spatial resolution in the horizontal direction of 100 m and in the vertical direction of 25 meters). The domain is 18 x 18 km^2 and the radiative transfer is calculated using a one-dimensional (only radiative transfer in the vertical direction, upper panels) and a three-dimensional-transfer radiative scheme (lower panels). These instantaneous horizontal cross-sections are taken at 12.30 UTC (zenith angle = 54.5 and azimuth: 196.3). The variability on the three variables is created on how clouds and the perturbation of radiation are calculated. The presence of clouds is marked by the continuous line. The prescribed background wind in all the numerical experiments is 0 ms^{-1}. In D–F, cloud shades are normally N-NEE from the position of the clouds. More information in Veerman et al. [68]

of three-dimensional radiative transfer to advance our understanding of the role of clouds[19,60] and canopy penetration.[20] Here, it would be convenient to leverage how new computational techniques based on calculations done using Graphic Processing Units can accelerate the calculations.[68] In concluding, accurate observations and calculations of radiative transfer will improve the representation of leaf-level photosynthesis which will subsequently lead improvements in our interpretation of the measurements and calculations of surface turbulent fluxes at the canopy level.

CHALLENGE 2: CLOUD AND ATMOSPHERE–CANOPY INTERACTIONS

When connecting leaf to canopy processes, there are still open challenges concerning properties that emerge at larger scales. As introduced and discussed by Baldocchi,[66] we define scale-emergent processes as the ones which become relevant (and have a different impact) at a larger scale such as: (1) the different responses of photosynthesis to diffuse radiation (important at the canopy scale), (2) the microclimate conditions in and above the canopy (important at the canopy scale), and (3) the partitioning of fluxes in and above the canopy, that is, how much of the net available radiative energy is used by plant transpiration and photosynthesis and the rest to warm the atmospheric boundary layer (ABL). The different partitioning that depends on the functional type and soil properties becomes important at canopy and regional scales and it is closely linked to the heterogeneity of surface properties. To advance our understanding of these scale-emergent processes, we need to better quantify the relationships between the radiation driver, such as the photosynthetically active radiation (PAR), to the turbulent fluxes at the canopy. Figure 6 provides an example of how the turbulent fluxes of evapotranspiration and NEE vary due

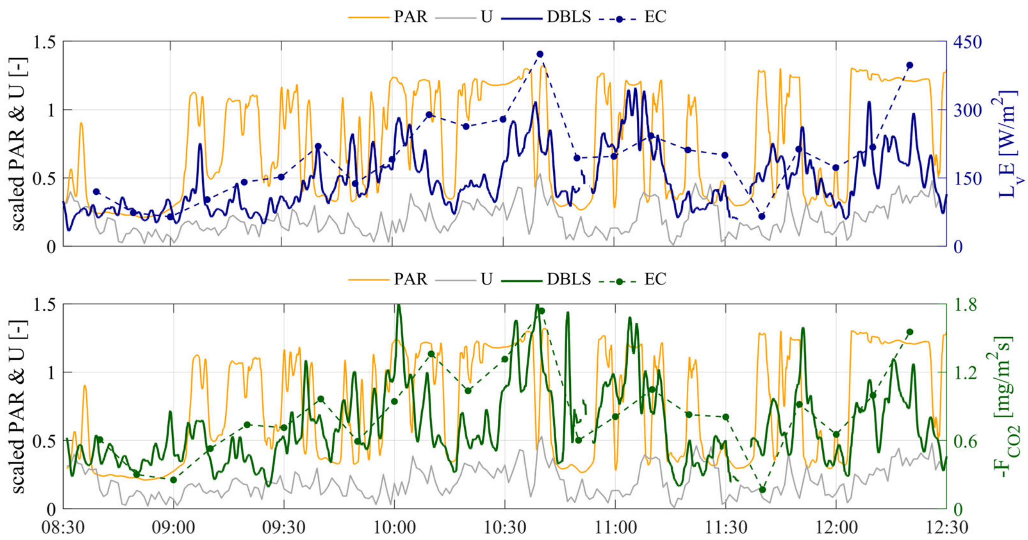

FIGURE 6 Collocated observations taken during the CloudRoots experiment[23] (June 15, 2018). Time-series of (top) latent heat fluxes (LvE) at 1 min intervals with a displaced-beam laser scintillometer (DBLS, continuous line) and at 10 min intervals with an eddy covariance system (EC, dashed line) combined with scaled time series of photosynthetically active radiation (PAR, scaled by 1500 μmolm^{-2}s^{-1} and wind speed (U, scaled by 6 ms^{-1}). Bottom: CO_2 flux (NEE) measured under the same conditions as LvE.

to the PAR fluctuations that depend on the duration of the cloud passage and the thickness of the cloud, normally quantified with the cloud optical depth variable that depends on the cloud liquid water content. Measurements were taken using the double-beam laser scintillometer (DBLS) technique to measure turbulent fluxes at a high temporal resolution (1 min).[69] The DBLS measures the scintillation intensity of two displaced laser beams (wavelength of 670 nm and separation distance of 2.7 mm). The beam scintillation intensities are related to the structure parameter of temperature and the dissipation of turbulent kinetic energy. From these, we can estimate the turbulent flux of sensible heat and momentum following Monin–Obukhov similarity theory.[69] These advanced measurements of canopy turbulent fluxes enable us to study how the vegetation responds to these rapid cloud-induced perturbations in radiation and intensity variable cloud radiation perturbations. Note that the scintillometer technique, unlike eddy-covariances, does not rely on integration over all eddy scales that contribute to the turbulent transport. Rather, it determines turbulence variables, structure parameters of temperature, and dissipation rate TKE on eddy scales that lie in the inertial range of the refractive index spectrum which are linked to fluxes using MOST. The disadvantage of the technique is that it is more indirect because it relies on inertial range behavior of the observed eddies. The advantage is that it yields turbulent fluxes at much shorter timescales (Figure 6).

As shown in Figure 6, and compared to the widely used temporal resolution of the 30-min average eddy-covariance technique, the 1-min DBLS observations not only closely follow the cloud passages that lead to radiation fluctuations, but also reveal that there are delays in the responses of evapotranspiration and NEE fluxes to radiation. For this concrete situation, the lag between radiation and evaporation and the NEE is 2 min.[23] We argue that this way of measuring NEE could lead to more precise estimations in quantifying the CO_2 assimilation by plants in ecosystems, such as the Amazonian or Boreal forests, where clouds are frequently present.

These rapid fluctuations of radiation and surface turbulent fluxes are present during the entire day. They introduce a strong variability on key drivers of photosynthesis (radiation, temperature, and water VPD) that leads to modifications of the partitioning of the net available radiative energy into sensible or latent heat fluxes. Due to its relevance in governing boundary-layer dynamics, surface flux partitioning is, therefore, a key process in land–atmosphere interactions.[22] A representative example of the impact of these dependencies is the asymmetric relationship under diurnal clear sky conditions between evaporation and NEE as a function of the water VPD. As shown in Figure 7, there is an asymmetry in photosynthesis and transpiration rate before and after midday. This nonlinear relationship is driven by the stomatal aperture reacting to the different impact of shortwave radiation in the morning and the afternoon (roughly defined as 12 local time). Under similar and symmetric shortwave incoming radiation levels, the normally higher temperature in the afternoon leads to higher water VPD which causes the stomatal aperture to close. As a result, there might be a shift in the partitioning of the surface energy balance to higher sensible heat flux that could influence the boundary layer dynamics. As shown in Figure 7A, the asymmetry is characterized by more elliptical shapes in the case of low vegetation (winter wheat) as compared to the tall canopy of the Pine Forest (Figure 7B). Our explanation is that more active sweeping and ejection motions at the canopy–atmosphere interface as shown in Figure 8 introduce additional random motions to the turbulent ones leading to more chaotic patterns in the diurnal variability in the canopy fluxes of heat, water, and carbon.

