# Energy partitioning of inland water bodies

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# Outlines

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- 2. Objective
- 3. Theoretical consideration
- 4. Methods
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- 6. Next step

# 1. Introduction

- Bowen ratio is critical in determining hydrologic cycle (*Yin et al., 2012*), boundary layer dynamics (*Schär et al., 1999*), weather and climate (*Wilson et al., 2002*).

- Bowen ratio yields an estimate of turbulent fluxes when the variable energy is known (*Andreas et al., 2013*).

- Constituting 4% of world land area, inland water bodies can influence regional climate (*Subin et al., 2012*).

- Energy partitioning process at water surface differs from those at terrestrial surface (*Henderson-Sellers, 1986*).

# Introduction-continued

- Relationship between air temperature and Bowen ratio from observations (*Cho et al., 2012; Wilson et al., 2002*) and theoretical models (*Priestley and Taylor, 1972; Bateni and Entekhabi, 2012*).

$$\beta = \frac{1}{\alpha}\frac{\gamma}{\Delta} + \frac{1}{\alpha} - 1 \qquad \frac{1}{\beta} = \delta\frac{\Delta}{\gamma}$$

- Inland waters showed rapid surface warming since 1985 (average $0.045 \pm 0.011^{o}C\ yr^{-1}$, maximum $0.10 \pm 0.01^{o}C\ yr^{-1}$) (*Schneider and Hook, 2010*).

- Inland waters morphology influence heat content(*Ambrosetti and Barbanti, 2002)*, thermal structure (*Mazumder and Taylor, 1994*), surface temperature (*Becker and Daw, 2005*), radiation transmission, eddy mixing (*Subin et al., 2012*) and transfer coefficients *(Panin et al., 2006* ).

# 2. Objective

- Spatially, what variable (air temperature or depth, size) controls the energy partitioning of inland water bodies?

- Does Bowen ratio have seasonal variation? If so, what is the dominantly contributing factor?

- Interannually, does the sensitivity of Bowen ratio to air temperature projected by GCMs agree with the historical trend? If not, what is the main reason for this discrepancy?

# 3. Theoretical consideration

The Priestley-Taylor (PT) model

$$\beta = \frac{H}{\lambda E}$$

$$R_n - G = H + \lambda E$$

$$H = \rho_a c_p C_H u (T_s - T_a)$$

$$\lambda E = \rho_a \lambda C_E u (q_s - q_a)$$

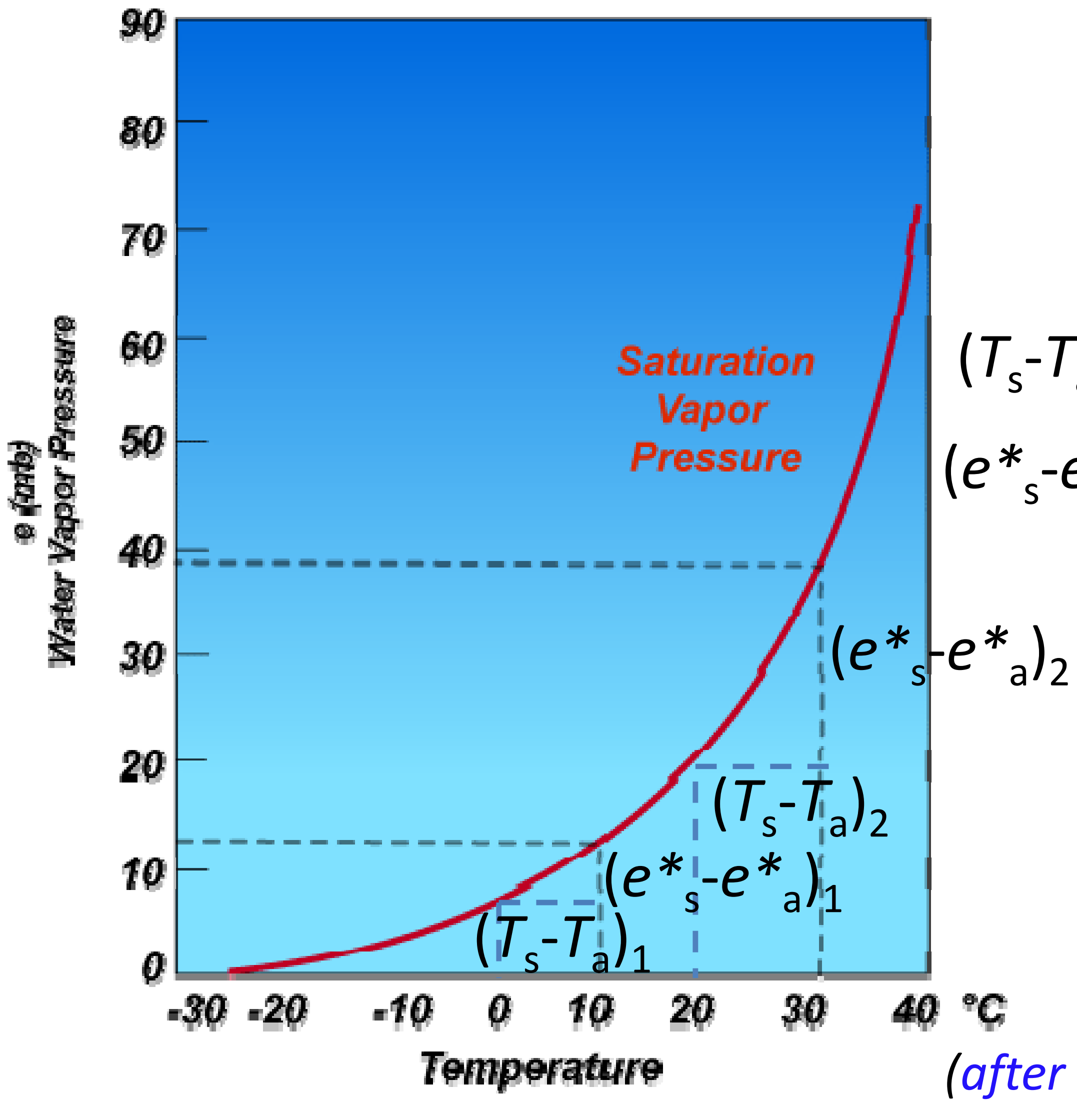
$$\lambda E = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G)$$

$$\beta_e = \frac{\gamma}{\Delta}$$

$$\beta = \frac{1}{\alpha}\frac{\gamma}{\Delta} + \frac{1}{\alpha} - 1$$

(*Brutsaert, 1982; Garratt, 1992; Priestley and Taylor, 1972*)

