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# Validating modeled turbulent heat fluxes across large freshwater surfaces

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## Introduction

The turbulent fluxes of latent and sensible heat are important physical processes that influence the energy and water budgets of the North American Great Lakes. Validation and improvement of bulk flux algorithms to simulate these turbulent heat fluxes are critical for accurate prediction of lake hydrodynamics, water levels, weather, and climate over the region. Here we evaluate five heat flux algorithms from several model systems that are used in research and operational environments and concentrate on different aspects of the Great Lakes' physical system.

## Method

Table 1. Bulk flux algorithm details

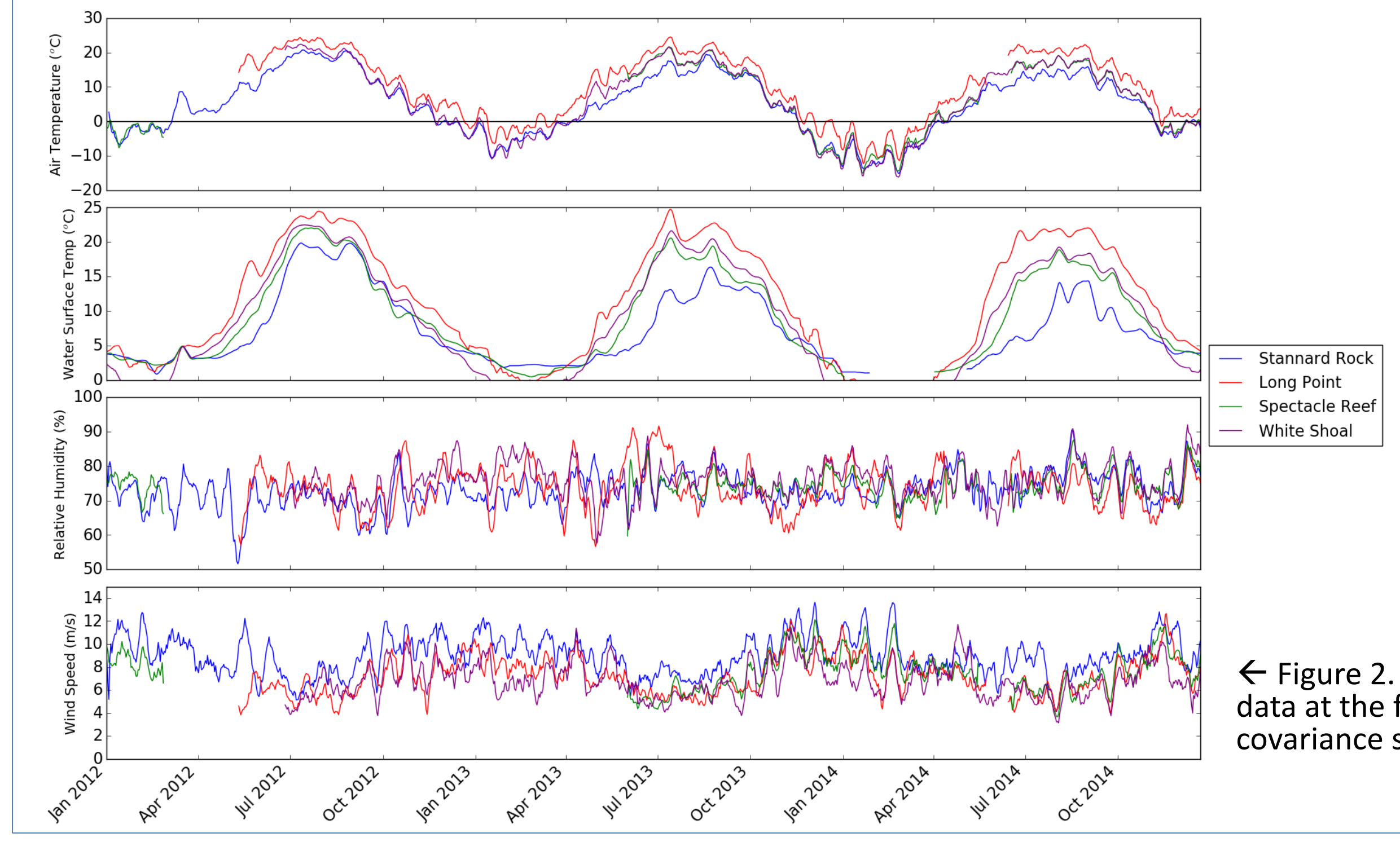
| Algorithm name | Stability func. | | Roughness length for | | Gustiness | Parent Model |
|---|---|---|---|---|---|---|
