An Affordable Method of Thermal Infrared Remote Sensing of Wadeable Rivers using a Weather Balloon

By Tim Beach, Sarah Null, PhD, and Curtis Gray, MS
Utah State University, Utah

Abstract

Stream temperatures influence instream habitat and the health and function of aquatic organisms by affecting metabolic rates, life histories, and productivity. Affordable and repeatable methods to monitor stream temperatures with appropriate temporal and spatial resolution are needed to detect thermal refugia for species of interest or identify thermal pollution. This study describes an approach to measure high resolution water temperatures in relatively short (~1-3 km), wadeable river reaches using a weather balloon-mounted thermal infrared camera. We tested this approach in November of 2014 at a confluence mixing zone of the Logan River and Blacksmith Fork in northern Utah, USA. Overall, thermal infrared imagery captured directly overhead reduced reflectance, which occurs at oblique angles (e.g., taken from stream banks).

Also, radiant surface stream temperatures were representative of kinetic stream temperatures measured at depth in the water column. Our method provided high spatial resolution of a confluence mixing zone that is poorly described using conventional stream temperature measurements, such as temperature loggers or higher altitude fixed-wing aircraft remote sensing, which may represent lateral stream surface temperatures with few pixels. Finally, our approach costs less than $400 per flight (not including a thermal infrared camera) and is not constrained by battery-life, so can be easily repeated to monitor spatio-temporal stream temperature change.

Introduction

Stream temperatures are instrumental to the health and function of aquatic ecosystems, influencing dissolved oxygen, nutrient cycling, and chemical properties of rivers and in turn, affecting metabolic rate, life history, and productivity of aquatic organisms.[1,2] Stream temperatures are known to limit biota in some systems, particularly cold-water fish species such as salmon and trout.[3,4] For these reasons, developing inexpensive and repeatable monitoring approaches to easily collect high-resolution stream temperature data is needed.[5,6]

Methods for measuring stream temperatures include temperature loggers, distributed temperature sensing (DTS), and thermal infrared (TIR) remote sensing.[7,8,9] Temperature loggers and DTS measure kinetic (internal) temperature at discrete locations in the water column.[10] Temperature loggers are cheap and relatively easy to use, but are often sparsely deployed in rivers and are susceptible to damage and loss.[11] DTS has high spatial (~ 5 min) and temporal (~ 5 min) resolution over the length of a fiber optic cable, although deploying DTS systems require considerable expertise and time.[12] TIR imaging provides a spatially continuous representation of radiant river surface temperature, and kinetic temperatures are calculated from radiant TIR observations using Planck's Law.[11] TIR cameras measure and store stream temperatures as individual pixels in a digital image. Forward Looking Infrared (FLIR) cameras have previously been used to capture TIR imagery from stream banks and aircraft.[13,14] For a thorough comparison of strengths and weaknesses of each temperature monitoring approach, see Briggs et al. and Handcock et al. [12,11]

TIR remote sensing measures emitted TIR radiation (8-14 micrometer [μm] wavelengths) from the water surface.[9,16] Water emits radiation as a function of temperature and emissivity, which is typically 0.95-0.97.[16,17] TIR remote sensing measures water surface temperatures at the top 0.1 mm of the water column.[9] Although water temperature at the surface of a river may vary from temperature deeper in the water column in slow-moving water, surface temperature is typically assumed to represent the entire water column in flowing rivers (i.e., dominated by advection).[18]

Remotely sensed TIR radiation has inherent error. Radiation can be partially absorbed by the atmosphere from humidity, air temperature, and distance between the TIR sensor and surface of the water.[16] Atmospheric absorption is minimized by reducing the distance between sensors and streams and collecting data during low humidity conditions. Distortion at image borders is another problem, but can be partially corrected by removing outer pixels when mosaicking multiple images together. Oblique angles greater than approximately 60° increase reflectance and overestimate water temperatures.[17] Heterogeneity of water surface and radiation from other objects like stream banks or riparian vegetation also increase error.[9,15,17]

