ETWatch: models and methods

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Abstract: Evapotranspiration (ET) is not only an important part of the coupled Eco-Hydrological processes, but also primary way of eco-agricultural consumption. A better description of the temporal-spatial pattern of a watershed greatly will enhance people's understanding of hydrological processes and the water management approach. As quantitative measurement of surface heterogeneity, remote sensing and surface observations are combined to develop operational methods and determine eco-hydrological variables. ETWatch is such an operational platform which is designed for practical needs of watershed planning and agricultural water management using remote sensing techniques that can describe the spatial distribution and time process of surface net radiation, sensible heat, and latent heat (ET). The reviewing of algorithms and approaches show that the parametric approach is the core component to improve the accuracy of ET estimation at regional scale and apply remote sensed ET for practical goals. The other bottlenecks include scaling, multi-source data integration and validation of modeling. Potential approaches used in ETWatch to the above issues are summarized and commented.

Key words: remote sensing, evapotranspiration, parametric method, ETWatch, validation, calibration

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1 INTRODUCTION

Evapotranspiration (ET) is not only an important part of the coupled Eco-Hydrological processes linked energy and material balance of the watershed, but also a primary way of eco-agricultural consumption. A better description of the temporal-spatial pattern of a watershed greatly will enhance people's understanding of hydrological processes and the water management approach. As heat exchange of land surface is influenced largely by environmental factors, including terrain, geographical location, and characteristics of the underlying surface, the surface evaporation of different underlying surfaces varies greatly. In order to access actual ET, scientists established several ground measurement and calculation approaches, including micro-meteorological, the Bowen ratio, the soil water depletion method, and the eddy covariance system. These methods can only provide point values at local scale, while the ET estimation often is required at watershed scale for the practical goals in hydrological project designing, drought monitoring, and water resources assessment (Liu, 1997).

Evapotranspiration is highly variable in time and space due to the meteorological conditions, precipitation, soil hydrological parameters, vegetation type and density (Turner, *et al*., 1995). Remote sensing methods can provide variables as input for the surface energy balance model, such as surface albedo, soil moisture, surface temperature and roughness, and other important parameters. A number of remotely-sensed models are applied widely in different areas (Allen, *et al*., 2005; Bastiaanssen, *et al*., 1998; Nishida, *et al*., 2003; Su, 2002; Wu, *et al*., 2008). Remote sensing could provide regional ET data to meet the needs of hydrology, ecology, agriculture, forestry, and related research (Kalma, *et al*., 2008).

Due to the complex process of the evaporation process, much uncertainty remains, including the accuracy of surface parameters input, the applicability of the theoretical model, time-scaling, and the advection impact (Gao & Long, 2008; Huang, *et al*., 2004). The quantitative retrieval of evapotranspiration using remote sensing needs to make full use of surface dynamic monitoring ability of multi-source remote sensing data, to develop transforming methods between different spatial-temporal scales, and to keep a balance between the parametric method and model validation. It must be remembered that a significant improvement in the algorithm may not obtain a good result. The lack of adequate and effective precision validation of data products greatly will limit the application in the industry.

The reviewing of algorithms and approaches show that the parametric approach is the core component to improve the accuracy of ET estimation at regional scale and apply remote sensed ET for practical goals. The other bottlenecks include scaling, multi-source data integration and validation of modeling. Potential approaches used in ETWatch to the above issues are summarized and commented.

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2 THE ETWATCH MODEL

Remote sensing is considered to be an efficient approach that can obtain a wide range of surface energy and water dynamics. Since 1990s, the large number of papers are published on the use of remotely sensed land surface data to estimate ET using different models (Kalma, *et al*., 2008), which can be divided into two categories.

The first category is based on the single-layer model of Penman-Monteith (P-M) (Cai, *et al*., 2007). The P-M model provides a equation to reflect the instantaneous exchange of the approximate analytical equation of energy with an approximation to aerodynamic temperature using air temperature (Widmoser, 2009). Through simplifying the surface conductance expressions, Mu developed a global scale ET algorithm based on MODIS and a meteorological dataset (Murray, *et al*., 2007; Cleugh, *et al*., 2007). Canopy and aerodynamic resistance still require a great many ground observations (Sun, *et al*., 2009), which are crucial information and are difficult to obtain even unknown for large scale applications (Raddatz, *et al*., 2009).

The second category is the "Residue Approach," which takes sensible heat flux (H) as the core inversion parameter from the energy balance. Besides aerodynamic resistance and wind velocity, the other types of input can be obtained by means of remote sensing (Mallick, *et al*., 2007; Matsushima, 2007). In order to reduce the model dependence on aerodynamic resistance, the atmospheric surface layer similarity theory is applied to establish empirical methods (Bastiaanssen, *et al*., 1998; Jia, *et al*., 2003; Su, 2002), which can work well under the high vegetation coverage and even underlying surface(Allen, *et al*., 2005, Kalma, *et al*., 2008). Shuttleworth and Wallace (1985) promoted a two-layer model for sparse canopy coverage to consider evaporation and transpiration separately within the canopy of water vapor and energy exchange. Due to the inconsistency that exists between radioactive temperature and air temperature, the operational algorithm should be improved further.

