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Spatial heterogeneity in geothermally-influenced lakes derived from atmospherically corrected Landsat thermal imagery and three-dimensional hydrodynamic modelling

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ABSTRACT

Atmospheric correction of Landsat 7 thermal data was carried out for the purpose of retrieval of lake skin water temperature in Rotorua lakes, and Lake Taupo, North Island, New Zealand. The effect of the atmosphere was modelled using four sources of atmospheric profile data as input to the MODerate resolution atmospheric TRANsmission (MODTRAN) radiative transfer model. The retrieved skin water temperatures were validated using a high-frequency temperature sensor deployed from a monitoring buoy at the water surface of Lake Rotorua. The most accurate atmospheric correction method was with Moderate Resolution Imaging Spectroradiometer (MODIS) atmospheric profile data (root-mean-square-error, RMSE, 0.48 K), followed by radiosonde (0.52 K), Atmospheric Infrared Sounder (AIRS) Level 3 (0.54 K), and the NASA atmospheric correction parameter calculator (0.94 K). Retrieved water temperature was used for assessing spatial heterogeneity and accuracy of surface water temperature simulated with a three-dimensional (3-D) hydrodynamic model of Lake Rotoehu, located approximately 20 km east of Lake Rotorua. This comparison indicated that the model was suitable for reproducing the dominant horizontal variations in surface water temperature in the lake. This study demonstrated the potential of accurate satellite-based thermal monitoring to validate temperature outputs from 3-D hydrodynamic model simulations. It also provided atmospheric correction options for local and global applications of Landsat thermal data.

1. Introduction

Lakes are known to be sentinels of climate change, as physical, chemical and biological properties respond strongly to atmospheric forcing and changing climate (Williamson et al., 2008; Adrian et al., 2009). A key indicator is water temperature, which is crucial to understanding lake ecosystem functioning (Hutchinson, 1957). High-frequency *in situ* sensors are commonly used to monitor vertical variations in temperature in lakes (Yeates et al., 2008), however, such techniques are not commonly used to monitor horizontal variations.

The use of measurements obtained from satellites potentially provides a solution to this problem (Hook et al., 2003). Of particular note is the large increase in the use of Landsat visible, infra-red and thermal-infrared imagery for earth observations, prompted by the release of the entire data archive for free public use. Furthermore the Landsat thermal band encompasses fine–scale (60 m resolution) thermal features. Atmospheric correction (AC) is a crucial step for ensuring accuracy of satellite data, as differences between bulk water temperature and uncorrected satellite-derived water skin temperature can be as large as 4.55 K (Fisher and Mustard, 2004). Limited availability of meteorological data and difficulty of radiative transfer-based AC have previously limited temperature retrieval algorithms to empirically based methods (e.g., Lathrop and Lillesand 1987; Baban 1993). Single channel algorithms for AC of Landsat data have used the Low Resolution Transmission model (LOWTRAN) for retrieval of water surface temperature in Lake Ontario (Schott and Volchok, 1985). The LOWTRAN 7 model (spectral resolution measured by spectroscopic wavenumber at 20 cm^{-1}) has now been superseded by Moderate Resolution Transmission (MODTRAN) which uses spectral resolutions ranging from

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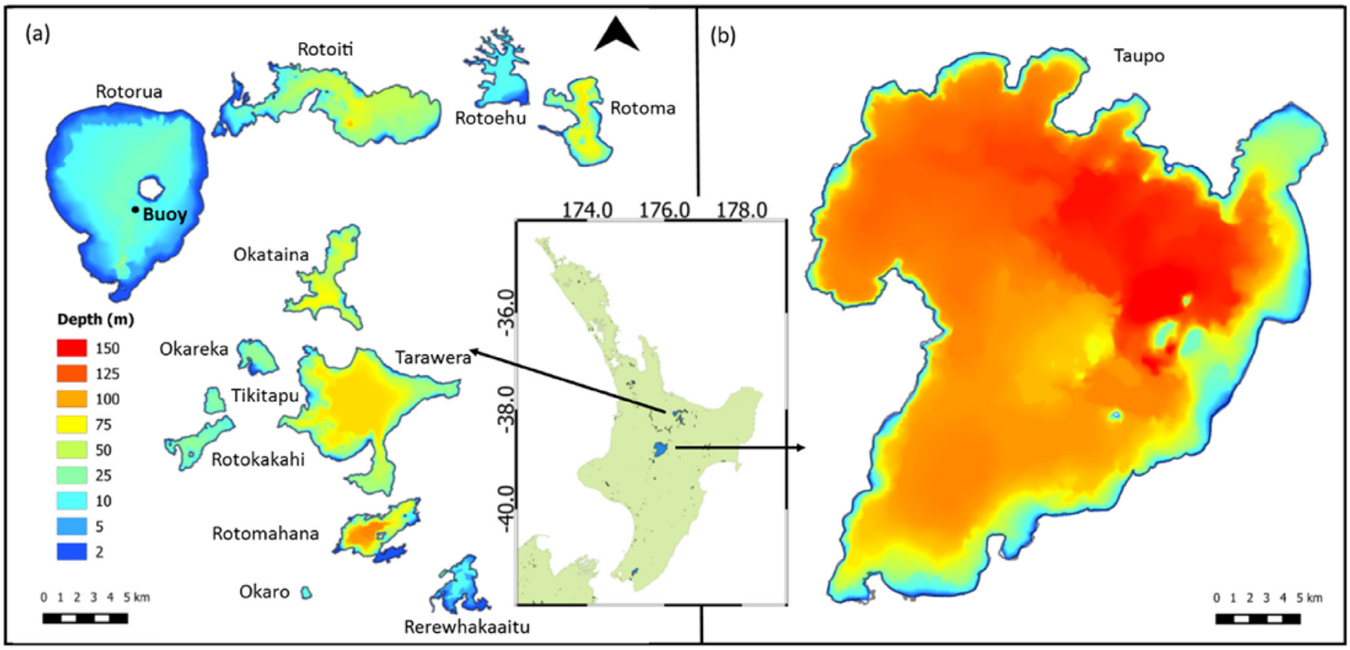