There are numerous techniques for acquiring TIR imagery, including: satellites, fixed-wing aircraft, low-flying helicopters, unmanned aerial vehicles (UAVs) or drones, bankside collection, and weather balloons or blimps.[19,21,16] Study scale, repeatability, budget, and river access may influence which collection method is most appropriate. Satellite TIR imagery is generally not used for small rivers and creeks because spatial and temporal resolution is coarse.[19] Fixed-wing aircraft and low-flying helicopters commonly collect TIR data at the watershed-scale.[9,20] Aircraft allow for variable spatial resolution, creating opportunities to collect data that meets specific research needs. Flights may capture 50 river kilometers per day; however, they are expensive.[15] Because of the expense, data collection is repeated less frequently, producing poor temporal resolution. UAVs and drones are increasingly used to collect TIR data; however, drones must have a sufficient payload to support thermal cameras. Our camera weighs 0.9 kilograms (kg). This requires multicopter-type drones (which cost approximately $20,000 - $40,000) rather than less expensive hobby drones. Larger drones are limited by battery-life, uncertain Federal Aviation

Administration rules and status, and are prohibited from locations such as National Parks.[24,25] Bankside TIR photography is inexpensive, detecting temperature change over time when multiple images are captured. This method is appropriate only for very small spatial areas with bankside access, so it may be used for reconnaissance to locate hyporheic flows, springs, and seeps.

Weather balloons have collected TIR imagery of surface water pollution in large, non-wadeable rivers or confluences of rivers with the ocean in a handful of instances. Lega and Napoli used an ultralight fixed-wing plane, tethered balloon, unmanned blimp, and Lighter than Air UAV to monitor surface water pollution.[26] They found TIR remote sensing was successful to detect pollution, but did not include a thorough analysis of alternative aerial platforms. Horner-Devine et al. pulled a balloon-mounted TIR camera with a boat to describe river plume shape and turbulence as the plume front moved seaward.[23] Doneker et al. used a blimp-mounted TIR camera pulled by a boat to monitor pollution mixing temperatures in a large, unwadeable river.[22] No previous papers have described weather balloon platforms to monitor stream temperatures of small streams, analyzed the accuracy and spatial resolution of weather balloon platforms compared to temperature loggers, or presented costs of weather balloon platforms.

Handcock et al. showed that when at least three pixels of remotely sensed images span the width of streams, measured stream temperature error averages approximately 2% of actual stream temperature.[27] Error increases to 13% when fewer than three pixels represent river width, as occurs when TIR imagery is captured from high-flying fixed-wing aircraft at altitudes above 1 km, or satellites. They conclude that TIR imaging should be limited to large rivers.[27] We challenge that finding, and provide an alternative method for collecting high resolution TIR imagery over relatively short (~1-3 km) reaches in wadeable rivers using a weather balloon-mounted TIR camera. Weather balloons have previously been recommended to collect TIR imagery of stream temperatures where bridges are not present on rivers for overhead sampling.[28] We present a method for collecting stream temperature data in wadeable rivers.

Study site

Our study site is the confluence of the Logan and Blacksmith Fork rivers in Logan, Utah, USA (41.7062, -111.8521) (Figure 1). Elevation is 1,382 meters above sea level. Blacksmith Fork is a smaller tributary to the Logan River. The study region is characterized by cold, snowy winters and hot, dry summers (mean January and July maximum air temperatures are 0°C and 31°C, respectively). The Logan and Blacksmith Fork rivers drain the west slope of the Bear River Range in northern Utah. Downstream the Logan River flows into the Bear River, which drains into the Great Salt Lake. These rivers are dominated by snowmelt runoff in spring, although groundwater maintains baseflow through summer and fall. These rivers supply water for agricultural and urban use, accommodate recreation, and provide habitat for waterfowl, shorebirds, and cold water fish, and contribute freshwater to the Great Salt Lake. The confluence of the Logan and Blacksmith Fork Rivers has tall riparian trees (> 30 m), lending itself to tethered weather balloons that can be maneuvered to image stream temperatures below the dense riparian canopy (Figure 2). Riparian canopies block the line of sight for aircraft that fly above the canopy.

