Stream-temperature estimation from thermal infrared images

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Abstract - Stream temperature is an important water quality indicator. Spatial gradients of stream temperature can also be used to identify ground water and surface water input locations in channel systems. Endangered fish populations are sensitive to elevated stream temperature, especially in the summer when low precipitation and high solar insolation increase temperatures beyond established thresholds. The removal of riparian vegetation and increases in surface run-off, that results from land-use change, also contribute to elevated stream temperatures. Thus, if critical watersheds are to be managed properly, accurate and spatially extensive temperature measurements are needed. For these purposes, it is necessary to know water surface temperature within 1°C. Thermal infrared images (TIR) have long been used to estimate water surface temperatures, especially of the ocean where split-window techniques have been used to compensate for atmospheric effects. Streams are a more complex environment because 1) most are unresolved in typical thermal infrared images, and 2) stream corridors may consist of tall trees that irradiate the stream surface. Therefore, key additional problems to solve in measuring stream temperatures include both subpixel unmixing and multiple scattering. Over a watershed in the Cascade mountains of southern Washington, USA, we use fine-resolution airborne MODIS/ASTER Simulator (MASTER) data, and coarse-resolution ASTER data, to develop an approach for successful extraction of stream temperatures. We combine a physically based radiative transfer model (MODTRAN) and an in-scene relative correction adapted from the ISAC algorithm to compensate the data for atmospheric effects. Because water thermal reflectivities are low (1-2%), recovered stream temperatures are relatively insensitive to downwelling irradiance, unless air temperatures are much higher than stream temperatures. Laboratory values for water emissivities are used as a baseline estimate of stream emissivities. Emitted tree radiance reflected by the stream is estimated from the height and canopy temperature, using a radiosity model. Linear spectral mixture analysis is used to isolate the fraction of land-leaving radiance originating from unresolved streams.

I. INTRODUCTION

Emitted thermal infrared radiation (TIR) (λ=8-12 μm) can be used to monitor the surface or "skin" temperature (top 100 μm) of streams that have important environmental and economic value. We present a rationale for studying stream temperature, a method for determining the spatial distribution of stream temperature using TIR imagery, a description of how atmospheric compensation, emissivity and multiple scattering affect the accuracy of stream temperature, and a discussion of how the temperature of unresolved streams can be extracted using sub-pixel analysis.

II. WHY STREAM TEMPERATURE

Stream temperatures are important to water quality and land-use monitoring. The ecological integrity of many water basins is threatened by elevated stream temperatures, especially in the summer when critical thresholds (16°C for coldwater fish) are exceeded. Although debate exists about the effect of urbanization on stream temperature, land-use change can elevate stream temperatures through two mechanisms: 1) The removal of riparian vegetation leads to a reduction in shade and an increase in direct solar radiation incident on streams. 2) The degradation of surrounding soils to a thin topsoil with decreased organic content and lower resistance to erosion, allows warmer surface run-off to overpower contributions from cooler ground-water inputs. In addition to helping monitor ecosystems and land-use change, spatial gradients of stream temperature can be used to identify the location of ground and surface water inputs in watersheds. A spatial distribution of "skin" stream temperature can also serve as a boundary condition for hydrologic models that predict stream characteristics throughout a watershed. For all of these applications, water surface temperature should be accurate within 1°C.

III. PREVIOUS WORK

Although many studies have focused on illustrating the temporal variation of stream temperature at specific locations, the benefit of TIR remote sensing over field-based measurements is a spatial understanding of temperature distribution. TIR has been widely used to estimate sea surface temperatures (e.g. [5]) and lake temperatures (e.g. [1]); however less work has been done with streams and rivers because they are often unresolved in remotely sensed data. Reference [8] evaluated the accuracy of remotely sensed stream temperature measurements using very high-resolution imagery (0.2-0.4 m) obtained by an airborne thermal imager. Although several sources of error were identified (reflected longwave radiation, thermal boundary layer effects at the water surface and vertical thermal stratification), comparison with in-situ measurements suggested that remotely sensed temperatures were accurate within 0.5°C, and provided an effective way of determining spatial patterns at a resolution and extent previously unattainable through in-stream data recorders.