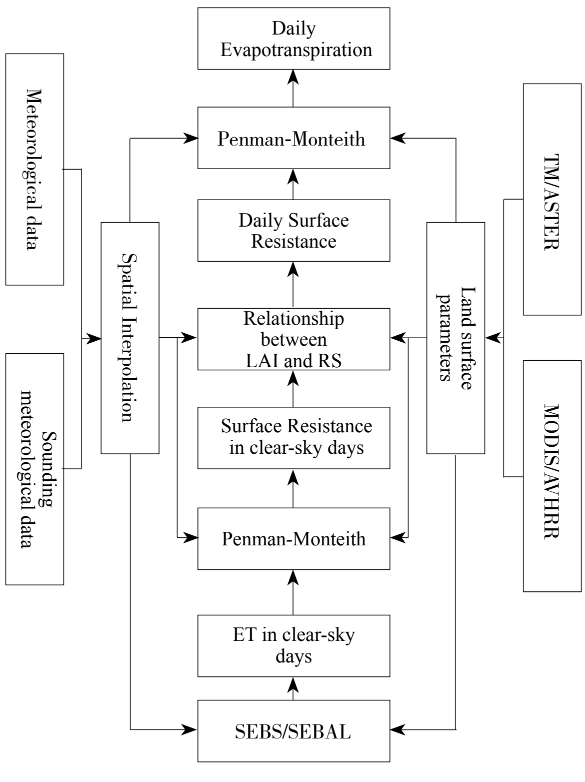

Fig. 1 ETWatch Process Flowchart

ETWatch is an integrated innovation of "Residue Approach," and Penman-Monteith (P-M)(Fig. 1). Firstly, SEBAL and SEBS model are combinations of the energy balance theory and the mass transfer method and are used to compute the evaporation from cropped surfaces based on the standard climatological records of sunshine, temperature, humidity, and wind speed by introducing resistance factors, and the P-M model determines the spatio-temporal variability of the regional evaporative condition. Secondly, we chose available surface resistance (RS) as the temporal-scaling factor. While bulk surface resistance is properly defined, the P-M equation is valid for both soil and vegetation canopy (Wu, *et al*., 2008a). Thirdly, a fusion algorithm is applied to integrate ET maps at different resolutions. In that case, ETWatch can provide a useful dataset for water resources assessment and management of agricultural water (Wu, *et al*., 2008b).

3 PARAMETERIZATION IN ETWATCH

Parameterization of the heat and water exchange process is the core issue of the ET model. Since all of the surface variables are both highly spatial and temporally heterogeneous, the application of an empirical formula established at the local scale is very limited. To achieve quantitative description of a wide range of surface variables requires validation and optimization in combination of ground truth data. The parametric method varies due to different scales. Therefore, a parameterization scheme could be more flexible, and an atmospheric turbulence model could be more complex when low-resolution remote sensing data is used. A simplified empirical model calibrated by local data will perform well when high-resolution remote sensing data is used.

Currently, net radiation is calculated from the land surface energy balance, while the soil heat flux is retrieved from an empirical relationship with net radiation (Su, 2002) or a more comprehensive parameterization using vegetation, soil texture, and water on the heat flux (Murray, *et al*., 2007). Sensible heat flux is determined only by surface temperature and air temperature at the reference height, which should be revised through iterative calculation to force its value to be fitted with the available energy.

Surface temperature has been accepted as a relatively mature production that can be obtained by using remote sensing (Wan, *et al*., 2004). In order to reduce the sensitivity of the surface temperature product in the ET model, Anderson, *et al*. used multi-time observation of land temperatures from a geostationary satellite to develop a two-layer model (Anderson, *et al*., 1997; Anderson, *et al*., 2007), and adopted the DisALEXI algorithm to disaggregate 5 km to 10 km pixels into a micro-meteorological scale (100 m to 1 km). An improved split-window method is used (Mao, *et al*., 2005; Wan & Dozier, 1996) for retrieving surface temperature and then calibrating it by ground measurement. A sine transform was applied to adjust temperatures of the boundary layer from 12:00 am to 1:30 am (which was the satellite overpass time) to reduce the difference between the measurement time of the satellite and a meteorological balloon (Xiong, *et al*., 2010).

Estimation of the daily net radiation flux greatly influenced the daily ET value. Daily solar radiation is often calculated by using meteorological observations, which is usually not very representative of the heterogeneous underlying. Generally, weather stations are located in flat, small-obstacle areas, while terrain factors have significant impact on radiation especially in middle and high latitudes, which should be parameterized in the model (Tian, *et al*., 2007). We fit the monthly shortwave radiation equations, establishing a lookup spatial map by longitude and latitude based on seven radiation stations located in the Hai Basin.

Surface fluxes are functions of surface aerodynamic roughness, which is difficult to retrieve directly by using remote sensing. Aerodynamic parameters are quite sensitive to regional plant vegetation density, height, canopy density, and wind speed variations (Zhu, *et al*., 2004). For different types of land surfaces, due to the variable geometric characteristics, the error can reach several orders of magnitude (Zhang, 2002). The simplified relationship between roughness and vegetation height, and empirical value based on a land-use map is limited (Allen, *et al*., 2007). Using radar data has potential because SAR backscattering coefficient maps are determined largely by the rough surface conditions (Prigent, *et al*., 2005). In ETWatch, three factors were taken into account to obtain the regional roughness length for momentum transfer z0m, including vegetation, topography, and non-vegetation obstacles, to express the region's comprehensive and effective roughness (Wu, *et al*., 2008; Xiong, *et al*., 2010).

4 TEMPORAL-SCALING IN ETWATCH

Due to cloud cover, the ET data contain large spatial and temporal gaps. For example, MODIS provided on average 22% daily clear-sky coverage over Hai Basin from 2002 to 2008. To facilitate investigations of monthly or seasonal surface water consumption, techniques for filling gaps have been investigated. Previously, gap-filling approaches assumed a degree of "self-preservation" in the evaporative fraction (EF) from a clear day to consequent days (Brutsaert, *et al*., 1996; Porté-Agel, *et al*., 2000). Allen, *et al*. (2007) found that the fraction of equilibrium ET (proportional to potential ET) is more conservative over a period of several days than are other reference flux indices, such as the evaporative fraction or the Bowen ratio, while adjusting for soil moisture depletion. In the previous studies, a smoothing algorithm usually was used on temporal-scaling in longer periods (Xi, *et al*., 2008) on the assumption that changes in daily weather conditions and surface conditions could be ignored.

Anderson, *et al*. (2007) promoted a concept model using soil water content to calculate the daily change of surface ET. Jang, *et al*. (2010) assimilated energy fluxes of clear days into a meso-scale climate model to compute ET on cloudy days using a four-dimensional assimilation technique. The temporal-scaling module in ETWatch is the integration of the above methods. In order to digest daily meteorological data, the P-M model was found to be adequate to estimate the magnitude and seasonal variation of evaporation in both temperate and tropical ecosystems.

The gap-filling of ET on cloudy days was accomplished by a combination of flux outputs and the P-M equation (Liu, *et al*., 2011). The minimum surface resistance was updated via an inversion of fluxes result from clear days. On cloudy days, the P-M equation was reapplied directly to predict the ET value as in the prognostic approach (Fig. 2). The gap-filling result showed good correlation ($R^2 = 0.7$) compared to a ground lysimeter at the Yuchange Site, which is better than the EF-const method (Xiong, *et al*., 2008).

The most difficult part in temporal-scaling is the ET estimation during cloudy and rainy weather according to microwave surface temperature and moisture (Zhang, 2009).