| | unstable | stable | momentum $z_0$ | temperature $z_\theta$ and humidity $z_q$ | | |
| **LS87** | Businger et al. (1971) | Holtslag et al. (1990) | $\alpha\frac{u^{*2}}{g}+0.11\frac{\nu}{u^*}$, $\alpha$=0.011 | Assume equal to $z_0$. | No | Unstructured grid, finite-volume community ocean model (FVCOM) (ocean model) |
| **C89** | | | $\alpha\frac{u^{*2}}{g}$, $\alpha$=0.0101 | | No | Large Lake Thermodynamic Model (hydrology model) |
| **Z98L** | | | 0.001 m | | Yes | Weather Research and Forecasting-lake (WRF, atmospheric model) |
| **J99** | Businger et al. (1971) | Beljaars and Holtslag (1991) | $z\exp\left[-\kappa\left(\frac{2.7\times10^{-3}}{U}+1.42\times10^{-4}+7.64\times10^{-5}U\right)^{-1}\right]$ | | No | FVCOM-UGCICE (ice-ocean model) |
| **COARE** | Businger et al. (1971) & Fairall et al.,(2003) | Beljaaes and Holtslag, (1991) | $\alpha\frac{u^{*2}}{g}+0.11\frac{\nu}{u^*}$<br>$\alpha$ : function of wind speed | $\min(1.6\times10^{-4}, 5.8\times10^{-5}Rr^{-0.72})$ | Yes | FVCOM and many other applications |