As discussed by Zhang et al.,[70] the understanding and analysis of these asymmetric curves enable us to better identify which are the

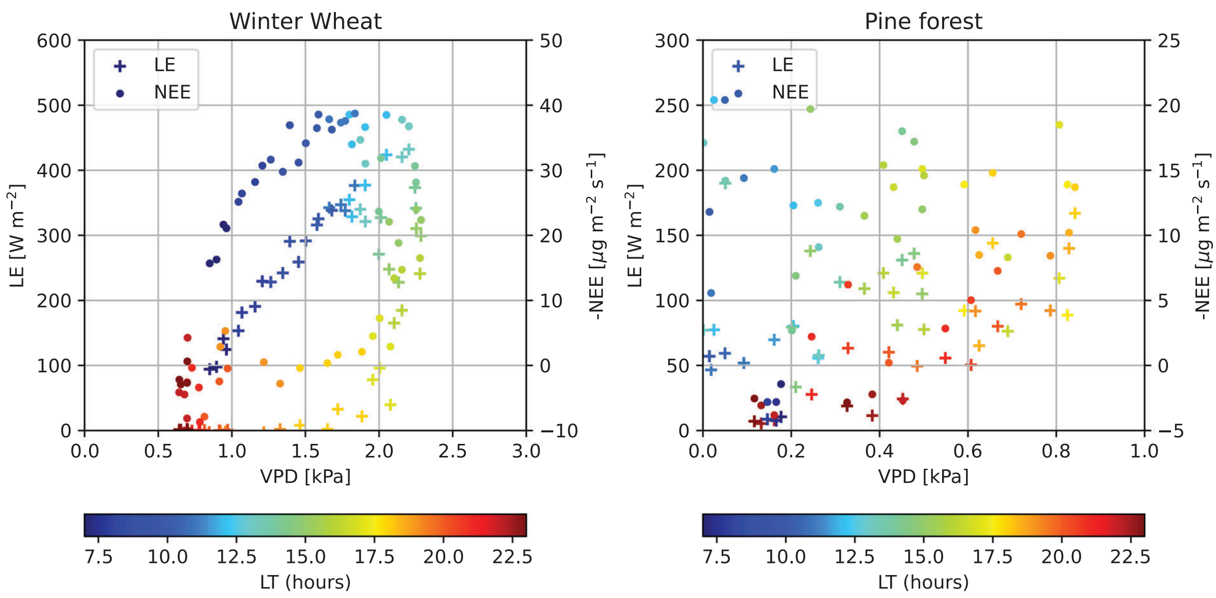

FIGURE 7 Diurnal variability of latent heat flux (cross) and net ecosystem exchange (circles) as a function of the water vapor pressure deficit and the time of the day (color bar). The eddy-covariance observations are 30-min averages collected over a winter wheat during the CloudRoots18 campaign in Germany[23] and at over a pine forest at the Loobos station in the Netherlands. For both sites, measurements were taken on cloudless days (May 7 and 8, 2018).

processes that control the heat, water, and carbon budget at the subdiurnal scale.[71] Here, the measuring[72,73] and modeling[74,75] of the stable isotopologues (molar fractions and isofluxes) of carbon dioxide and water vapor as well as atmospheric oxygen concentration[76] can help to identify the sources and sinks for evaporation and NEE, that is, partitioning of sensible versus latent heat flux and CO_2 plant assimilation versus CO_2 soil respiration. At larger scales, and for weather and carbon-climate models, the challenge is whether these large-scale models are able to represent how these surface fluxes are distributed and evolve at varying at subhourly scales.[12,77] More accurate representations can help to advance our understanding and reduce uncertainty in the relationships between evapotranspiration and precipitation under conditions such as the transition between shallow to deep convection that triggers convection and precipitation in the afternoon, as analyzed with remote sensing observations by Taylor et al.[78]

In linking surface fluxes to clouds, it is necessary to stress the role of the dynamics of the boundary layer as the atmospheric layer that integrates, buffers, and modulates surface processes to free atmospheric conditions. Figure 9 is an example of the need to continuously monitor the ABL thermodynamic state, specially considering current conditions where weather extremes are becoming more frequent. The three profiles of potential temperature and specific moisture were collected for three different ecosystems: rainforest, temperate, and boreal forests (Figure 1). For the last two ecosystems, the thermodynamic profiles were collected under synoptic conditions characterized by the presence of high-pressure systems. In both cases, unusually warm temperatures were recorded, and very deep boundary layers were formed above the temperate[79] and boreal forests (>2000 m).[80] This coupling of the land and boundary layer dynamics is not only important for the development of boundary-layer clouds[81] but also for the diurnal variability of greenhouse gases[82] and chemically reactive species.[83] Therefore, it is necessary to design, develop, and apply a new approach that includes more frequent, comprehensive, and collocated surface and upper atmospheric observations in space and time[23,58,84] with a global coverage of surface stations,[85] the use and analysis of soundings,[86,87] and ground and satellite remote sensing.[88,89] We also advocate to keep well-equipped and comprehensive sites at representative ecosystem sites as shown in Figure 1. Current supersites that are providing these surface and upper-air observations are: the ATTO site[30] in the Amazonian rainforest (https://www.attoproject.org/), the Ruisdael observatory[90] (https://ruisdael-observatory.nl/), and the Atmospheric Research Radiation site at the Southern Great Plains[91] (https://www.arm.gov/capabilities/observatories/sgp) both in a temperate climates and the SMEAR site in the boreal forests[92] (https://www.helsinki.fi/en/research-stations/hyytiala-forestry-field-station). These supersites would be complemented by complete surface measurement networks.[51]

Therefore, we advocate combining advanced measurements and instrumental techniques, and high-resolution numerical experiments as the path to advance knowledge of land–atmosphere interactions, as shown in Figures 4 and 6, respectively. With respect to fine-scale land–atmosphere simulations, Figure 8 is a representative example of the level of detail needed to solve the interactions between canopy and the atmosphere.[93–95] Figure 8 shows an instantaneous cross-section of the specific humidity, liquid water potential temperature, and carbon dioxide calculated with the LES model DALES.[96] Figure 8 (the three central panels) shows the in and above canopy vertical spatial distribution of moisture, heat, and CO_2 concentration of a 1000 m long cross- section of the simulated domain in which the

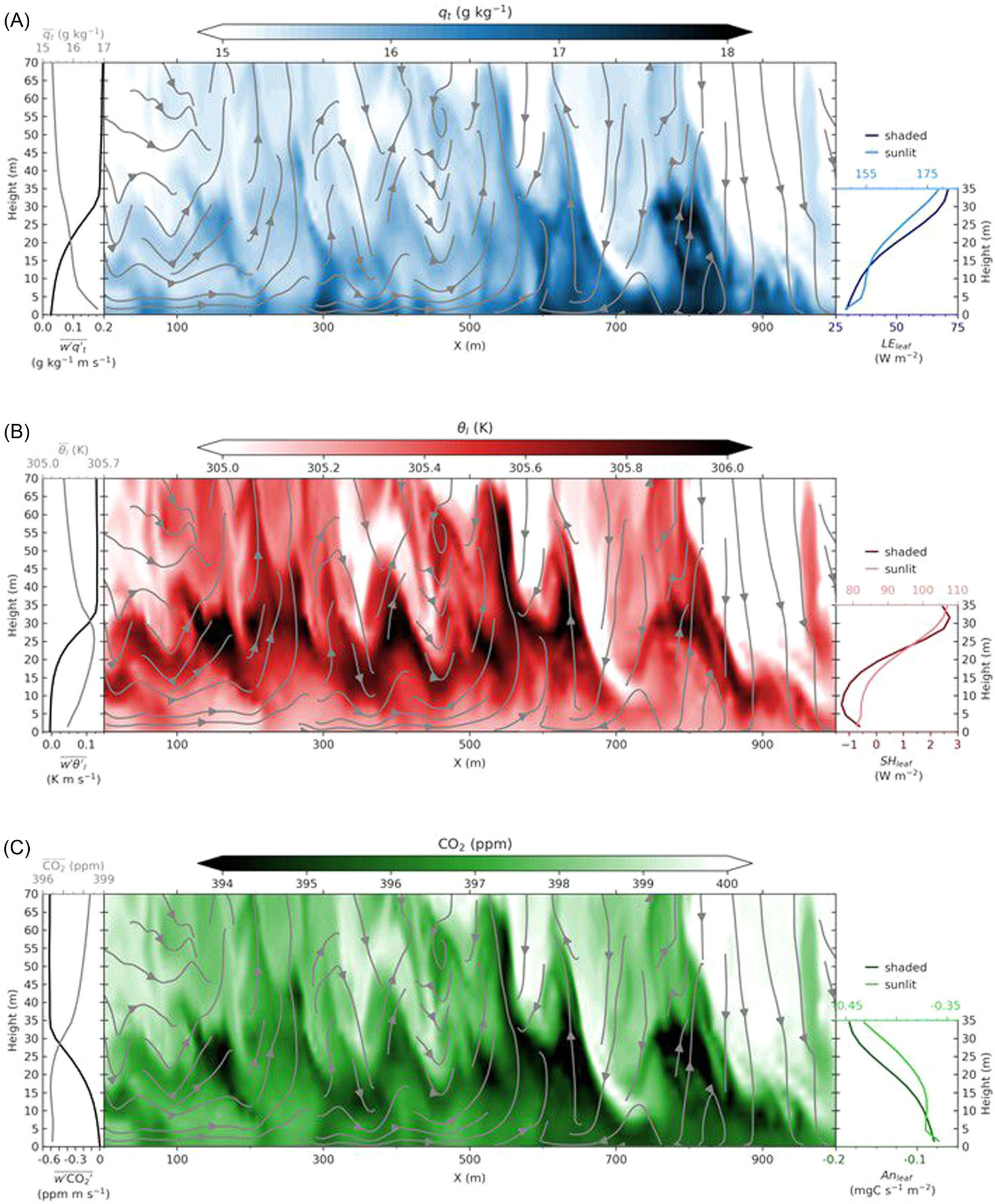

FIGURE 8 Instantaneous vertical cross-sections at 12 LT of the lowest 70 meters of the atmospheric boundary layer, namely, the roughness sublayer, displaying the instantaneous fields for specific humidity ($\overline{q_t}$) (A), liquid potential temperature ($\overline{\theta_l}$) (B), and carbon dioxide ($\overline{CO_2}$) concentration (C) in the colored part of the simulated domain. Wind direction is shown in gray streamlines. On the left of each cross-section, slab-average values of the shown variable in gray and the associated turbulent fluxes are in black. On the right of each cross-section, slab-average values of the associated flux at the leaf level for shaded (dark) and sunlit (light) leaves. Note that the canopy is present only up to 34.5 m. The numerical experiment resolution was 3 x 3 x 3 m^3.

