Satellite-Based Modeling of Evapotranspiration and Uncertainties in Eddy Covariance Flux

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Outline

I: Satellite-based Modeling of ET at Fine and Large Scales

1. How does the satellite work for ET estimate?
2. What is the Performance of this modeling at field scale?

II: Uncertainty in Eddy Covariance Measurements

1. Flux spatial context *vs*. Sensor Heights
2. High frequency flux loss *vs*. Sensor Heights
3. Low frequency flux loss *vs*. Sensor Heights
4. WPL corrections for CO2 and N2O Flux
5. Trace gas analyzer's requirements for EC

Satellite's Approach

Satellite-Based Land Surface Energy Balance:

Thermal images approach T_R for a simple or complicated relation of T_R vs. T_{AC}.

Visible and infrared images are responsible for the surface radiances, NDVI, LAI, albedo, biomass, and other biophysical variables.

Models for Large Scales:

1. One-source model
   a) Surface energy balance algorithm for land (SEBAL, Bastiaanssen, et al 1998).
   b) Surface energy balance system (SESB, Su, 2003)
   c) Mapping evapotranspiration with internalized calibration (METRIC, Allen, et al., 2007).
2. Two-source model
   a) Two-source model (TSM, Norman et al., 1995).
   b) Two-source time-integrated model (TSTIM, Andersen et al, 1997 & 2007).

How does Satellite Information do for ET ?

Satellite-Based Land Surface Energy Balance:

--- Thermal images provide T_R Information.

--- Visible and infrared images are used for calculating:

- ❖ Spectral radiances,
- ❖ Spectral reflectance and transmittance,
- ❖ NDVI, LAI, albedo, biomass, and
- ❖ Other biophysical variables.

Sensible Heat Flux:

$$H = \rho C_p \frac{T_{AC} - T_A}{R_A}$$

Aerodynamic and Radiometric Temperatures:

