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Modeling sub-daily near-surface turbulent fluxes at a glacier surface: bulk methods versus eddy-covariance

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Most surface energy balance models require parameterization of turbulent heat, but these approaches are error prone. Our objective is to evaluate commonly used bulk methods to simulate turbulent heat fluxes at a sloped glacier surface and compare these methods with approaches based on a simple katabatic flow model. We evaluate six bulk schemes for estimating 30-min turbulent fluxes of momentum, sensible and latent heat and compare these estimates against observed fluxes measured with the open path eddy-covariance (OPEC) method. A one-level meteorological station collected turbulent fluxes for two melt seasons over a mountain glacier in British Columbia. We performed a set of quality control corrections prior to our analysis. Few 30-min data segments met the criteria for the near-neutral static stability and the steady-state turbulence conditions, revealing a challenge to perform this type of analysis at sites dominated by the stable conditions and drainage (katabatic) flows. Our analysis of the two independent seasons yielded these findings: (1) The bulk methods, with or without the commonly used Monin-Obukhov (M-O) stability functions, overestimate the turbulent heat fluxes over the observational period. This overestimation is most pronounced during the katabatic flow conditions, corroborating the previous findings that the M-O theory works poorly in the presence of a shallow wind speed maximum; (2) The bulk method based on a katabatic flow model agrees closest to observed momentum fluxes among all the tested methods; (3) A 'hybrid' method which combines the bulk method based on the katabatic model and a bulk method that assumes the logarithmic wind profile yields the best overall performance in simulating the heat fluxes; and (4) Our error analysis reveals that the differences in modeled and OPEC-derived fluxes are greater than the errors due to uncertainties in measured meteorological variables and roughness lengths. Our findings imply that further advances in modeling the turbulent fluxes for mountain glaciers will require improvement to model theory rather than better measurements of input variables to the bulk methods.