The interaction of scales between carbon cycling in the atmosphere and in the terrestrial biosphere

Wouter Peters, Wageningen University, the Netherlands

Global transport models are used in a wide array of applications that range from short time scales (air-quality predictions) to much longer ones (greenhouse gas budgets). It has been shown repeatedly that the ability of these models to simulate transport across these time scales varies: most do poorly on diurnal time scales because night-time stable boundary layer conditions are poorly captured, all do really well on synoptic time scales because reanalyzed meteorological fields are used as driver data, and at seasonal to interannual time scales performance varies strongly for reasons that are not well understood. Stephens et al., (2007) for instance showed that models predict very different vertical gradients between the surface and 4 km altitude, likely because of different dry and wet convective exchange. Vila et al. (2004), and Pino et al., (2012) point strongly to entrainment and boundary layer growth as dominant controls on CO2 mixing ratios under convective conditions. But recent analyses from Williams et al. (2012), Sinclair et al (2010), and Parazoo et al., (2011) suggest that exchange of trace gases is dominated by synoptic systems and their ability to vent the PBL in large 5-10 day sweeps. In that light, it is interesting to note that even within one modeling framework (TM5 in this case) the large scale transport properties can vary strongly depending on which (mainly vertical) driver data is used from its parent ECMWF model. Together, these diverse studies raise the question: which scale is important to capture in transport models when one wants to investigate regional CO2 budgets?

In the presentation, two examples are given of carbon-water-energy exchange on relatively short time scales. One is crop-atmosphere interactions on hourly time scales, and the other one is interactions between the atmospheric PBL development and the CO2 budget on diurnal scales. Both studies share a simple but powerful diagnostic tool, the mixed-layer model of the atmosphere. And in both studies, we pay special attention to the coupling points between the carbon-water-energy systems, given by the simulated stomatal resistance and the PBL height.

In our first example we demonstrate that the crop model is an excellent tool so simulate the progression of carbon and water exchange along the seasonal growth curve of the plant. However, it falls short on simulating the energy budget that goes along with that exchange, producing negative sensible heat fluxes on many days. The reason is that the simulated crop nearly always operates at full potential evaporation, taking energy from the atmosphere if needed to continue carbon uptake. In the crop model, this normally does not affect the atmosphere because it is a prescribed reservoir (from observations). But in a coupled mode with the mixed-layer providing dynamic top boundary conditions, this obviously would lead to a rapid cooling of the lower atmosphere blocking vertical trace gas exchange even on a sunny day. While stomatal resistance, net ecosystem exchange, crop growth, water-use efficiency, and latent heat are thus all reasonable for this crop growth model, it would fail completely to predict the observed PBL height, stressing the need to simultaneously assess vegetation dynamics and atmospheric dynamics.

Similarly, our second example shows a straightforward method to estimate errors in daytime simulated CO2 (or inversely, the CO2 surface flux) as a function of errors in dynamical variables in the mixed-layer. These errors were estimated based on a suite of simulations with the WRF-CHEM transport model using three popular parameterizations for vertical mixing near the surface (YSU, MYJ, MYNN2.5), and two different CO_2 surface flux implementations (SIBCASA, A-Gs). By selecting a set of >100 mixed-layer days/locations over Europe for the month of June, these errors were categorized and shown to be potentially very large: errors in the early morning PBL height (setting the mixing volume for night-time CO_2) can lead to errors of 0.5 to 5.0 ppm during the day (0.75 ppm median), while a misrepresentation of the CO_2 abundance above the PBL height (the concentration to be entrained) is in the same order of magnitude. Typical errors in the simulation of the PBL height itself (estimated to be a median of 260 meters) cause typical errors in estimated fluxes of 20% or more. This is not just an effect of the depth of the mixing volume, but also because different PBL growth rates introduce different amounts of free tropospheric CO_2 into the PBL, and further affect surface dynamics by increasing evaporative demand (dry air is entrained).

These examples together demonstrate the important coupling between numerical weather prediction (NWP) and the CO_2 budget. Not only would CO_2 modeling profit from having the best atmospheric (vertical) transport available, but also an estimate of the NWP errors (for instance from an ensemble of surface-atmosphere exchange couplings) can help to improve estimates of CO_2 fluxes. Finally, better understanding of surface exchange of CO_2 also directly benefits the surface water and energy balance through the coupling points identified in the presentation (stomatal resistance and PBL height), and thus help to improve weather forecasts. This conclusion underlies some of the recommendations made in the workshop that followed.

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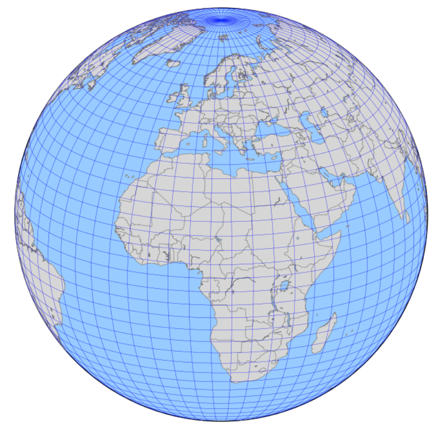
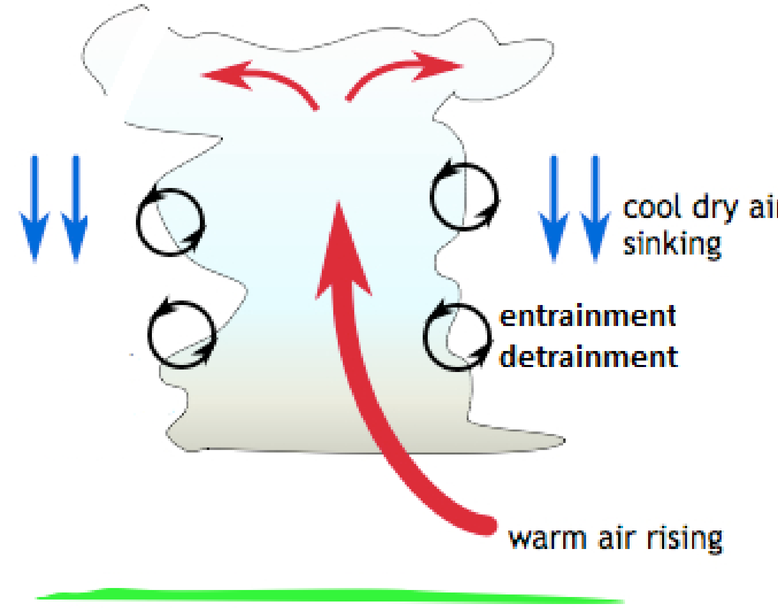
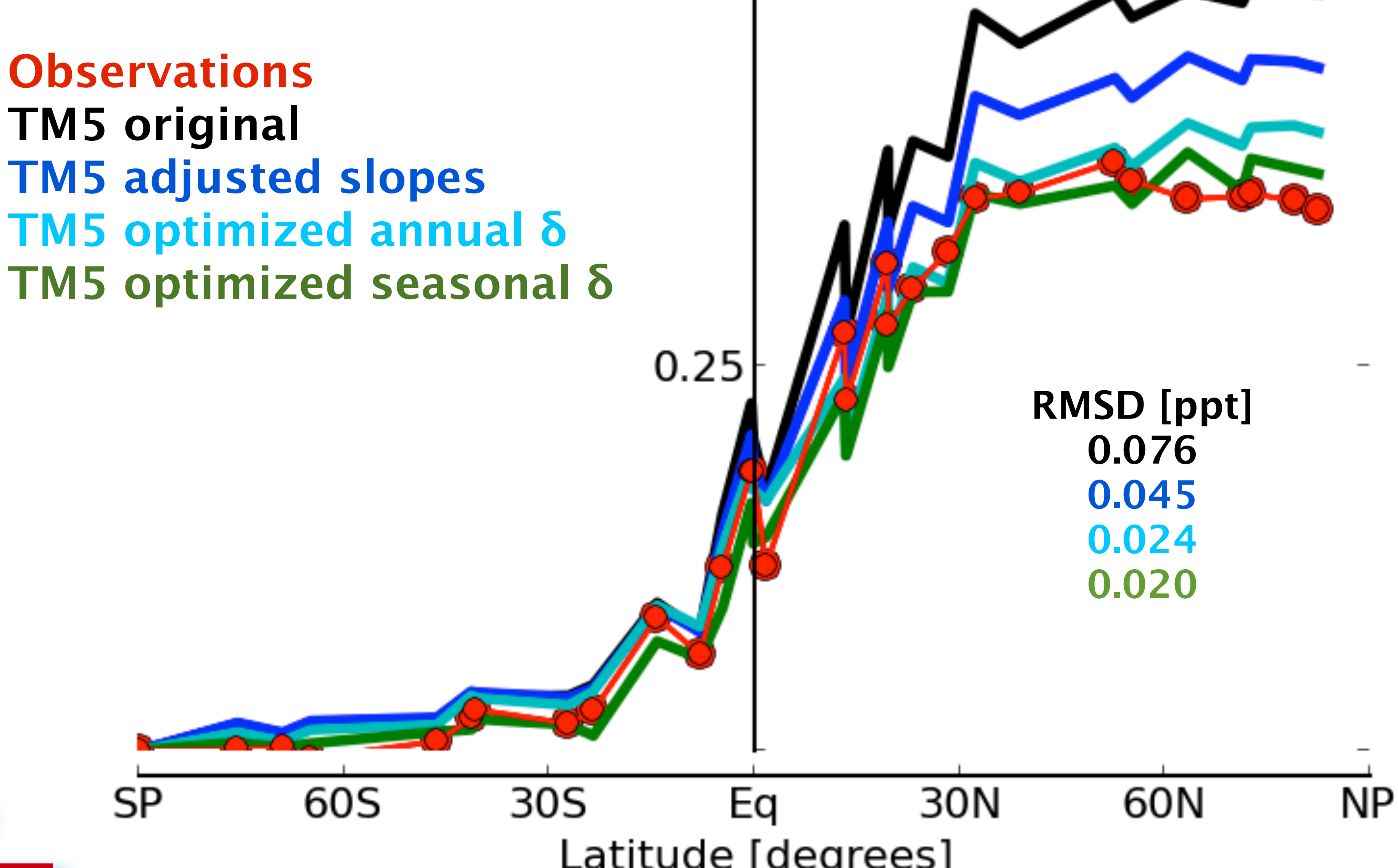
university of groningen