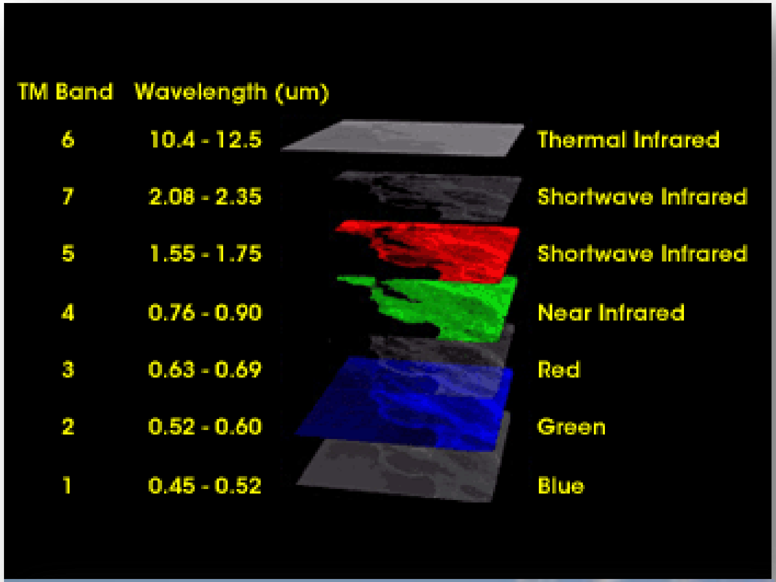
$$T_{AC} \propto T_R$$

Inputs: Landsat 5/7 and Weather Station/EC Tower

Discontinuous Spatial Info

+

Continuous Temporal Info



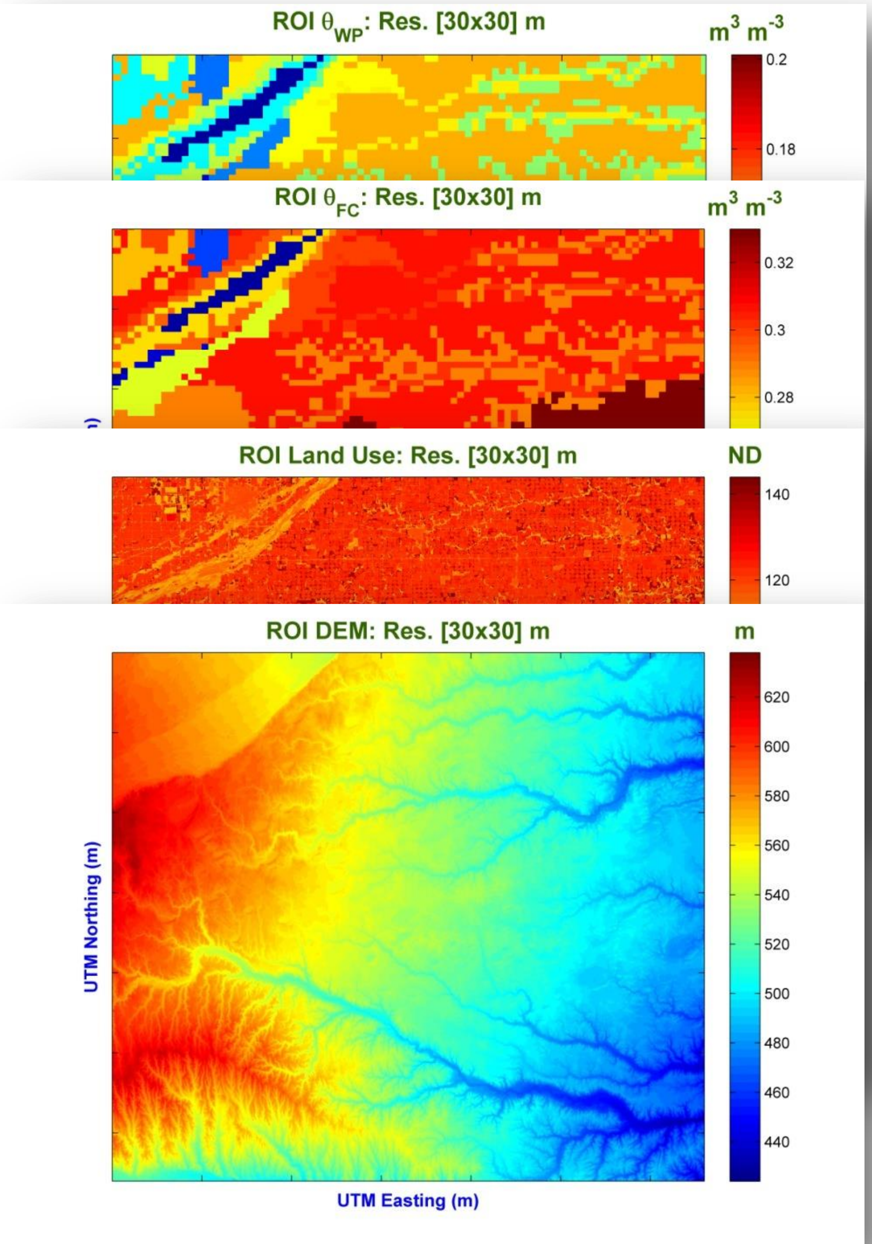
- All TM bands
- Calibrated pixel value [DN]
- Resampled thermal band

Spatial Resolution: 30x30m

- Air Temp, Air humidity
- Solar radiation, Precip.
- Wind speed and DIR

Temporal Resolution: 1 Hour

Inputs: Static Land Surface Data



Estimate initial surface soil water balance

adjust Zom – Very effective

1) adjust solar radiation
2) adjust Zom

Basic Computations

Spectral Radiances

$$L_\lambda = G_{rescale}\, Q_{cal} + B_{rescale}$$

$$\rho_p = \frac{\pi \cdot L_\lambda \cdot d^2}{ESUN_\lambda \cdot \cos\theta_s}$$

---Chander et al. 2009.