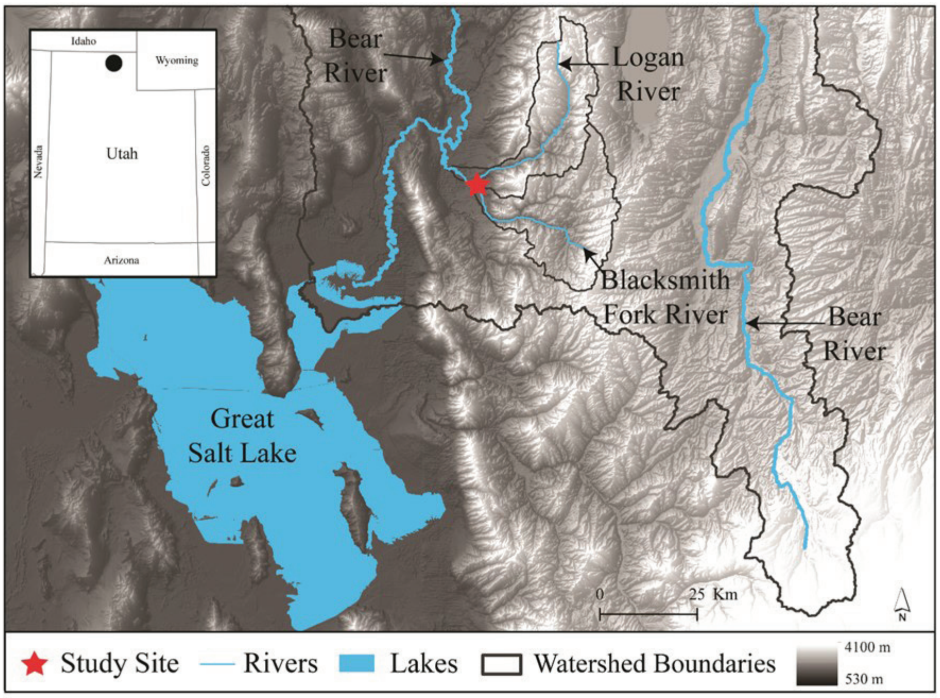

Figure 1. Confluence of the Logan and Blacksmith Fork Rivers study site.

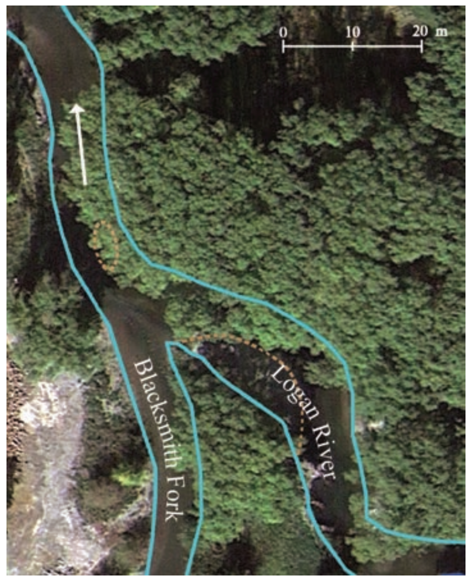

Figure 2. Google Earth aerial imagery showing riparian vegetation in October 2014 with stream banks and sandbars superimposed.29 Arrow shows flow direction.

The headwaters of the Logan River provide critical habitat for the bonneville cutthroat trout (*Oncorhynchus carki utah*), a 'species of special concern' currently protected under a multi-agency conservation agreement intended to preclude listing under the federal Endangered Species Act.[30] Other fish species present in the Logan River and Blacksmith Fork include non-native brown trout (*Salmo trutta*), stocked and wild rainbow trout (*O mykiss*), brook trout (*Salvelinus fontinalis*), native mountain whitefish (*Prosopium williamsoni*), and sculpin (*Cottus spp.*).[31] Generally, native trout species are restricted to upstream reaches while non-natives like brown trout are present in the lower elevations of the system. Trout species, such as bonneville cutthroat trout, are sensitive to stream temperature changes from habitat degradation and climate change, so affordable and easily repeatable stream temperature monitoring is desirable.[32] Adult cutthroat trout (all subspecies) require stream temperatures less than 22 °C, although optimal temperatures for embryos are 10 °C, juveniles require temperatures of 11 – 21 °C, and spawning adults prefer temperatures of 6 – 17 °C.[33]

Methods

Thermal camera and temperature loggers

We used a FLIR T450sc compact infrared camera to capture both visible light and TIR imagery in the 7.5 to 13 μm spectral range.[34] TIR images represent radiant stream temperatures. Our camera had an 18 mm lens for thermal imaging with a 19 ° to 25 ° field of view. TIR camera resolution is 320 x 240 pixels and operating temperature ranges from -15 to 50 °C. Visible image resolution is 2048 x 1536 pixels. The accuracy of the TIR camera is +/- 1 °C or +/- 1% (limited range) of the reading. Our temperature range during sampling was 11 °C (including air temperatures that are not presented). The camera weighs 0.9 kg, which is one of the lightest FLIR science and research TIR cameras.