***Simulation:*** The heat flux algorithms were isolated from each model and driven by meteorological data from four over-lake stations within the Great Lakes Evaporation Network (Fig. 1)

***Evaluation:*** The simulation results were then compared with eddy covariance flux measurements from the same stations.

***Improvement:*** Evidence suggests $z_0$ can be significantly larger than $z_{0\theta,q}$, because momentum is transported across the air-sea interface by pressure forces acting on roughness elements, while heat and water vapor must ultimately be transferred by molecular diffusion across the interfacial sublayer.. Only the COARE algorithm takes account of this effect in the five algorithms. To improve the $z_{0\theta,q}$ representation, we apply COARE's $z_{0\theta,q}$ parameterization to the other algorithms.

Figure 1. Map of the Great Lakes the the four eddy covariance stations. Adapted from Lenters et al. (2013)



← Figure 2. Meteorological data at the four eddy covariance stations.

## Results

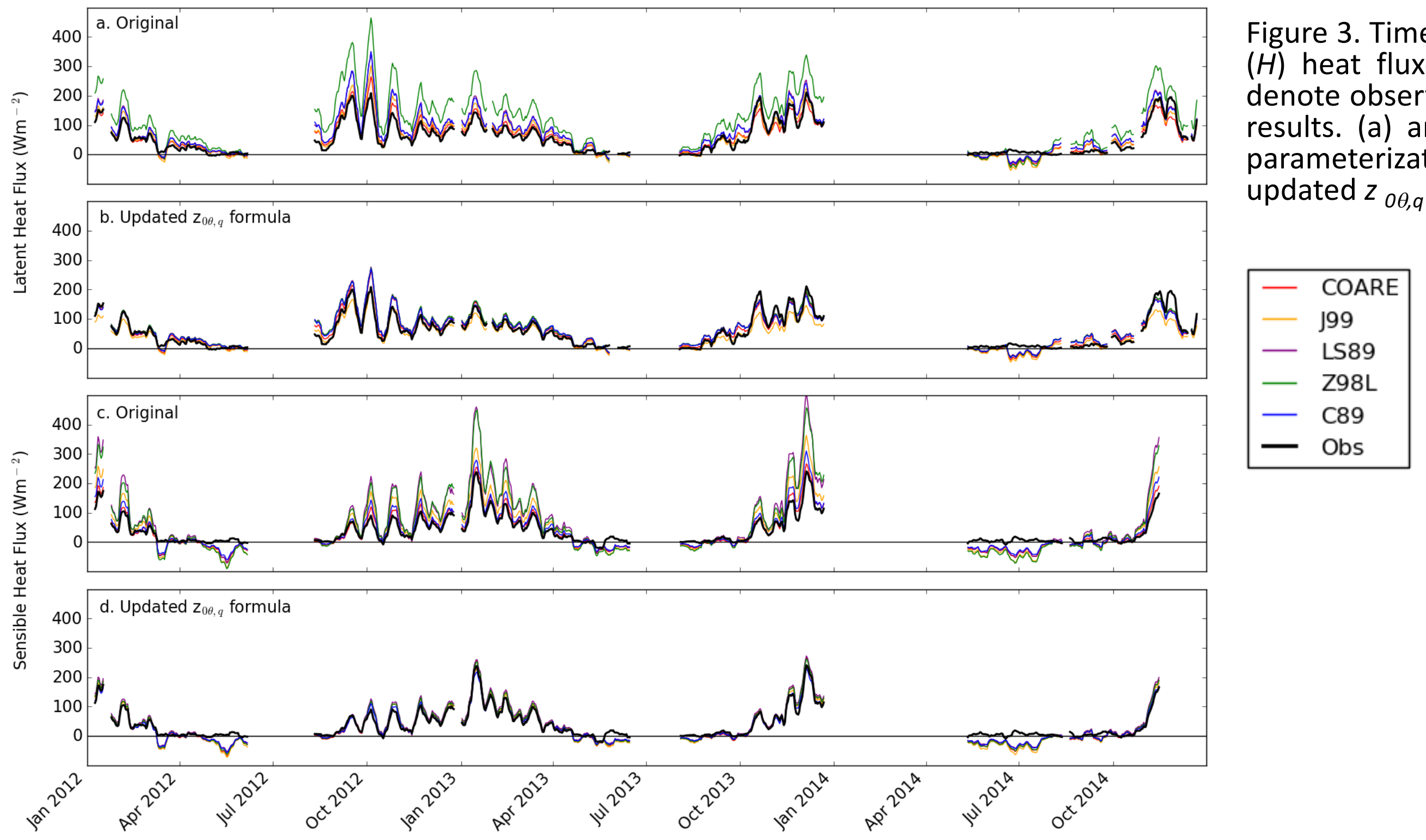


Figure 3. Time series of latent ($\lambda E$) and sensible ($H$) heat fluxes at Stannard Rock. Black lines denote observations. Color lines are simulation results. (a) and(c) are with the original $z_{0\theta,q}$ parameterization and (b) and (d) are with the updated $z_{0\theta,q}$ parameterization.