Surface Scalar Quantities

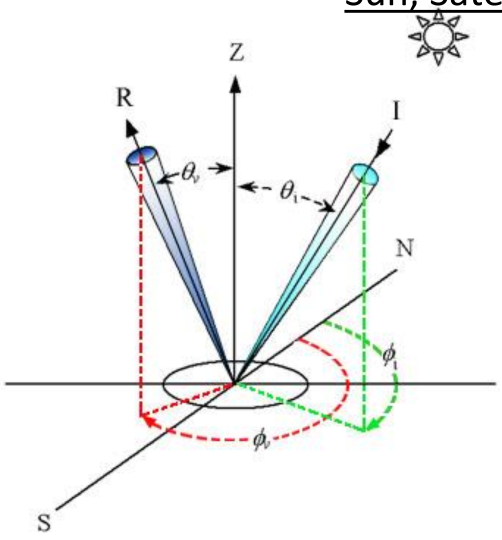
$$T_R = \frac{K_2}{\ln\left(\frac{\varepsilon_{NB} K_1}{R_c}\right) + 1}$$

$$NDVI = \frac{\rho_{(x,y,4)} - \rho_{(x,y,3)}}{\rho_{(x,y,4)} + \rho_{(x,y,3)}}$$

$$\alpha = \int_{b=1}^{7} \rho_{s,b} w_b \, db$$

---Allen et al. 2007.

Sun, Satellite and Earth



Surface Available Energy

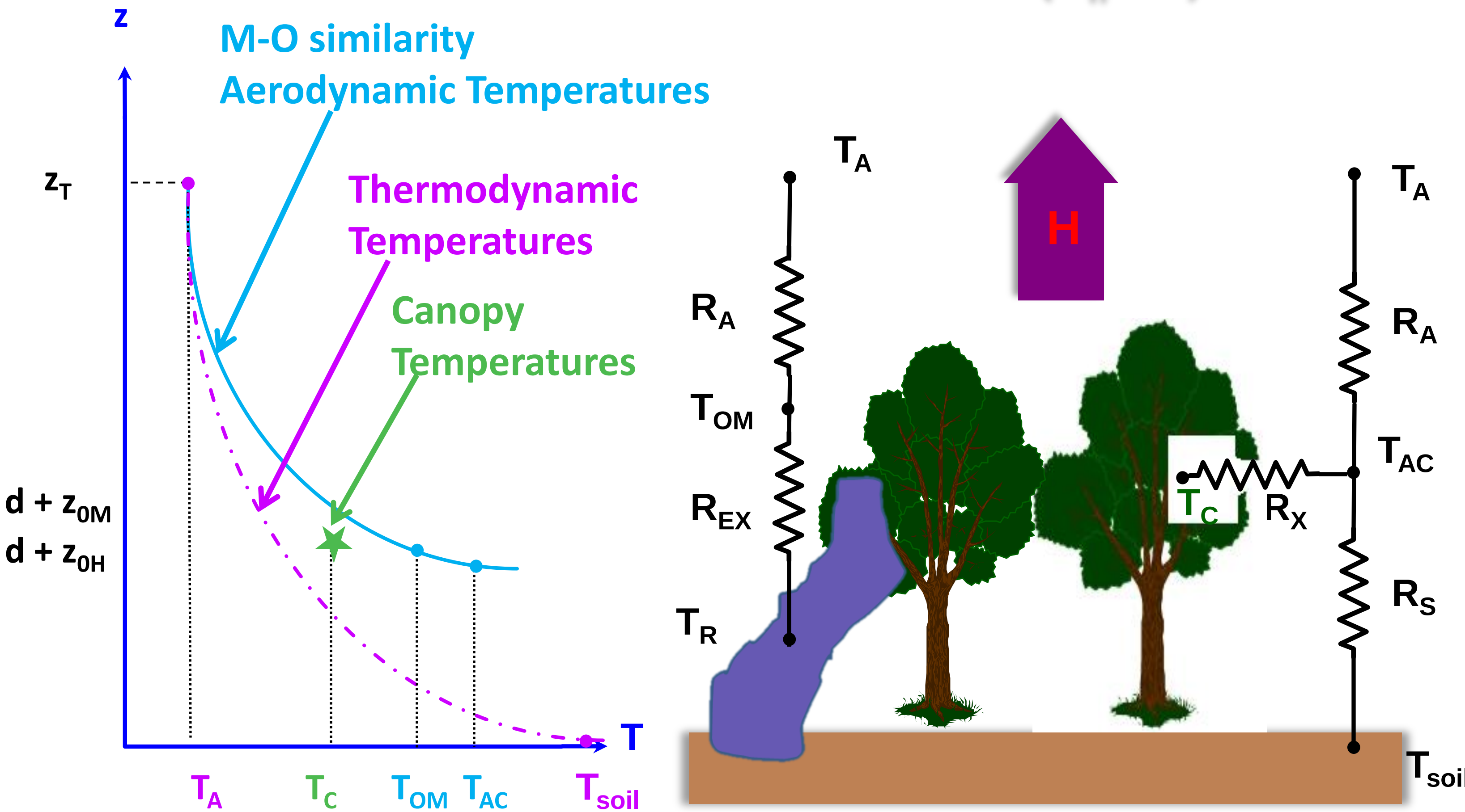
$$R_n = (1-\alpha) R_s \downarrow + \varepsilon_a \sigma T_a^4 - (1-\varepsilon_s)\varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