To validate the measurements of the FLIR TIR camera, we placed twelve Thermochron 1921G iButton temperature loggers (Maxim Integrated) in the water column approximately six inches above the streambed. One iButton was installed on land to measure air temperature. The iButton temperature loggers were programmed to collect stream temperatures every ten minutes, placed in waterproof capsules, and deployed in a rough grid above the bed of both rivers to validate TIR temperatures. Our placement of data loggers was based on the spatial plume of water from the Blacksmith Fork tributary, a known tributary mixing zone. Temperatures of both tributaries were taken with a handheld probe prior to our flight, although the exact spatial dimensions of the mixing zone were unknown. Both rivers have riffle morphology and are advection-dominated so assumed both rivers are vertically well-mixed outside of the confluence mixing zone. Typically shallow rivers may stratify in deep pool geomorphic units, but not in riffles.[35] Data loggers are accurate to +/- 1 °C in the -30 to +70 °C range. Future research could verify the accuracy of iButtons near 0 °C using a more accurate thermometer.

Weather balloon

The weather balloon had a suspended case to house the FLIR camera and three ground tethers to guide and control the balloon (Figure 3). We used a 600 gram professional weather balloon, which was filled with helium to approximately 1.8 m in diameter. The case containing the camera was attached to the neck of the balloon via a Picavet system, allowing for self-equalization and a nadir view angle.[36] Our Picavet system is anchored to the four corners on top of the case and is created by a continuous, two meter long, 0.3 cm diameter mason line. The neck of the balloon was outfitted with a small, 3.8 cm diameter PVC pipe to support the 0.9 kg camera.

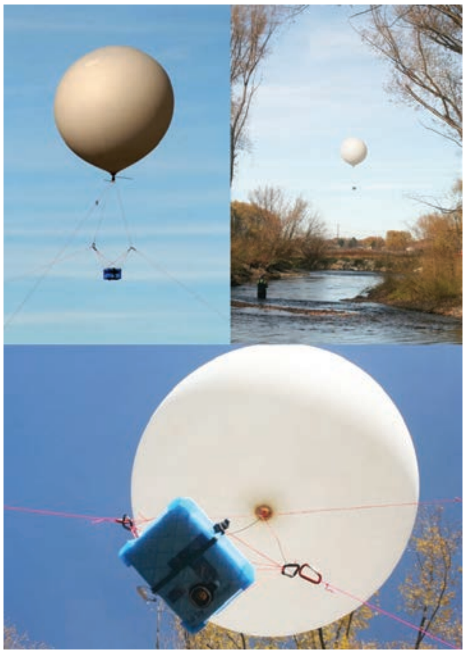

Figure 3. The TIR balloon platform comprises three main parts: the balloon, camera case, and tether system.

Stream temperatures were measured by temperature loggers and TIR imagery from approximately 13:00–13:30 on November 18, 2014. Air temperature reached a maximum of 1.1 °C. Stream discharge was 2.8 cubic meters per second (cms) (99 cubic feet per second [cfs]) and 1.6 cms (55 cfs) in the Logan and Blacksmith Fork Rivers, respectively (USGS site numbers 10109000 and 10113500). One hundred and twenty TIR and 120 visible light images were captured from the weather balloon that was flown at an altitude of approximately 20 meters. The camera was programmed to simultaneously capture both visible and infrared images automatically every 15 seconds.

We planned the flight to coincide with high pressure (actual air temp was 1.1 °C, cloud cover was approximately 15%, maximum wind speed was less than 10 km per hour, and there was no precipitation). We also preselected our flight location based on a known river mixing zone at the confluence of two tributaries. Our flightpath began by moving downstream in the Logan River, then subsequently moving up river along the confluence and finally upstream in the Blacksmith Fork River (Figure 4A). Three field technicians moved the balloon by simultaneously walking upstream or downstream, where each person controlled one of the balloon's tethers. Tall trees are plentiful in the area, requiring the field crew to utilize all three tethers as well as someone on the bank with a good view of potential hazards to guide field crew. Occasionally, one person holding a tether would step around obstacles on the bank or in the river, which was achievable as the remaining two people steadied the balloon. A few branches extended over the channel, which is typical of riparian corridors, and careful cooperation was needed between all four field technicians to fly the weather balloon.