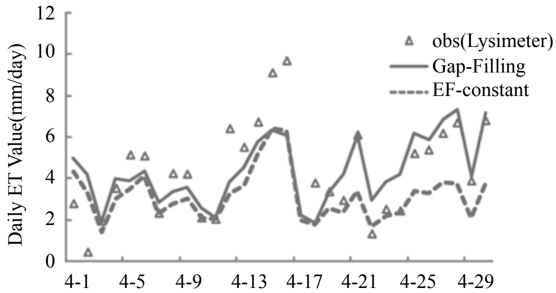

Fig. 2 Comparison of the daily ET measurement (lysimeter) and the gap-filling estimation at the Yucheng site, April, 2003

5 INTEGRATION OF MULTI-SOURCE DATA FROM REMOTE SENSING

It is in urgent need for high-resolution maps of ET to monitor water consumption at field scale. Landsat satellites can provide detailed information about vegetation and temperature without crop growth curves, and MODIS/AVHRR can provide sufficient temporal resolution, but the spatial resolution cannot achieve the accuracy requirements. Hafeez, *et al*. (2002) compared fluxes estimation using LandSat TM / ETM +, TERRA / MODIS, TERRA / ASTER DATA, and the results showed that MODIS retrieval accuracy is relatively high, with an average error of about 20%. The use of a single sensor such as ETM+ is feasible, but having only one thermal infrared band limits its precision (Ma, *et al*., 2004). Therefore, scientists also develop approaches to integrate multi-source data to estimate ET, such as joint ET inversion using MODIS and CERBS-02 data in Baiyangdian (Xin, *et al*., 2005) and applying the combination of TM and MODIS data into a hydrological model in a tropical rain forest (Wu , *et al*., 2006). We extended the STARFM model (Meng, *et al*., 2010) to thermal infrared band in ETWatch, realizing the data-fusion of moderate-resolution ET maps and high-resolution ET maps. The parameterization, temporal-scaling, and data-fusion form an applicable framework of operational ET monitoring approach.

6 VALIDATION OF THE REMOTELY-SENSED ET PRODUCT

Available ground flux measurement is increasing every year, but the lack of flux precision standards hinders effective validation to remotely-sensed products. Farahani, *et al*. (2007) pointed out that the error between the Bowen ratio and an eddy correlation instrument is often up to 20%. For well-maintained and calibrated sites, this error can be reduced to 10% (Glenn, *et al*., 2007), but it also increases rapidly when the underlying heterogeneity is increased.

Li, *et al*. (2004) performed a comprehensive evaluation of energy balance closure at the China FLUX Network, finding that sensible heat and latent heat turbulent fluxes tend to be underestimated, and the available energy may be overvalued. The disclosure of energy balance measure in AmeriFlux sites is summarized in Wilson's (2002) paper. Therefore,the evaluation based on a water-balance equation at the sub-basin scale is optional (Wu, *et al*., 2009).

In recent years, the large aperture scintillometer (LAS) has been used to measure average sensible heat flux from 200 m to 10 km, and the measurement can be comparable to the pixel-scale fluxes obtained using remote sensing, but the influence of source area and the mixing height needs further study based on a ground experiment (Marx, *et al*., 2008). For a heterogeneous, fragmented land surface, how to calculate fluxes at the pixel scale matched with remote sensing images is an unresolved important question that remains. A footprint model was used to relate source area distribution with surface roughness, wind velocity, and atmospheric stability, providing a theoretical framework to study the representative assessment of flux data. However, the existing footprint models are established on the assumption of near-neutral atmospheric conditions, which is hard to meet under a stratification stability condition (Gockede, *et al*., 2005).

It is still in dispute that under complex underlying and stable-stratification conditions, the surface flux estimation needs to consider canopy heat storage, flux divergence and advection influence. (Baldocchi, 2003; Massman & Lee, 2002). Kalma, *et al*. (2008) summarized a total of 30 cases of flux validation in recent years (mainly based on eddy covariance systems, the Bowen ratio, and flux towers networks). The results showed that the precision of ET results is influenced by many factors, including uncertainty in ground-based observations, temporal-scaling algorithm, footprint, high-frequency averaging, and noise removal, and effective methods still have not been developed to calculate some key parameters in the model, such as resistances or roughness length. For example, Wang, *et al*.(2009) promoted a post-process procedure for soil heat flux in the Arou site, including soil heat storage and high-frequency loss correction, and then calibrated it with LAS observation. The results showed that the energy closure of the energy balance is up to 90%.

ETWatch has been verified in the Hai Basin by using a variety of methods, including field measurement from lysimeter, eddy covariance system, LAS instrument, and the water balance result of the sub-watershed at different scale (Wu, *et al*., 2011). Validation using data from eddy-covariance and LAS shows that the estimation can be well correlated with ground observation (R^2> 0.9; Fig. 3).

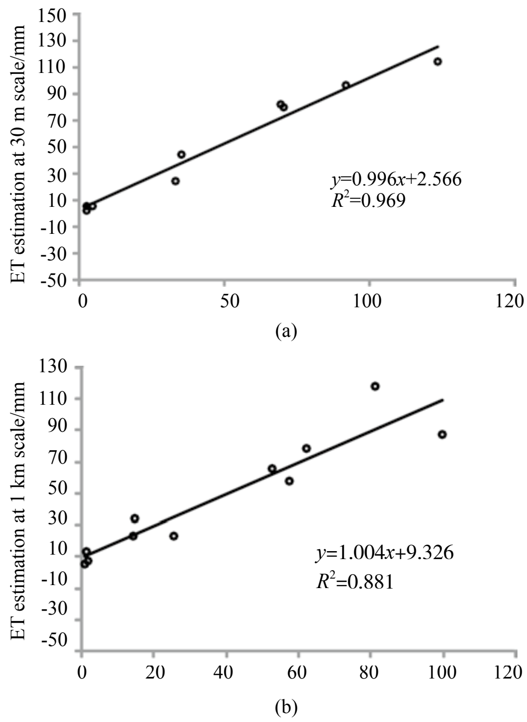

Fig. 3 Comparison between ground observations and ETWatch estimation, Miyun site, 2007
(a) Monthly ET from EC measurement, Miyun,2007;(b) Monthly ET from LAS measurement, Miyun,2007

7 CALIBRATION OF THE REMOTE-SENSED ET MODEL

How to calibrate a model with limited ground data is another difficult problem. Although researchers carried out a series of observations in the Qinghai-Tibet Plateau, extremely dry areas, dry desert regions, semi-arid grasslands, transitional zone, and