IV. PROJECT DESCRIPTION AND GOALS

Using multispectral imaging data from the MODIS/Aster Airborne Simulator (MASTER) and the ASTER sensor on Terra EOS-AM1 platform, we assess the ability of airborne and satellite remote sensing to provide an accurate spatial distribution of stream temperatures. If stream temperatures can be estimated with TIR, at known and acceptable levels of confidence, regional temperature assessments will be less sensitive to the uncertainty associated with sampling temperature at a relatively small number of ground stations. Ground-truthing remotely sensed temperatures is therefore essential; in this study field data will be spatially distributed using a hydrological model to validate our results. Comparison of high-resolution (5-15m) airborne MASTER images with lower resolution (15-90m) spaceborne ASTER images will permit scaling studies and

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enhance comparisons with in-situ measurements. Both MASTER and ASTER data will be obtained in August, 2001 for the Green River in southern Washington, WA (Figure 1).

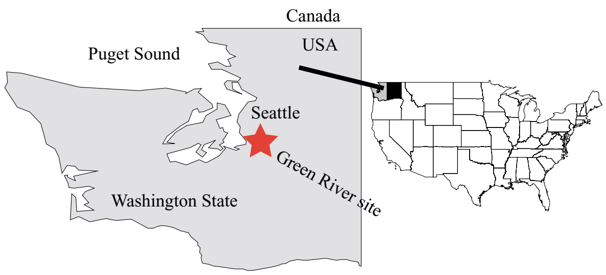

Fig. 1. Location of study site.

V. METHODS AND SENSITIVITY ANALYSIS

Many factors must be considered to determine kinetic temperature (T_k) from remotely sensed data (Figure 2). The difference between a remotely sensed brightness temperature (T_b) and the kinetic temperature (T_k) of an object can be attributed to four factors: 1) instrument noise, 2) atmospheric effects, 3) emissivity and 4) multiple scattering between scene elements.

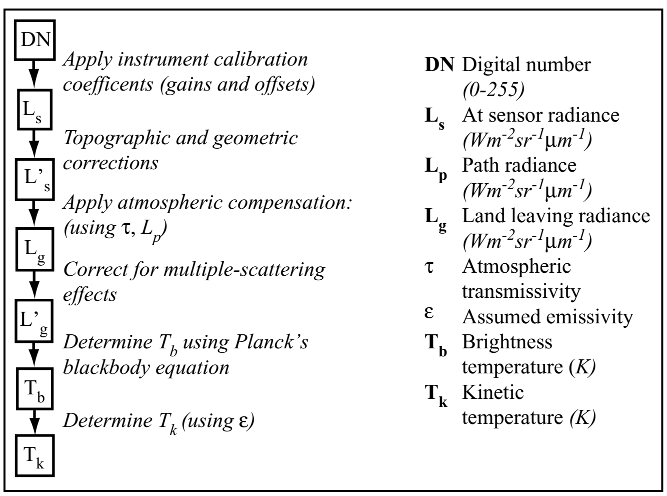

Fig. 2. Flow diagram showing determination of Tk from TIR data

Instrument Limitations: Accurate measurement of radiation is limited by instrument sensitivity and noise. For ASTER, radiometer noise has been converted to a noise-equivalent temperature (NEΔT) of 0.3°C at 27°C [2]. Since kinetic temperature (T_k) is independent of the measurement wavelength, the observed T_k should be within NEΔT for all bands. Analyzing differences in estimated T_k between bands provides a check on our ability to remove the spectrally variant effects of the atmosphere and the material-specific emissivity.