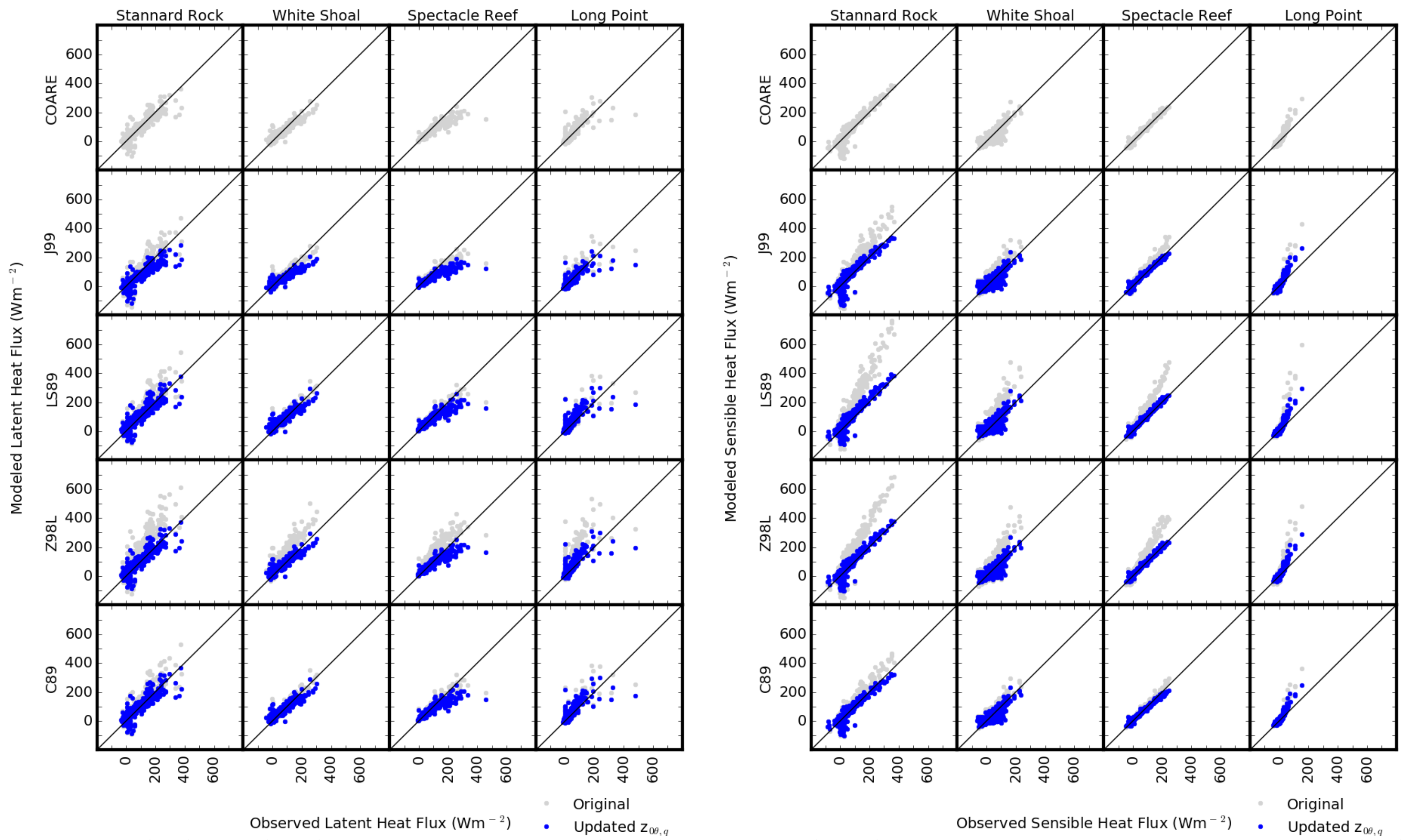


Figure 4 (left) and 5 (right). Scatter plots of observed (x-axis) and modeled (y-axis) turbulent heat fluxes. Latent heat flux in fig. 4 (left) and sensible heat flux in fig. 5 (right).

***The seasonal variation:*** The algorithms successfully reproduced seasonal cycle of latent and sensible heat fluxes (Fig. 3, 6, and 7). On the other hand, the original algorithms except for COARE showed significant overestimation of fall-time heat fluxes (Figs. 3, 4,and 5). Overall, the COARE algorithm presented the best agreement with the observations (Table 2).

***Improvement using the updated $z_{0\theta,q}$ parameterization:*** With the new $z_{0\theta,q}$ parameterization, the overestimation by the LS87, C89,Z98L, and J99 algorithms was significantly improved (Figs. 3,4, and 5).

***Geographical influence:*** At the Long Point station, which is located on the shore, the measured $\lambda E$ and $H$ appeared to be influenced by the land surface and the agreement with the simulation results was not as good as at the other stations (Figs. 6 and 7).

Table 2. Root Mean Square Errors (RMSEs) of simulated latent and sensible heat fluxes or 2012-2014. Error reduction ratios denote the mean RMSE decreases by the updated $z_{0\theta,q}$ parameterization that is normalized by mean observed fluxs.

| | RMSE [W/m$^2$] | | | | | Error reduction ratio [%] | Mean observed flux [W/m$^2$] |
|---|---|---|---|---|---|---|---|
| | COARE | J99 | LS87 | Z98L | C89 | | |
| Latent Heat $\lambda E$ | 46.7 | 53.2 (46.8) | 48.2 (47.2) | 48.1 (81.6) | 48.3 (47.6) | 11.4 | 39.0 |
| Sensible Heat $H$ | 27.3 | 27.9 (42.6) | 27.7 (68.1) | 27.2 (66.5) | 25.3 (30.6) | 48.0 | 70.0 |