Data processing

We processed and mosaicked approximately 40 visible images using known reference points with Adobe Photoshop CS5 software. Then, we substituted corresponding TIR imagery using the mosaicked configuration identified with the visible light images. We removed pixels that extended beyond the stream or that had fractions of stream banks, and interpolated radiant stream temperatures along banks using nearby pixels within each stream. We used ArcGIS to geo-reference the resulting TIR image using known reference points. FLIR Systems, Inc. provides Researcher IR software to automatically estimate kinetic stream temperatures from radiant stream temperatures using emissivity estimates of water; however, we compare radiant TIR imagery captured directly overhead with kinetic temperatures measured by iButtons as a conservative estimate in this proof-of-concept study, to understand the accuracy of our method if water emissivity estimates are uncertain.

We linearly regressed 13 iButtons in the mixing zone with TIR measurements at the same locations to quantify the difference between surface (TIR) and water column (iButton) temperatures using the statistical program R (Figure 6).[37] The regression relationship between FLIR measured surface temperatures and iButton measured water column temperatures were calculated using a general linear model (simple regression) on the values of the iButton verses the pixel values of the FLIR at the corresponding location. While this inherently includes error between radiant TIR and kinetic iButton measurements, it differentiates between surface and water column stream temperatures.

Results

The iButton data recorded during the balloon flight were averaged through time to show stream temperatures of the two rivers (standard deviation of sites through time was

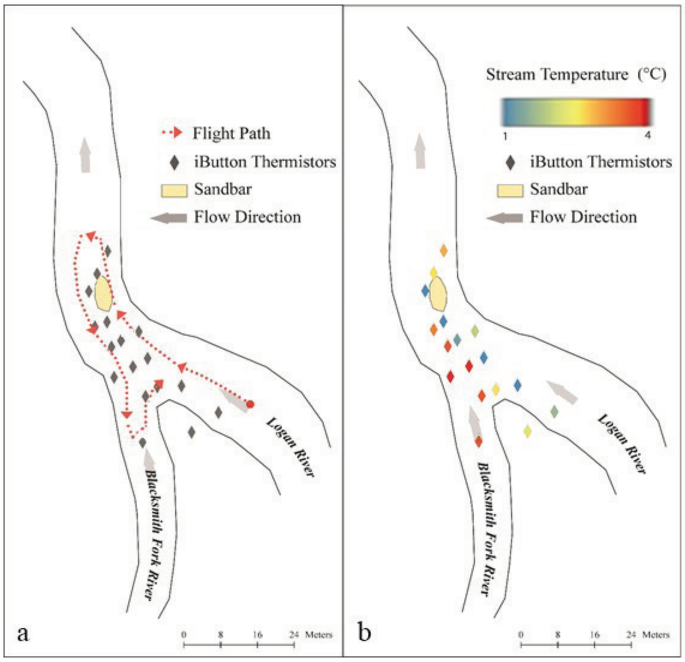

Figure 4. Stream survey data from the weather balloon platform and iButton temperature loggers on November 18th, 2014. (a) Flightpath of weather balloon in relation to temperature loggers, focusing on mixing zone of the Logan and Blacksmith Fork Rivers; (b) Measured iButton stream temperatures