# Variation of saturated vapor pressure with air temperature

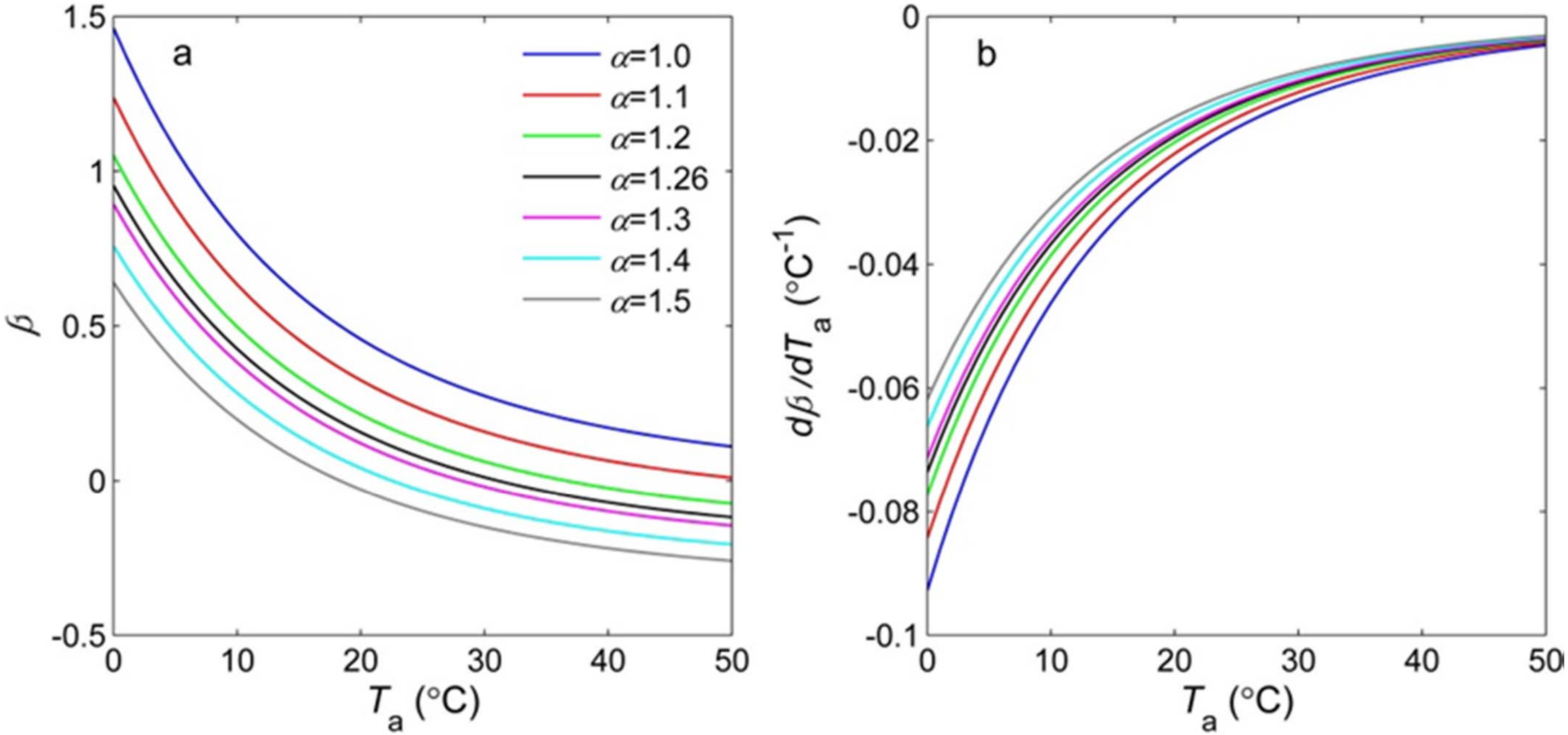



$(T_s - T_a)_1 = (T_s - T_a)_2$

$(e^*_s - e^*_a)_1 < (e^*_s - e^*_a)_2$

(*after Monteith, 1981*)

# Temperature dependence of (a) Bowen ratio and (b) Bowen ratio sensitivity to air temperature



# 4. Methods

| Type | Spatial resolution | Source | Temporal resolution | Spatial resolution | Variables |
|---|---|---|---|---|---|
| Spatial | 34 inland waters | Literature | Annual, open water | | $T_a, H, \lambda E$ |
| Seasonal | 16 inland waters | Literature | Monthly, open water | | $T_a, H, \lambda E, G$ |
| Historical | Lake Taihu | MERRA, SLM | 1979-2012 | 1/2°lat×2/3°lon | $T_a, q_a, U, P_a, K_\downarrow, L_\downarrow$ |
| | Ross Barnett Reservoir | MERRA, SLM | 1979-2012 | 1/2°lat×2/3°lon | $T_a, q_a, U, P_a, K_\downarrow, L_\downarrow$ |
| Interannal | the Great Lakes | OAFlux | 1979-2012 | 1°lat×1°lon | $T_a, H, \lambda E$ |
| | | ERA-Interim | 1979-2012 | 0.75°lat×0.75°lon | $T_a, H, \lambda E$ |
| | | NARR | 1979-2012 | 0.3°lat×0.3°lon | $T_a, H, \lambda E$ |
| Future | Lake Taihu | CESM1-CAM5, SLM | 2006-2100, 3RCPs | 0.94°lat×1.25°lon | $T_a, q_a, U, P_a, K_\downarrow, L_\downarrow$ |
| | Ross Barnett Reservoir | CESM1-CAM5, SLM | 2006-2100, 3RCPs | 0.94°lat×1.25°lon | $T_a, q_a, U, P_a, K_\downarrow, L_\downarrow$ |
| | the Great Lakes | CanESM2 | 2006-2100, 3RCPs | 2.81°lat×2.79°lon | $T_a, H, \lambda E$ |