$$\frac{G}{R_n} = (T_R - 273.15)(0.0038 + 0.0074\alpha - 0.98 NDVI^4)$$

---Bastiananssen et al. 2000.

Key Computations in Modeling

$$ET = (R_n - G) - H$$



$$R_{EX} = \left[\sum_{i=1}^{6} a_i LAI^i \right] u_*^{-1}$$

Iterative Estimate of Sensible Heat

$$R_A = \frac{[\ln(\frac{z_U - d}{z_{OM}}) - \psi_M)][\ln(\frac{z_T - d}{z_{OM}}) - \psi_H)]}{k^2 U}$$

$$R_X = \frac{180}{LAI}(\frac{L_w}{U_{d+z_{OM}}})^{0.5}$$

$$R_S = \frac{1}{a(T_S - T_C)^{\frac{1}{3}} + bU_S}$$

$$T_R = f_c(\varphi)T_C + (1 - f_c(\varphi))T_S$$

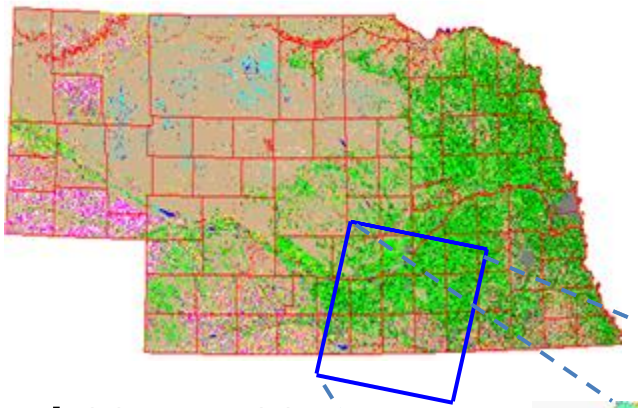
$$H_C = \rho C_p \frac{T_C - T_{AC}}{R_X}$$

$$H_S = \rho C_p \frac{T_S - T_{AC}}{R_s}$$

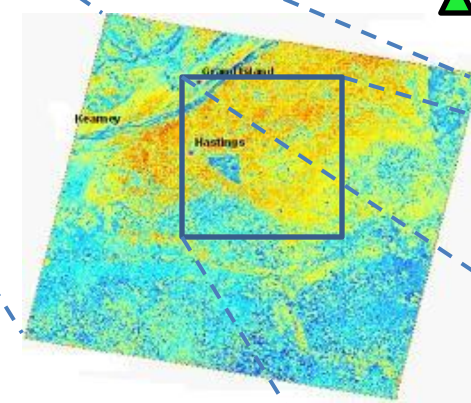
$$H = H_C + H_S = \rho C_p \frac{T_R - T_A}{R_A + R_{EX}}$$