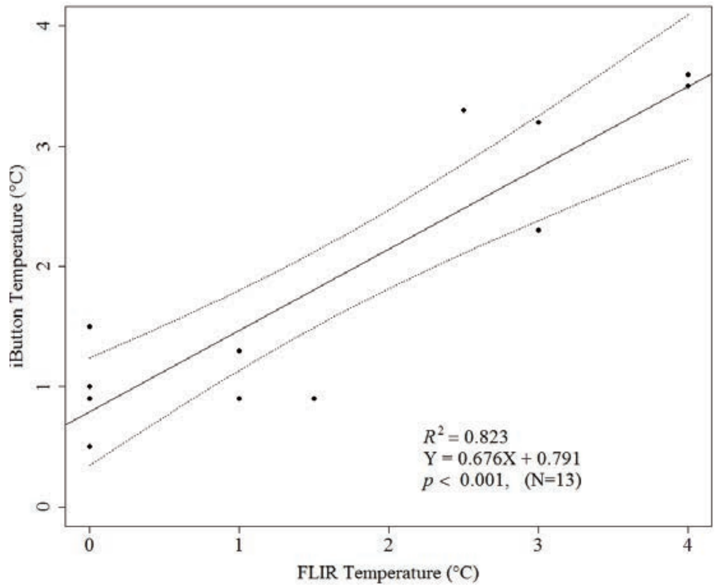

Figure 6. Linear regression between FLIR TIR (surface) and iButton (water column) temperatures. Solid line indicates the predicted regression values and the dashed lines show 95% confidence intervals.

0.09 °C) (Figure 4B). Stream temperatures ranged from approximately 1 to 4 °C, with warmer temperatures in the Blacksmith Fork River and cooler temperatures in the Logan River. We deduced that the two rivers mixed near the confluence, but iButtons were insufficient to measure the spatial extent and detail of the mixing zone (Figure 4B).

Logan River stream temperatures were measured at approximately 1 °C and 1.5 °C with TIR and iButtons, respectively, and Blacksmith Fork stream temperatures were measured at approximately 4 °C for both TIR and iButtons (Figure 4B and 5). TIR surface temperatures were thus representative of the water column and reflectance did not confound data collection when imagery was collected with the weather balloon. This suggests radiant stream temperatures measured directly above streams using a weather balloon-mounted FLIR camera are within 1 °C of kinetic temperatures collected by temperature loggers. This corroborates prior research showing remotely sensed radiant temperatures were within 0.5 °C of measured kinetic temperatures.[14]

The mosaicked TIR imagery clearly delineates and quantifies the mixing zone between the Logan River and Blacksmith Fork (Figure 5). The number of pixels representing the lateral stream extent varied by stream width, but was approximately 580 pixels just upstream of the sandbar (Figure 5). Thus, pixel size was approximately 3 cm.

Linear regression significantly predicted water column temperature ($p < 0.001$), however an unexplained variability remained ($R2 = 0.823$) (Figure 6). Potential factors that explain variability include air temperature, the amount of solar radiation, shading from canopy cover, and differences between surface and water column temperatures. The TIR camera underestimated stream temperatures near 0 °C. Our method delineates the mixing zone on the surface and gives a reasonable predictor of the temperatures in the water column, proving the utility of image-based temperature measurements.

Discussion

Discussion of costs

The tethered weather balloon method for collecting TIR imagery is inexpensive, costing less than $400 per flight (not including a TIR camera purchase or rental). The TIR camera we used cost $15,000 in 2013 and could be rented for $1150 for one week.[38] Table 1 itemizes non-camera costs. Helium is the most costly expense and in late 2014 was about $39/cubic meter. One tank of helium enabled two flights and most weather balloons can be used five to six times. More importantly, because this method is inexpensive, it can be easily repeated for short reaches to: improve understanding of daily, seasonal, or inter-annual stream temperature change: monitor stream temperatures prior to and following restoration or disturbance: identify thermal refugia: or evaluate changing instream habitat conditions.

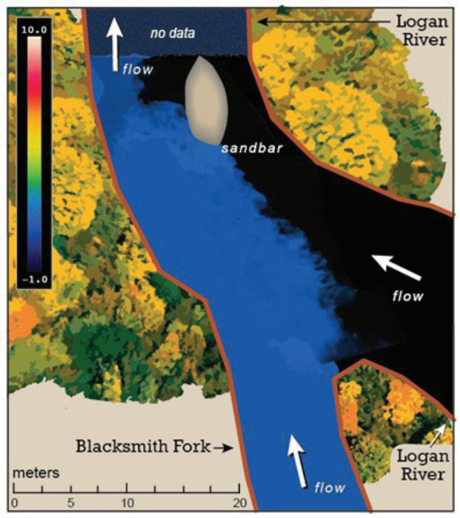

Figure 5. Mosaicked TIR imagery of Blacksmith Fork and Logan River surface mixing zone collected November 18th, 2014. Stream temperatures are in degrees Celsius. TIR image of water surface is combined with visual representation of streambank vegetation to aid the sense of space of the map.