# Simple lake model (SLM)

$$(1-\alpha)K_{\downarrow} + \varepsilon L_{\downarrow} - \varepsilon\sigma T_s^4 = H + \lambda E$$

$$H = \rho_a c_p C_H u (T_s - T_a)$$

$$\lambda E = \rho_a \lambda C_E u (q_s - q_a)$$

Linearization of $T_s$ and $q_s$

Meteorological drives

Solution of $T_s$

$H$, $\lambda E$, $\beta$

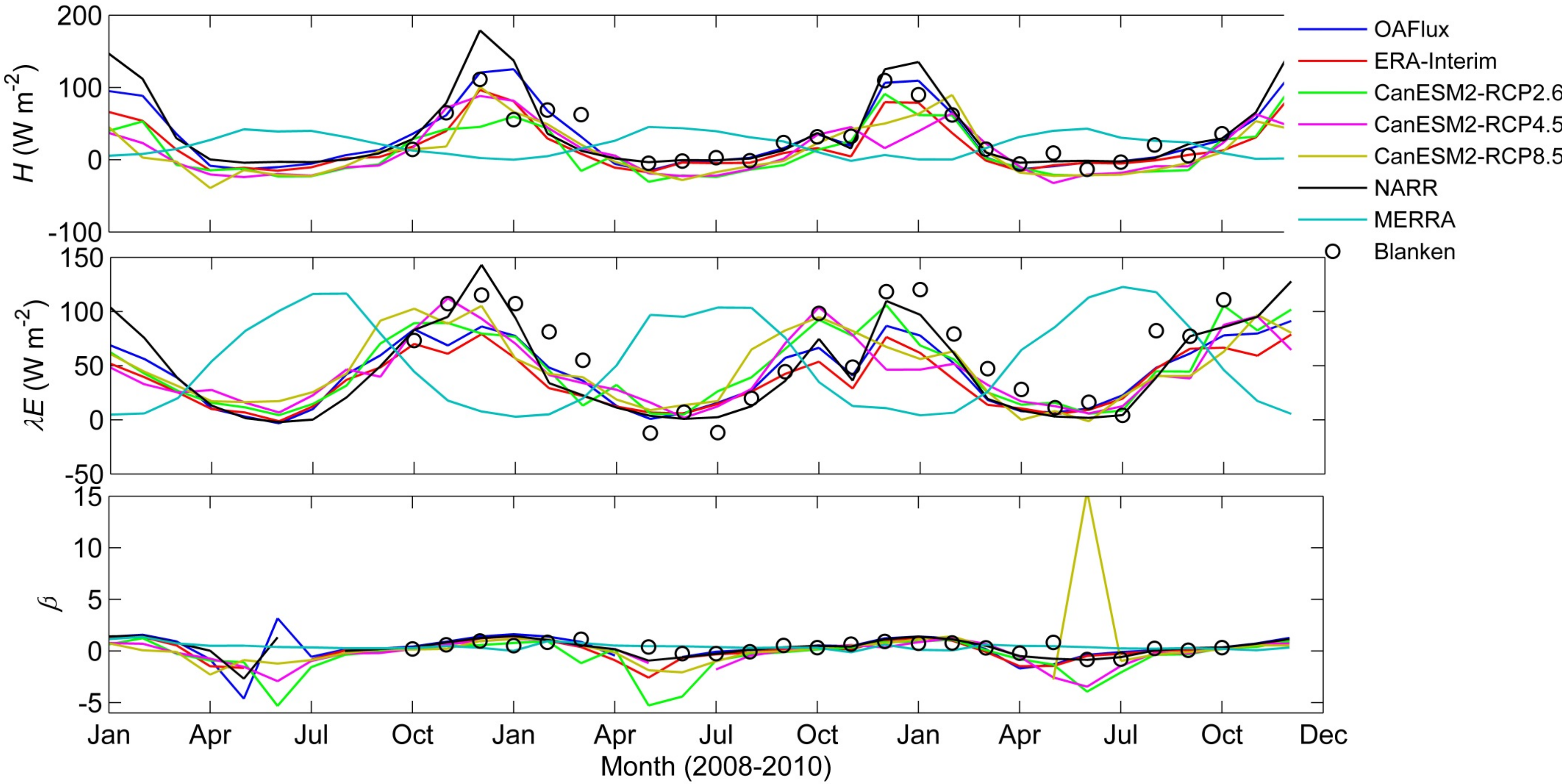
$\beta$ slightly sensitive to wind speed
$\beta$ not sensitive to radiation
$\beta$ decrease with air temperature

(*Developed by Lee, 2012*)

# Calibration of MERRA inputs and accuracy assessment of SLM simulations

| Waters | Data | $T_a$ | $q_a$ | $P_a$ | $u$ | $K_\downarrow$ | $L_\downarrow$ | $T_s$ | $q_s$ | $H$ | $\lambda E$ | $\beta$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | °C | g kg$^{-1}$ | kPa | m s$^{-1}$ | W m$^{-2}$ | W m$^{-2}$ | °C | g kg$^{-1}$ | W m$^{-2}$ | W m$^{-2}$ | |
| Taihu 2011 | MERRA | 17.4 | 0.011 | 101.1 | 1.1 | 181.4 | 341.0 | 27.9 | 0.023 | 22.2 | 37.5 | 0.59 |
| | Observation | 16.2 | 0.009 | 101.5 | 2.7 | 143.8 | 356.9 | 17.2 | 0.014 | **9.7** | **76.1** | **0.13** |
| | Calibrated | 16.2 | 0.009 | 101.5 | 2.7 | 143.8 | 356.9 | | | | | |
| | Simulated | | | | | | | 18.1 | 0.013 | **9.6** | **76.4** | **0.13** |
| Ross Barnett Reservoir 2008 | MERRA | 17.9 | 0.011 | 100.6 | 0.4 | 196.7 | 349.7 | 35.7 | 0.036 | 9.0 | 34.3 | 0.26 |
| | Observation | 17.7 | 0.010 | 100.0 | 3.9 | 177.5 | 356.9 | 19.1 | 0.015 | **17.1** | **87.1** | **0.20** |
| | Calibrated | 17.7 | 0.010 | 100.6 | 3.9 | 177.1 | 356.7 | | | | | |
| | Simulated | | | | | | | 21.0 | 0.015 | **17.8** | **84.8** | **0.21** |