ECMWF workshop, Reading, 22-24 Oct

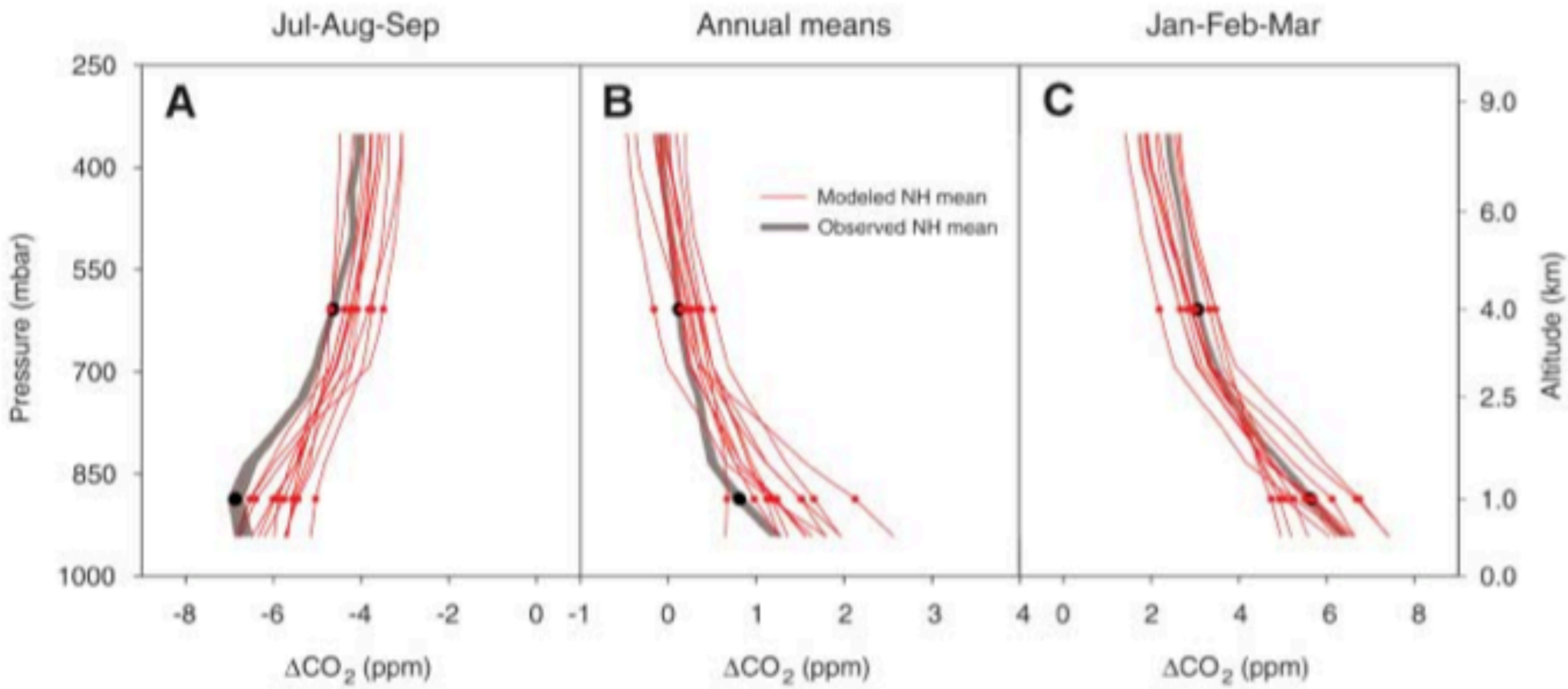
SF_6 North–South gradient in TM5







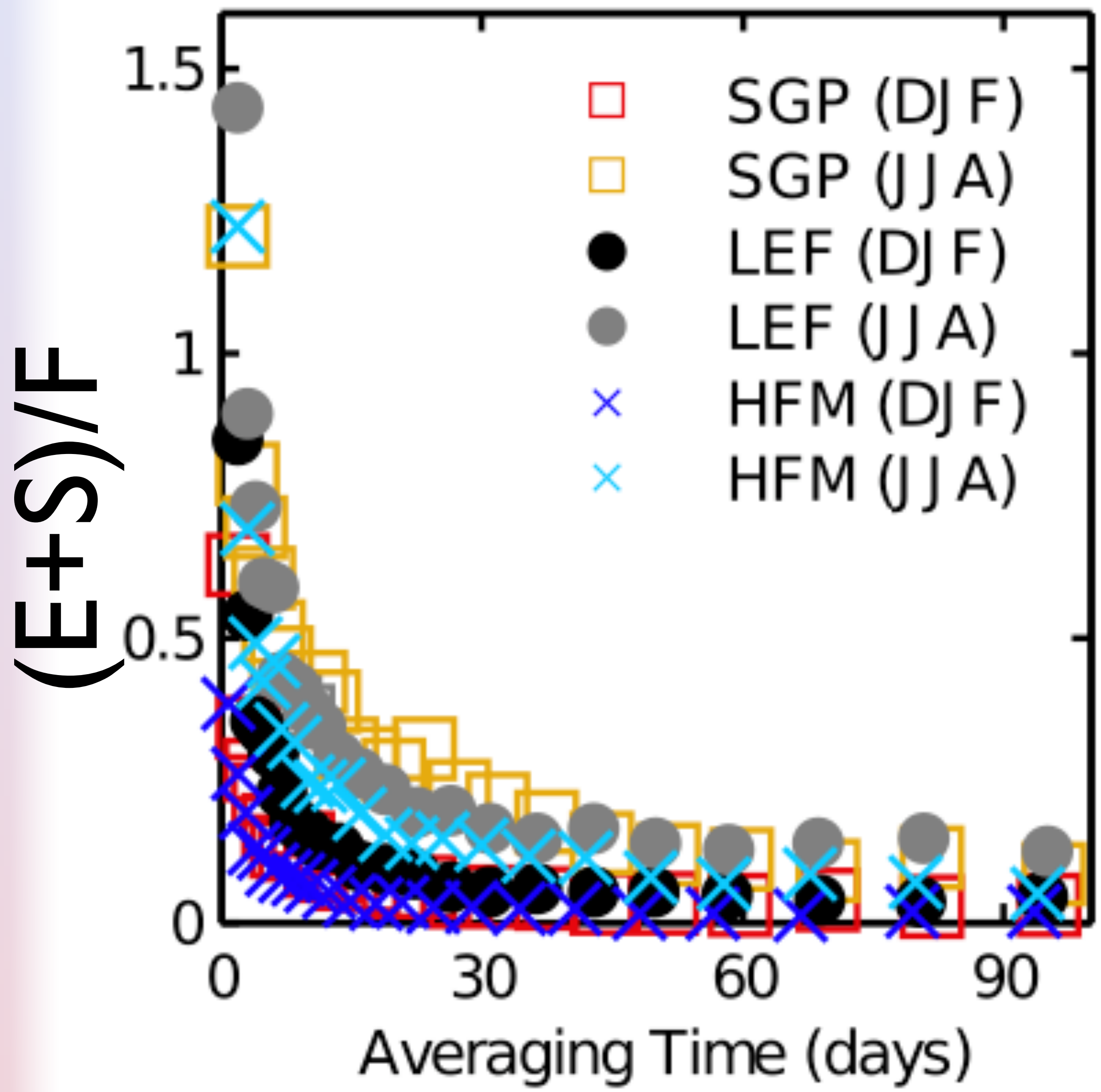
CO_2 gradients in transport models



Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO_2

Britton B. Stephens,[1*] Kevin R. Gurney,[2] Pieter P. Tans,[3] Colm Sweeney,[3] Wouter Peters,[3] Lori Bruhwiler,[3] Philippe Ciais,[4] Michel Ramonet,[4] Philippe Bousquet,[4] Takakiyo Nakazawa,[5] Shuji Aoki,[5] Toshinobu Machida,[6] Gen Inoue,[7] Nikolay Vinnichenko,[8]† Jon Lloyd,[9] Armin Jordan,[10] Martin Heimann,[10] Olga Shibistova,[11] Ray L. Langenfelds,[12] L. Paul Steele,[12] Roger J. Francey,[12] A. Scott Denning[13]

What controls the exchange of CO_2 (and other gases) across the top of the planetary boundary layer height?



$$F = S + E + V + H$$

F = surface flux
S = storage
E = entrainment
V = vertical advection
H = horizontal advection

Using boundary layer equilibrium to reduce uncertainties in transport models and CO_2 flux inversions

I. N. Williams[1], W. J. Riley[2], M. S. Torn[2], J. A. Berry[3], and S. C. Biraud[2]

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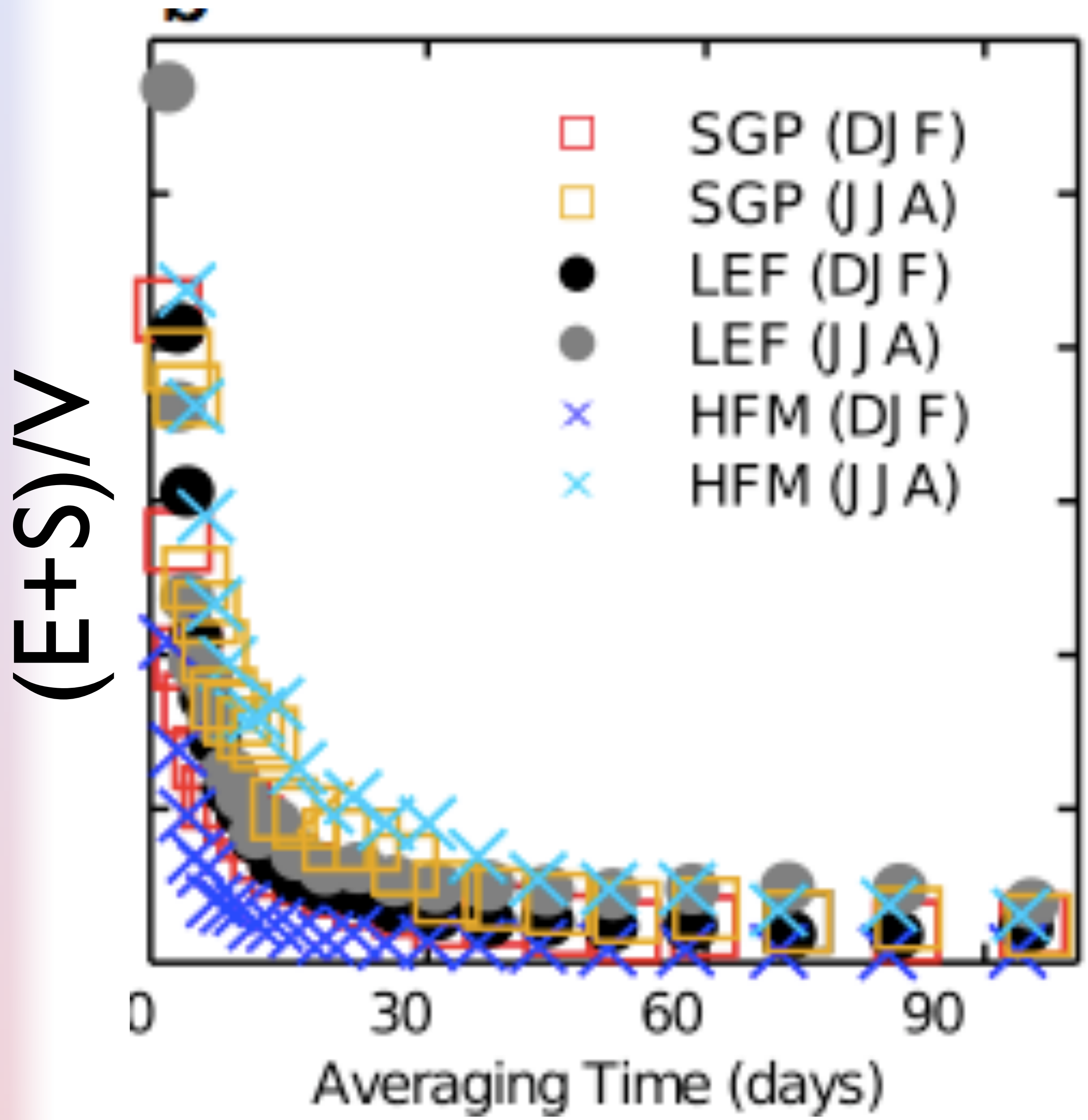

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Controls on boundary layer ventilation: Boundary layer processes and large-scale dynamics

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Moist synoptic transport of CO_2 along the mid-latitude storm track

N. C. Parazoo,[1] A. S. Denning,[1] J. A. Berry,[2] A. Wolf,[3] D. A. Randall,[1] S. R. Kawa,[4] O. Pauluis,[5] and S. C. Doney[6]

Large-scale (synoptic) control on CO_2 exchange!

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Large-scale (synoptic) control on CO_2 exchange!

...but small scales control near surface CO_2 variations

Two examples, two scales

- **(1) Crop-Atmosphere interactions**

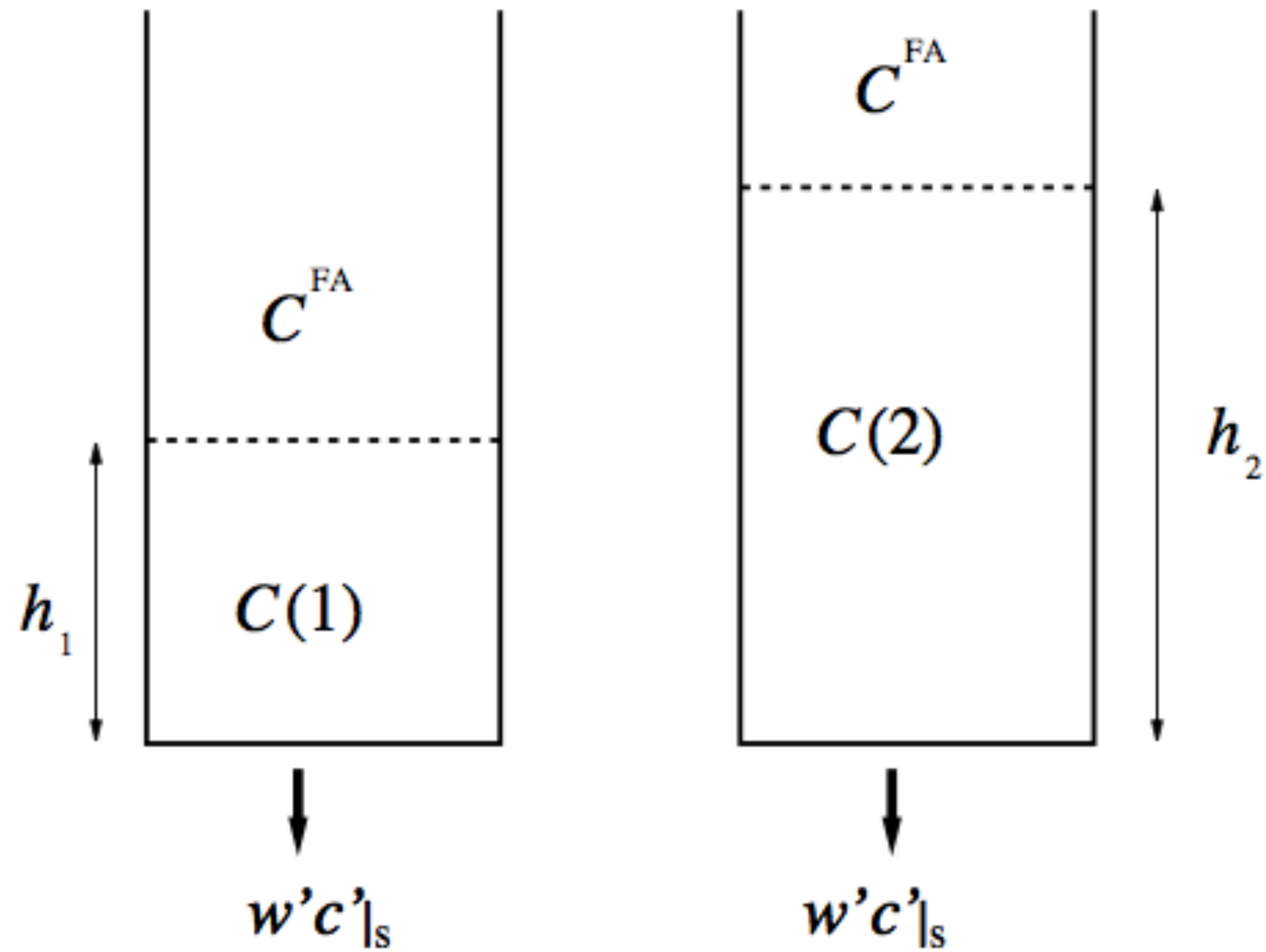
The boundary layer and biosphere form one dynamic system with two main coupling points