ET = (R_n - G) - H

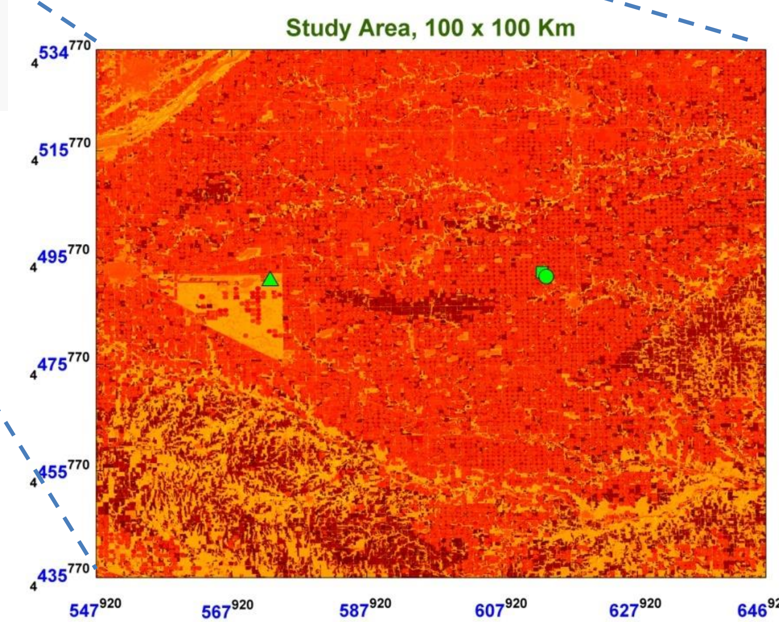
Study Area



Path29 Row32



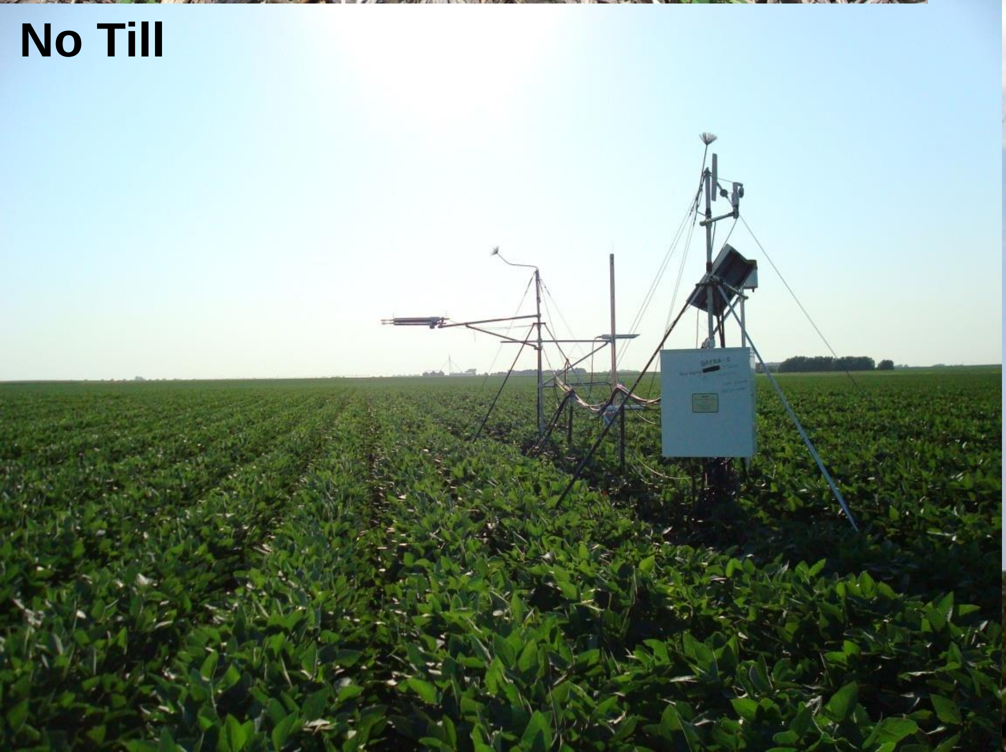
- ■ No till corn field, Bowen ratio tower
  Lat. 40.5801°, Lon. -97.6552°, Ele: 573.6 m
- ● Disk till corn field, Bowen ratio tower
  Lat. 40.5729°, Lon. -97.6481°, Ele: 576.0 m
- ▲ Weather Station
  Lat. 40.570°, Lon. -98.13°, Ele: 552.0 m