# Accuracy assessment of flux products at the Great Lakes

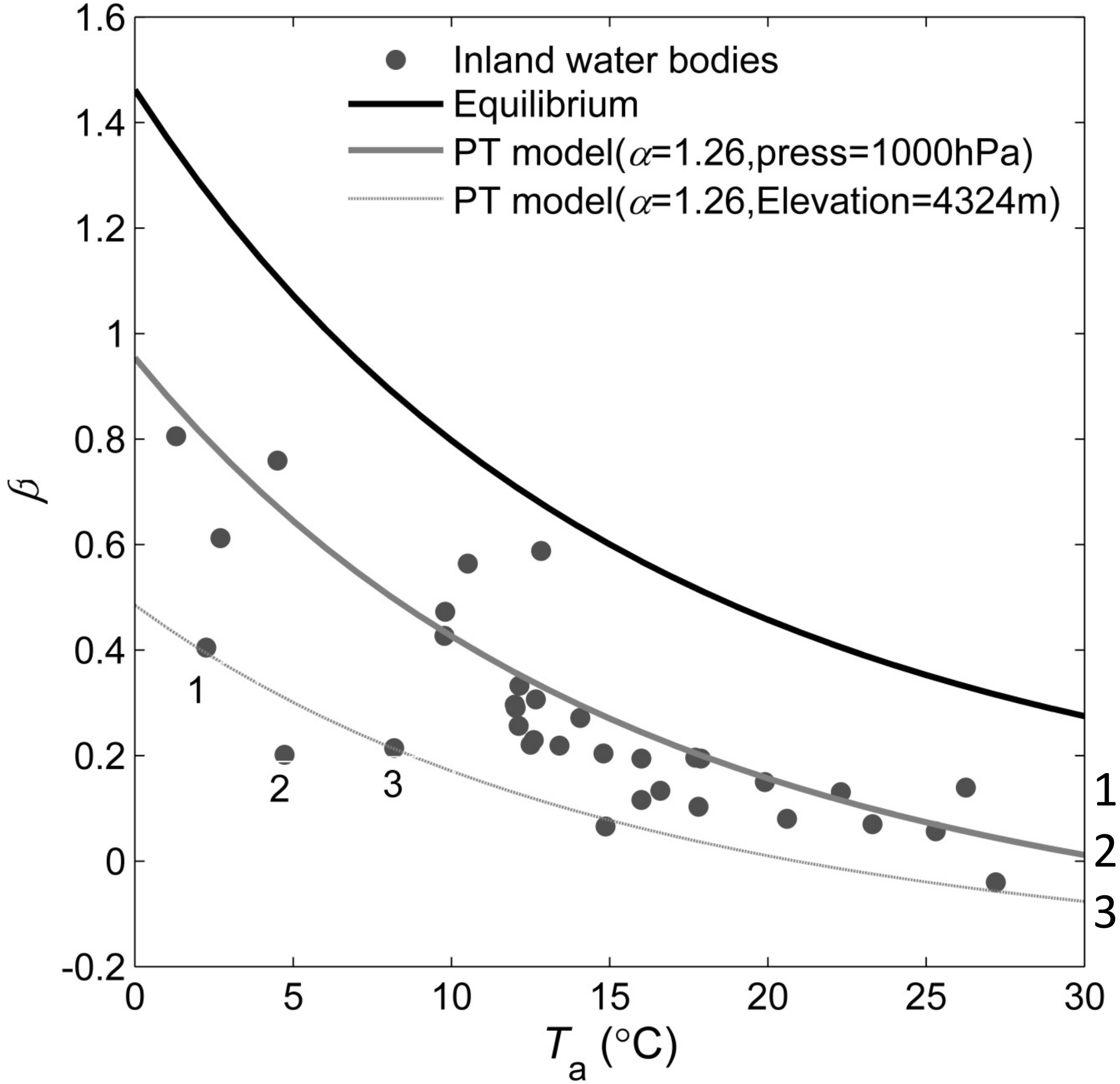



(*Blanken et al, 2011*)

# 5. Results

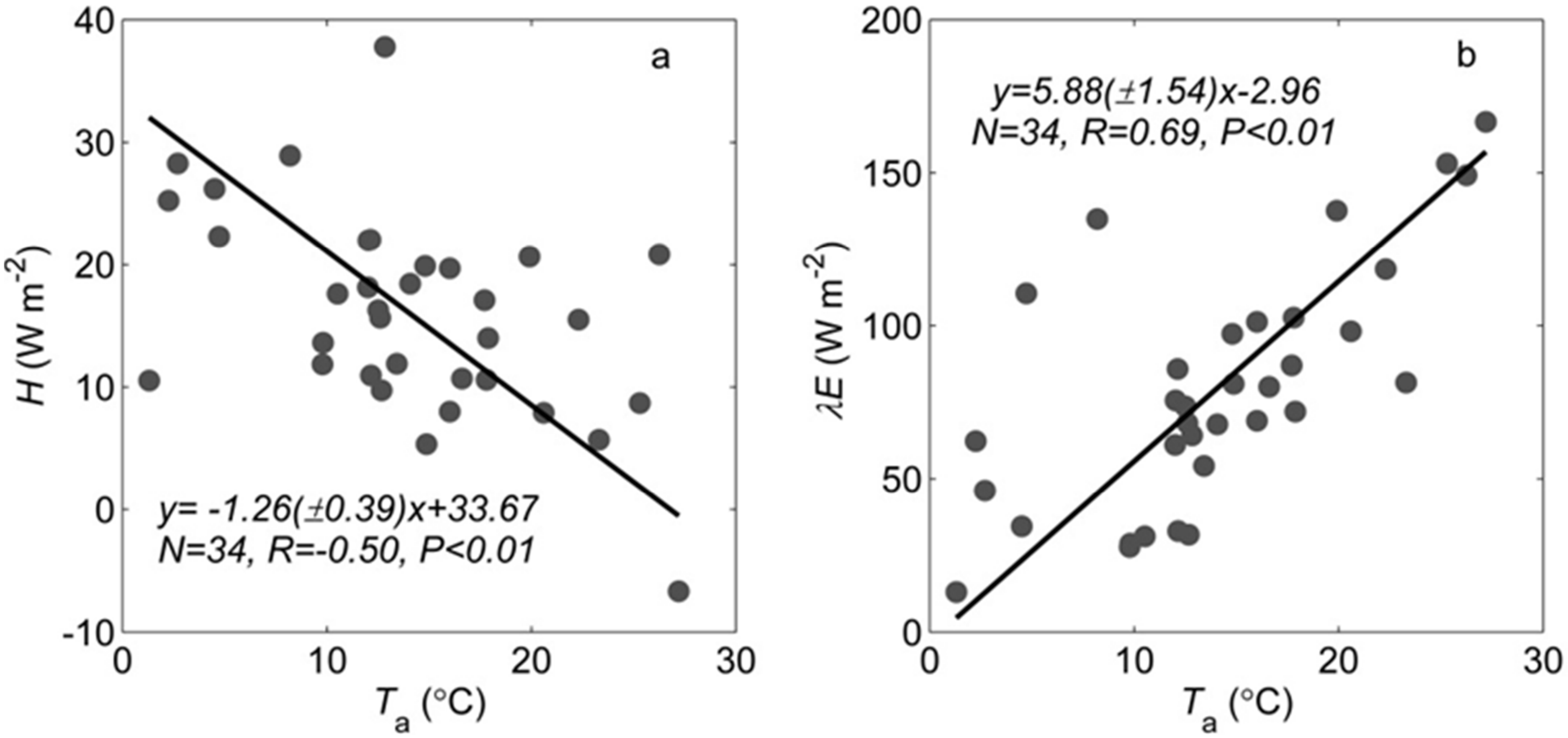
- Spatial variation
- Seasonal variation
- Interannual variation

