Synergy of Thermal and Solar-induced Fluorescence Remote Sensing for Crop Water Stress Monitoring

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Effective and timely monitoring of crop water stress is critical for achieving agricultural sustainability. In our Dragon 6 project, we aim to synergistically utilise thermal infrared (TIR) and solar-induced fluorescence (SIF) observations from ESA and Chinese satellites to monitor crop water stress The key scientific objectives of this project are: 1) refining the land surface temperature (LST) retrieval method, 2) advancing evapotranspiration partitioning into soil evaporation and plant transpiration using an analytical model driven by LST, 3) developing models for estimating plant transpiration using SIF observations, 4) developing downscaling methods for LST and SIF data to fine spatial resolutions, and 5) enhancing crop water stress monitoring capability based on plant transpiration and SIF estimates. The progress in these five work packages (WP) for the last year is described as follows:

WP1. LST retrieval algorithm.

A new LST retrieval algorithm was developed by integrating the physical mechanisms of the split window (SW) and temperature emissivity separation (TES) algorithms into the deep learning (DL) model, constructing the DL-SW-TES framework. This new framework directly retrieves LST from easily accessible parameters without requiring any prior knowledge of LSE information and atmospheric profiles.

WP2. ET partitioning.

An advancement of the analytical surface energy balance (SEB) model STIC is envisaged. A “top-down” decomposition approach will be adopted based on the SW85 model. Such a method requires lumped estimates of energy fluxes (latent heat flux (ET), sensible heat flux, net radiation, and ground heat flux) in conjunction with air and dewpoint temperatures, LST, canopy-air vapor pressure, and aerodynamic conductance (g_A). The energy fluxes, canopy-air vapor pressure, and g_A are retrievable from STIC.

WP3. Modelling transpiration from SIF.

Two modelling approaches are planned. The first one is based on the connection of plant transpiration and photosynthesis through stomatal conductance. The second method is based on the FEST-2X2-EWB model. The FEST-2X2-EWB model computes continuously in time and distributes in space the total ET as well as the soil and vegetation components, and soil moisture at multiple soil layers. FEST-EWB computes LST as an internal variable and has physically-based non-residual formulations for the energy balance components (and can be used for model calibration or for updating the model state through data assimilation.

WP4. LST and SIF downscaling

The LST downscaling is planned to use a deep-learning based method. The estimated LST using the developed LST retrieval algorithm in WP1 will be input into the deep-learning framework. High spatial resolution LST will be obtained by combining ECOSTRESS and SEVIRI LST estimates.

To address systematic errors in SIF downscaling caused by canopy shadow, we implemented BRDF correction for vegetation indices and utilized SIF_n to minimize angular and PAR effects, generating a 500m SIF product. Subsequently, a Random Forest model was developed using VPD, LAI, and the generated SIF to estimate evapotranspiration, achieving high fitting accuracy across cropland, broadleaf forests, and needleleaf forests.

WP5. Crop water stress indicator development

we developed a novel crop water stress indicator, SIF_n, by minimizing the impact of angular effects and PAR variations on satellite-derived solar-induced fluorescence (SIF). During the 2019 North China Plain drought event, SIF_n exhibited an earlier decline and greater sensitivity in detecting the onset of water stress compared to traditional vegetation indices, raw SIF, and fluorescence quantum yield (ΦF). Furthermore, SIF_n anomalies showed a notable correlation with rainfall and meteorological factors, revealing the dynamic contributions of both canopy structure and vegetation physiology to SIF across different drought phases. These findings underscore SIF_n's potential to enhance the accuracy and timeliness of crop water stress monitoring.

Overall, these advancements in LST and plant transpiration retrieval, SIF downscaling will support the crop water stress monitoring with soil-independent information at high spatial resolutions.

热红外与太阳诱导荧光遥感协同作物水分胁迫监测

有效、及时地监测作物水分胁迫对于实现农业可持续发展至关重要。在龙计划六项目中，我们旨在协同利用来自欧空局（ESA）和中国的热红外（TIR）和太阳诱导荧光（SIF）卫星观测数据来监测作物水分胁迫。本项目的主要科学目标包括：

1）优化地表温度（LST）反演方法；

2）利用LST驱动的解析模型，将蒸散（ET）划分为土壤蒸发和植物蒸腾；

3）基于SIF观测开发植物蒸腾估算模型；

4）开发LST和SIF数据的空间降尺度方法；

5）基于植物蒸腾和SIF估算，提升作物水分胁迫监测能力。

过去一年中，针对上述五个研究目标（WP）， 我们取得的进展如下：

WP1. 地表温度（LST）反演算法

开发了一种新的LST反演算法，将分裂窗口（SW）和温度-发射率分离（TES）算法的物理机制融合进深度学习（DL）模型中，构建了DL-SW-TES框架。该新框架可直接利用易获取的参数反演LST，无需预先了解地表发射率（LSE）信息和大气廓线。

WP2. 蒸散分离（ET Partitioning）

计划推进解析表面能量平衡（SEB）模型 STIC 的发展。将采用基于 SW85 模型的“自上而下”分解方法。该方法需要对能量通量（潜热通量 ET、显热通量、净辐射和地热通量）进行整体估算，同时结合空气和露点温度、LST、冠层-空气蒸汽压差以及空气热动力学导度。能量通量、冠层-空气蒸汽压差和空气热动力学导度可通过STIC模型获取。

WP3. 基于SIF的植物蒸腾建模

计划采用两种建模方法。第一种方法基于植物蒸腾与光合作用之间通过气孔导度连接的关系；第二种方法基于FEST-2X2-EWB模型。该模型可在时间上连续运行、空间上分布地计算总ET以及土壤和植被的蒸散分量，并能模拟多层土壤湿度。FEST-EWB将LST作为内部变量计算，采用物理基础的非残差能量平衡分量计算方法，可用于模型校准或数据同化过程中的模型状态更新。

WP4. LST和SIF的空间降尺度

LST 空间降尺度计划采用基于深度学习的方法。WP1 中开发的 LST 反演算法生成的 LST 将作为输入，通过结合ECOSTRESS和SEVIRI的LST估算，获得高空间分辨率的LST。

为解决冠层阴影导致的 SIF 下推系统误差，研究引入了植被指数的 BRDF 校正，并使用 SIF_n 来最小化角度和光合有效辐射（PAR）的影响，生成了 500m 分辨率的 SIF 产品。随后，利用 VPD、LAI 和生成的 SIF 数据构建了随机森林模型，用于估算蒸散，在农田、阔叶林和针叶林区域均表现出较高的拟合精度。

WP5. 作物水分胁迫指标开发

我们开发了一种新型作物水分胁迫指标 SIF_n，通过最小化卫星 SIF 数据中的角度效应和 PAR 变化影响，实现了更准确的监测。在 2019 年华北平原干旱事件中，SIFn 相较传统植被指数、原始 SIF 和荧光量子产率（ΦF），表现出更早的下降趋势和更强的水分胁迫响应能力。同时，SIF_n 异常值与降水及气象因子密切相关，揭示了不同干旱阶段冠层结构和植被生理状态对 SIF 的动态影响。这些发现突显了 SIF_n 在提升作物水分胁迫监测准确性和及时性方面的潜力。

总体而言， 在 LST 与植物蒸腾反演、SIF 空间降尺度等方面的进展，将为剔除土壤背景信息、高空间分辨率的作物水分胁迫监测提供有力支持。