Landsat 5 Three Scenes:

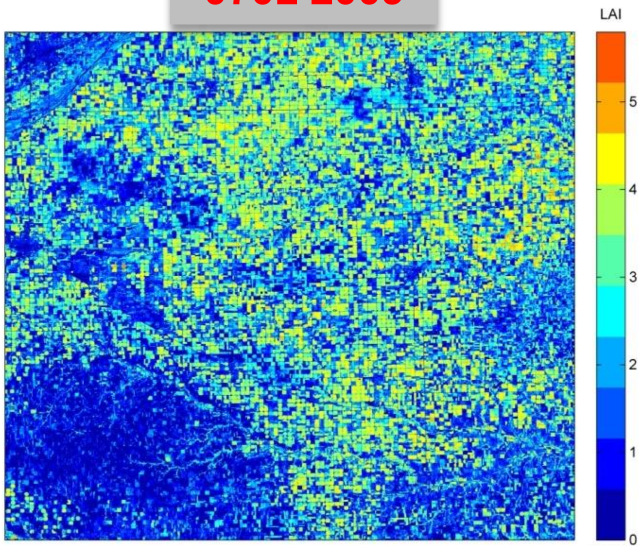
- July 01 2009, 17:01:11 (GMT)
- July 17 2009, 17:01:27
- Aug. 02 2009, 17:01:42