# Spatial: Literature survey
# (34 inland waters, open water period)

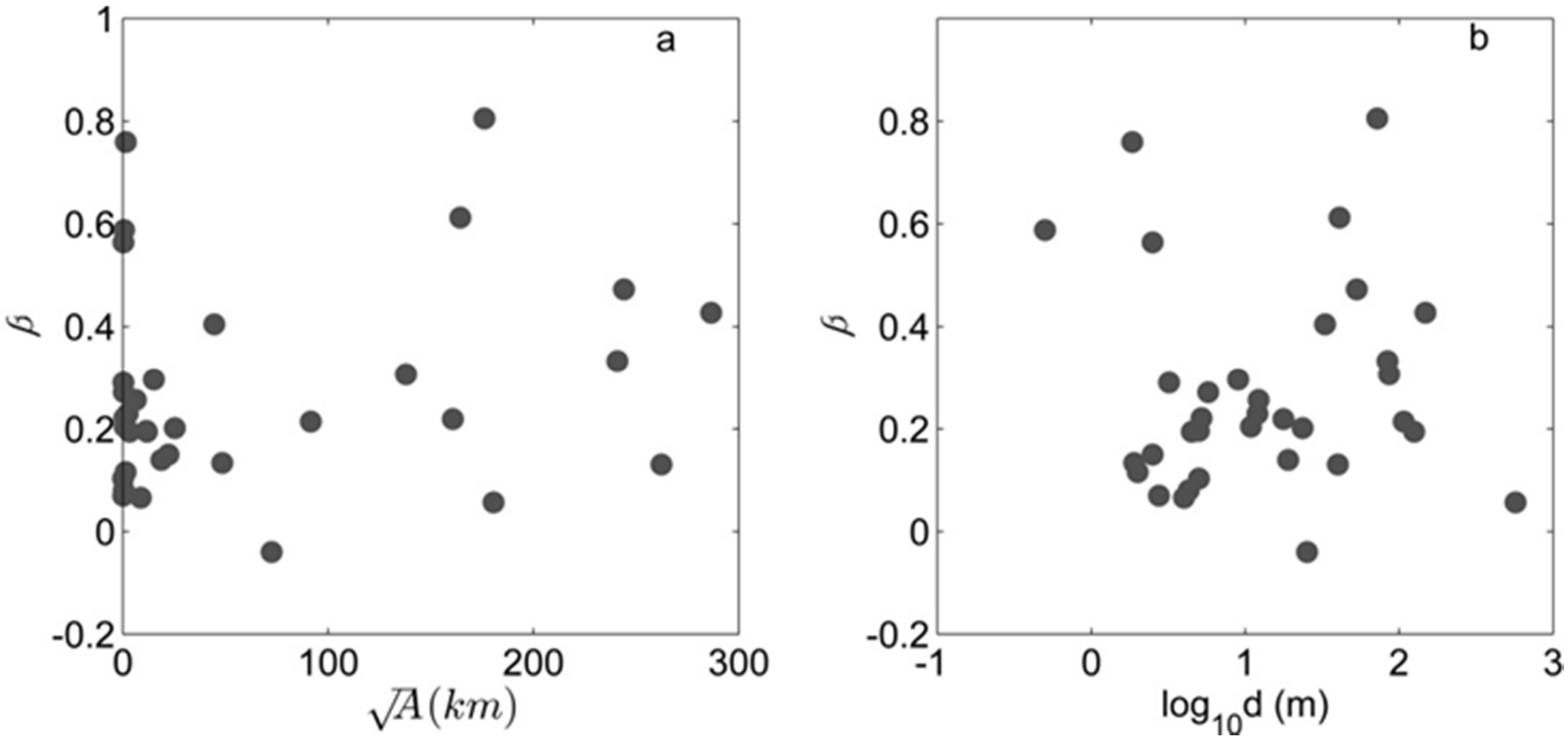



1: Nam Co (4718 m)
2: Yamdrok Yumco (4442 m)
3: Lake Titicaca (3812 m)