Fig. 1. Study site map including depth for (a) Rotorua lakes and (b) Lake Taupo. An overview of the location of study site in the North Island, New Zealand shows latitude longitude. The depth key applies to (a) and (b).

2 cm^{-1} (MODTRAN 3.7–4.0) to 0.2 cm^{-1} (MODTRAN 5.0). Errors from water temperature retrieval with Landsat satellites can be quantified (Padula et al., 2010; Schott et al., 2012), but there is little information regarding the accuracy of applying satellite derived atmospheric profiles of temperature and relative humidity (*RH*) used in radiative transfer modelling for thermal atmospheric correction. Precise characterization of atmospheric profiles has been identified as a critical factor to derive accurate surface temperature when using radiative transfer models (Li et al., 2013). Several single channel algorithms have also been developed which do not require atmospheric profiles and use empirical relationships between atmospheric transmittance, water vapour, mean atmospheric temperature and near surface air temperature (Qin et al., 2001). More recently Cristobal et al. (2009) demonstrated the use of a single channel algorithm that uses water vapour content and near surface air temperature. However the aforementioned algorithms are inaccurate at high water vapour content (Jiménez-Muñoz and Sobrino, 2010). Thus for robust earth surface temperature estimations, atmospheric profile data are required.

Satellite thermal imagery has been used for a wide variety of lake applications including: geologic exploration (van der Meer et al., 2014), temperature monitoring of volcanic (Oppenheimer, 1993) and other lakes (Alcântara et al., 2010; Giardino et al., 2001; Lamaro et al., 2013; Sima et al., 2013; Simon et al., 2014); characterising upwelling and circulation (Steissberg et al., 2005a); observing surface current speed/direction (Steissberg et al., 2005b) and near-shore thermal bars (Schott et al., 2001); identification of groundwater discharge areas (Tcherepanov et al., 2005); estimating the influence of lake morphology and clarity on water surface temperature (Becker and Daw, 2005); and validation of physically based 3-D hydrodynamic models (Pahlevan et al., 2012). Remote sensing radiometers measure the lake water 'skin' temperature (upper 100 μm) rather than the bulk surface temperature usually measured with *in situ* sensors. Skin temperature differs from bulk temperature due to heat transfer at the air-water. The skin temperature is usually lower than the bulk temperature due to net heat loss (0.1–0.5 K), however, shallow diurnal thermoclines can sometimes cause skin temperature to be warmer than the bulk temperature by ~3 K (Fairall et al., 1996). Bulk and skin temperature differences have been found to be at a minimum (average daily temperature difference of −0.1 K) from 0900 to 1100 h (Schneider and Mauser, 1996), which corresponds to the nominal mean sun time of the Landsat 7 descending node at the Equator (1000 h). Hook et al. (2003) found consistent differences between near-real-time measurements of lake skin temperature from radiometers and bulk surface water temperature measurements in Lake Tahoe (California, USA) over a diurnal cycle, with daytime and night time skin temperatures cooler by an average of 0.11 K and 0.46 K, respectively.

Process-based modelling of lake water temperature offers opportunities to interpolate temporal data gaps derived from satellite and routine monitoring data, and to extrapolate surface water temperatures to an entire waterbody. Validation of three-dimensional (3-D) models is difficult using traditional point-based monitoring, but the synthesis of satellite thermal imagery with high-frequency temperature measurements from thermistor chains presents an opportunity to evaluate the spatial and temporal outputs of temperature from 3-D hydrodynamic models. Determination of initial conditions over a whole model simulation domain can also be especially challenging, but may be usefully addressed in the horizontal dimension with satellite imagery (e.g., Alvarez et al., 2007). A high level of accuracy and confidence is required in satellite data for it to be useful in validation of 3-D models.

The major objective of this work was to compare AC of Landsat thermal imagery using MODTRAN with four sources of atmospheric profile data, thereby informing users of Landsat data about the most appropriate AC methods. A further objective was to use remotely sensed temperature data to validate output from a 3-D hydrodynamic model of a polymictic lake that has high horizontal variability in water temperature due to the influence of a warm geothermal inflow.