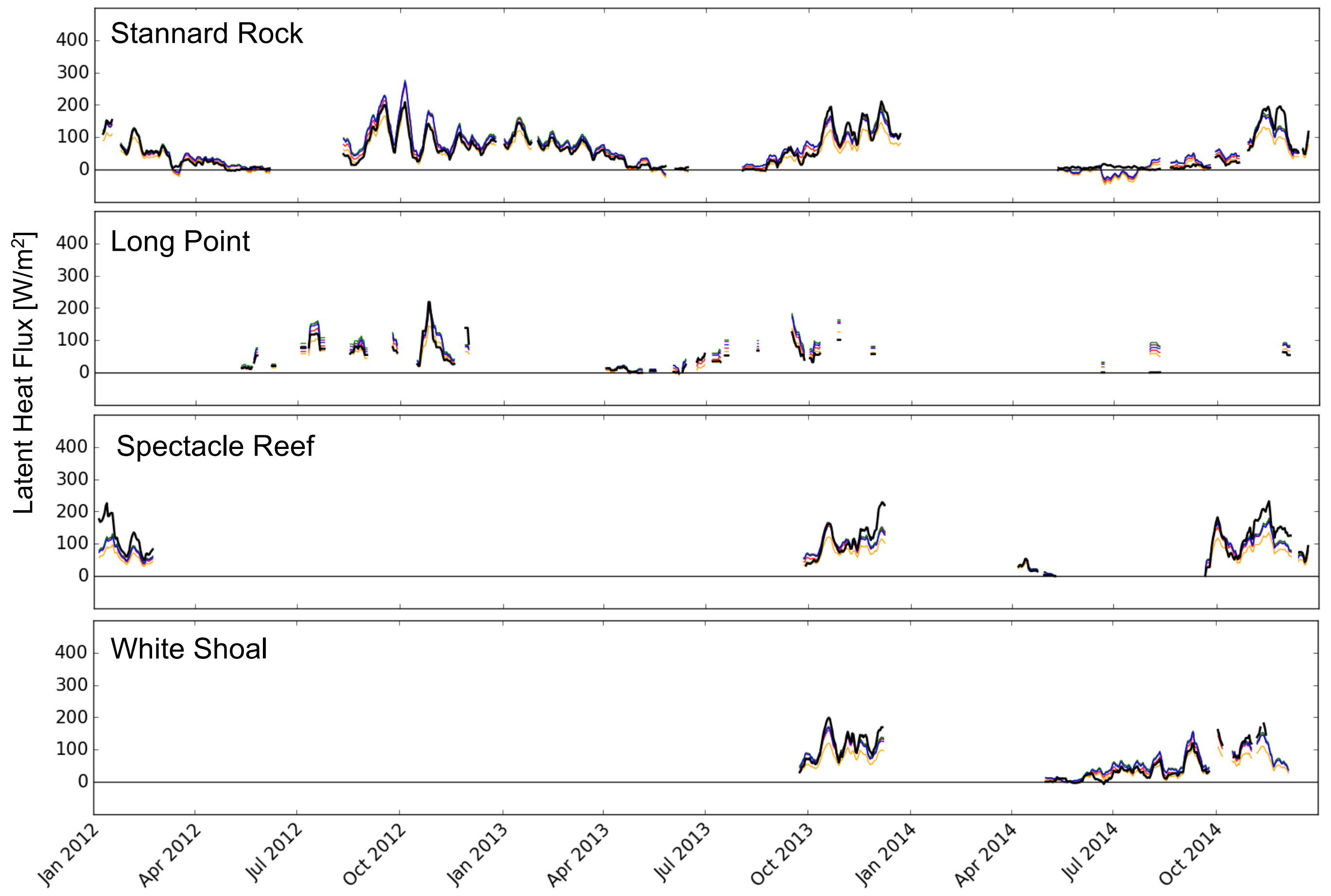


Figure 6. Time series of latent heat flux ($\lambda E$) at Stannard Rock, Long Pont, Spectacle Reef, and White Shoal. Black lines denote observations. Color lines are simulation results with the updated $z_{0\theta,q}$ parameterization.