# Spatial: Turbulent fluxes vs. air temperature

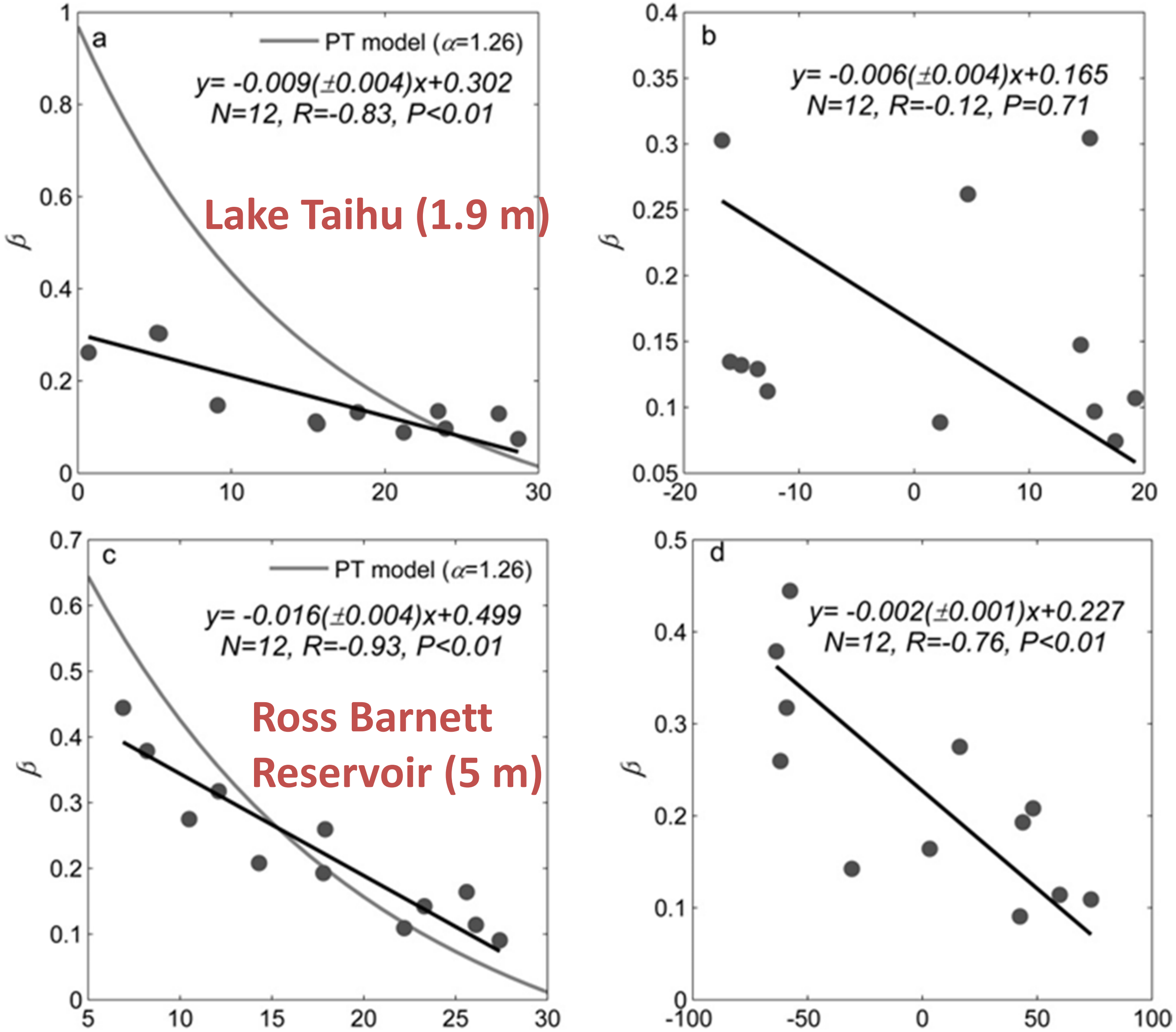


# Spatial: Bowen ratio vs. morphology

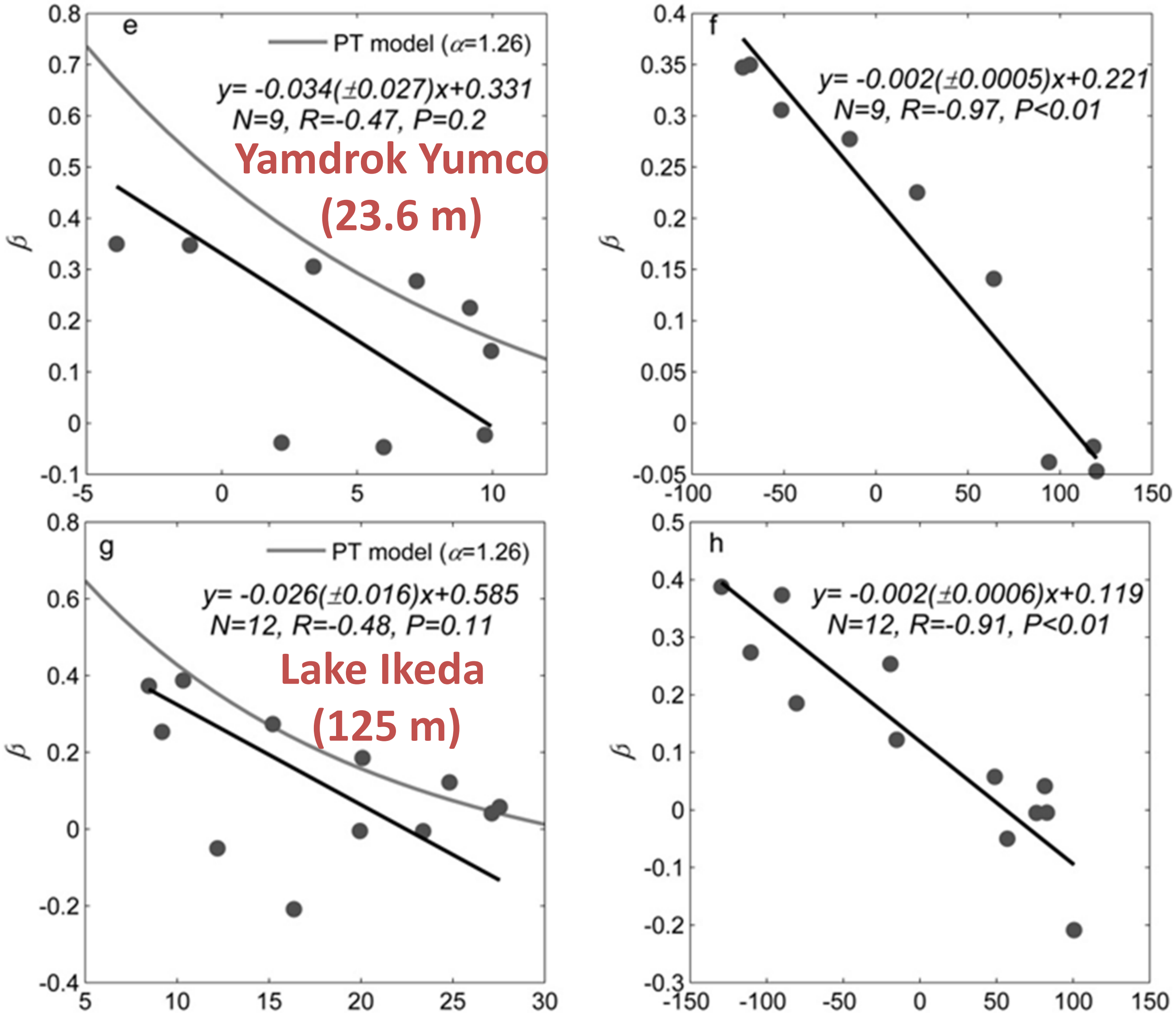



Partial correlation coefficients between Bowen ratio and surface area and mean depth was 0.22 (*p* 0.23) and -0.02 (*p* 0.92), respectively.