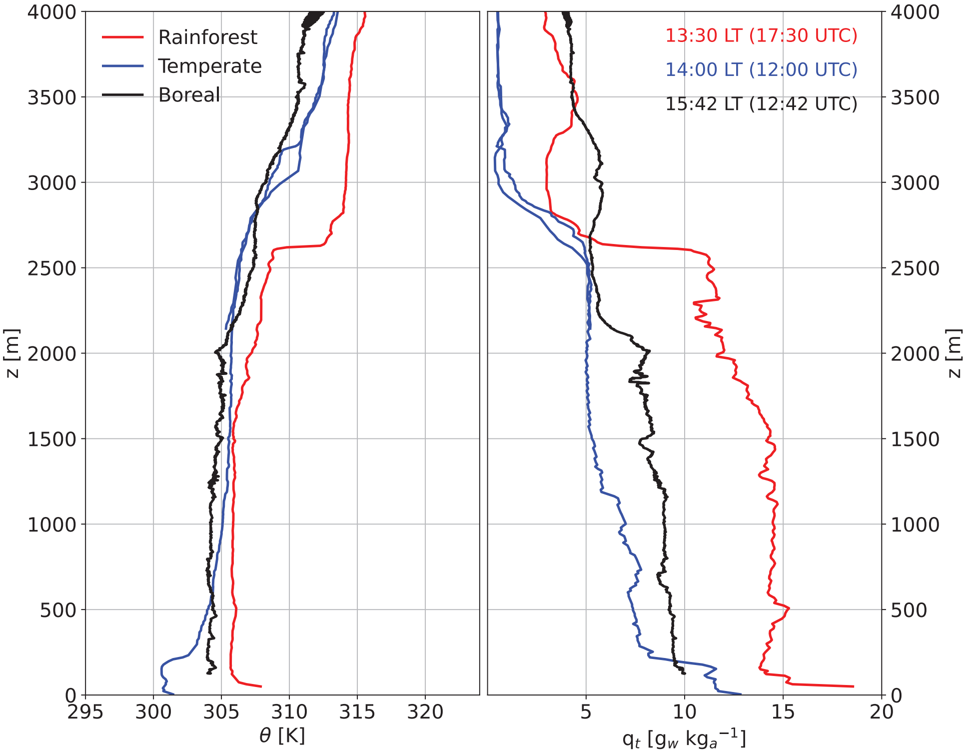

FIGURE 9 Vertical profiles of potential temperature and specific humidity measured above the rainforest, temperate, and boreal ecosystems (Figure 1) after midday when the boundary-layer development is reaching a more steady development. The soundings were launched during the field campaigns GOAMAZON14,[33] Ruisdael19 (https://ruisdael-observatory.nl/), and OXHYYGEN campaigns (2018 and 2019).[76]

radiative transfer and the flow are influenced by the presence of a tall canopy. As shown, the canopy is characterized by more moist and CO_2-rich air, and by a potential temperature profile that increases with canopy height and peaks above the level of maximum canopy density. Similar patterns were also found by Patton et al.[95] Such height-dependency of the potential temperature, specific humidity, and carbon dioxide mixing ratio is visible in the gray lines in the left side of the subfigure in Figure 8A-C. These vertical profiles are the slab-average of a quantity across both horizontal directions. Similarly, the slab-averaged fluxes at leaf level for sunlit and shaded leaves are displayed on the right of Figure 8A-C. The differences in the profiles of the leaf fluxes depend on sunlit and shaded radiation again stresses the need for measuring and calculating radiation (Figures 4 and 5) and connecting it to observations of turbulent fluxes (Figures 6 and 7) to simultaneously analyze the dynamics of the ABL (Figure 9).

In connecting these findings to atmospheric chemistry, it is important to mention that this level of spatiotemporal detail in solving the interaction between the canopy and the atmosphere is also necessary to study the production of new particles and product formation due to chemical reactions within the canopy. These processes are controlled by the distribution of sunlit/shaded radiation, that is, photolysis rate (see Figures 4 and 5), as well as the three-dimensional spatiotemporal distribution of temperature, differences in water vapor pressure, and turbulent mixing, which strongly vary in the canopy, as shown by Figure 8. The interaction between turbulent mixing and chemistry is a clear example of the need to treat processes simultaneously and as explicitly as possible. As quantified by Jonker et al.[97] and Ouwersloot et al.,[83] this interaction is governed by the respective time scales of chemistry and turbulence, and it is altered by the presence of clouds[97] and surface heterogeneity.[83]

CHALLENGE 3: FROM CANOPY TO CLOUD AND REGIONAL SCALES

Challenge 3.1: Organization of atmospheric flow influenced by land properties

In land–atmospheric studies, how the interaction between the canopy and the atmosphere connects to boundary-layer dynamics and weather and impacts atmospheric composition are all questions that remain unanswered. More specifically, how does the type, condition, and state of vegetation (including spatial distribution) influence the atmospheric flows on scales ranging from local to regional? From a meteorological perspective, this connection depends on the available radiative energy and how this energy is partitioned between canopy sensible (heat) and latent (moist) turbulent fluxes. Questions concerning the imbalance of the surface energy budget over land are still open to debate.[98] From a carbon cycle perspective, the challenge is to determine what controls the NEE, either the CO_2 plant assimilation or the soil respiration. To understand this, partitioning methods are used, but they are far from perfect.[99]

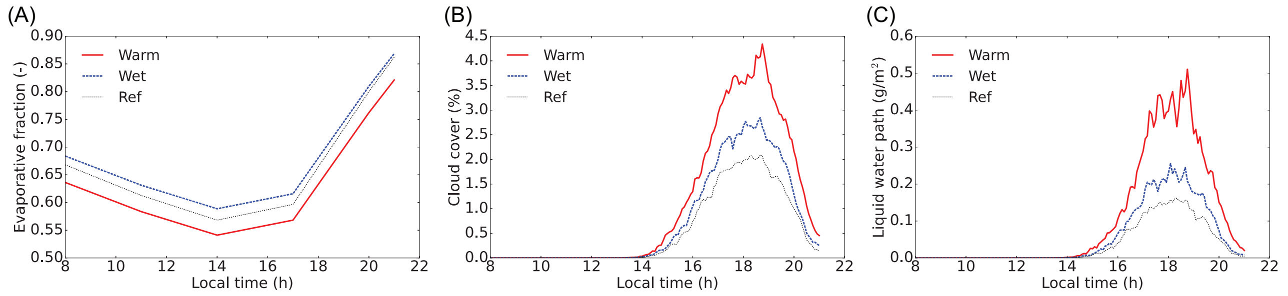

FIGURE 10 (A) Evaporative fraction, (B) cloud cover, and (C) liquid water path for the *Warm*, *Wet*, and reference numerical experiments.[41] Cloud cover is calculated by projecting all clouds onto the surface. Cloud cover and liquid water path are averaged over the horizontal extent of the domain.