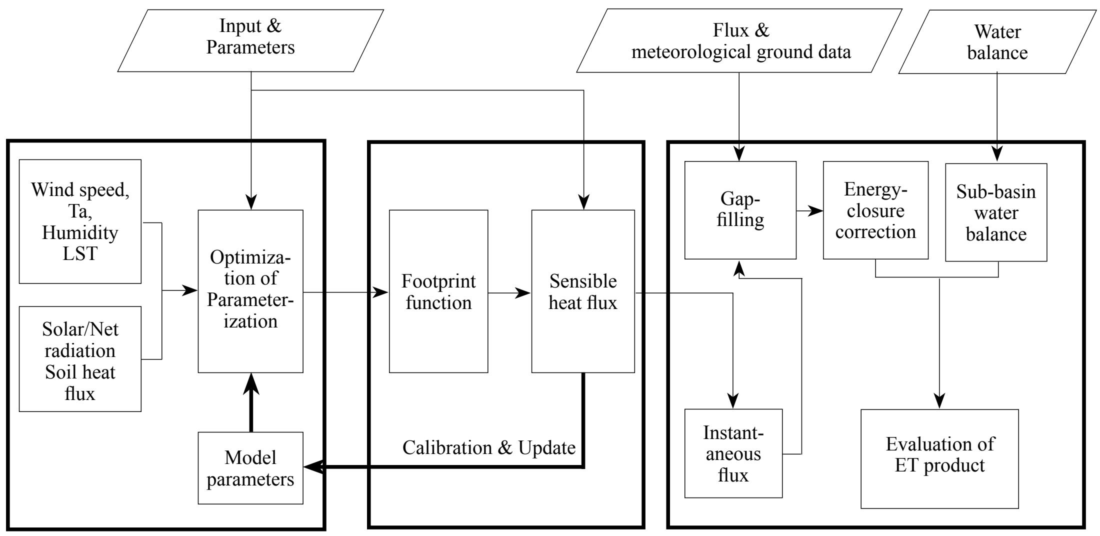

Fig. 4 The calibration procedure flowchart in ETWatch

Loess Plateau region (Wu J, *et al*., 2005; Wang, *et al*., 2007), little of observation data is used to optimize current parameterization schemes in a satellite retrieval algorithm. Li, *et al*. (2008) promoted a framework to develop scaling methods, taking aviation remote sensing for the bridge and improving satellite retrieval algorithms and indirect estimation methods of various components in the water cycle. We divided the calibration into variable retrieval and flux calculation, temporal-scaling part to calibrate them separately (Fig. 4). Validation results based on ground observations show that calibration is essential for the application of remotely-sensed products (Xiong , *et al*., 2011). The daily outputs from a calibrated model can achieve a 0.7 correlated coefficient in a year and the average percentage error can be reduced to 10% over a longer term (month, quarter, or year).

8 CONCLUSION

Watershed evaporation estimation is a newer one with time topic in the quantitative remote sensing field. It is towards operational and application-oriented direction based on proceeding of land procedure models, climate models, and data assimilation in the coming future. The remotely-sensed approach will bring new datasets for the research in ecological processes and water resources management, to call for new methods in the end. In this paper, we reviewed issues among remotely-sensed approaches for watershed ET estimation and introduced relevant components of ETWatch. We will focus on the following improvements:

Estimates of surface evaporation involving parameterization of non-uniform underlying, scaling, and truth validation at the pixel scale are typical issues in quantitative remote sensing. Further understanding of the process of heat transfer and its spatial-temporal scaling requires: effective roughness model; generalizing the application condition of the theory of atmospheric turbulence, modeling the relationship between land surface heterogeneity and height of boundary layer.

Since the influence of terrain and non-uniform vegetation cover to thermal infrared bands is full of uncertainties, local incidence angle significantly affects the surface brightness temperature, and topography causes significant changes in the multiple scattering of surface thermal radiation properties. Therefore, a parameterization scheme for complex topography should be further developed.

Microwave soil moisture is a primary information source which is not fully integrated with atmosphere-land exchange model to develop new temporal-scaling methods to scale the Instantaneous flux to daily scale or even longer period.

Scaling problems is still the main obstacle in the application and evaluation of ET products. It is required to combine different spatial and temporal scaling methods to develop an effective verification platform in combination with the ground-flux network and the hydrological modeling approach. Further study should be carried out on the comparison between simulation result from a distributed hydrological model and remote sensing estimation on the certain watershed, to give out a convinced verification of application-level data products.

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ETWatch的模型与方法

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摘 要：作为定量描述地表异质性和时空分布规律的主要方法，遥感需要与模型相结合，才能对陆表蒸散进行估算。ETWatch是面向流域规划与管理和农业水管理的实用需求，针对遥感应用而设计的遥感蒸散监测系统，可用于计算流域地表净辐射、感热、潜热(ET)的空间分布及其时间过程，提高ETWatch模型的精度和可靠性的关键在于发展多源遥感数据的参数化方法。本文在调研国内外研究进展的基础上，总结了流域蒸散遥感估算参数化中存在的主要问题，包括非均匀下垫面参数获取、时空尺度转换、多源遥感数据集成、真实性检验与模型校正等，并结合上述问题介绍了ETWatch中的模型与方法。

关键词：遥感，蒸散，参数化方法，ETWatch，真实性检验，模型校正

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1 引 言

蒸散是流域水文–生态过程耦合的纽带，是流域能量与物质平衡的结合点，也是农业、生态耗水的主要途径。掌握了流域的蒸散时空结构，将极大地提升人们对流域水文和生态过程的理解和水资源管理能力。由于陆表水热交换受到局地环境（包括地形、地势、地理位置及下垫面）的影响，不同下垫面的地表蒸散量存在很大的差异，为得到地表实际蒸散，研究者建立了微气象法、波文比法、土壤耗水法、涡度相关法等地面实测方法。这些方法大都基于局地尺度，得到的都是单点资料，然而在大型水利工程设计、干旱监测、水资源评价等方面都需要估算流域或区域尺度的蒸散量（刘昌明，1997）。

蒸散在时间上和空间上是高度变化的（Turner 等，1995），与气象条件、降水、土壤水文参数、植被类型和密度的时空格局密切相关。遥感不能直接监测蒸散，但可以直接监测许多影响蒸散的因子，如地表反照率、土壤湿度、地表温度和粗糙度等重要参数，因此需要在因子遥感监测的基础上利用模型估算蒸散，如地表能量平衡模型，实现从点到面上的拓展。众多蒸散估算模型在不同地区获得了应用（Allen 等, 2005; Bastiaanssen 等, 1998; Nishida 等, 2003; Su, 2002; 吴炳方 等, 2008）。用遥感方法估算区域蒸散的精度能够满足水文、生态、农业和森林等相关研究的需要（Kalma 等, 2008）。