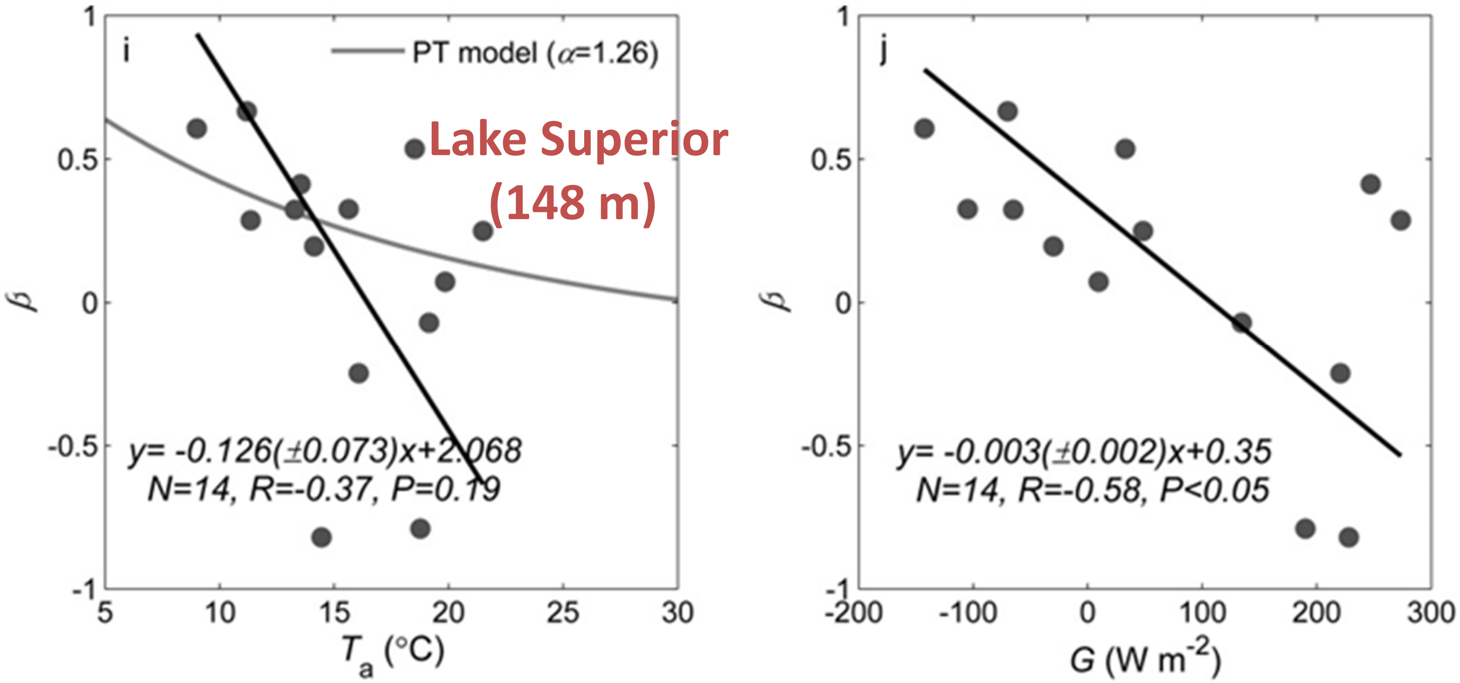
# Seasonal: Bowen ratio vs. (left) air temperature and (right) heat storage