As described by van Heerwaarden et al.,[37] the scales of a patch, defined as a surface with different characteristics than the surrounding area, creating surface heterogeneities, could lead to differences in the intensity and structure of turbulence and mesoscale flows (see Figure 2). Using multiple METEOSAT remote sensing scenes,[100] Teuling et al. identified and discussed how forests can enhance the formation of clouds under specific surface and weather conditions. Inspired by these findings, and in line with this current paper in connecting observations with fine-scale modeling,[41] Bosman et al. performed three numerical experiments over land (Figure 10) to disentangle the role of the partitioning of surface fluxes in the formation of clouds. Taking the control run as reference, in the numerical experiments to study the sensitivity of clouds to surface conditions, the surface fluxes were altered by adding 5% of the sum of the latent and sensible heat flux (which together add up to the available energy) to either the sensible or latent heat flux. In the *Warm* experiment, this amount was added to the sensible heat flux, while in the *Wet* one, it was added to the latent heat flux. As expected, both the *Warm* and *Wet* runs showed an increase in cloud cover compared to the reference run due to an extra input of energy (Figure 10B). However, the effect of adding extra energy was clearly larger when the energy was added to the sensible heat flux. In the *Warm* run, the maximum cloud cover amounted to 4.3%, but in the *Wet* experiment, it was 2.8% (Figure 10B). Additionally, during the period from 1400 LT to the end of the simulation period (2100 LT), the mean cloud cover amounted to 2.1% for *Warm*, and only 1.4% for *Wet*. The differences are not only visible in the cloud cover, but also in the liquid water path which directly impacts the disturbance of radiation by the cloud (Figures 4 and 5). Differences as large as a factor of 2 occur between the numerical experiments (Figure 10C). To a certain extent, this result is counterintuitive. The explanation is that due to the more intense turbulent eddies that reach higher heights, condensation is favored by colder temperatures. As such, the vertical and horizontal organization of clouds is strongly driven by the land conditions that might bring the ABL conditions out of equilibrium with local (surface) processes and nonlocal processes (entrainment, advection, and subsidence).

It is necessary to stress that this case is highly idealized and other relevant factors, such as the presence of aerosols, thermodynamic, and boundary-layer dynamics, as well as synoptic/mesoscale features, such as subsidence and the presence of localized shear (see discussion in Figure 11), also play a relevant role as described by Teuling et al.[100] Expanding on this, and illustrated by Figure 1, it is important to understand how clouds organize during the transition from marine to land conditions. Here, we propose to connect studies on self-organization by clouds carried out under marine ABL conditions[50] to research studies that focus on the spatial distributions of biophysical and surface properties, such as albedo and canopy resistance.[37,101]

Inspired by these marine studies, we argue here that it is necessary to study whether these findings of cloud self-organization over the sea,[102] key in determining the cloud dynamics, radiation disturbance, and precipitation, are relevant over land.[16] In short, these studies of marine clouds have shown that emergent mesoscale circulations driven by small-scale processes, that is, surface fluxes and atmospheric turbulence, might be influenced by the partitioning of surface fluxes over land and by self-reinforcing feedbacks. As such, those generated mesoscale circulations, which are responsible for the convergence of additional moisture transport into the region characterized by convection, may thus accelerate the transition to deep convection. Within the aims of this paper, the main goal is to uncover the role of vegetation conditions on cloud self-organization and whether these land conditions control key aspects during the transition between shallow to deep convection at the subdiurnal scales. To this end, this cloud self-organization and its variability needs to be further studied in LES studies to complement the analysis of cloud remote sensing scenes. This integration of methods will advance our understanding of how the biophysical and surface processes,[101] characterized by the surface energy partitioning and surface heterogeneity, lead to different forms of cloud organization over ecosystems characterized by different plant functional types, soils, and vegetation/soil coverage.

To advance in this direction, we first need a description of how clouds organize themselves. In other words, can we determine the main metrics that define the cloud patterns? Using the method developed by Janssens et al.,[103] Figure 12 classifies multiple remote sensing scenes taken over the Amazon region as a function of cloud size and spatial extent of clear-sky regions. The method enables us first to identify and quantify how many metrics are required to describe the variance associated with cloud organization. Second, it allows us to determine, at least for the Amazonian basin, the directions of the projected plane of metrics, such as for the cloud fraction and cloud cover from cloudless regions to regions associated with large cloud

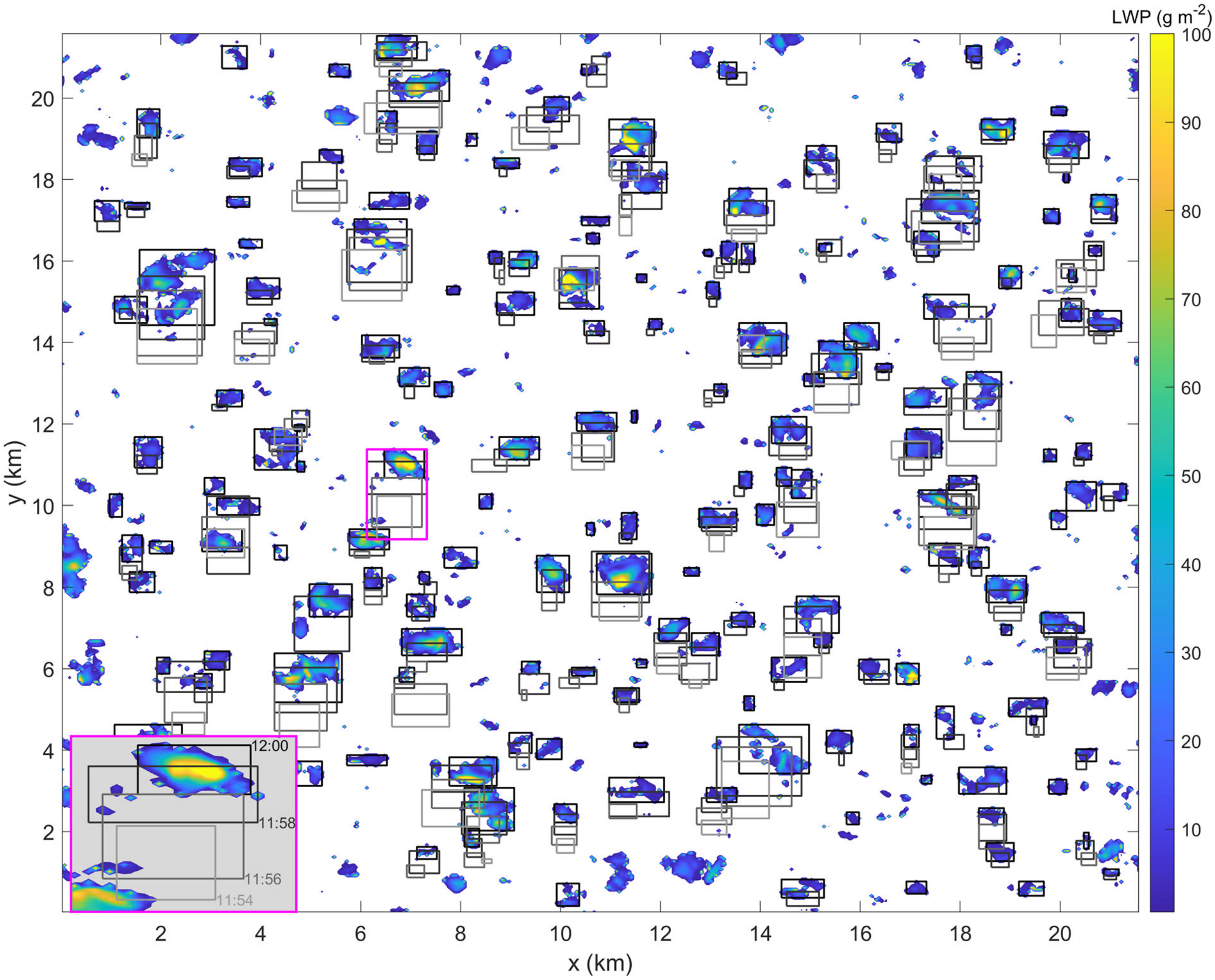

FIGURE 11 Movement of clouds calculated with a fine-spatial scale resolution model (horizontal 50 x 50 meters, vertical 20 meters) in a spatial domain of 20 x 20 km^2. The variable that represents the cloud is the Liquid Water Path (LWP) field (between 800 and 1500 m) at 12:00 local time. LWP is the vertically integrated value of the liquid water content. Wind shear is not included in the simulation. The tracked clouds are highlighted by rectangles, where black lines represent the current time step. Earlier time steps are represented by progressively lighter gray colors, to a maximum of three time steps earlier than the LWP field. See example at the bottom left corner in which the four rectangles follow the cloud at four times: from 11:54 to 12:00 local time. Additional information can be found in Cecchini et al.[106]

cover due to deep convective events. As mentioned above, a question that remains open is the dependence of cloud organization on the land surface properties. Here, we propose to combine cloud scenes with vegetation scenes that will contain information about variables, such as the Normalized Difference Vegetation Index or near-infrared reflectance of terrestrial vegetation.[104] By identifying regions with different photosynthetic capacities due to leaf ages, C3/C4 pathways, and/or water availability,[105] we will attempt to obtain correlations between vegetation-state patterns and cloud organization.