- **(2) Mixed-layer modeling of CO_2 errors**

These coupling points can be a key diagnostic for simulations of the carbon balance

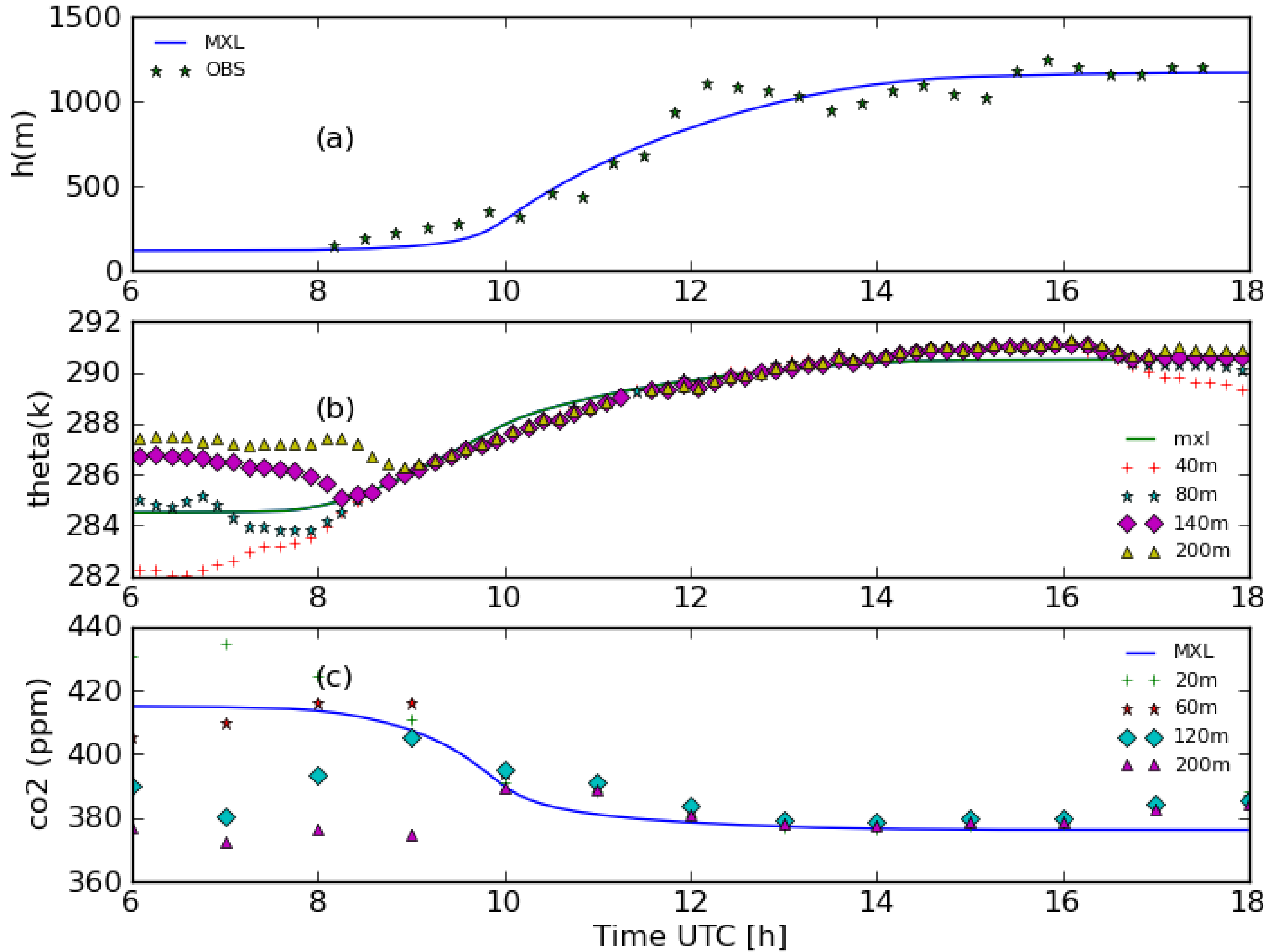
Mixed-layer modeling

C = CO_2 mole fraction
h = PBL height
w'c' = CO_2 surface flux
FA = Free Atmosphere
t= time



$$\frac{\partial(Ch)}{\partial t} = \overline{wco2}|_s + C^{fa}\frac{\partial(h-h_0)}{\partial t} ,$$

Mixed-layer modeling



Mixed-layer modeling

A conceptual framework to quantify the influence of convective boundary layer development on carbon dioxide mixing ratios

D. Pino[1], J. Vilà-Guerau de Arellano[2], W. Peters[2], J. Schröter[2], C. C. van Heerwaarden[3], and M. C. Krol[2]

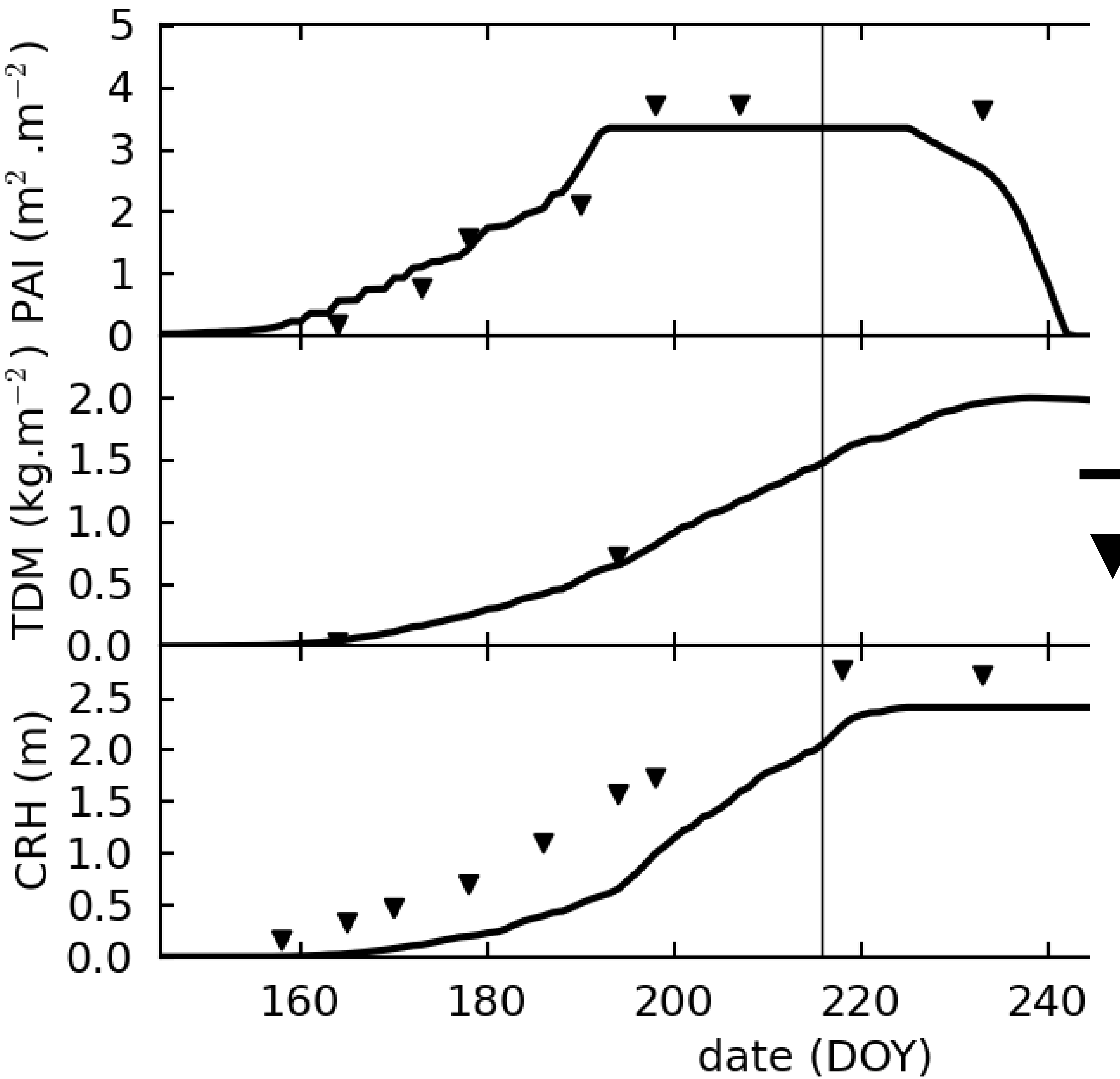
$$C = C_0 \frac{h_0}{h} + C_0^{fa}\left(1 - \frac{h_0}{h}\right) + \frac{\gamma_{co2}}{2h}(h - h_0)^2 + \frac{t - t_0}{h} < \overline{wco2|_s} >,$$

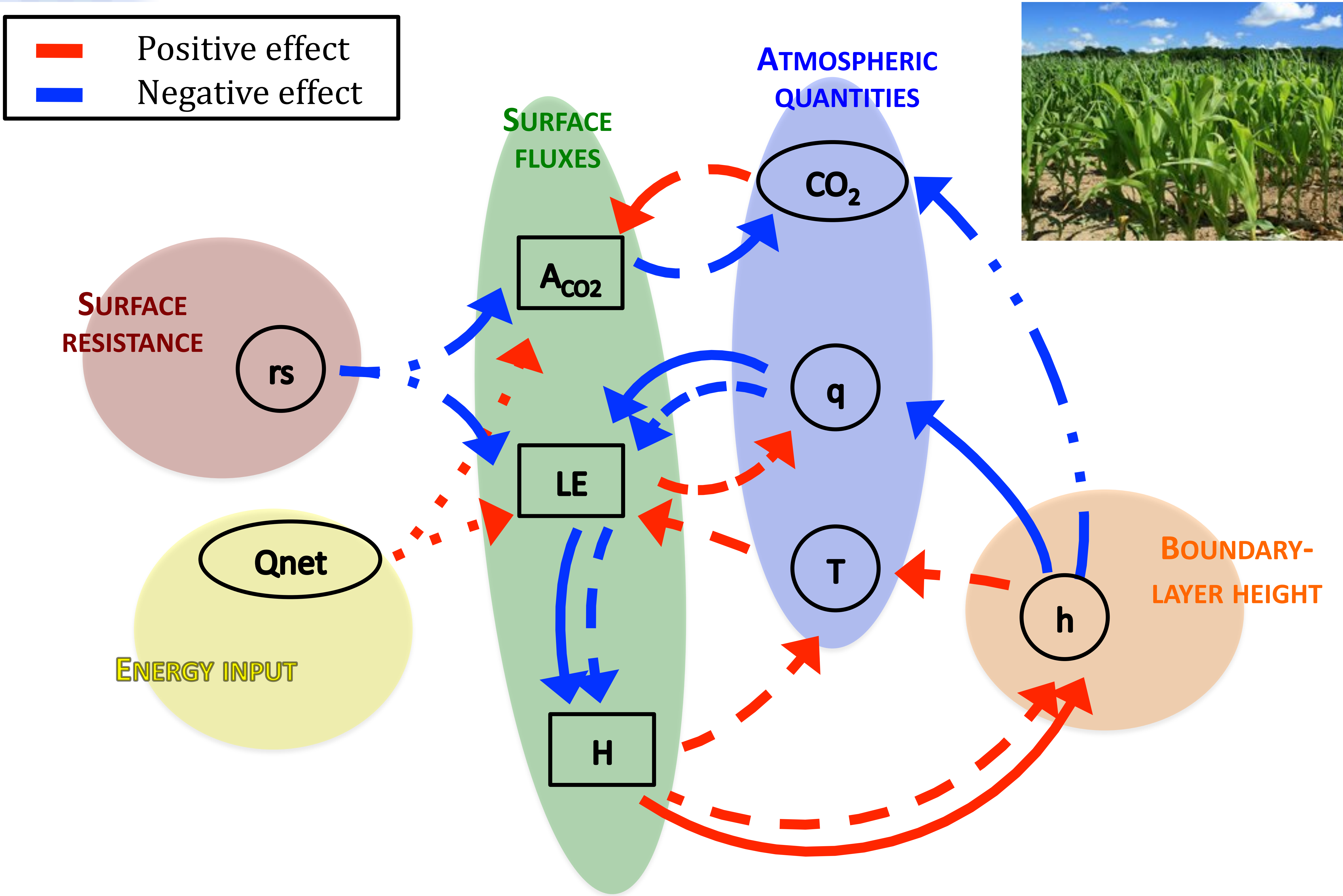
$$< \overline{wco2|_s} > = \frac{1}{t - t_0}\left[Ch - C_0 h_0 - C_0^{fa}(h - h_0) - \frac{\gamma_{co2}}{2}(h - h_0)^2\right].$$