由于蒸散过程的复杂性，影响估算精度的不确定因素非常多，如地表参数反演精度、蒸散模型适用性、时间扩展、平流与局地环境的影响等（黄妙芬 等，2004；高彦春和龙笛，2008）。以定量化和高精度为目的的蒸散反演，需要充分发挥遥感技术在空间、时间动态监测上的优势，利用多源遥感数据的特点，研究局地尺度、模型尺度和像元尺度的模型与方法，解决遥感瞬间过境与蒸散连续变化的矛盾；欲推动蒸散数据产品在水文、农业和生态领域中的实际应用，还需要处理好模型方法与真实性检验的关系，在理论上有很大改进的算法，运行结果并不一定好；缺少充分有效的精度验证，又会极大限制数据产品在行业中的应用。

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本文在调研国内外研究现状的基础上，总结了该领域存在的问题，介绍ETWatch采用的思路、模型和方法，以及进一步的研究方向。

2　ETWatch蒸散模型

20多年来，遥感一直被视为实现大范围地表能量和水分动态监测的有效手段，研究者从不同角度和思路出发，构建了不同复杂程度的遥感蒸散模型，因其模型原理、对非遥感要素的依赖程度以及前提假设的不同，具有各自不同的实用特点和反演精度（Kalma 等，2008）。目前主要的遥感蒸散模型可分为两类：

一类是基于Penman-Monteith的单层模型(Cai 等, 2007)。P-M公式提供了一个能反映瞬时能量交换的近似解析表达，将无法确定的蒸散面上的空气动力学温度用气温近似，避免了不确定性较大的地表温度产品的引入(Widmoser, 2009)。通过简化模型所需的地表导度(surface conductance)的参数化表达，Mu等人基于MODIS和气象模拟数据开发了全球尺度的蒸散量产品(Cleugh 等, 2007; Murray 等, 2007)。然而，冠层和空气动力学阻抗等模型中的大量参数还是基于地表观测得到的(Sun 等, 2009)，这些关键性信息对于大尺度上的应用是难于获得甚至是未知的(Raddatz 等, 2009)。

另一类是以显热通量（H）为核心反演参量的能量平衡余项法。由于在梯度原理下，显热通量的主要信息可由地表温度与近地面气温提供，因此除了空气动力学阻抗（其中含有风速信息）外，其他主要的输入项都可由遥感手段获得（Mallick 等，2007；Matsushima，2007），同时为减少模型对未知空气动力学阻抗项的依赖，结合大气表面层相似原理，在少量地面数据的支持下采用了经验的参数化估算方法（Bastiaanssen 等，1998；Jia 等，2003；Su，2002），在植被覆盖度较高、下垫面均匀的条件下得到了广泛应用（Allen 等，2005，Kalma 等，2008）。针对稀疏冠层湍流热通量，可分别考虑土壤和植被在冠层内部进行的水汽和能量交换（Shuttleworth和Wallace，1985）。但由于辐射地温产品与近地层气温观测的不一致性、湍流交换模型的前提假设以及蒸散量时间扩展环节中的存在种种不确定性，使得在范围大的区域或地表复杂的地区应用能量平衡余项法的精度尚无完整评估，而运行化的、能够提供应用级产品的算法急待进一步改进和完善。

ETWatch采用了余项法与P-M公式相结合的方法计算蒸散(图1)。首先根据数据影像的特点选择适用的模型，在高分辨率、空间变异较小、地物类别可分的情况下使用SEBAL模型与Landsat TM多波段数据反演晴好日蒸散，而在中低分辨率、空间变异大、混合像元占多数的情况下使用SEBS模型与MODIS多波段数据反演晴好日蒸散；遥感模型常常因为天气状况无法获取清晰的图像而造成数据缺失，为获得逐日连续的蒸散量的，引入Penman-Monteith公式，将晴好日的蒸散结果作为“关键帧”，将关键帧的地表阻抗信息为基础，构建地表阻抗时间拓展模型，填补因无影像造成的数据缺失，利用逐日的气象数据，重建蒸散量的时间序列数据(吴炳方　等, 2008)，并通过数据融合模型，将中低分辨率的蒸散时间变化信息与高分辨率的蒸散空间差异信息的相结合，构建高时空分辨率蒸散数据集，同时提供流域级尺度的(1 km)和地块尺度(10 m—100 m) 的蒸散监测结果，满足水资源评价与农业耗水管理的需求(Wu 等, 2008)。

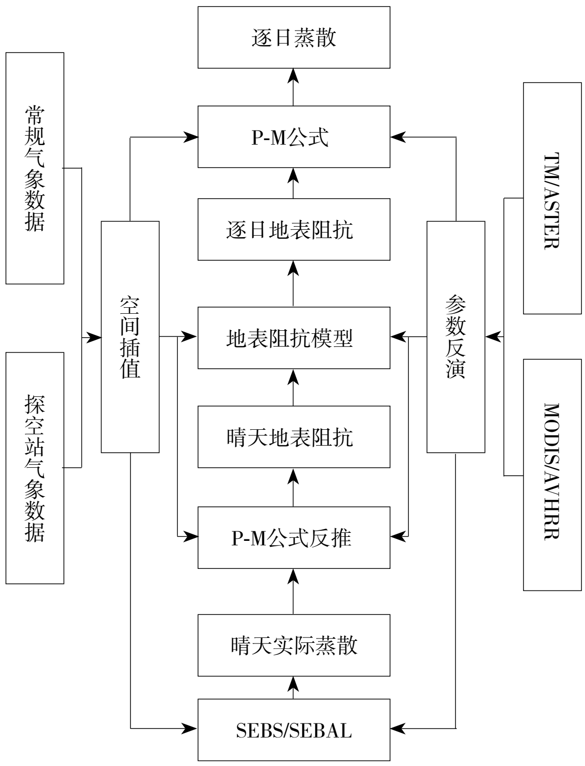

图1　ETWatch方法流程图

3　ETWatch的参数化方法

蒸散遥感估算的核心问题是对地气相互作用和水

热交换过程的参数化方法。由于所有地表变量在时间和空间上都具有高度的异质性，而在局地尺度建立的经验公式在适用性上非常有限。实现对大范围地区地表参量的定量表达，需要结合地面实测数据进行建模和求优。在不同应用尺度，模型的参数化方法也不一样。空间分辨率低时，气象要素的空间分布趋势和变幅等因素影响较大，而下垫面影响相对较小；空间分辨率高时，模型驱动的数据相对不易获得，气象要素的分异较小，而下垫面的影响增加。因此，在使用中低分辨率遥感数据时，可以选用参数化方案较为灵活、大气湍流方案较为复杂的模型；而在使用高分辨率遥感数据时，可以使用经本地数据标定后的、相对简单的经验模型。