Challenge 3.2: Short- and long-range transport of moisture and greenhouse gases

When connecting and coupling local processes with regional patterns of vegetation and clouds, it is essential to identify how remote air masses are interacting with the local radiative, turbulent, and atmospheric composition conditions. The description shown in section 3.1 is a step forward, but the methods and results remain static in time and space. To identify how air masses change as they come into contact with ecosystems conditions, we can use Lagrangian or other tracking methodologies at short-range (less than 50 km) and long-range (up to 1000 km). Here, we provide two examples of transport studies using (1) turbulent explicit models and (2) regional-global models. They can help to illustrate how we determine source regions of moisture or carbon dioxide on a wide range of spatial scales (local to regional) and temporal (daily to yearly) and show the advantages of using these tracking tools in land–atmosphere studies analyzing either turbulent explicit model results or regional-global model results.

Figure 11 displays an example of the tracking of simulated shallow clouds in the Amazonian basin during the dry season (July–October).[23,106] The numerical experiments were done using high-resolution simulations constrained by the GOAMAZON14 experiment.[107] Here, we focus on the canopy-cloud scales. We are

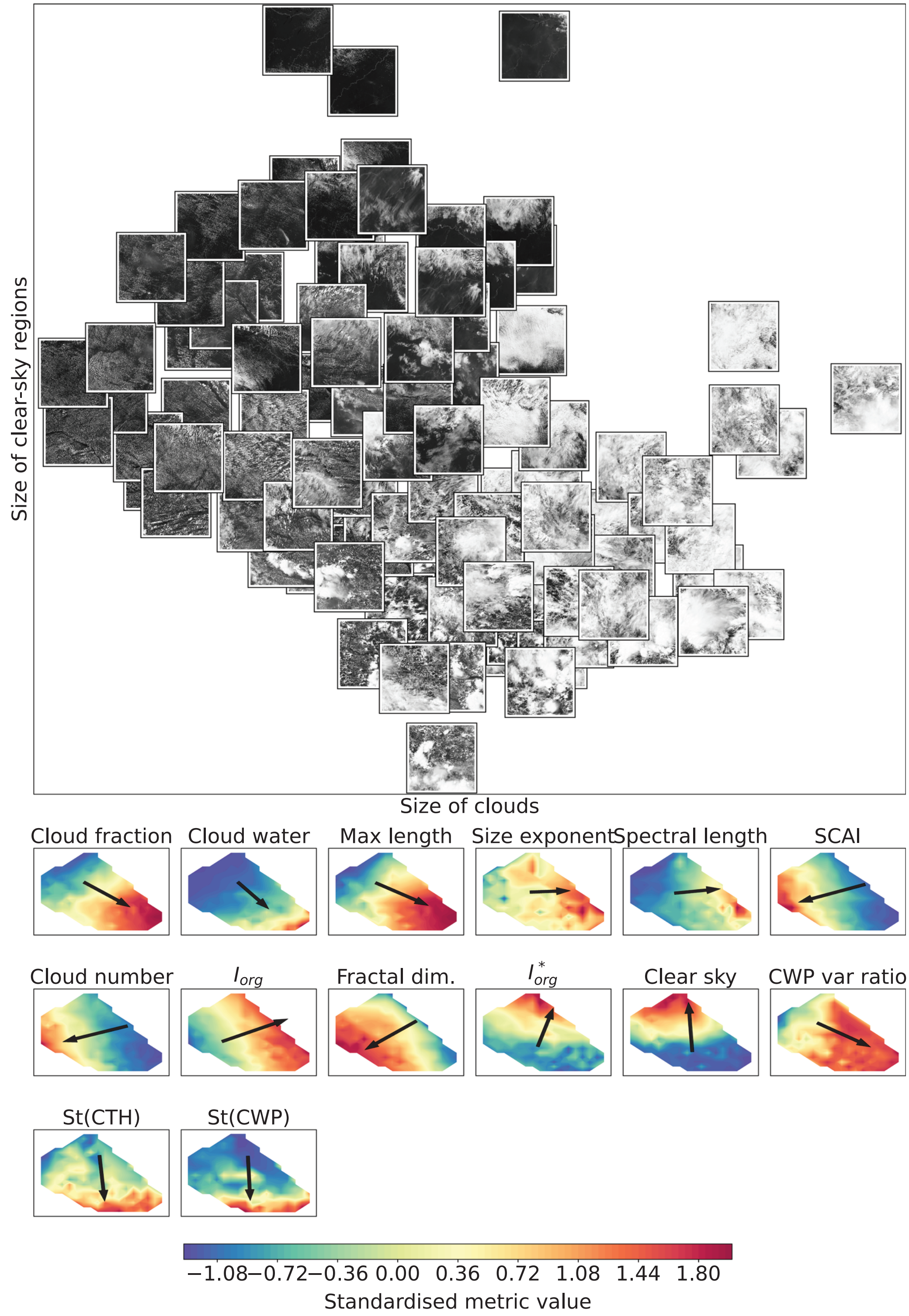

FIGURE 12 Top: Images of Amazonian remote scenes projected onto planes spanned by the size of the clouds and the size of the clear-skies. Bottom: Filled contours of standardized metric values that have in excess of 50% of their variance explained by the size of the clouds and the size of clear-skies. The 14 parameter space (cloud fraction, cloud cover, cloud maximum length, size exponent of the cloud object size distribution modeled as a power law, simple convective aggregation index, cloud number, organization index (I_org), the box-counting dimension of cloud boundaries in the cloud mask field [fractal dim.], variance ratio for "mesoscale aggregation" of moisture [CEP] and the cloud top height [CTH], and their respective standard deviations) is constructed by piecewise linear barycentric interpolation and overlaid by an arrow with direction and length set by each metric's in-plane mean gradient orientation and magnitude. The complete information of variables and methods can be found in Janssens et al.[103]

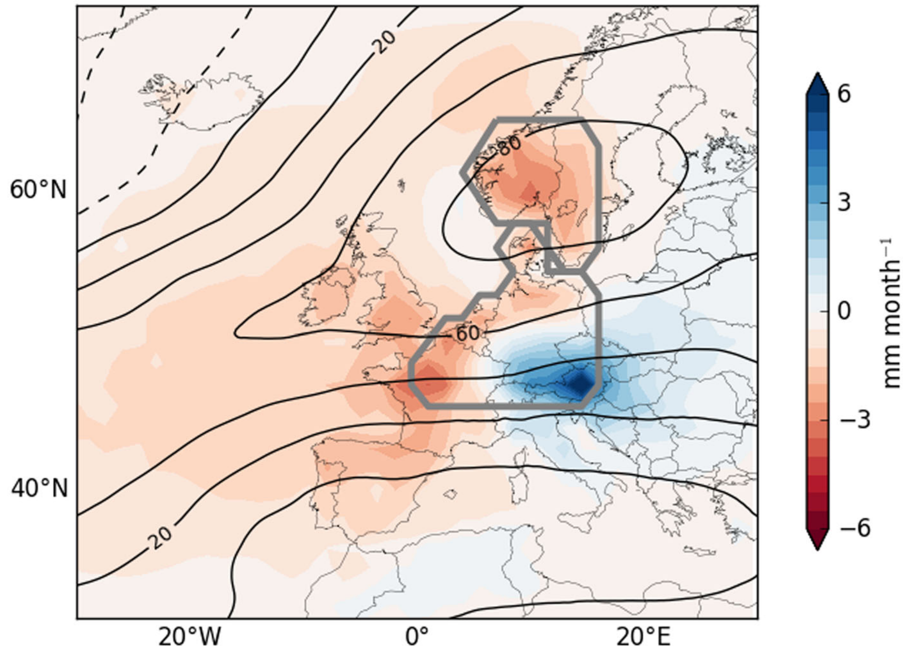

FIGURE 13 Absolute moisture source anomalies for western Europe indicated with gray lines (mm month^{-1}) and 500-hPa geopotential height (m, contours: May–Aug 2018, climatology of May–Aug 1979–2018). More information in Rosner et al.[108]

interested in studying whether shear located below and in the cloud layer influences and controls the growth and intensity of shallow cumulus clouds as shown in Figure 1. A suite of numerical experiments to study the flow from shear-less to situations characterized by different magnitude and locations of shear enable us to systematically study how shear influences cloud formation, development, and patterns. In Figure 11, we present the liquid water path field (between 800 and 1500 m) at 12:00 local time. The rectangles show up to four different time steps at which we track cloud properties, as shown at the bottom left in the figure. Using a combination of LES with Lagrangian tracking, Cecchini et al.[106] found out that vertical wind shear inhibits the convective strength by increasing the horizontal dimensions and reducing the cloud transport velocities. However, the deepest individual cloud was simulated under the strongest wind shear, indicating other indirect effects of wind shear. As such, the study concludes that the direct effect of shear causes cloud tilting, more evaporation near the cloud, and weaker cores. Shear can also have indirect effects since the enhanced evaporation of the clouds may lead to a more unstable atmosphere, and therefore, triggering deeper convection. Both effects have implications on the transition from shallow to deep convection. The remaining questions concern how these findings connect to the specific land properties and how the long-range transport of moisture connects to the specific ecosystem (Figure 1).