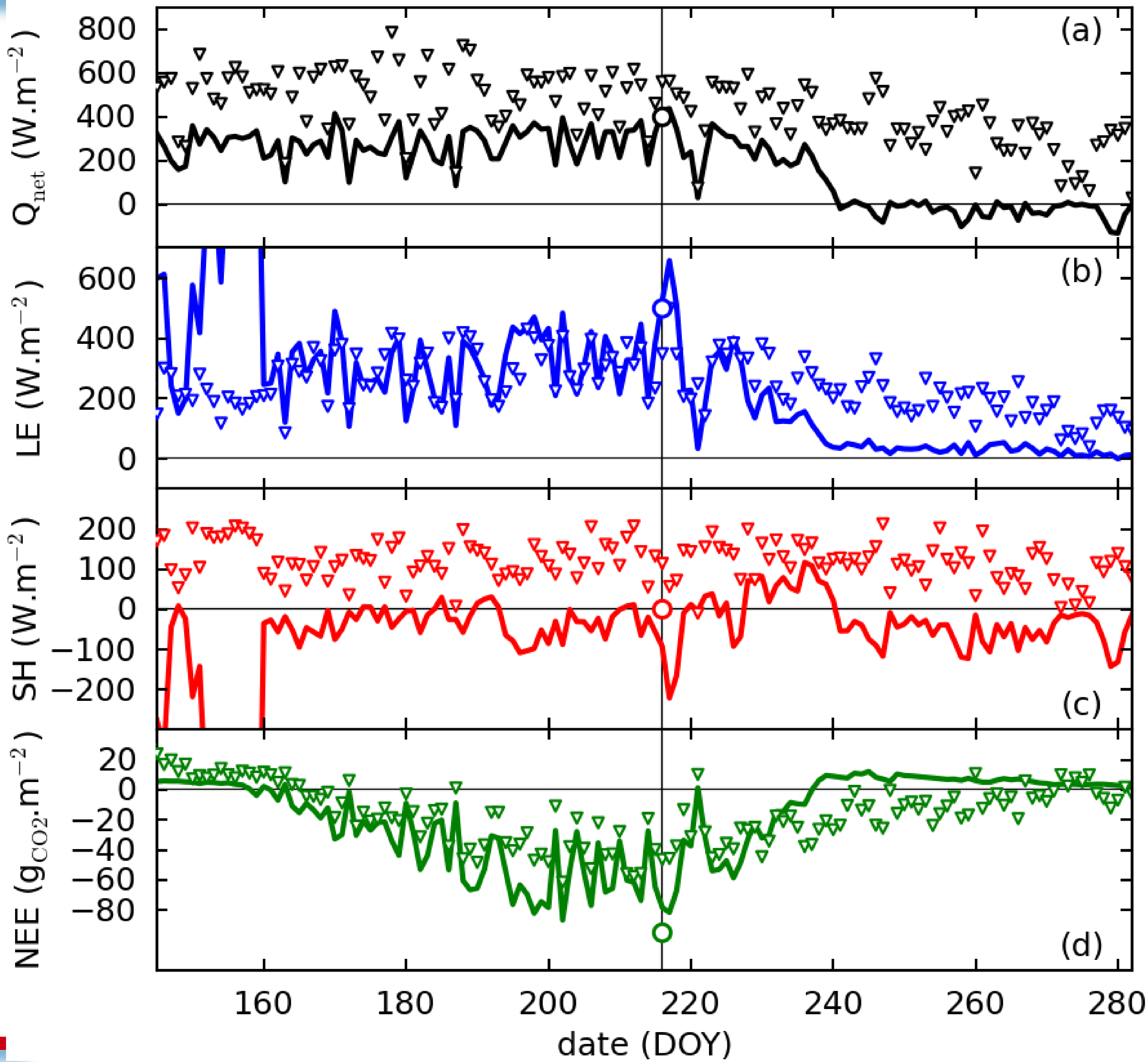
C = CO_2 mole fraction
C_0 = morning CO_2 mole fraction
h = PBL height
h_0 = morning PBL height

<w’c’>= mean CO_2 surface flux
FA = Free Atmosphere
γ = lapse rate CO_2

(1) Crop-Atmosphere interactions

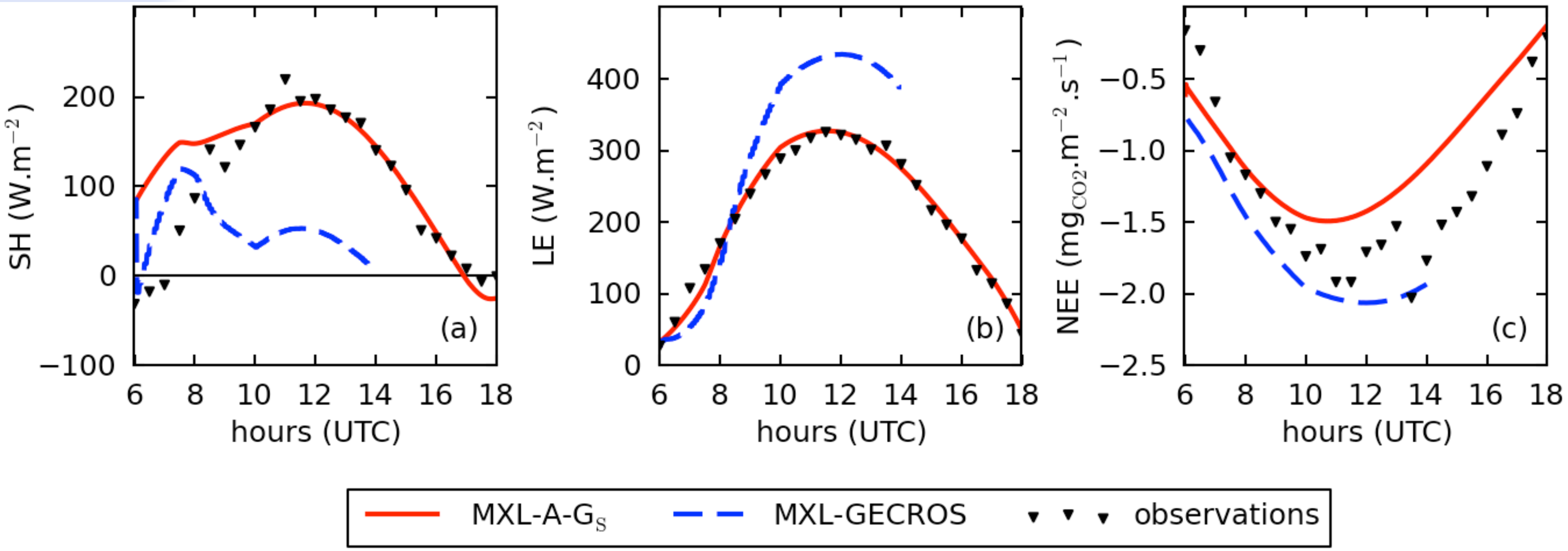



Positive effect
Negative effect
SURFACE FLUXES
ATMOSPHERIC QUANTITIES
SURFACE RESISTANCE
rs
A_{CO2}
CO_2
q
LE
T
Qnet
ENERGY INPUT
H
h
BOUNDARY-LAYER HEIGHT

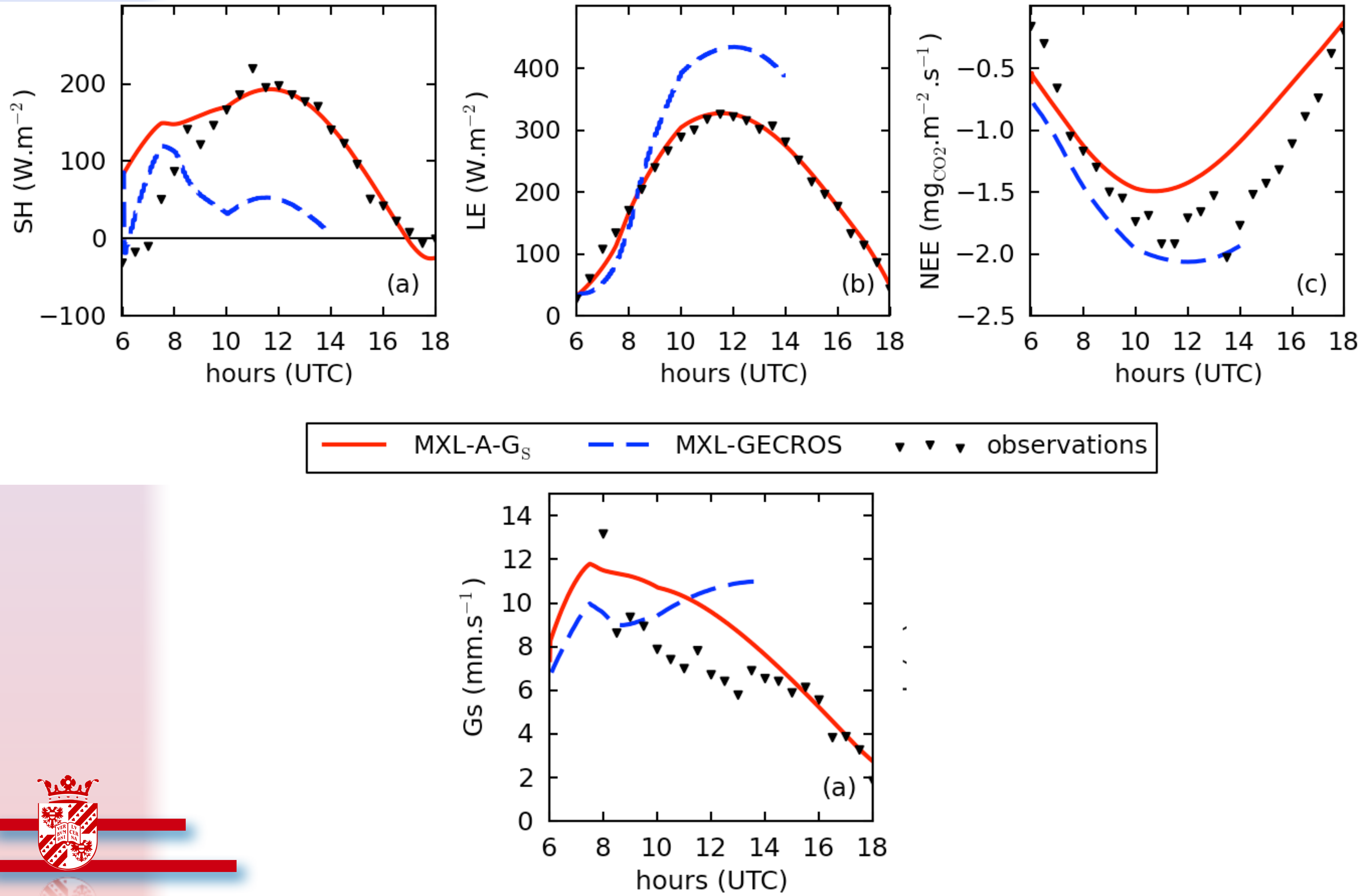


(a)
(b)
(c)
(d)
Q_{net} (W.m^{-2})
LE (W.m^{-2})
SH (W.m^{-2})
NEE (g_{CO2}.m^{-2})
date (DOY)
800
600
400
200
0
−100
−200
20
−20
−40
−60
−80
160
180
200
220
240
260
280