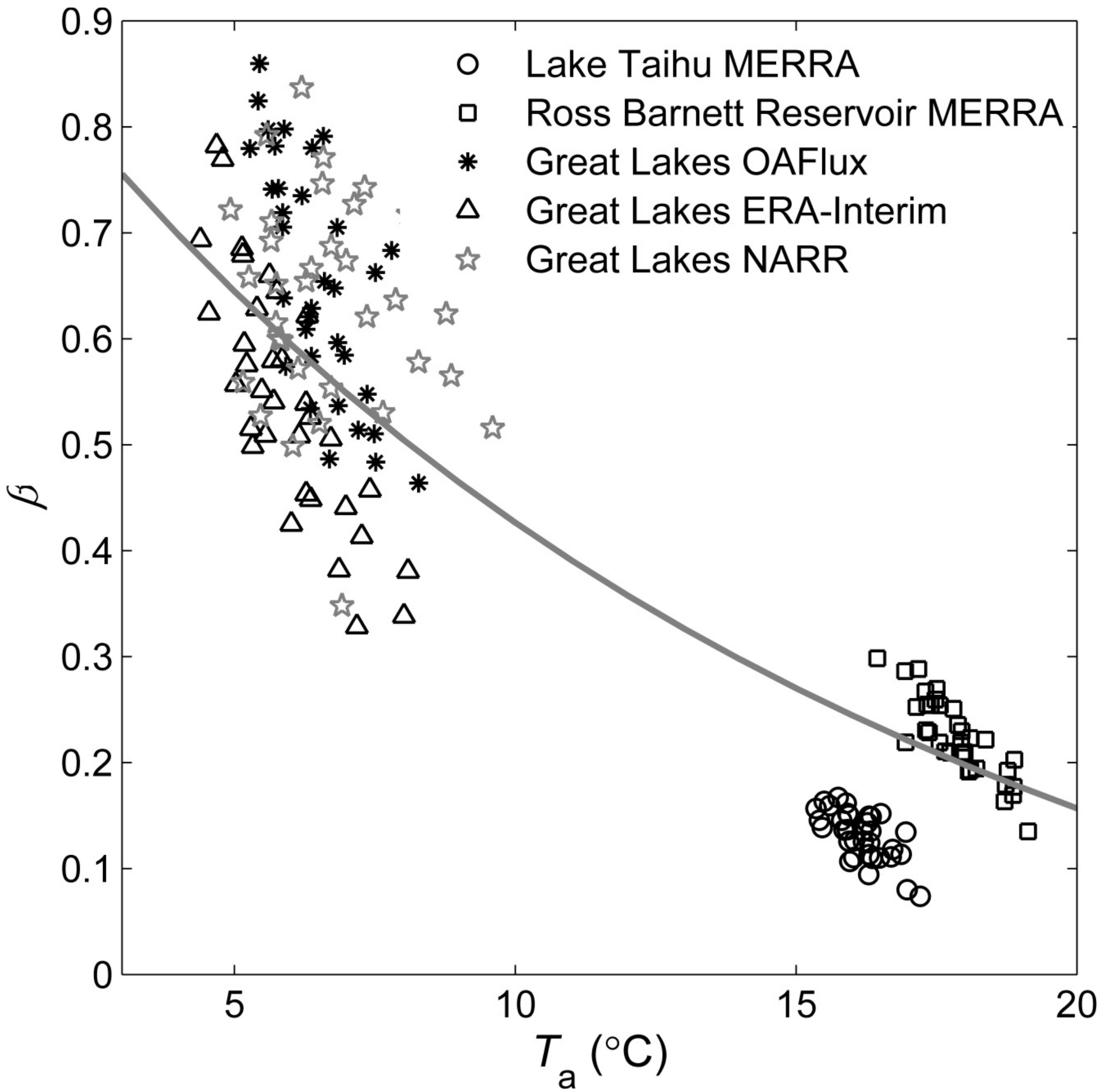
# Seasonal-continued



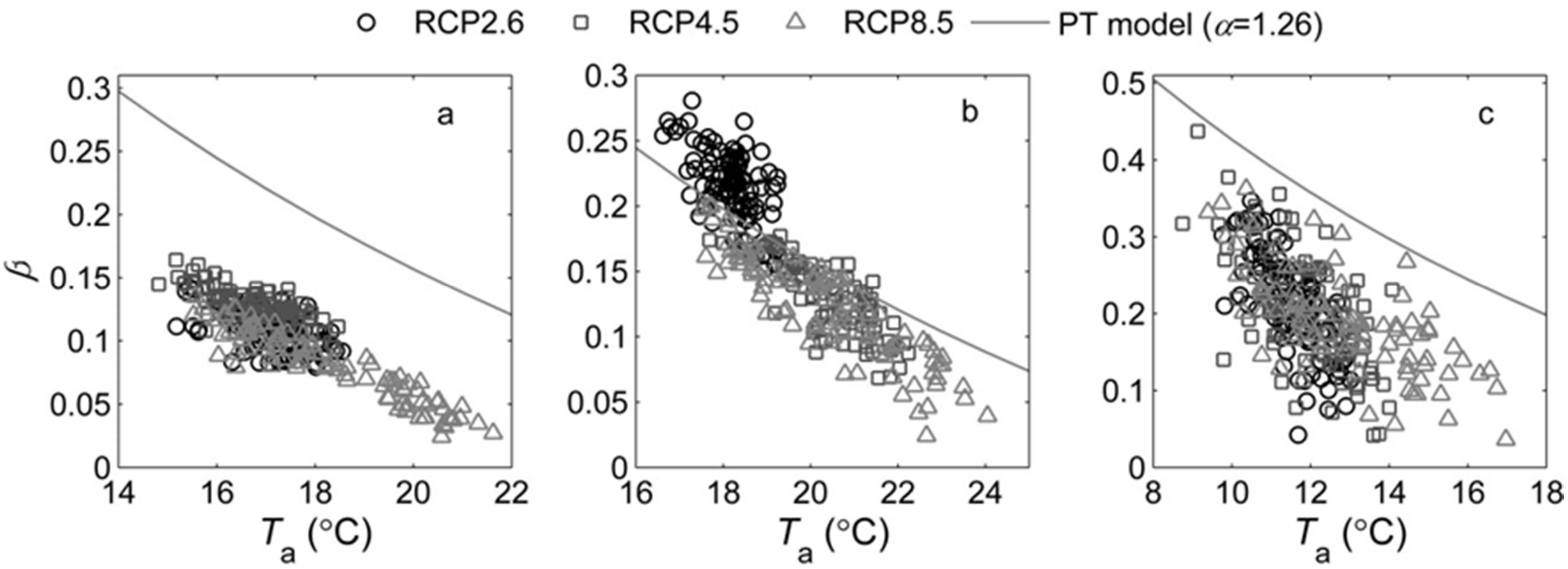
# Seasonal-continued



# Historical: Bowen ratio vs. air temperature



# Future: Bowen ratio vs. air temperature




(a) Lake Taihu, (b) Ross Barnett Reservoir, (c) the Great Lakes.

# Interannual summary

| Type | Waters | Data Source | Sensitivity $^{o}C^{-1}$ | R | *p* |
|---|---|---|---|---|---|
| Historical 1979-2012 | Lake Taihu | SLM MERRA | **-0.05±0.013** | -0.67 | <0.01 |
| | Ross Barnett Reservoir | SLM MERRA | **-0.058±0.011** | -0.86 | <0.01 |
| | the Great Lakes | OAFlux | **-0.149±0.039** | -0.70 | <0.01 |
| | | ERA-Interim | **-0.121±0.025** | -0.82 | <0.01 |
| | | NARR | **-0.087±0.030** | -0.28 | =0.11 |
| Future 2013-2100 | Lake Taihu | SLM CESM1-CAM5 RCP2.6 | **-0.02±0.004** | -0.49 | <0.01 |
| | | SLM CESM1-CAM5 RCP4.5 | **-0.018±0.002** | -0.74 | <0.01 |
| | | SLM CESM1-CAM5 RCP8.5 | **-0.017±0.001** | -0.94 | <0.01 |
| | Ross Barnett Reservoir | SLM CESM1-CAM5 RCP2.6 | **-0.043±0.007** | -0.55 | <0.01 |
| | | SLM CESM1-CAM5 RCP4.5 | **-0.027±0.003** | -0.82 | <0.01 |
| | | SLM CESM1-CAM5 RCP8.5 | **-0.024±0.002** | -0.89 | <0.01 |
| | the Great Lakes | CanESM2 RCP2.6 | **-0.086±0.013** | -0.69 | <0.01 |
| | | CanESM2 RCP4.5 | **-0.064±0.01** | -0.63 | <0.01 |
| | | CanESM2 RCP8.5 | **-0.037±0.006** | -0.70 | <0.01 |

# Energy partitioning in response to global warming

$$\frac{-\Delta\beta}{\beta\Delta T_s} = \frac{dq^*}{q^* dT} + \left[ \frac{RH \cdot \beta\lambda q^*\left(T_a\right)}{c_p} \frac{dq^*}{q^* dT} \right] \frac{\Delta\left(T_s - T_a\right)}{\left(T_s - T_a\right)\Delta T_s} - \frac{1}{1-\mathrm{RH}} \frac{\Delta \mathrm{RH}}{\Delta T_s}$$

7.5% $K^{-1}$ 6-6.5% $K^{-1}$ 2.4-2.7% $K^{-1}$ 0.1-0.3% $K^{-1}$

(*Lu and Cai, 2009*)

# Conclusion

- Spatial variation in annual Bowen ratio was excellently predicted by the PT model. No statistical relationship was found between annual Bowen ratio and the size, depth of inland water bodies.

- Depth influences energy partitioning of inland waters through changes in heat storage at monthly scale for deep waters.

- All the 21$^{st}$ century predictions have underestimated the decreasing trend of Bowen ratio to global warming. The PT model showed unsatisfactory prediction of interannual variations of Bowen ratio, especially for historical series.

# Next step

- Simulating energy partitioning process of inland water bodies by coupled GCMs and Lake model.

- Manuscript refinement.

# Thank you!

# Suggestions and questions are welcome.