Moving to a larger-scale perspective, over the last few years, several methods have been used to identify the sources and sinks of moisture related to specific weather situations and their dependencies on seasonality and climate. Here, we present an example of the anomalous moisture source regions during the drought which occurred over western Europe in the summer of 2018.[108] The drought was the result of an anomalous weather situation, with a persistent high-pressure system over Scandinavia for most of the summer (illustrated with the anomalous 500 hPa geopotential height in Figure 13). The moisture sources during this period were identified with the Eulerian offline tracking tool WAM-2layer,[109] using ERA-Interim reanalysis data for May–August, and the results were compared against tracking results for the long-period (1979–2018) summer mean. The anomalous sources (Figure 13) were of continental origin more than oceanic origin as compared to climatology. The high-pressure system redirected the westerly moist flow from the Atlantic away from western Europe toward the southern Alps and southeastern Europe. The precipitation that fell in western Europe during the drought was mostly from local origin or originated from eastern Europe following the anomalous anticyclonic flow. The evaporation recycling ratio over southern Scandinavia was 6% in 2018 compared to 10% for the base period. This indicates that the drought in that region self-intensified due to positive soil moisture–evaporation–atmosphere feedbacks. In the context of this paper, it shows that the importance of land–surface feedback might be enhanced during certain weather events, such as droughts,[79,110] which might become more dominant in the future (Figure 3). Therefore, we emphasize the need to include a detailed analysis of the surface exchange and transport of heat, moisture, momentum, and atmospheric composition in regional and climatological studies, with the aim of investigating how the land–atmosphere interactions are changing under current climate conditions and more frequent weather extremes.[79,111]

Furthermore, on a regional level, it is necessary to integrate the long-range tracking of moisture and carbon to determine the similarities and differences in their sources and sinks. For example, several studies have focused on deriving the CO_2 balance for the Amazon.[112,113] Here, local and regional scale long-term observations

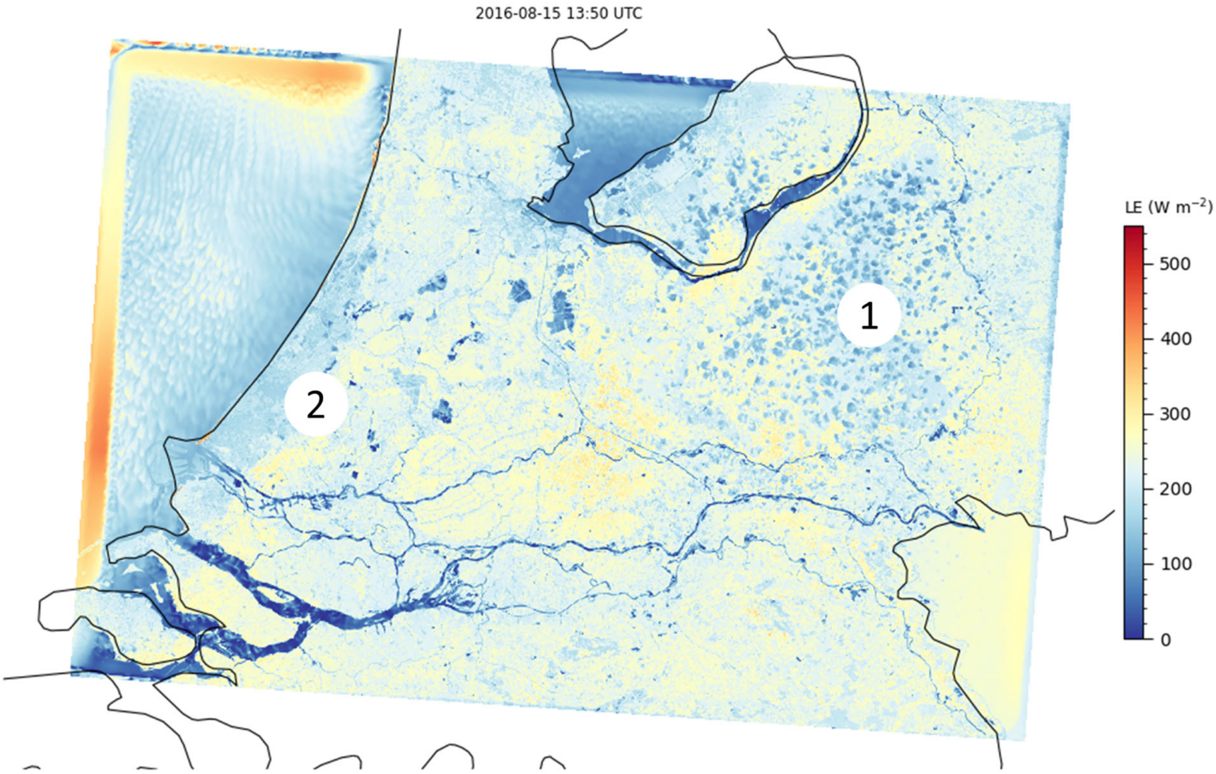

FIGURE 14 Fine-resolved simulation of evapotranspiration in a field in the Netherlands influenced by the presence of a shallow cumulus by shading the surface (1) and the penetrations of a sea breeze front that leads to decrease the water vapor deficit (2). The simulation is performed using a fine-scale large-eddy simulation of atmospheric flow and land properties (100 x 100 m^2 resolution). These simulations have HARMONIE-AROME boundary conditions set at 2.5 km^2. The situation corresponds to August 15, 2016 at 13.50 UTC.

are crucial and complement each other to better determine the sources and sinks of CO_2.[45] The aircraft network by Gatti et al.[113] collects air samples at four locations across the Amazon, and the Amazonian Tall Tower Observatory (ATTO[30]) provides observations of atmospheric composition and meteorology at a 321 m tall tower in the middle of the Amazon region. The combination of these local- to regional-scale observations allows us to derive the carbon balance for the Amazon, where droughts and fires lead to a reduced capacity of the carbon sink, and therefore, are highly relevant to our understanding. In summary, observations and models on local (Figure 11) to regional (Figure 13) scales enable us to identify and separate the local and nonlocal contributions from moisture and carbon dioxide budgets.

CHALLENGE 4: INTEGRATING SCALES AND PROCESSES: PRESENT AND FUTURE

In this perspective article, we argue that both the short- and long-range tracking methodologies will benefit from new numerical techniques that combine both the explicit treatment of the land use and atmosphere exchange as well as clouds as a continuum, that is, LES, with realistic and accurate embedding on large meso- and synoptic-weather scales. To be consistent with the fine mesh of the numerical atmospheric dynamics and physics part, this should be done with land and topographic information at the same fine spatial resolution as the atmospheric model. Figure 14 shows the level of detail gained with this combined numerical technique that aims to solve the land–atmosphere interaction as a continuum and as explicitly as possible. As such, this technique resolves without parameterizing the different flows driven by surface heterogeneity patterns as shown in Figure 2. In this concrete example, the surface spatial patterns of evaporation show the low values of evaporation driven by the decreases in radiation due to cloud shading (number 1 in Figure 14) that generates a dynamic heterogeneity at the surface.[59] Also impacting the evaporation patterns, but now at larger scales, we find a decrease in evaporation due to the arrival of the sea-breeze front (number 2 at Figure 14) governed by the decrease in the values of the water vapor deficit.