Limitations

General data errors associated with TIR imaging have previously been described.[9,27] Although reflected longwave radiation errors are minimized when the camera is directly above the target, errors from clouds, fog, and humidity may occur. These data errors can be minimized with careful mission planning. When data collection timing is flexible, TIR imagery should be collected on days with high pressure and mild winds. Atmospheric distortion data errors from humidity, clouds, fog, or wind may be minimized by reducing the altitude of the weather balloon. They could also be corrected for with modeled estimates of atmospheric transmissivity to standardize TIR stream temperature data despite variable atmospheric conditions.

Maintaining constant weather balloon altitude was a major challenge due to wind, tree branches, varying bank height, etc. Our weather balloon TIR platform was sensitive to wind and data are best collected on calm days (wind speed less than 10 km/hr). Visible light images were distorted when mosaicked together from changing balloon altitude and stream temperatures are thus also distorted. This has long been a problem with early remote sensing techniques.[39] Determining the necessary height of the balloon to capture desired stream extent requires pre-flight planning. Like all stream temperature data collection, our method relies on field technicians. For this application, we used a field crew of 3-4 people. Careful collection of ground control points measured with GPS adds spatial accuracy if known reference points are unavailable.

The visible and TIR cameras on the FLIR 450sc camera are not the same resolution or spatial extent. Visible light images capture a larger area than TIR images and are higher resolution. This makes mosaicking images complicated and time consuming. We recommend mounting an additional visible light camera of the same resolution and focal length as the TIR camera to facilitate image mosaicking in future flights and for future FLIR camera development.

Benefits of weather balloon platform for TIR stream temperature imaging

Collecting TIR imagery with a ground-tethered weather balloon is a useful and viable approach to measure stream temperatures in wadeable rivers. Monitoring continuous, high resolution surface stream temperatures allows for mixing zones from seeps, tributaries, return flows, or reservoir releases to be spatially delineated. Continuity is improved over temperature loggers deployed in grids or DTS cables snaked throughout rivers to capture longitudinal and lateral thermal variability. Our method may facilitate data collection compared to higher flying TIR platforms when riparian vegetation blocks streams. Stream temperatures can be collected for longer periods of time than from drones because the weather balloon is not constrained by battery life. For example, a quick test of a DJI Premium+ octocopter with a payload of approximately 6 kg lasted about 20 minutes with four batteries. This method is also a viable alternative where drones are not permitted, such as National Parks (although weather balloons are not permitted at altitudes exceeding 150 m, within 150 m from the base of clouds, within 8 km of airports, or where visibility is less than 5 km).

Item	Cost
600 gram, 8 foot diameter "Sky Probe" chloroprene weather balloon	$72.42
Helium tank rental with 7.1 cubic meters of helium gas	$275.00
Plastic case for camera	$4.27
Mason line	$20.91
3 carabiners (non-climbing grade	$7.90
Zip ties	$4.36
Styrofoam padding	$5.25
Total	**$390.11**

Table 1. Itemized costs of weather balloon TIR platform

A benefit of our approach over satellite, helicopters, or aircraft methods is that stream temperatures can be resampled, as needed, at little expense. The weather balloon-mounted TIR imagery approach described here is beneficial for small rivers and relative short study reaches (less than approximately 3 km in length) when repeated or multi-hour temperature collection is a priority. Images can be obtained frequently to examine spatial and temporal (sub-daily, daily, seasonal, and inter-annual) patterns in stream temperature at high spatio-temporal resolution. Fixed-wing TIR imagery is more appropriate in large study reaches where many miles of stream surface temperatures are collected.[27] We improve upon bankside TIR collection because the field of view is widened so that a greater extent of river can be captured with each image, yet resolution remains high with hundreds of pixels representing cross-sections of streams. Also, imagery collected directly overhead reduces reflectance errors that may skew stream temperature data.

Our research corroborates findings that fine-scale TIR imagery is useful for identifying thermal variability in streams, and describes a method to collect TIR imagery with a weather balloon-mounted TIR camera.[28] Our method could be applied to quantify thermal refugia for temperature-limited aquatic species with high spatial and temporal resolution over study reaches a few kilometers long. The weather balloon platform that we describe is a method that is helpful for quantifying longitudinal stream temperature patterns that fit poorly with geographical or theoretical expectations and is an approach that can support comprehensive thermal refugia management strategies to identify and preserve existing thermal refugia in rivers.[40,41]

Acknowledgments

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