目前在地表通量项计算中，净辐射地表辐射平衡主要来自于地表辐射平衡方程，而土壤热通量则来自于与净辐射的经验关系（Su，2002）或综合考虑植被、土壤质地、水分对热通量的影响（Murray 等，2007）。显热通量则仅是由地表温度及其参考高度上的气象条件所决定的，需要通过数学方法将其订正到与有效能量相适应的水平，因此存在一定的不确定性。

目前遥感地表温度已作为较成熟的定量数据产品为研究者所使用（Wan 等，2004），为降低遥感地表温度与参考高度处的空气温度之差对模型精度的影响，Anderson等人（1997）利用静止气象卫星的多次观测发展了基于地温变率的双层模型，应用GOES卫星的午前观测获取北美地区5 km—10 km分辨率的通量估算值（Anderson 等，2007），并采用了Norman提出的DisALEXI算法将其分解到微气象尺度（100 m—1 km）。ETWatch则使用改进的分劈窗方法（Wan和Dozier，1996；Mao 等，2005）提取地表温度，并经地面站点标定来保证地温数据的精度。并将12点的边界层空气温度以正弦变换调整到卫星过境时刻，缩小因观测时间不同造成的两者差异（Xiong 等，2010）。

日净辐射通量对日蒸散量反演精度有很大影响。日太阳短波辐射往往通过气象观测计算得到，但气象台站的辐射或日照观测数据的代表性需充分评估。气象台站一般都处于地势平坦、周围少障碍物的区域，如果研究区地形复杂，坡度、坡向和周围地形遮蔽均会对辐射产生显著影响，尤其是在中高纬度地区，反演蒸散将会带来较大误差。这就需要考虑地形和气象条件，用参数化的方法计算日平均净辐射（田辉 等，2007）。ETWatch从实用角度出发，用分区拟合的方法对覆盖研究区的辐射台站的散射和直射经验回归系数进行逐月的空间化，并制成按经纬度、月份的查找表，根据这一查找表进行太阳短波辐射的计算。

计算地表通量的遥感模型需要参考高度处的地表动量、热量和水汽阻抗等地表参数。它们都是地表空气动力学粗糙度的函数，目前使用遥感手段还难以直接获取。空气动力学参数对植被区域植株的密度、高度、郁闭度和风速变化都非常敏感（朱彩英，2004），对于不同的陆面类型，由于几何特征和环境变量的差异性而产生的变化量可能会达到几个数量级（张仁华，2002），对地表通量模型的反演计算影响很大。仅考虑植被高度对粗糙度的影响，或者根据土地利用分类来指定经验值（Allen，2007），在地形起伏条件下的适用性较差。而使用雷达数据计算地表粗糙度的做法逐渐为研究者所重视，这是因为SAR图像的后向散射系数在很大程度上由地表的几何粗糙状况所决定（Prigent 等，2005）。ETWatch使用植被、地形、非植被覆盖表面的几何粗糙度等因素来表达区域的综合有效粗糙度（吴炳方 等，2008；Xiong 等，2010），综合考虑了植被、微地貌和地形起伏的影响。

4 ETWatch的时间扩展方法

由于云对可见光和热红外波段的干扰，只能获得有限的晴好日蒸散数据，而在计算作物的真实耗水、水分利用率、农业水管理等需要的是逐日蒸散信息和时段内的累积蒸散量。因此地表蒸散时间扩展的目标是将遥感瞬时地表蒸散扩展到某一时段的累积量，包括由瞬时到日蒸散以及由日蒸散到更长时段。在以往的研究中，往往假设相对蒸散或蒸发比等指标在全天不变来进行日的扩展（Brutsaert 等，1996；Porté-Agel 等，2000；Allen 等，2007），而在时段扩展时则使用遥感蒸发比和时段净辐射来线性积分，或是使用平滑算法对非晴天条件下的日蒸散量进行插补（奚歌 等，2008），忽略了气象条件和下垫面状态的逐日变化，在实际应用中存在着较大不确定性。

Anderson等人（2007）提出了一种土壤含水量逐日变化的概念模型用于计算逐日地表蒸散变化（Anderson 等，2007）。Jang等人（2010）应用四维同化技术，通过将晴日能量通量的计算结果同化至中尺度气候模型中，完成了有云条件下日ET的计算。

ETWatch中的时间扩展模块则是上述两类方法的集

成，基于冠层阻力进行由瞬间到日蒸散扩展方法（刘国水 等，2011）；在晴好日到阴雨日的扩展方面，应用改进的SEBS模型和SEBAL模型计算晴好日的地表能量平衡各项，并选择叶面指数作为冠层阻抗的时间扩展参量，将晴好日的阻抗格局扩展至有云日，使用中科院禹城站2003年作物季的大型蒸渗仪数据对重建后的逐日蒸散结果进行了验证（图2），在作物生长季，模型结果相对于实测结果表现出了良好的相关性（$R^2 \approx 0.7$），优于作为对比的蒸发比不变法（熊隽，2008）。

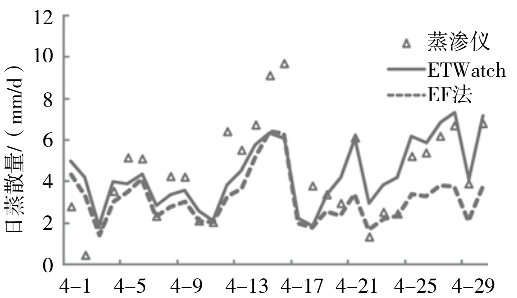

图2 禹城站蒸渗仪与遥感蒸散时间扩展结果（2003年）

地表蒸散时间尺度转换的难点在于多云和阴雨天气，通过微波遥感探测阴雨日地表的温度和湿度，推算多云天气下地表蒸散的日总量或旬总量将是未来的发展趋势（张仁华，2009）。