Close-up of Tower Locations

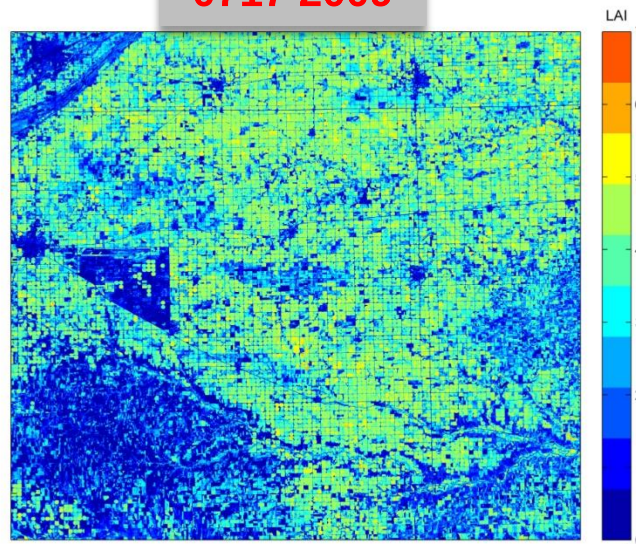


Scalar Outputs: LAI

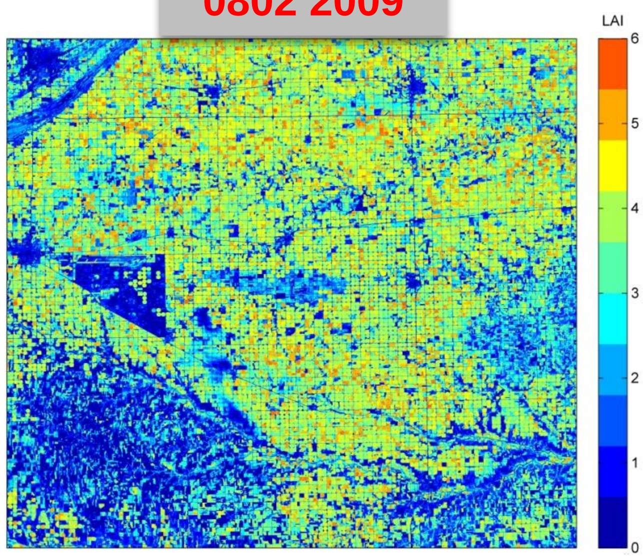
0701 2009



0717 2009

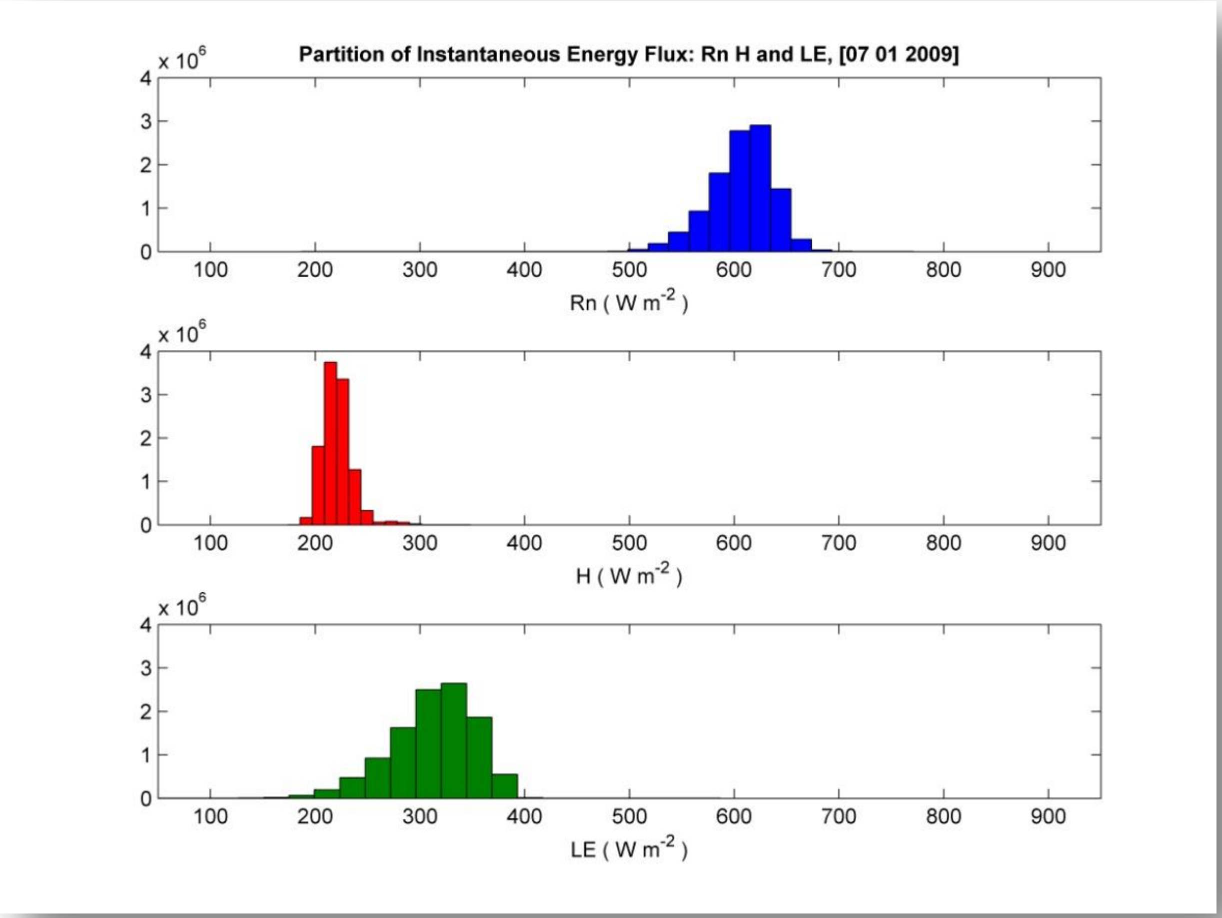