Atmospheric Effects: Accurate determination of geophysical variables from remotely sensed imagery requires thorough removal of atmospheric effects. These effects are encapsulated in a multiplicative transmissivity (τ) term that accounts for attenuation of ground-leaving radiation due to absorption and scattering by atmospheric gases, and an additive path radiance term (L_p) that accounts for upwelling emitted thermal radiance. Atmospheric correction coefficients (τ, L_p) are a function of 3 main factors: 1) path length through the atmosphere 2) the temperature, composition, and concentration of atmospheric gases (primarily water vapor), and 3) vertical layering and spatial variability in the atmosphere. Simple sensitivity studies completed using the radiative transfer model MODTRAN [6] demonstrate the importance of atmospheric correction to temperature accuracy. Assuming typical summer conditions in our study area, either a 1.2% increase in τ or a 0.11 $Wm^{-2}sr^{-1}\mu m^{-1}$ increase in L_p resulted in approximately a 1°C decrease in calculated T_k. Deviations from nadir viewing geometry, and changes in sensor height or topography, affect atmospheric correction coefficients (τ, L_p) by changing the path of land-leaving radiation. For example, at a sensor height of 2.1 km and a surface elevation of 0.1 km, MODTRAN calculates an average increase of 0.5 $Wm^{-2}sr^{-1}\mu m^{-1}$ in L_p and a 6.6% decrease in τ for a 40° look angle as compared to nadir. These predicted atmospheric effects introduce approximately a 1°C increase in calculated T_k on the edge of an airborne scene.

Given the importance of atmospheric effects, multiple methods to estimate τ and L_p have been developed. These include using an empirical in-scene determination, a radiative transfer model, or a combination of these approaches. We use a hybrid approach that incorporates both a physically based radiative transfer model (MODTRAN) [6] and an empirical scene-based relative correction adapted from the ISAC algorithm [4,9]. Given specific atmospheric variables as a function of height (water vapor, pressure, temperature profiles), MODTRAN calculates the spectrally variant atmospheric τ, L_p, and downwelling sky irradiance. We will use a radiosonde to obtain temperature and relative humidity profiles concurrent with sensor overpass.

The in-scene component of our hybrid approach makes two assumptions. First, a scene must contain a material with both a known emissivity (preferably a gray or black body) and a distribution of brightness temperatures (T_b). We use vegetation as it can be approximated as a blackbody in the TIR [7], and its spatial variability will provide the necessary distribution of brightness temperatures. Second, we assume that Planck's equation will predict the same T_k in all bands (within NEΔT), if atmospheric effects and emissivity are accurately determined. Given these assumptions, we set T_b equal to T_k in a reference band (λ_r). For each pixel, the T_k at λ_r is used to predict radiance as a function of wavelength in all other bands. If we plot the observed radiance for a non-reference band (independent variable) against the predicted radiance for that band (dependent variable), the slope and offset of a regression line correspond to the relative transmissivity and relative path radiance for this non-reference band, compared to other non-reference bands. In essence, if we plot these relative transmissivities and relative path radiances versus wavelength, the shape of this curve describes how atmospheric parameters vary between bands. However, this method only describes the relative differences between bands, not the magnitude of actual atmospheric coefficients. To determine the magnitude of atmospheric effects in each band, we use MODTRAN and available atmospheric data (radiosonde).

Although the MODTRAN-predicted relative difference in atmospheric coefficients between bands may not reflect scene-concurrent atmospheric conditions, the magnitude can be used to adjust in-scene relative predictions. Essentially, MODTRAN atmospheric coefficients are used to fix the offset of the curve whose shape reflects the relative atmosphere coefficients between bands. Preliminary results show that this hybrid approach can be used to predict τ and L_p, and remove atmospheric effects from ASTER scenes in our study area.

