# Satellite-derived canopy temperature measurements: Recent efforts, limitations, and implications

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Canopy temperature (Tc) refers to the effective radiative temperature of the vegetation canopy, which is a significant biophysical variable linked to water and carbon cycles in terrestrial ecosystems. As Tc is strongly influenced by transpiration, stomatal regulation, and energy-flux partitioning, it serves as a dynamic integrator of canopy physiological status and a key driver of carbon uptake and land–atmosphere interactions under climate variability. Compared to ground measurements with limited spatial representativeness, satellite remote sensing is expected to provide spatially continuous Tc estimations across ecosystems, enabling large-scale assessment of canopy thermal conditions in a changing climate. For decades, most studies have focused on developing land surface temperature (LST) products from optical/thermal and microwave observations.[1] While LST is used as a proxy for Tc, it often reflects a mixture of canopy and soil thermal signals, which restricts its applicability for Tc-specific purposes. Although recent efforts have attempted to separate Tc from satellite-derived LST, operational Tc products remain scarce, and either LST or air temperature (Ta) continues to be commonly utilized as a practical alternative for Tc. Such proxy-based substitutions are also pervasive in terrestrial ecosystem analyses, and high-precision Tc products derived from satellites have the potential to correct systematic biases in existing studies. In this context, this paper highlights recent progress in Tc product development, outlines key limitations, and discusses their implications across different research domains (Figure 1).

## RECENT DEVELOPMENTS OF SATELLITE $T_C$

At this stage, most satellite-based approaches for estimating Tc rely on separating soil and canopy signals from satellite LST using fractional cover and/or energy balance assumptions (Figure 1A). Therefore, the bottlenecks discussed here primarily arise from the reliance of current Tc estimation on LST and its subsequent decoupling. In addition, Tc estimation involves challenges specific to canopy–background thermal separation and canopy structural effects. Recent advances could be summarized into three categories: (i) Thermal infrared (TIR) algorithms, including single-channel, split-window, temperature–emissivity separation, and diurnal-cycle methods, provide relatively accurate LST under clear skies but are constrained by cloud contamination, uncertainties in surface emissivity, and sub-pixel heterogeneity, which propagate into Tc estimation. (ii) LST enhancements through multi-source integration of TIR and reanalysis data (e.g., ERA5), including spatiotemporal gap-filling, energy balance–based reconstruction, and fusion between polar-orbiting and geostationary sensors to improve diurnal sampling and continuity, which support more consistent Tc estimation. (iii) Microwave-based LST estimation and microwave–TIR fusion methods offer all-sky condition sensing and improved diurnal characterization, yet are limited by coarse spatial resolution and sensitivity to surface and vegetation conditions. These developments underpin the current paradigm of Tc estimation and largely shape its feasibility and performance.

Based on these advances in LST retrieval, Tc estimation has evolved from an implicit assumption that LST represents the canopy to a more explicit separation of canopy and soil temperatures. Early studies used multi-angular, spectral information, and spatial differences in TIR observations to constrain the mixed signals of canopy and soil, showing that Tc can be retrieved when viewing-angle differences or variations in vegetation cover provide additional constraints.[2] Physical approaches later incorporated radiative transfer models (RTM) and coupled soil–canopy energy balance constraints, which improved the consistency of Tc estimation but also increased sensitivity to uncertainties in vegetation cover, emissivity, and canopy structural parameters. Some efforts also combined multi-temporal TIR, auxiliary vegetation information, and reanalysis data to resolve the Tc component. These advances show that large-scale Tc estimation is feasible. Although methods have clearly moved beyond proxy-based assumptions, a reliable operational Tc product is so far not available.