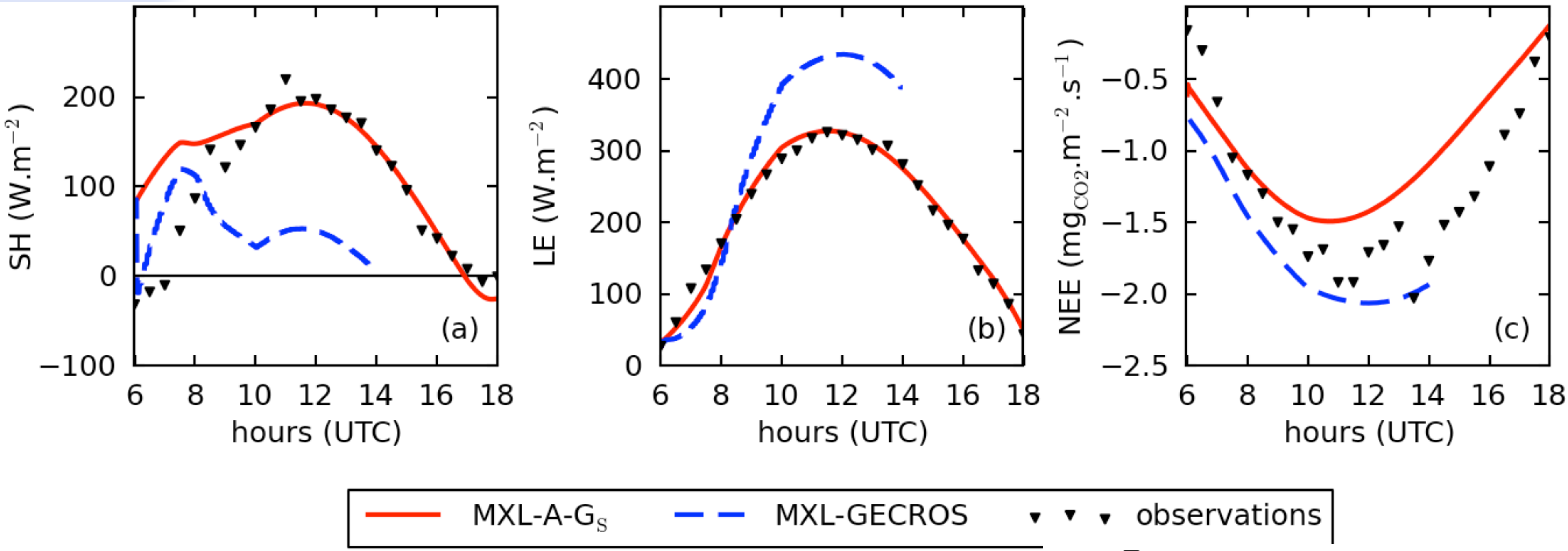
Surface fluxes

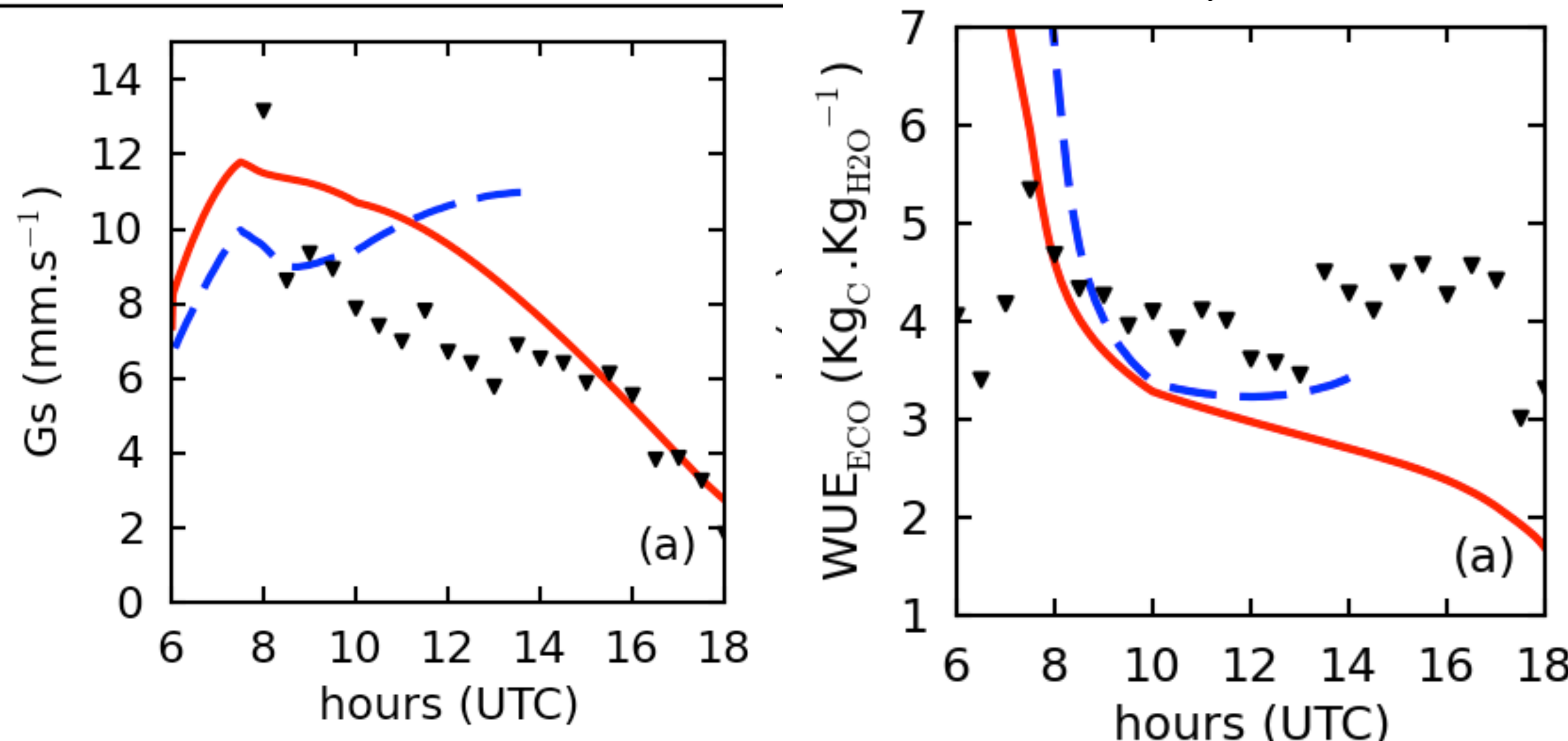


Surface fluxes

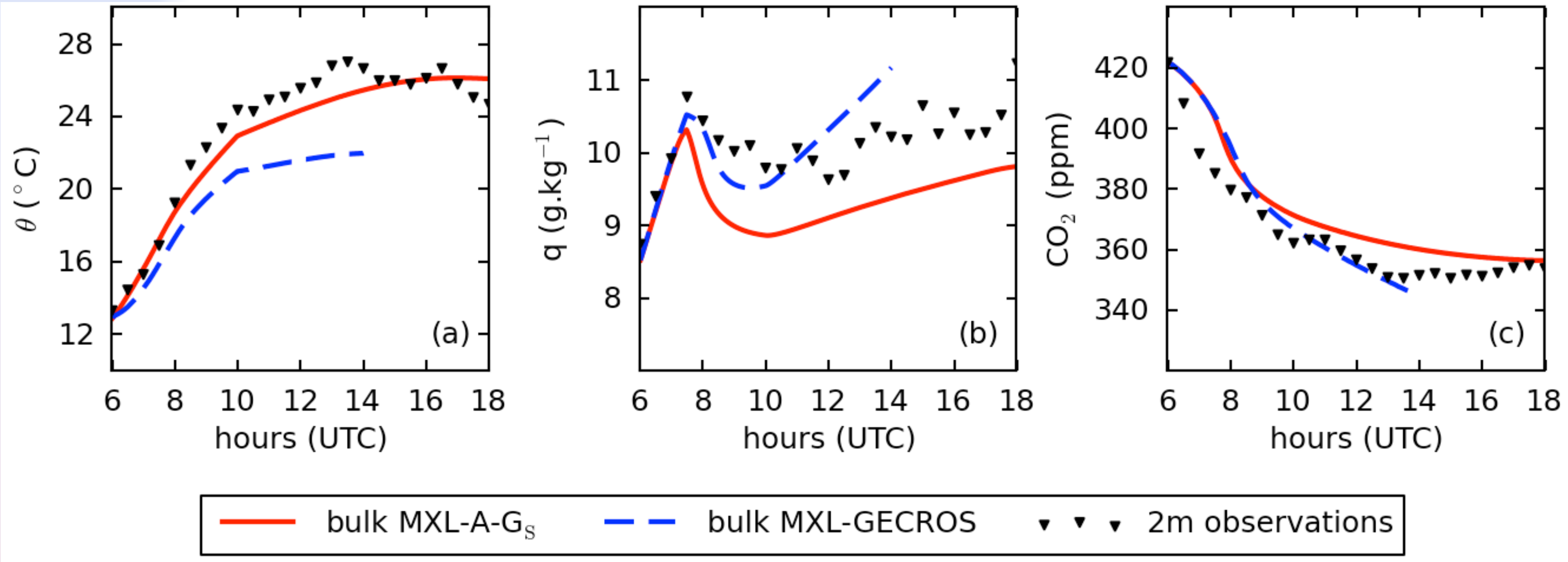


Surface fluxes

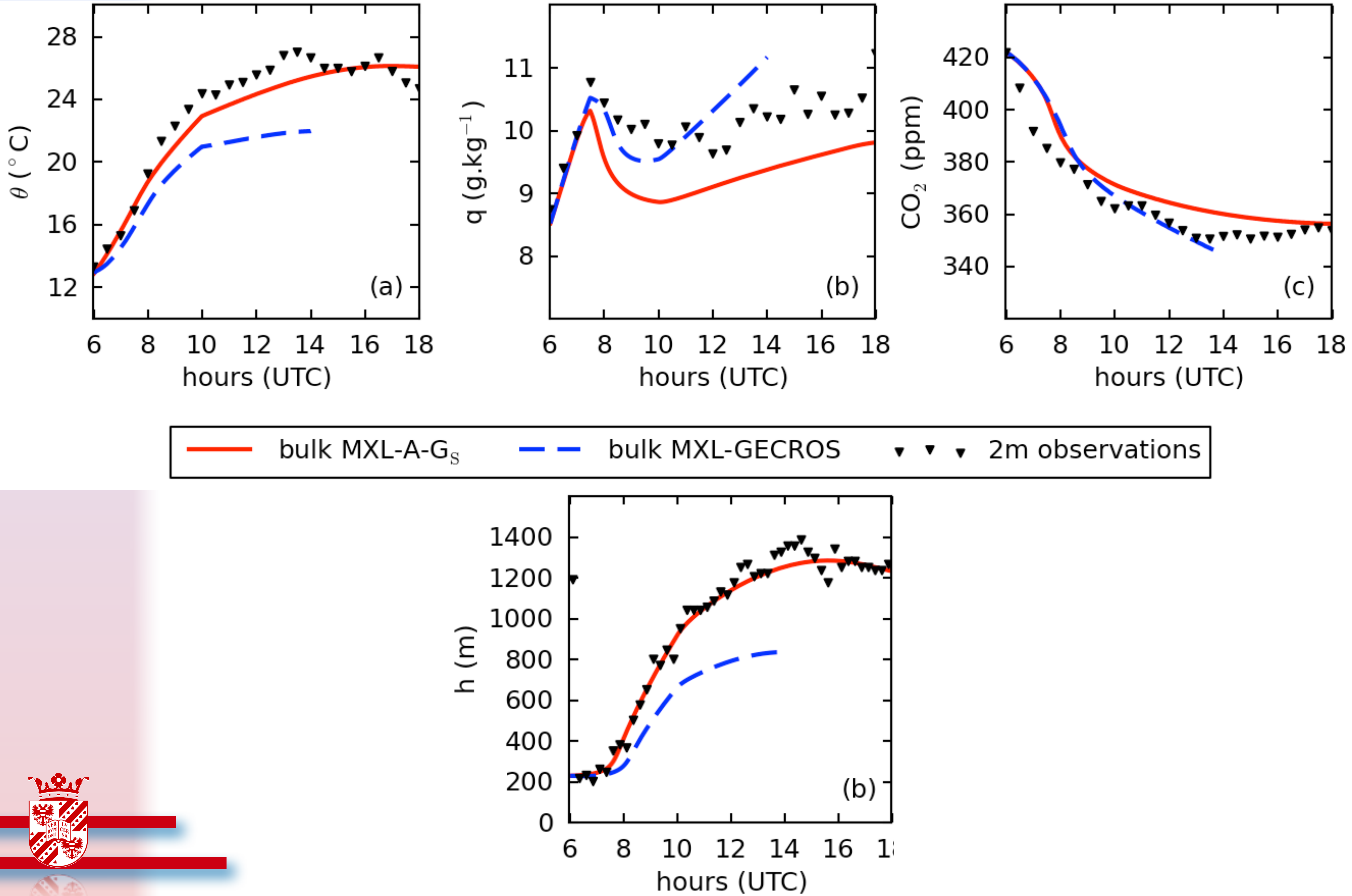




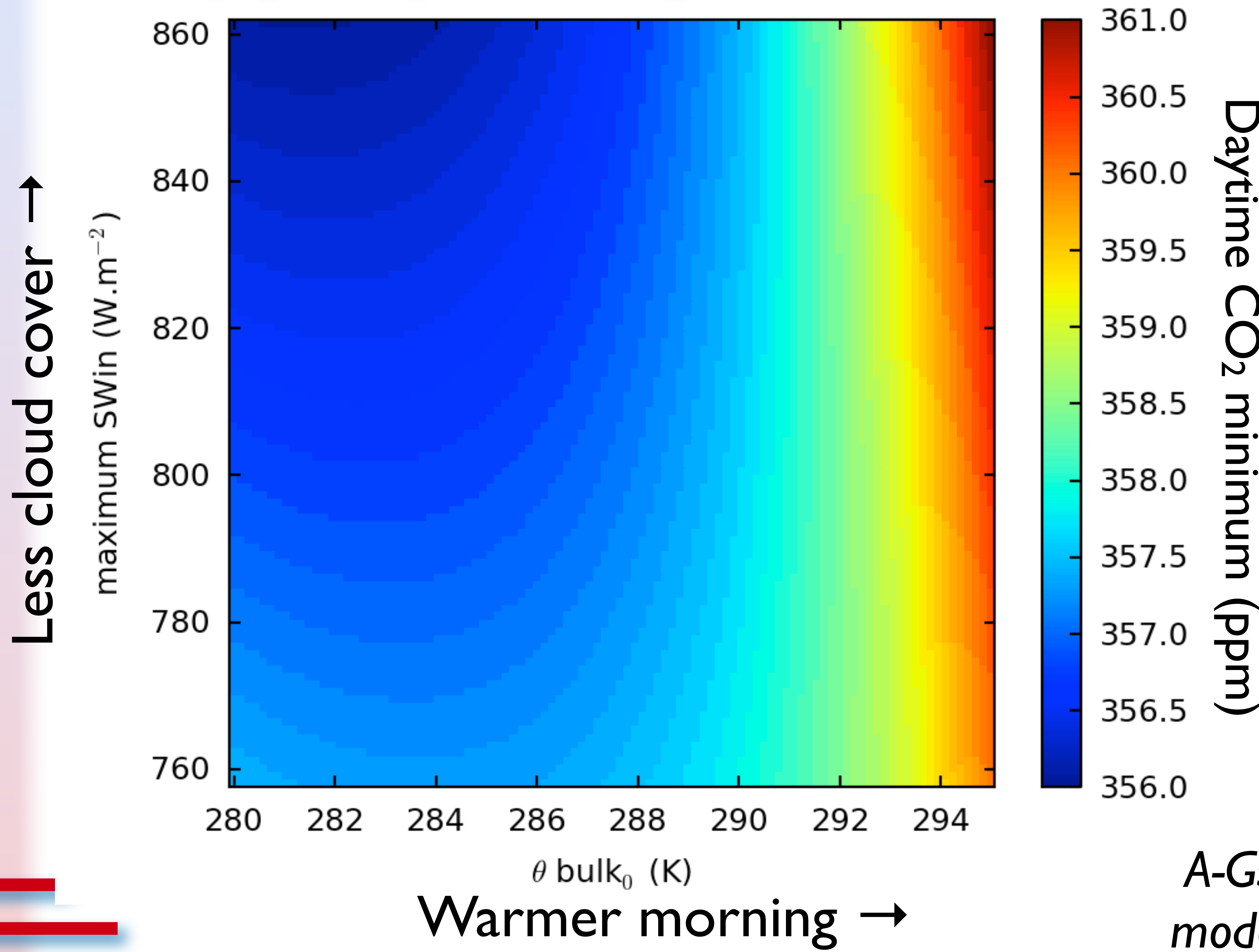
Atmospheric variables



Atmospheric variables



(1) Crop-Atmosphere interactions



A-Gs model

(2) CO_2 errors in the PBL

$$C = C_0 \frac{h_0}{h} + C_0^{fa}\left(1 - \frac{h_0}{h}\right) + \frac{\gamma_{co2}}{2h}(h - h_0)^2 + \frac{t - t_0}{h} < \overline{wco2|_s} >$$

$$< \overline{wco2|_s} > = \frac{1}{t - t_0}\left[Ch - C_0 h_0 - C_0^{fa}(h - h_0) - \frac{\gamma_{co2}}{2}(h - h_0)^2\right].$$

take partial derivatives $\partial C / \partial X$

where X are six independent

driver variables:

C_0, C_0^{FA}, γ, h, h_0, wco_2

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(1) $$\frac{\partial C}{\partial C_0} = \frac{h_0}{h},$$

(2) $$\frac{\partial C}{\partial h} = \frac{\gamma_c}{2} + \frac{1}{h^2}\left[h_0\left(C_0^{\mathrm{FA}} - C_0\right) - \frac{\gamma_c h_0^2}{2} - (t - t_0)\langle\overline{w'c'|_s}\rangle\right]$$

(2) CO_2 errors in the PBL

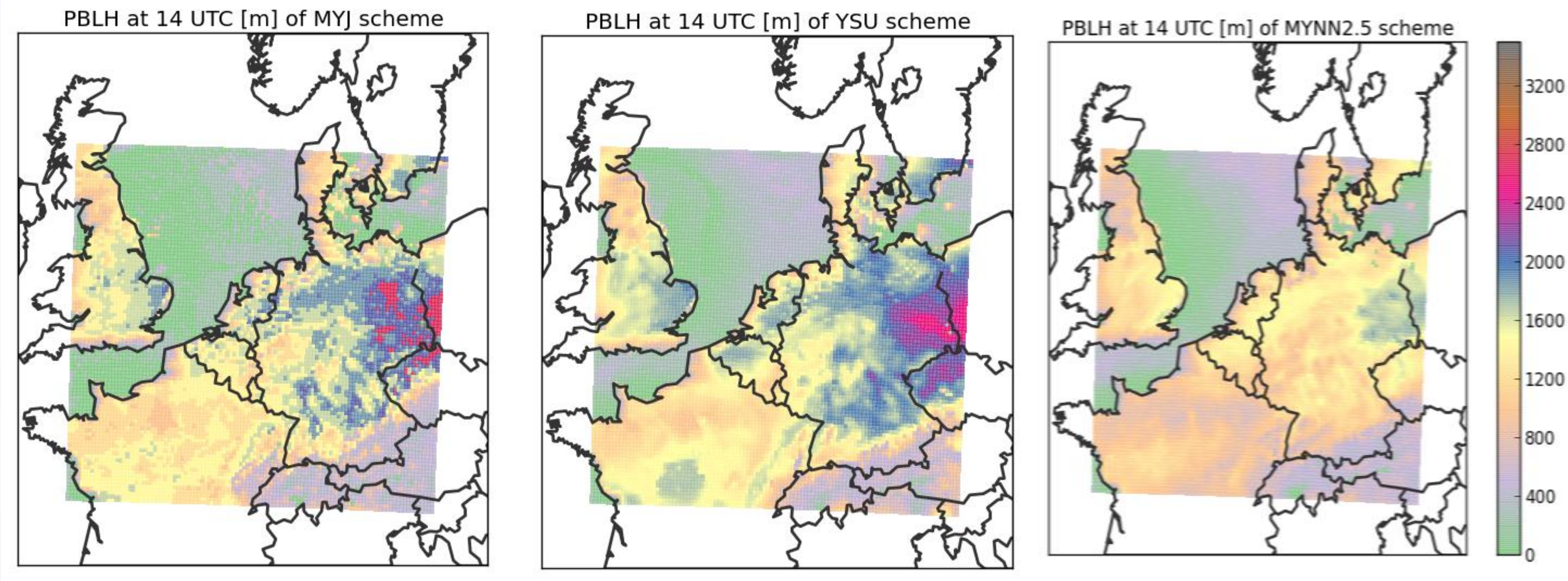
$$C = C_0 \frac{h_0}{h} + C_0^{fa}\left(1 - \frac{h_0}{h}\right) + \frac{\gamma_{co2}}{2h}(h - h_0)^2 + \frac{t - t_0}{h} < \overline{wco2|_s} >$$

$$< \overline{wco2|_s} > = \frac{1}{t - t_0}\left[Ch - C_0 h_0 - C_0^{fa}(h - h_0) - \frac{\gamma_{co2}}{2}(h - h_0)^2\right].$$

(3) $$\frac{\partial < \overline{wco2|_s} >}{\partial h_0} = \frac{1}{t - t_0}[C_0^{fa} - C_0 + \gamma_{co2}(h - h_0)],$$

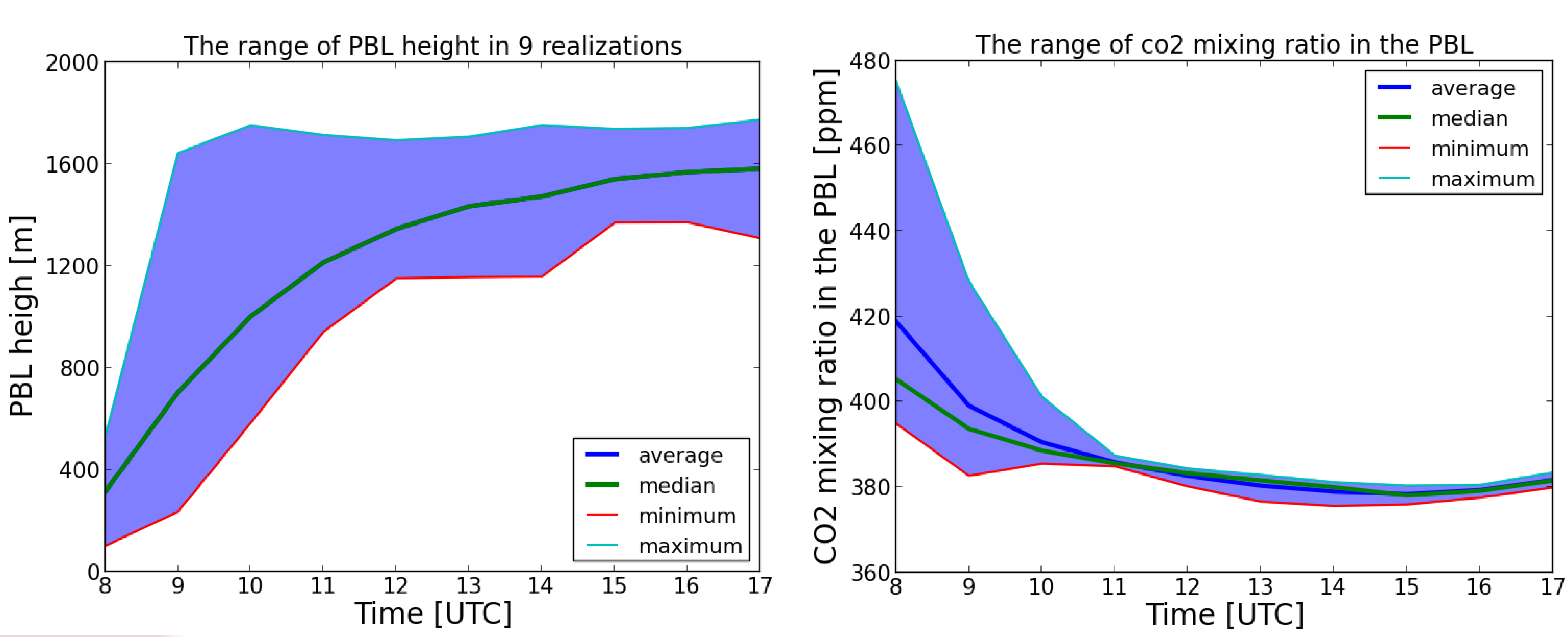
(4) $$\frac{\partial < \overline{wco2|_s} >}{\partial h} = \frac{1}{t - t_0}[C - C_0^{fa} - \gamma_{co2}(h - h_0)],$$

(2) CO_2 errors in the PBL



WRF modeling with three PBL schemes (MYJ, YSU, MYNN2.5), T and light dependent surface CO_2 flux (A-Gs)

Example of PBL heights and CO_2 mole fractions derived with WRF



N = 9 (schemes/methods)

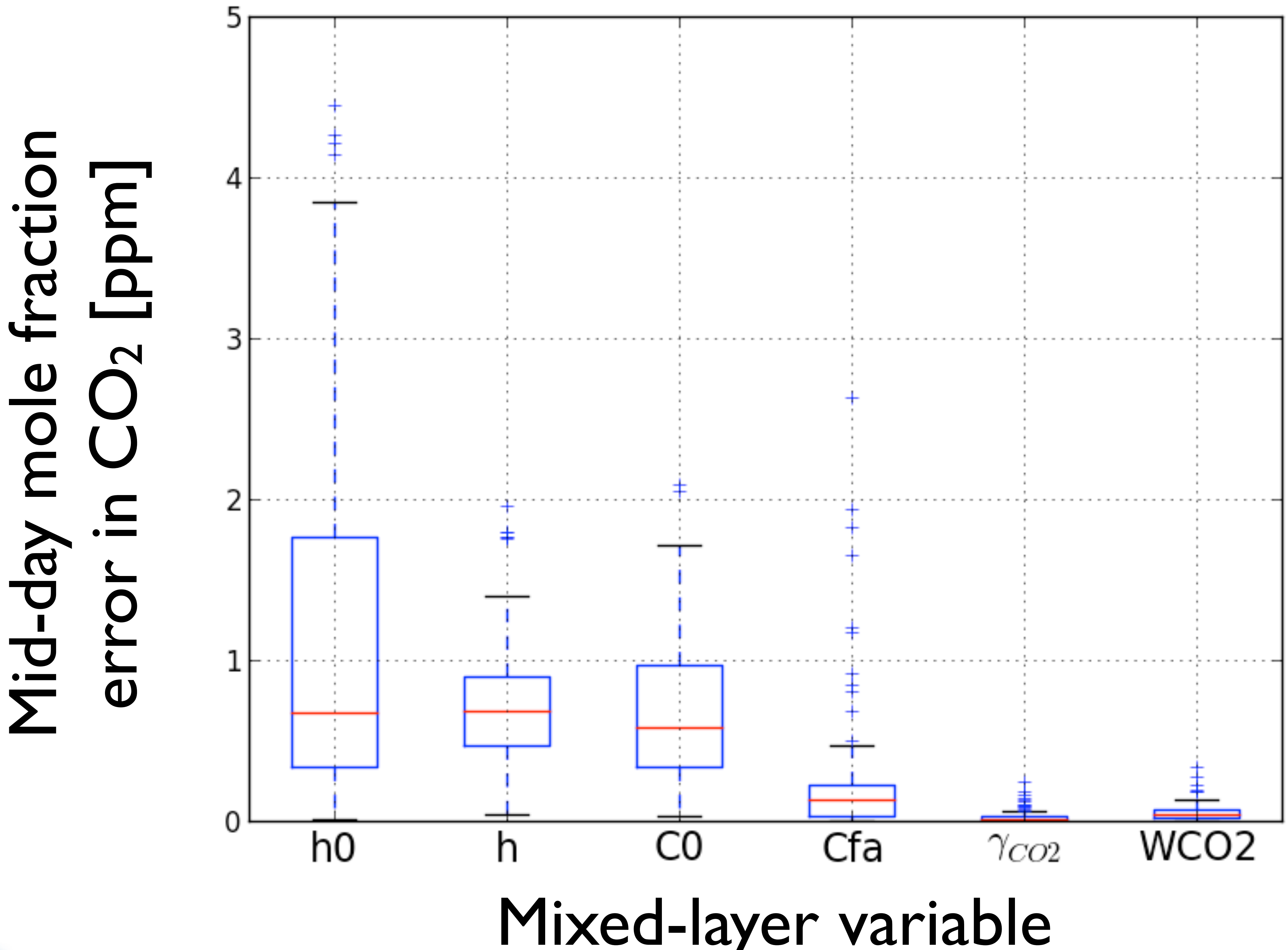
M = 116 (selected mixed-layer cases June)