Emissivity: Significant errors in remotely sensed temperatures can result from not accounting for the spectrally variant emissivity of an object. For example, in a spectrally-averaged analysis that assumes typical values for our study area, a 0.017 decrease in emissivity (ε) introduces approximately a 1°C increase in calculated T_k. While water is often assumed to be a blackbody (ε=1), its emissivity does have spectral variability and may change with viewing geometry, surface roughness, and sediment load. Rough water surfaces, especially at off-nadir viewing geometries, have a lower emissivity and may appear slightly warmer than placid water surfaces at the same temperature [8]. Laboratory measurements of reflectivity (related to ε by Kirchhoff's Law) reveal that suspended sediment in water can influence emissivity [7]. Although limited spectral contrast was recorded for small particles near the water's surface, larger grains brought to the surface by currents, or the accumulation of wind-blown sediment, decreased emissivity by 0.01. Suspended quartz grains with distinct reststrahlen bands had a greater effect on reflectivity than suspended clay-rich soil [7]. While we will use the emissivity of distilled water as a baseline estimate, we will make appropriate adjustments for the effects that roughness, viewing geometry and sediment may have on our measurements.

Multiple Scattering: In addition to radiation emitted at the surface, radiation emitted and scattered multiple times by adjacent scene elements will contribute to at-sensor radiation. If multiple scattering is not removed, it will artificially increase remotely sensed estimates of T_k. For TIR observations of streams, multiple scattering will be especially important where forest canopy overhangs the stream bank. As foliage and bark have high emissivities in the TIR (0.94-0.98) [7], one important component of multiple scattering is radiation emitted by the trees and reflected by the water. For example, we estimated the radiance attributable to this path with a simple theoretical radiosity model. We use a geometrical argument to show that no more than 25% of the radiation emitted by adjacent vegetation will reach the water's surface. By assuming emissivities [7] and typical summer T_k for adjacent vegetation and the stream, we calculate an increase in land-leaving radiance of appriximately 0.11 $Wm^{-2}sr^{-1}\mu m^{-1}$. If not accounted for, this increase in radiance corresponds to an increase of 0.4 °C in calculated T_k.

VI. SUB-PIXEL ANALYSIS

Although smaller streams are often unresolved in remotely sensed data, their temperatures can be extracted using sub-pixel analysis. Spectral mixing analysis (SMA) assumes that a pixel's radiance is a linear combination of the radiance emitted by a limited number of spectral endmembers. If the fractional percentage of each endmember is known, the components of radiation emitted by a pixel can be separated and the temperature of each endmember can be determined [3]. SMA considers the spectral signature, the topography, shadowing effects and the spatial resolution to determine pixel fractions. Supervised classification of visible bands is used to produce a thematic map of vegetation, soil, water and urban components. We then combine standard SMA of the thermal bands with supervised classifications to compare determined pixel fractions.

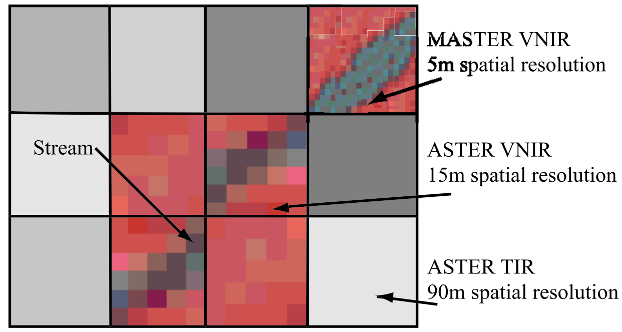

Fig. 3. Resolving a stream using different pixel sizes

VI. CONCLUSIONS:

Stream temperature is an important regional water-quality indicator. Although the surface (skin) temperature of water can be measured using TIR, multiple issues must be addressed before confidence can be attached to remotely sensed measurements. Potential sources of error include: instrument limitations, inadequate correction for atmospheric effects, the separation of emissivity and temperature effects, and multiply scattered and reflected long-wave radiation. The temperatures of streams that are unresolved in remotely sensed data can be determined using a combination of spectral mixing analysis and classification of high-resolution visible bands.

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