These fine-resolution simulations of the atmospheric flow[114] required new methods which would allow researchers to compare and integrate observations, that is, a TestBed framework. The seminal TestBed designed to simulate and observe the flow at the 213-meter Cabauw tower, and the initiatives taken by Neggers et al.[115] and Gustafson et al.[116] at the Atmospheric Research Facility are all paving the way to move beyond individual case studies. In doing this, the integration of observations and modeling becomes more statistically robust, allowing us to assess the performance of the model and its individual components, normally represented by

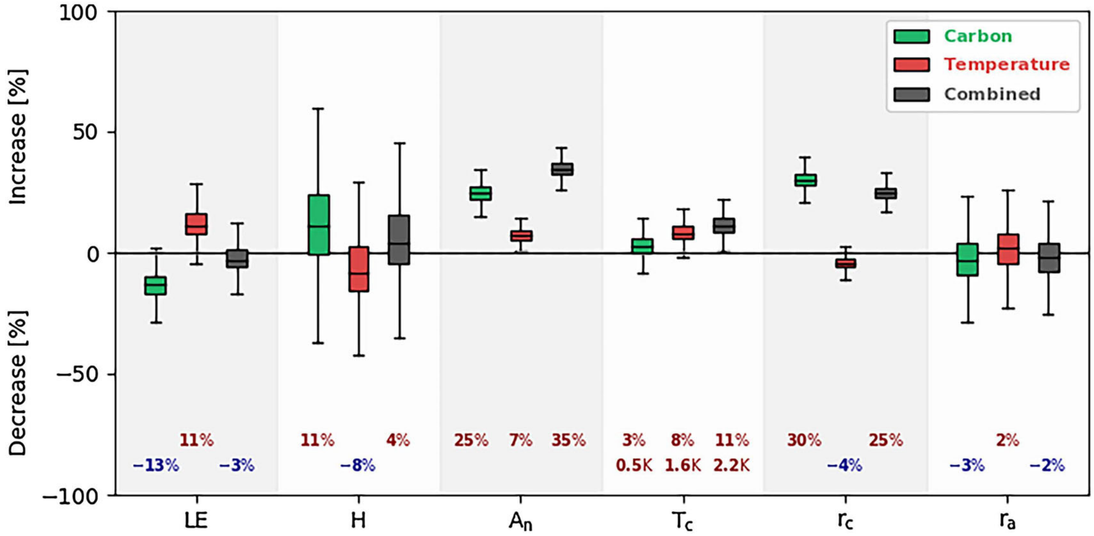

FIGURE 15 Spread in the increase or decrease in surface-related variables as compared to the current atmospheric conditions between 13:00 and 15:00 UTC. Each box plot encompasses 110 million virtual surface observations. The box extends from the lower to upper quartile values, with a line at the median. The whiskers extend from the box to show the range of the data. From left to right, the latent (LE) and sensible heat (H) fluxes, assimilation of CO_2 (A_n), canopy temperature (T_c), canopy resistance (r_c), and aerodynamic resistance (r_a) are shown. The numbers on the bottom show the increase or decrease of the median compared to current atmospheres. Regarding canopy temperature, the averaged differences in Kelvin are shown as well.

parameterization, more completely against a comprehensive observational data set.

This research strategy can be extended and completed using suites of numerical experiments with similar numerical settings to determine how strongly processes such as CO_2 assimilation by photosynthesis and plant transportation are interacting with clouds under future scenarios characterized by enhanced levels of CO_2 concentrations and regional warming.[117] We also argue that this integrative approach in connecting scales should be extended to chemically active species. As shown in the recent work by Ye et al.,[118] surface heterogeneities (in the case of river–land contrast) drive atmospheric circulation of important precursors of aerosol formation, such as isoprenes.

This integrative approach of scales and processes is also suitable to investigate how surface exchange processes will evolve under climate change (see Figure 15).[117] Numerical experiments performed with the LES technique produced three different scenarios influenced by climate change (Figure 3): (1) fertilization effects at the ecosystem level due to more optimal enhanced CO_2 conditions, (2) regional warming due to the enhancement of greenhouse gases, and (3) the combined effects of the first two scenarios. As an example, Figure 15 shows the most representative variables and flux exchange. Focusing on CO_2 assimilation and evaporation, mainly governed by plant transpiration in this numerical example, we find increases of up to 25% CO_2 uptake rates compared to present conditions in the scenario with only CO_2 fertilization, where the increase of CO_2 assimilation due to warming is only 7%. The combined scenario with high CO_2 concentrations and warming shows a nonlinear increase of 35%. With respect to evaporation, we find a decrease of 13% in the CO_2 assimilation scenario due to stomatal closure and an increase of up to 11% in the enhanced warming due to the higher capacity of the atmosphere to hold water. Here, we need to stress the offsetting of both, CO_2 fertilization and regional warming, which makes it more difficult to determine which effect will be dominant. The findings discussed above have an advantage in that processes and their couplings are explicitly represented under future conditions. However, the calculations are limited in the horizontal extent (maximum domain surface are hundred kilometers). To study the impact of land–atmospheric interactions from regional to global scales, we require the use of global climate models.

To understand the counteracting effects of enhanced warming and enhanced CO_2 concentrations, it is necessary to study the impact of plant physiology effects at the regional level. To show this, we base our discussion on the recent study by Park et al.[8] Figure 16 shows the results of 12 state-of-the-art Earth System Models (ESM) from Coupled Model Intercomparison Project Phase 6 (CMIP6). ESM models allow us not only to study the dominant effects as described in Figure 3, but also to determine how land–atmospheric interactions change at the regional level and at climatic temporal scales. They also reveal the discrepancies among the models with regard to representing these interactions. It also enables us to quantify the level of uncertainty in our future predictions of key variables, such as the NEE and cloud cover. We focus our analysis on the Amazonian basin and we show in Figure 16 the variability of cloud cover and NEE. Here, to isolate the plant physiology effect, the radiative effects are kept at preindustrial values but carbon cycle sees 1% yr^{-1} CO_2 increase to quadrupling for 140 years (from 285 to 1140 ppm). Therefore, the temperature changes in Figure 16 are solely driven by modifications in plant physiological processes.

The two upper panels of Figure 16 show how surface temperatures yield modifications in cloud cover and the NEE with respect to the preindustrial period. Here, two opposite effects are at play:

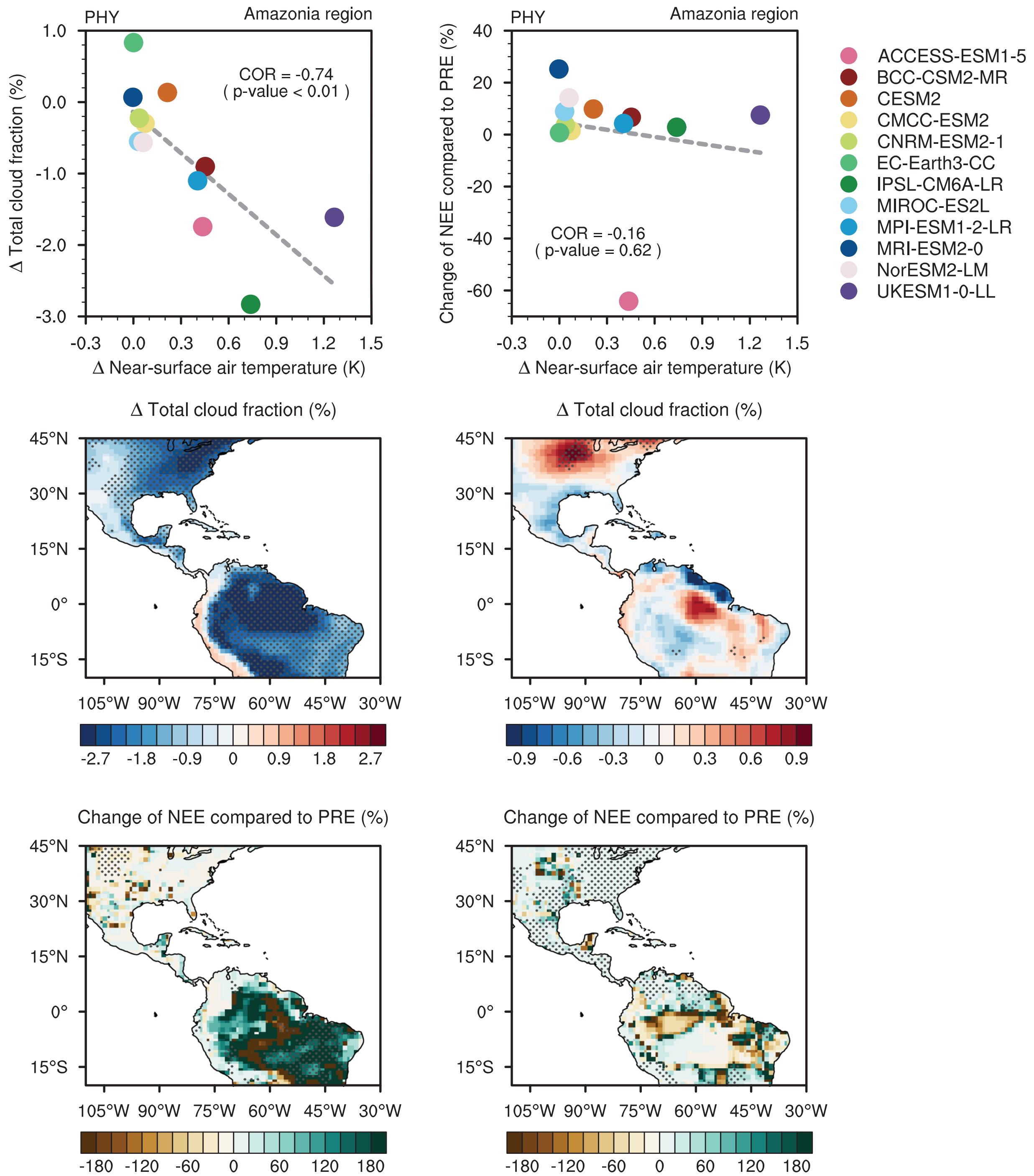

FIGURE 16 Upper two panels: Scatter plot of the differences in near surface temperature and cloud cover (left) and net ecosystem exchange (right). Middle and bottom panels: Composite maps of annual mean changes resulting from CO_2 physiological forcing in total cloud fraction (top), and net ecosystem exchange (bottom) for the top four models with the greatest temperature responses (left) and the bottom four models characterized by the weakest temperature anomalies (right) in the Amazon region from Park et al.[8]