5 多源遥感数据的集成应用方法

在进行面向地块的作物耗水监测时，需要高空间分辨率的遥感蒸散结果。陆地卫星能提供关于下垫面植被、热量的细节信息，但无法提供作物生长的时间过程；极轨气象卫星能够提供足够的时间分辨率，但空间分辨率又不能达到精度要求。在蒸散遥感估算研究中，常用的传感器有MODIS、TM/ETM+、ASTER和AHVRR 等，用这些遥感资料结合能量平衡模型来估算陆面日蒸发量的研究中普遍存在着单一传感器时空分辨率有限、不能完整覆盖研究区和时间序列不足等问题。利用LandSat TM/ETM+、TERRA/MODIS和TERRA/ASTER三种不同分辨率的遥感数据估算蒸散量时，MODIS反演精度相对比较高，平均误差在20%左右（Hafeez 等，2002）。利用ETM+反演非均匀地表区域地表参数和能量通量，由于只有一个热红外波段，精度相对较低 （马耀明 等，2004）。因此，国内外研究者也通过多源遥感资料的联合来估算区域蒸散的研究，如利用CERBS-02和MODIS资料联合反演了白洋淀地区的地表蒸散量（辛晓洲 等，2005），利用TM和MODIS数据通过水文模型模拟了热带雨林地区的蒸散（Wu 等，2006）。在ETWatch中，综合利用TM/ETM+、ASTER、MODIS、AVHRR数据和主动雷达数据，并将时空适应性反射率融合模型STARFM（蒙继华 等，2010）扩展到热红外波段，实现了中分辨率的区域蒸散结果与高分辨率蒸散空间格局的数据融合，将蒸散模型参数化、时间扩展和数据融合连接起来，形成蒸散数据产品的运行化生产框架，为多源遥感数据在蒸散估算上的集成提出了应用思路，其中主动雷达数据用于提取微地貌对地表粗糙度的贡献（吴炳方 等，2008；Xiong 等，2010）。

6 蒸散产品的真实检验

随着地面通量观测网络的建设和水文资料的汇集，可用于通量验证和分析的地面资料每年都在增加，但缺乏有效评价遥感反演通量精度的标准方法和地基观测资料成为阻碍遥感方法得到广泛认可的主要因素。

Farahani等人（2007）在其综述中指出，经常用于通量验证的波文比和涡度相关仪的自身测量误差也常常可达到20%；对于仪器的维护和校正做得较好的站点，这一误差可减小到10%（Glenn 等，2007），但会随着下垫面的非均匀性的增加而迅速增大。李正泉对ChinaFLUX各站点的能量平衡闭合状况进行了综合评价，发现在现有通量观测系统中，显热和潜热湍流通量往往会被低估，而有效能量项则会被高估（李正泉 等，2004）。普遍的站台能量不闭合现象在国外也有报道（Wilson 等，2002），并且点观测推广到面上都会遭遇困难，主要原因是地形效应、植被类型差异和地面特征突变而引起的平流（Li 等，2008）。因此以小流域水文闭合和通量塔点面结合的综合评价思路不失为一种选择（吴炳方 等，2009）。

近年来兴起的大孔径闪烁仪（LAS）可以测量200 m—10 km范围内的平均感热通量，通量计算结果不仅对时间，也对空间作了平均，其测量尺度能够与卫星遥感的像元尺度相匹配。但测量过程中涉及的源区影响、地表特征参数、掺混高度等问题还需要更加深入的实验和理论研究（Marx 等，2008）。对于异质、破碎的下垫面，如何准确、客观地分析与解释观测数据的空间代表性是通量观测中还没有解决好的

重要问题。足迹模型（footprint model）或源区（即测得通量与上风向地表通量的空间分布之间的关系）通过将通量贡献区域的空间分布与测定高度、表面粗糙度和大气稳定度等因素联系起来，提供了一个评价通量观测数据空间代表性的研究基础。然而，现有的足迹模型都是在基于近中性大气条件下的湍流扩散理论建立的，难以对稳定层结状况下的通量给予客观评价（Gockede 等，2005），而且受主观因素影响较大。

而在下垫面复杂和大气处于稳定层结等非理想条件下，地表通量的计算需要考虑冠层内的大气储存、通量辐散和平流等因素的影响，对以上因素的数据验证方法，在通量观测界仍没有形成一致的意见（Massman 和 Lee，2002；Baldocchi，2003）。Kalma（2008）总结了共30项近年来将遥感估算结果与地面实测数据（主要基于涡度相关系统/波文比系统/通量塔网）进行对比验证的研究工作，结果表明，目前的地表验证工作受到诸多因素的影响，造成遥感通量的精度问题非常复杂。来自地面观测数据的不确定性与下垫面的空间非均匀性、时间扩展方式、足迹模型和高频涡度通量平均和去噪的方式等都有关系且难以分析；而模型中的一些关键参量（如各项阻抗、粗糙度长度）至今还无有效的确定方法。以土壤热通量为例，王介民等人（2009）计算了阿柔站土壤浅层热储存，在涡动相关资料再处理中加上高低频损失修正等，再参考该站大口径闪烁仪（LAS）观测对感热通量的提高，能量闭合率可达到90%以上。

ETWatch在海河流域通过了多种途径的验证，包括地块实测的蒸散量、蒸渗仪、涡度相关系统、大口径闪烁仪，以及子流域和小流域等不同方法和不同尺度的验证（Wu 等，2011）。并利用涡度相关系统和大口径闪烁仪对计算过程中的参数变量和数据产品进行了不同尺度的第三方地表验证，结果表明，遥感估算的1 km和30 m蒸散结果与地面观测结果在时间过程上有着良好的相关性（R^2>0.9）（图3）。