(2) CO_2 errors in the PBL

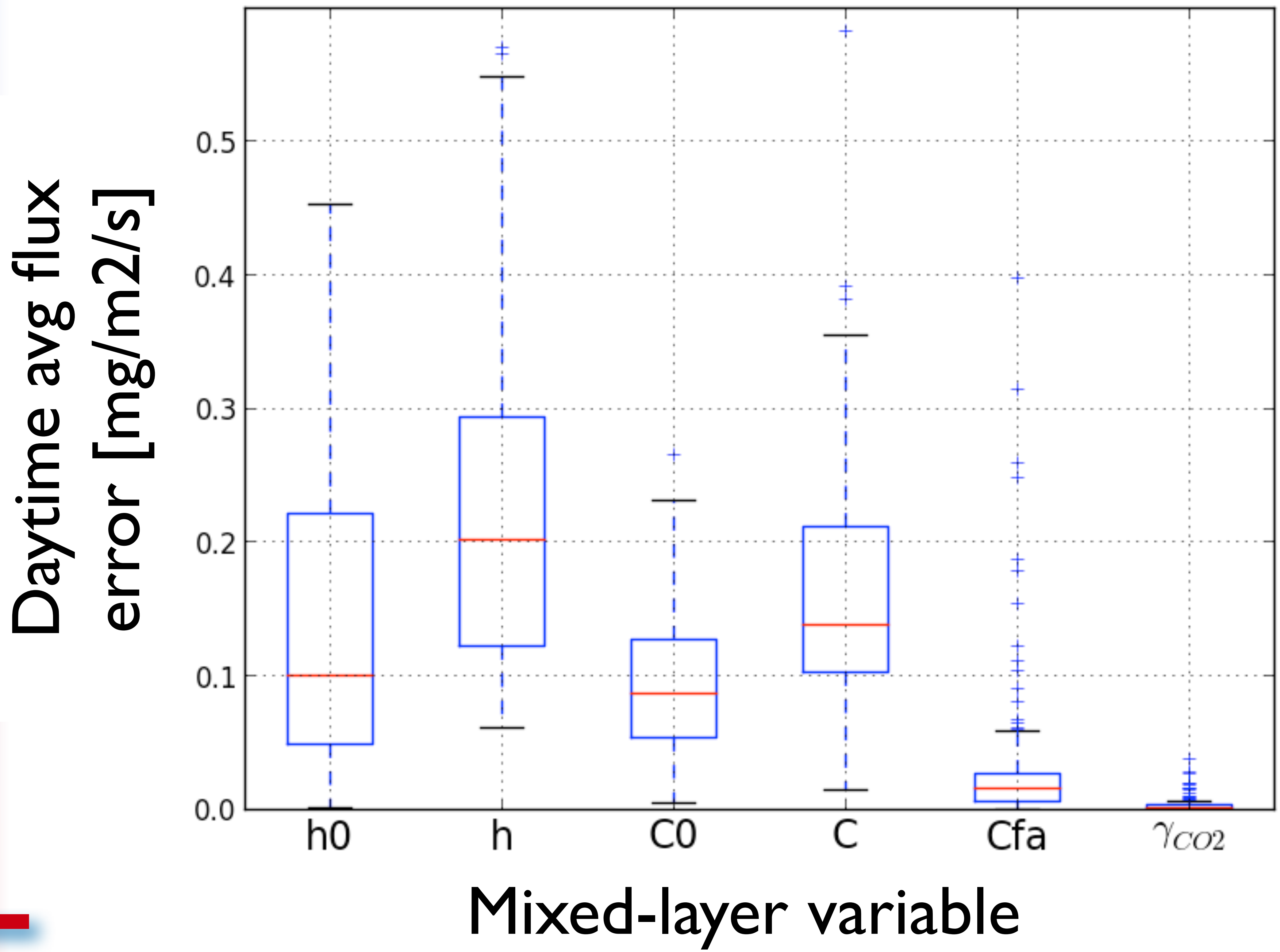
Variable	***Error****
h_0	84 m
h	262 m
C_0	2.2 ppm
C_0^{FA}	0.1 ppm
γ_{CO2}	0.02 ppm/km
$\overline{w'c'}$	7 μg m^{-2} s^{-1}

* = half range of min-max values simulated, median of 116 cases shown

(2) CO_2 errors in the PBL



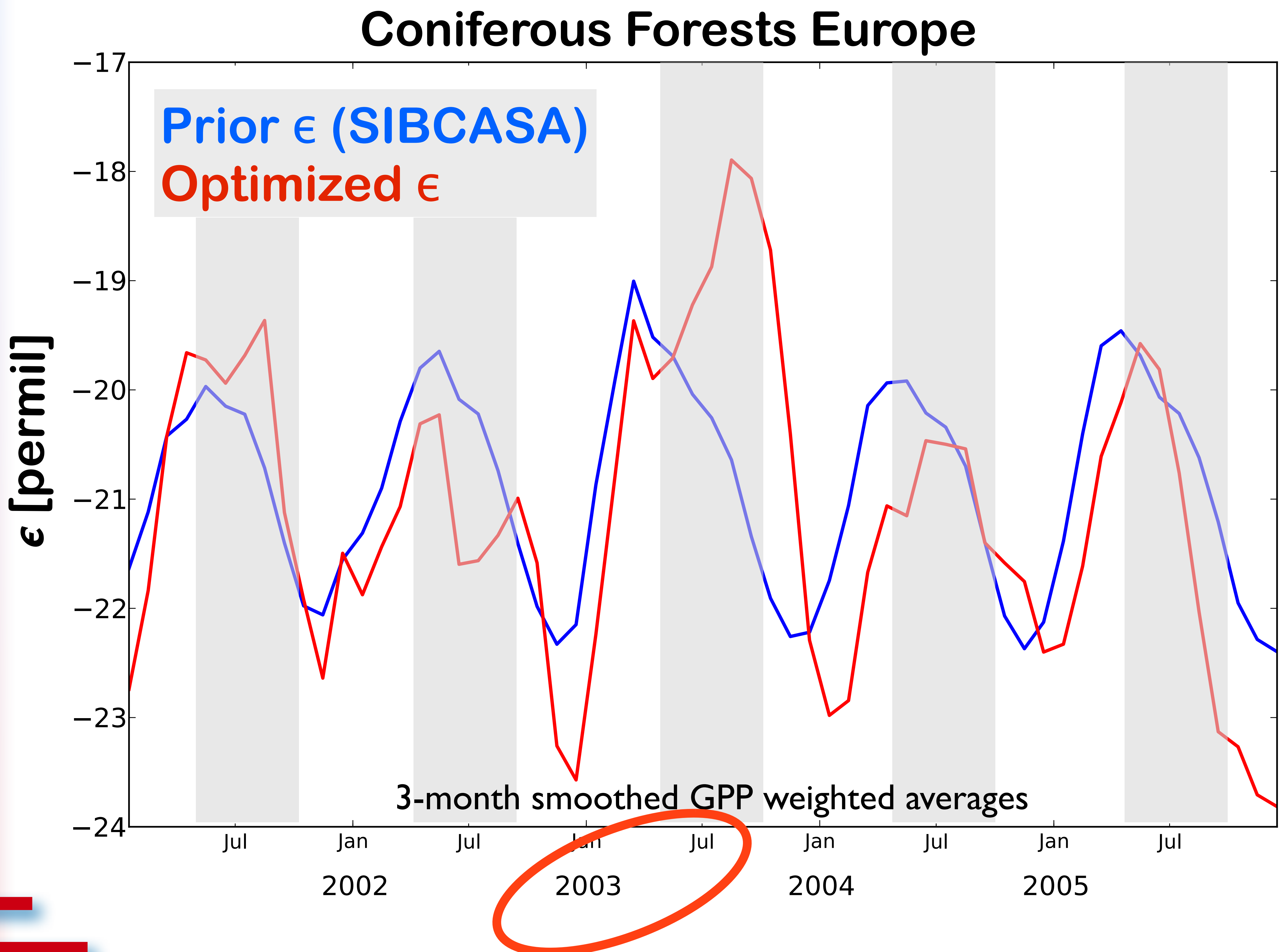
(2) CO_2 errors in the PBL



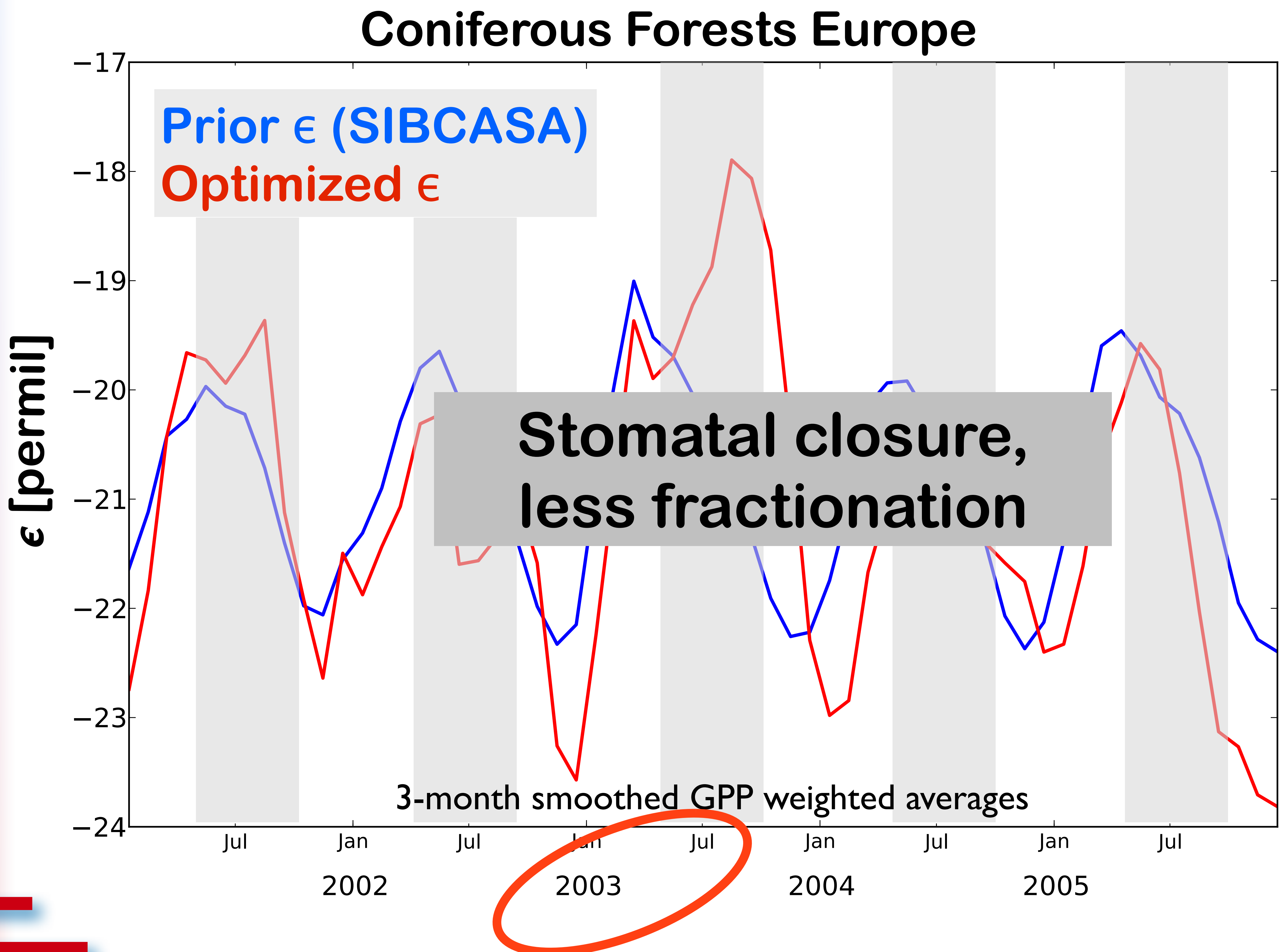
Conclusions

- Coupled carbon-water-energy exchange key to understanding multiple scales
- Dynamics can be a main source of errors in simulated CO_2 mole fractions and estimated surface fluxes
- The effect of local errors is to some degree dampened beyond the synoptic time scale, where main control is bulk ventilation rate
- Increasing role for NWP in understanding carbon cycle behavior, ECMWF has an important role to play