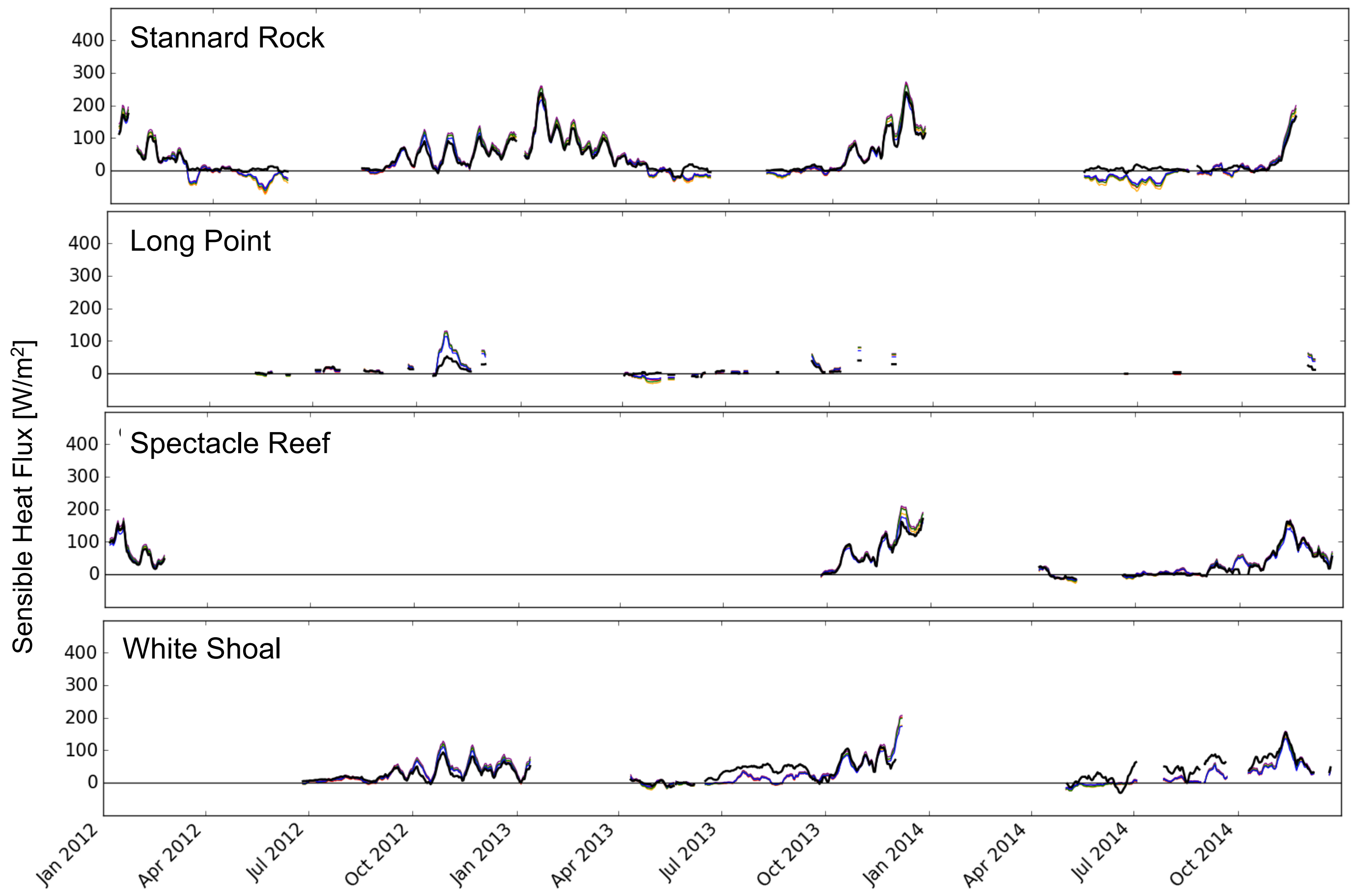


Figure 7. Time series of sensible heat flux ($H$) at Stannard Rock, Long Pont, Spectacle Reef, and White Shoal. Black lines denote observations. Color lines are simulation results with the updated $z_{0\theta,q}$ parameterization.

## Conclusion

We successfully evaluated the flux algorithms by comparing the simulation results with the eddy covariance measurements, as well as identified and reduced errors in simulated heat fluxes from these algorithms by updating the parameterization of roughness length scales for temperature and momentum. Accurate simulation of the turbulent heat fluxes from the lake surface is important to a wide range of lake-atmosphere and earth system applications. The continued monitoring of turbulent heat fluxes at the offshore stations is critical for such models to be improved in future studies.

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