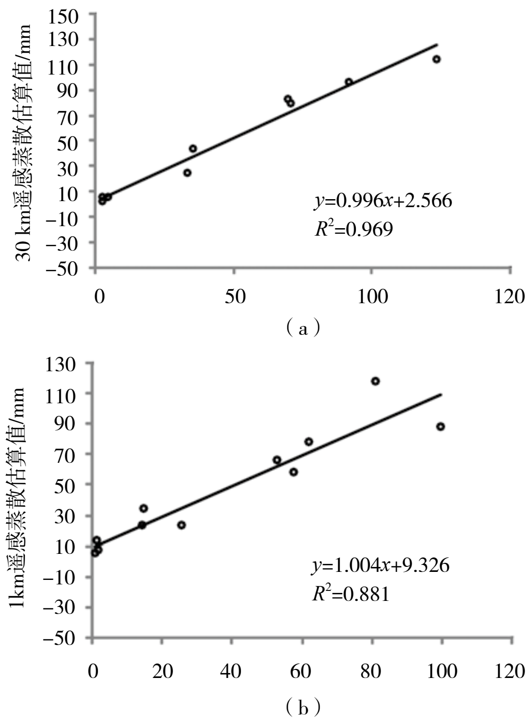

图3　ETWatch逐月蒸散量与地面观测结果的对比，密云站，2007

（a）月蒸散量EC观测值；（b）月蒸散量LAS观测值

7　蒸散遥感模型校正

对照地面数据获取蒸散模型的应用精度后，如何对模型进行校正则是另一个难点，国内外在这方面的研究较少。国内虽然已有遥感蒸散模型的大量应用，但多数直接使用国外开发的模型，或未经校验的反演结果。由于没有考虑在应用时的陆表特征，不同时期、区域的产品没有可比性，极大地限制了数据产品的实际应用。虽然中国已经在青藏高原、极端干旱地区、干旱荒漠地区、半干旱草原地区、农牧交错带和黄土高原等典型区域开展了一系列以陆面过程为主的观测试验（吴家兵 等，2005；王春林 等，2007），但很少把这些观测结果有效转化为数值模式的陆面过程参数化方案或卫星遥感反演模式中所需要的参数，而仍是以典型下垫面单点试验研究为主，复杂下垫面问题还没有得到很好的解决。在黑河流域开展的航空-卫星遥感与地面观测同步试验中提出以航空遥感为桥梁，发展尺度转换方法，改善从卫星遥感资料反演和间接估计水循环各分量的模型和算法（李新 等，2008）。ETWatch从能量平衡余项式和时间扩展方法的特点出发，将蒸散估算过程分为地表温度获取、日净辐射和蒸发比等分别进行校正（图4）。利用通量站观测数据的验证结果表明（Xiong 等，2010），标定过程对于遥感蒸散产品应用精度的提高至关重要。通过标定，在全年内模型蒸发比结果与实测的时段平均蒸发比的相关系数可达到0.7左右，在更长的时间尺度上（月、季、年）平均百分比误差可以减小到10%以下（熊隽 等，2011）。

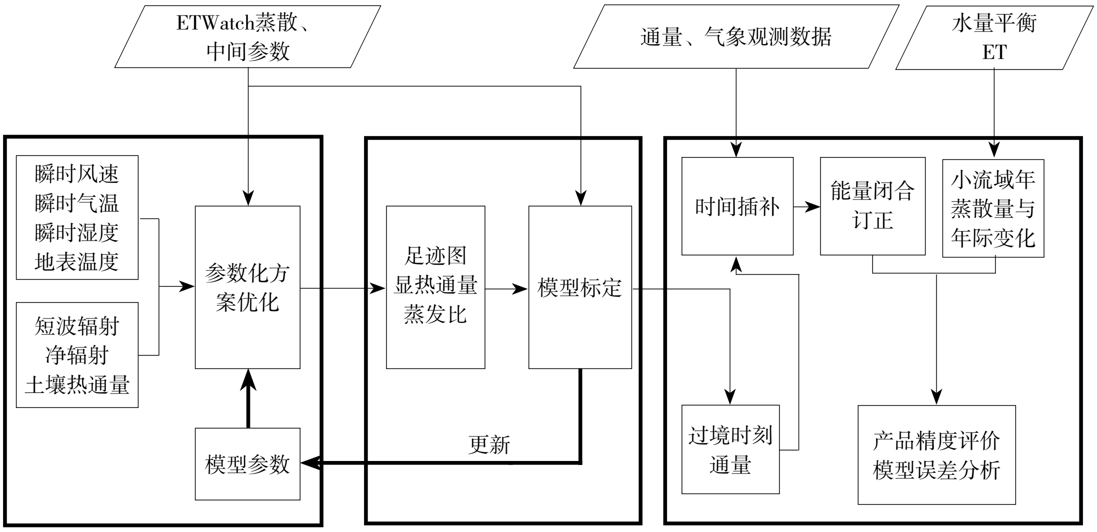

图4 ETWatch模型校正方法流程图

8 结语与展望

地表蒸散估算是定量遥感中历久弥新的领域，目前，它正在汲取陆面过程、气候模型以及数据同化的营养和工具的基础上向着业务化、应用化的方向发展，而遥感蒸散数据集的开发和应用，又必将为水文-生态过程耦合研究和流域水资源管理带来新的数据支撑，而新的数据又会带来新的方法。

本文在总结蒸散遥感模型方法的同时，介绍了流域（区域）蒸散遥感监测方法ETWatch的模型和方法及经验，涉及当前研究进展中的一些重点问题，ETWatch的特点是以地气传输过程为中心，充分发挥遥感技术在空间、时间尺度上的优势，研究局地尺度、模型尺度和像元尺度的参数化方法，针对水文、农业生态应用而设计的面向业务运行的方法。

ETWatch还将在以下方向重点开展研究和改进：

在基础理论方面，认识热力转输的时空过程及其尺度特征，构建能反映热力转输特征的粗糙度模型；为将大气湍流理论的应用条件从特殊到一般化，需要从局地平衡的水平尺度出发，通过模拟与观测的手段，了解卫星像元尺度、下垫面异质性与边界层参考高度之间的相关关系。

在多源遥感参数获取方面，要发展复杂地形下的通量参数化方案。复杂地形和非均匀植被覆盖对热红外观测的影响非常严重，局地入射角显著地影响着地表亮度温度，地形起伏引起的多次散射显著改变地表的热辐射特性。

在遥感瞬时通量时间拓展方法，需要与地气交换模型紧密结合，结合微波土壤湿度，获取土壤表面阻抗的变化状况，进而对逐日蒸散量进行合理估算。

蒸散数据产品的评估和应用是以尺度问题为主要特征的，需要以不同时空尺度的转换方法为桥梁，发展以地面通量网与流域水文模拟相结合的有效验证和校正方法。

地表蒸散遥感估算所涉及的非均匀下垫面参数化、时空尺度转换和像元尺度通量的有效检验，都是当前定量遥感中最具典型性的基础性问题；在应用上直接面向水文预报和水资源管理，因此选择具有一定代表性的流域作为实验场，采用分布式水文模型的蒸散模拟结果与遥感蒸散数据进行验证和对比，是发展应用级数据产品的必经之路。

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