First, we see the effect of fertilization of CO_2 that leads to a stomatal closure, and therefore, a decrease in plant transpiration that leads to a higher sensible heat flux. The second effect, opposite to CO_2 fertilization, is an increase in biomass and a higher leaf area, which leads to increased light interception and canopy transpiration. These effects enhance evapotranspiration and therefore lead to a decrease in the sensible heat flux. In spite of significant differences among the model results, the relatively high correlation between surface temperature and cloud cover indicates that the models more consistently reproduce the effect of enhanced warming leading to a reduction in the cloud cover. Our explanation for this, which is supported by previous studies of vegetation–boundary layer interactions by means of a conceptual model[24] and by vegetation-regional climate models,[8,13] is that CO_2 physiological forcing decreases the cloud cover due to the shift in the surface partitioning from evaporation to sensible heat flux. As a result, there is an increase in shortwave radiation, and consequently, this cloud forcing leads to an increase in the surface temperature. Although this surface temperature enhancement augments the atmospheric capacity to hold water vapor, the decrease of evaporation (and therefore specific humidity) dominates and leads to less cloud cover. In turn, the correlation between surface temperature and NEE remains low. Here, a plausible explanation could be the offsetting effects between lower assimilation at higher temperatures (negative effect on CO_2 uptake) versus the positive effect of higher assimilation due to the effects of CO_2 fertilization. In addition, higher temperatures promote CO_2 soil efflux (negative effect on the net exchange ecosystem). The magnitude of the offsetting depends on how plant physiology and soil efflux are represented in the respective CMIP6 models, and it is difficult to disentangle the individual contributions since they depend on site-specific limitations to growth (light, water, temperature, and nutrients) as studied by Fatichi et al.[119] In line with this perspective, Pietschnig et al. (2021)[120] show that the increase or decrease in precipitation is the result of a combination of local and remote effects in which the ocean-land contrast and dominance play a key role.

The difference in CMIP6 biophysical representations and its impacts are shown in the spatial maps: middle and bottom of Figure 16. Focusing on the Amazonian basin, the carbon-climate models characterized by large surface temperature sensitivity show a decrease in the cloud cover. Several interrelated processes can explain this behavior, but here we focus on the most relevant of the land–atmosphere interaction. As shown in Figure 13, CO_2 fertilization and enhanced warming lead to changes and shifts in evaporation and sensible heat flux. In model results in which the evaporation is dominant, and under similar conditions of available radiative energy, the sensible heat flux at the surface decreases, constrained by the surface energy balance. As a result, turbulence will become less intense and will have a smaller capacity of transporting moisture to the level of condensation, and consequently, less clouds will be formed. The models that are less sensitive to surface temperature show a minor decrease in the cloud cover. Similar patterns are found for NEE with much larger decreases for temperature-sensitive models. These larger differences in the spatial variability among model results illustrate the difficulties in accurate projection of plant physiology on meteorology and atmospheric composition, which in the long term may influence the regional climate. Here, we advocate for dedicated studies using CMIP6 models to determine and quantify the role of individual processes and their coupling under a wide variety of climate scenarios. Contrasting sensitivity analysis (Figure 3) as performed by Park et al.[8] is necessary to disentangle how cloud feedbacks interact with plant physiology effects. By combining turbulent and explicitly cloud–resolving simulations with weather and atmospheric composition at synoptic and mesoscales, we will be able to better asses the links between vegetation and clouds, and therefore, reduce uncertainties in the estimations of trends and spatial distributions in cloudiness and NEE.

CONCLUSIONS AND PERSPECTIVES

This perspective article aims to advance our ability to connect and integrate processes that are usually treated separately in the disciplines of biology, chemistry, or atmospheric physics. As key components of the water and carbon cycles, we focus on intrinsic relationships in photosynthesis and plant transpiration as the most representative land processes that influence cloud formation and carbon exchanges depending on the scales where they are acting, from leaf to regional scales. These processes play key roles in determining the surface energy balance, the boundary-layer dynamics, and clouds. In connecting as a continuum these local land–atmosphere interaction processes on the one hand with weather and climate on the other hand, we aim at improving our understanding of the transport and fate of greenhouse gases, reactive species, and aerosol formation. By improving the representations of these processes, normally characterized by small and short spatiotemporal scales, and their couplings, we aim to reduce uncertainties in estimations of NEEs and cloud feedback at regional scales. The four interactive challenges set out in this paper argue for the need to move forward in:

Challenge 1: Radiation and photosynthesis. Treating and observing radiative transfer needs to take into account three-dimensional aspects in order to improve the simultaneous effects of radiation perturbations by clouds and penetration in the canopy. These studies need to be completed using detailed measurements of photosynthesis and stomatal aperture at the leaf level during the day and as a function of the height of the canopy under shaded and sunlit conditions. More accurate calculations and measurements of radiative transfer also benefit atmospheric chemistry by improving estimations of photolysis rates perturbed by clouds and the canopy.

Challenge 2: Cloud and canopy–atmosphere interactions. We propose to first study the turbulent fluxes on shorter time and spatial averaging scales using observations collected with the scintillometer technique (1-min) and numerical experiments using the LES technique. In so doing, we can obtain better relationships between clouds, and the subsequent perturbation of radiation and the impact on the canopy turbulent fluxes. Second, we suggest including measurements of the fluxes of stable isotopologues to advance our understanding of the partitioning of evaporation/sensible heat flux and plant assimilation/soil respiration. Third, we propose extending the turbulent flux measurements to measure greenhouse gases and chemically reactive species together to quantify the role of turbulence in transporting, mixing, and controlling chemical transformations. The previous points based on advanced observations should be integrated in fine-scale modeling based on LES techniques to study the processes as explicitly as possible and as a continuum that links ecosystem processes with clouds. This is key to disentangling the contrasting effects of individual processes. For instance, under rising CO_2 concentrations, a reduction in leaf-level transpiration due to stomatal closure might be compensated by an increase in the total-leaf area that leads to shifts in the partition between sensible and latent heat flux at the surface. All these canopy–cloud interactions are region-specific and dependent on climate change.

Challenge 3: Organization of atmospheric flow influenced by land properties and regional weather and atmospheric composition. We suggest integrating these small and short spatiotemporal processes into regional weather and atmospheric composition since these are factors that continuously interact with the local conditions. In extending how these local conditions are influencing the spatial patterns of vegetation and clouds, we present methods that enable us to quantify which variables or processes govern the organization of clouds. A natural extension of these studies is to relate them to vegetation patterns to determine the level of coupling between cloud and ecosystem organizations. Both aspects are relevant to improving our current estimations of the regional precipitation and NEE. To advance our understanding, we propose methodologies that track clouds and air masses from local to regional scales to determine simultaneously sources and sinks of moisture and carbon dioxide.

Challenge 4: Integrating scales and processes: present and future. We advocate studying present and future scenarios by performing LES embedded in numerical weather prediction and carbon-climate models to attempt to reduce the uncertainties in the feedback of clouds on surface processes. We also need to investigate how locally driven surface processes influence weather and climate in forming and intensifying clouds. In the current analysis of climate model results, we have evidence that there are important differences between the present situation compared to preindustrial conditions that are keys for representative variables, such as cloud cover and NEE. We argue that these differences are due not only to crude representations of plant physiology effects and clouds, but also to the need to treat the atmospheric flow as a continuum that connects short- to large-scale processes and phenomena. If these effects prove to be relevant, we need to take them into account in weather and climate models along with the effects of spatiotemporal changes in atmospheric composition. Here, we should pay special attention to the fact that some effects occur at shorter time scales, such as stomatal closure or boundary-layer cloud formation. Others may take longer to emerge, such as canopy effects because of an increase of the LAI and the atmospheric radiative effects driven by an increase of the greenhouse gases.

AUTHOR CONTRIBUTIONS

J.V.-G.A. designed and wrote the paper. The rest of the co-authors provided figures and feedback during the last 5 years. All the authors read the paper and commented.

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COMPETING INTERESTS

There are no competing interests.

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