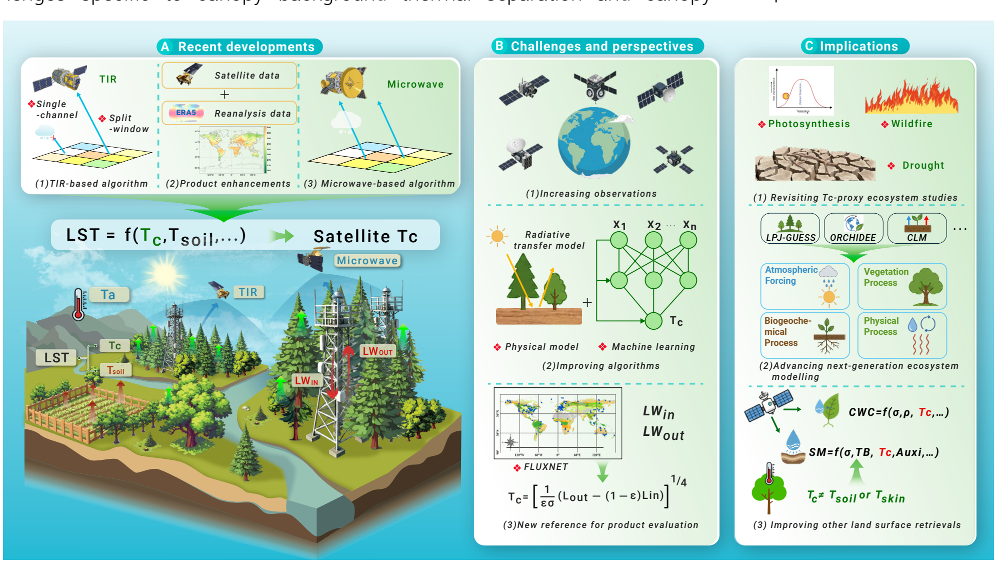


**Figure 1. Satellite remote sensing for Tc estimation.**

## CHALLENGES AND PERSPECTIVES FOR SATELLITE $T_C$

Current Tc estimation faces three major constraints: (i) It is difficult to derive Tc when satellite measurements do not provide sufficient angular, temporal, or vegetation cover variations to disentangle canopy and soil contributions, particularly in cloudy or complex surface conditions. This limitation is fundamentally related to the magnitude of the Tc–background (e.g., Tc–LST or Tc–Tsoil) temperature difference relative to retrieval uncertainties, which determines whether canopy thermal signals can be effectively distinguished. (ii) Many existing algorithms rely on multiple external inputs such as vegetation cover, emissivity, and reanalysis data, and uncertainties and spatiotemporal inconsistencies in these datasets can affect Tc estimation. (iii) For product evaluation, the lack of spatiotemporally representative Tc observations constrains a comprehensive assessment of satellite-derived products. In some existing studies, near-surface Ta has often been used as alternative solutions providing evaluation benchmarks assuming strong canopy-air coupling, yet this does not accurately reflect the true thermal state of the canopy, thereby limiting thorough validation across different ecosystems. And the limited representativeness of Ta stations, especially in tropical and mountainous regions, imposes constraints on the validation.

Regarding further directions for the improvements (Figure 1B): (i) integration of multiple satellite observations including TIR, microwave and model-based data has the potential to enhance temporal sampling and reduce cloud-related gaps for Tc estimation as done in some LST reconstruction studies, while accounting for differences in sensing depth and the resulting contributions from canopy and soil components. (ii) As for the method, a practical direction is to combine physical models (e.g., RTM) with machine learning approaches, which can learn systematic residual errors linked to external inputs and improve parameter adaptability across various ecosystems while maintaining physical interpretability. (iii) More importantly, as pointed out by recent studies,[3] in situ Tc could be approximated at ecosystem scale by globally distributed flux-tower networks over diverse ecosystems (e.g., FLUXNET and ICOS), using observations of longwave upwelling radiation, which is related to canopy radiative temperature. These observations provide a practical benchmark for calibrating Tc retrieval models and validating emerging Tc products, while complementary experimental and field-based investigations are still needed to better constrain the underlying physical relationships across scales.

## IMPLICATIONS OF SATELLITE-DERIVED $T_C$

Due to the absence of long-term operational global Tc products, most existing ecological studies on terrestrial ecosystems have relied on Ta or LST as substitutes for Tc. However, increasing in situ measurements have demonstrated that Tc can depart substantially from Ta, clearly challenging the limited-homeothermy theory.[4] Similar assumptions are also common in other remote-sensing applications; for instance, in microwave soil moisture retrieval, soil temperature or LST are frequently used as a practical proxy for Tc. Therefore, operational global Tc products at sub-daily temporal resolution are expected to provide new constraints for terrestrial applications, given the pronounced diurnal variation in Tc, by providing canopy-specific thermal information at diurnal timescales. We summarized three areas that benefit from sub-daily Tc products (Figure 1C). These applications also highlight key requirements for improving Tc retrieval from a remote sensing perspective: **(i) Revisiting Tc-dependent ecosystem studies**. With reliable Tc products, many past studies that used Ta or LST to investigate ecosystem processes can be re-examined. These include assessments of heat and drought stress, plant thermal regulation, and temperature-dependent ecosystem processes. Evidence from recent work shows that LST/Tc and Ta often differ by several degrees across seasons and high-latitude biomes,[5] and this difference can shift estimates of photosynthetic temperature optima, thermal acclimation patterns, and carbon–water coupling. Operational Tc products therefore are expected to provide an opportunity to revisit these studies using proxy data for Tc. **(ii) Advancing next-generation ecosystem modelling**. Many process-based ecosystem and land-surface models (e.g., LPJ-GUESS, CLM, and ORCHIDEE) internally diagnose canopy or leaf temperature through parameterized energy-balance formulations, but these simulated Tc fields have rarely been evaluated at large scales due to the historical lack of observational Tc products. A satellite-derived Tc product would provide observational benchmarks to calibrate these temperature responses. It would advance next-generation ecosystem models by directly constraining Tc, which improves parameterization in canopy energy balance and leads to more accurate simulations of carbon and water fluxes, and long-term vegetation dynamics. Additionally, satellite Tc data assimilation also provides a pathway to improve land surface modeling. **(iii) Improving other land surface retrievals**. Beyond microwave soil moisture retrieval, estimation of other terrestrial variables, such as evapotranspiration, vegetation water content from satellite observations, also depends on accurate parameterization of Tc in the retrieval algorithms. When Tc is proxied by soil temperature, LST, or near-surface Ta, canopy thermal and radiative properties can be misrepresented, and these errors may propagate into the developed products. With reliable Tc products becoming available, these limitations can be reduced, enabling more physically consistent land surface retrievals.

## SUMMARY AND OUTLOOKS

This paper presents the recent progress, challenges, and future directions on satellite Tc estimation, as well as its implications on terrestrial applications. Further efforts could be made by incorporating multi-source (e.g., TIR and microwave) satellite observations, using physically guided machine learning approaches, and introducing globally distributed flux-tower networks as the benchmark. These efforts and directions are expected to provide more accurate Tc estimation and further contribute to the global operational Tc products. Reliable Tc products from satellite observations will reshape several terrestrial applications, by revisiting Tc-proxy studies, promoting next-generation ecosystem process models, and improving the retrieval of related land surface parameters.

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## AUTHOR CONTRIBUTIONS

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## DECLARATION OF INTERESTS

The authors declare no competing interests.