Optimizing discrimination

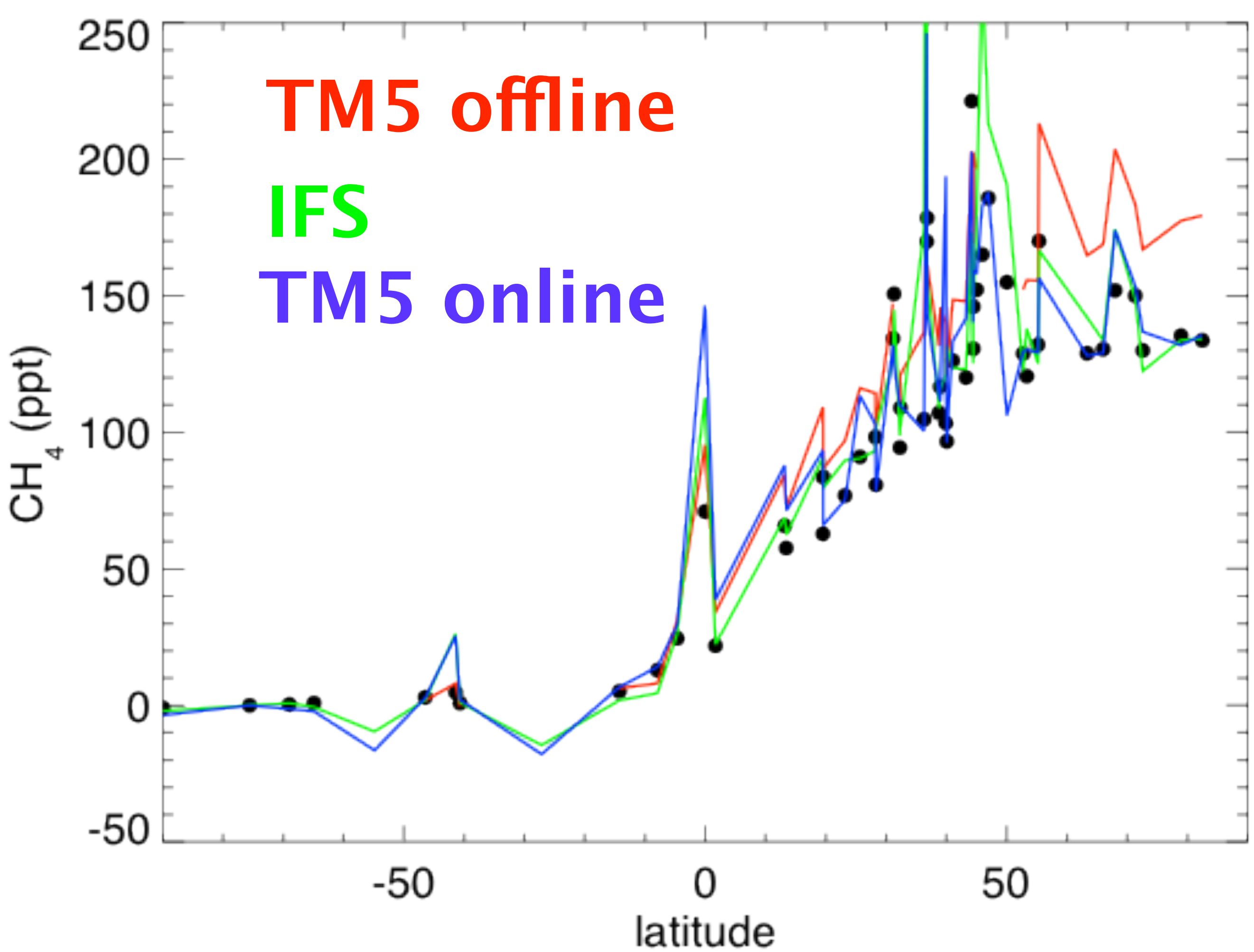


Optimizing discrimination

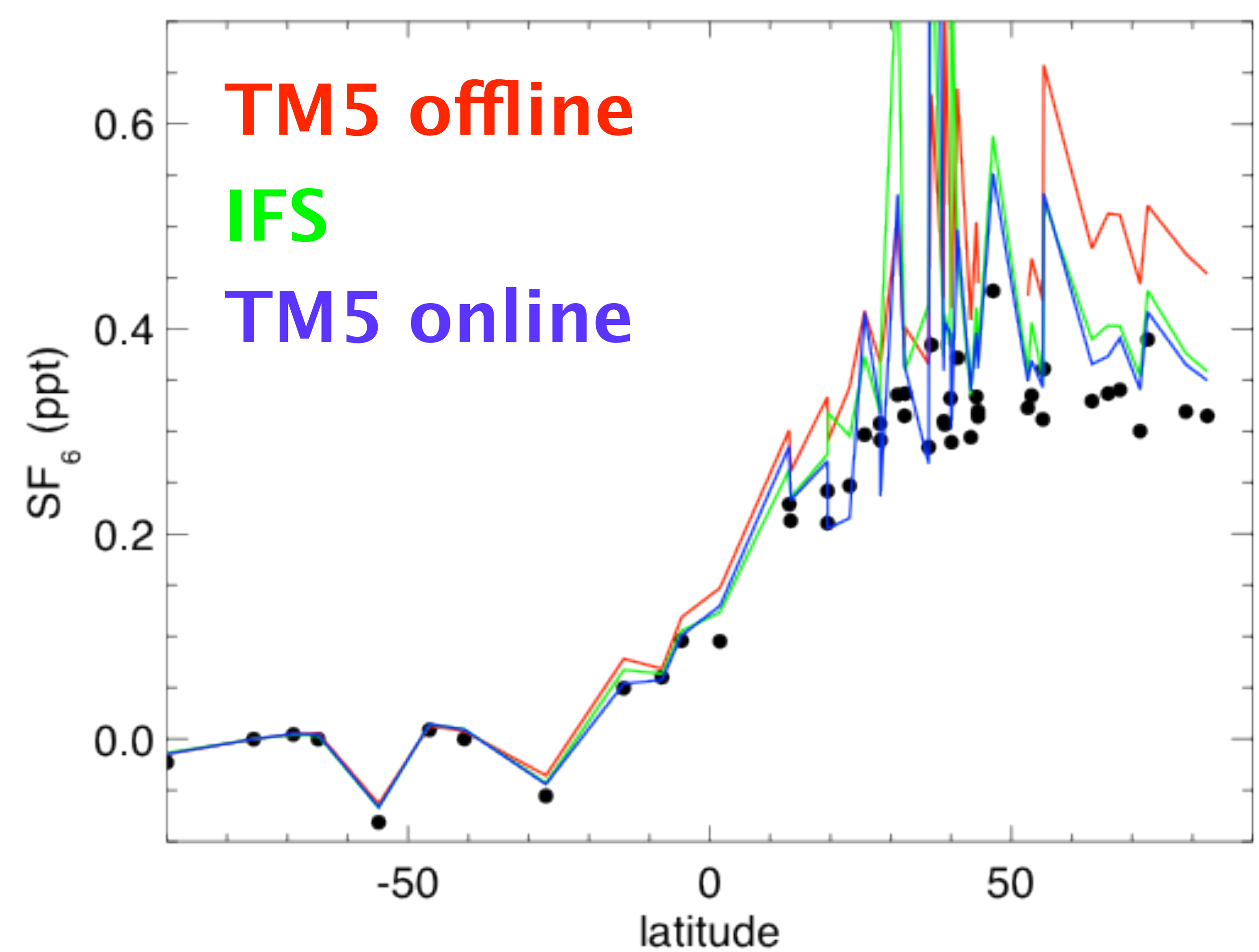


Comparison TM5 'offline', 'online' and IFS

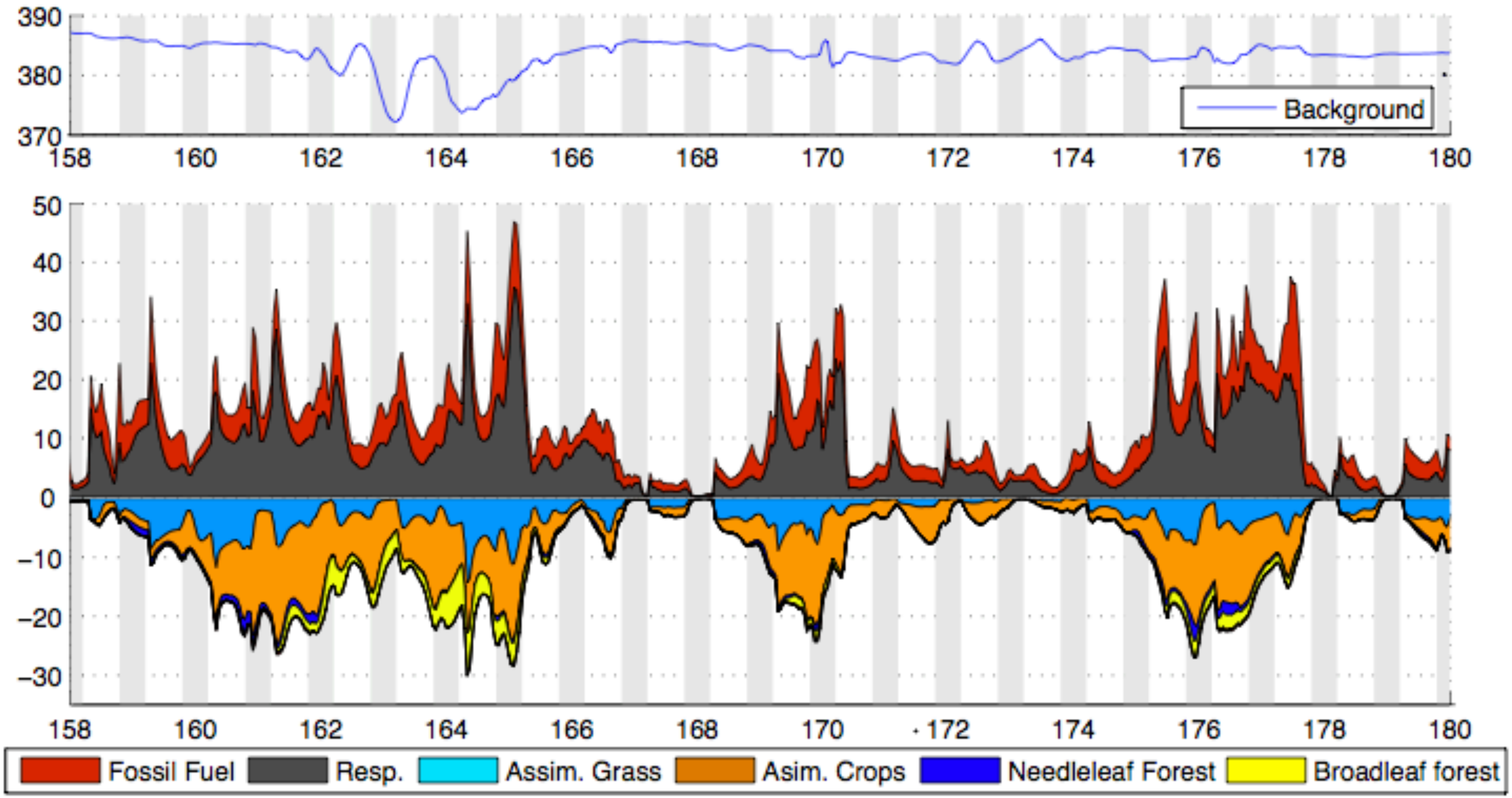
CH_4



SF_6

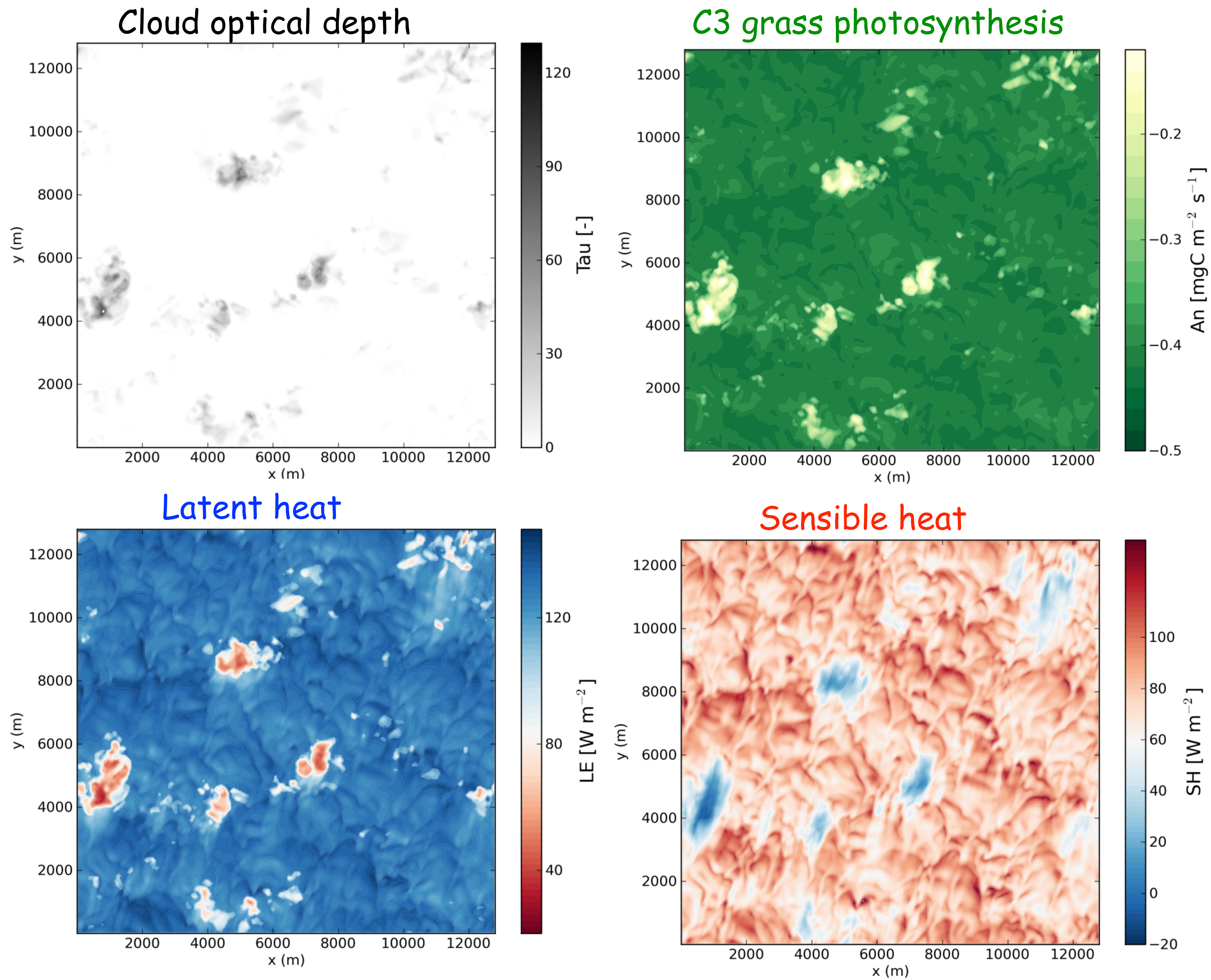


TM5 online (EC-Earth) performs pretty similar to IFS!



Modelling regional scale surface fluxes, meteorology and CO_2 mixing ratios for the Cabauw tower in the Netherlands

L. F. Tolk[1], W. Peters[2], A. G. C. A. Meesters[1], M. Groenendijk[1], A. T. Vermeulen[3], G. J. Steeneveld[2], and A. J. Dolman[1]



Cloud optical depth
Tau [-]
C3 grass photosynthesis
An [mgC m−2 s−1]
Latent heat
LE [W m−2]
Sensible heat
SH [W m−2]
x (m)
y (m)