0802 2009

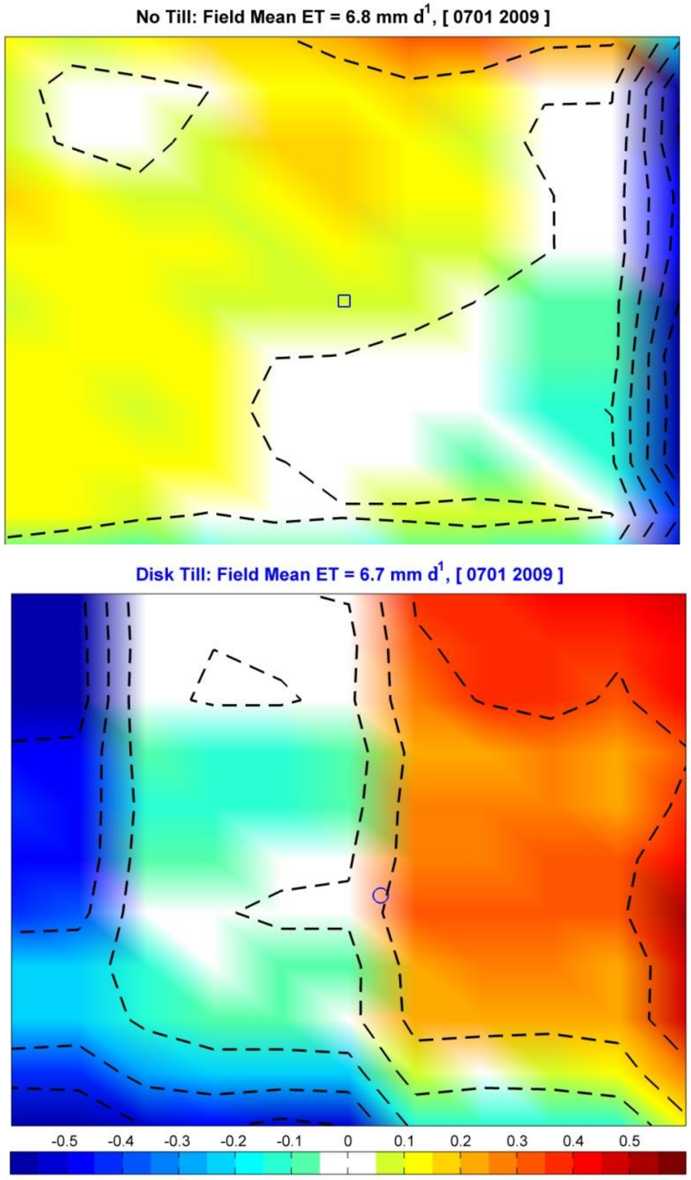


Scalar Flux Outputs

July 1st 2009



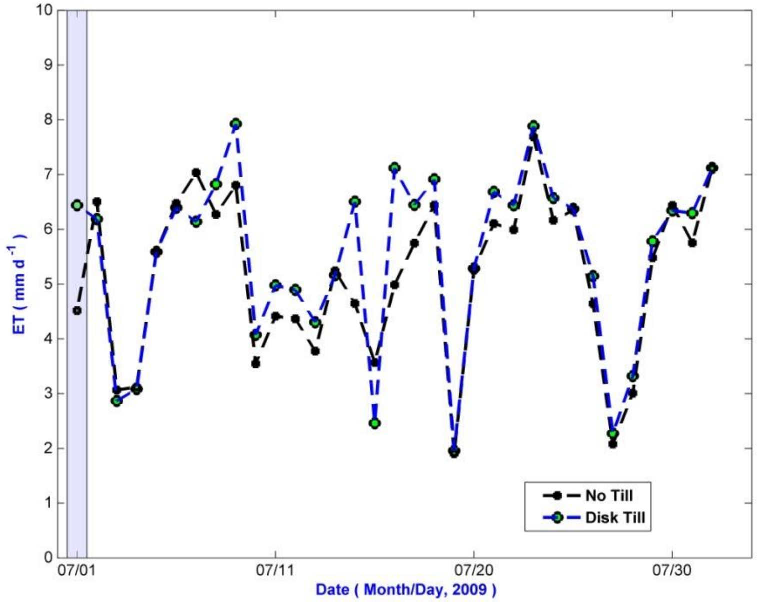
Validation: Daily ET [300 x 300m] for No Till vs. Disk Till



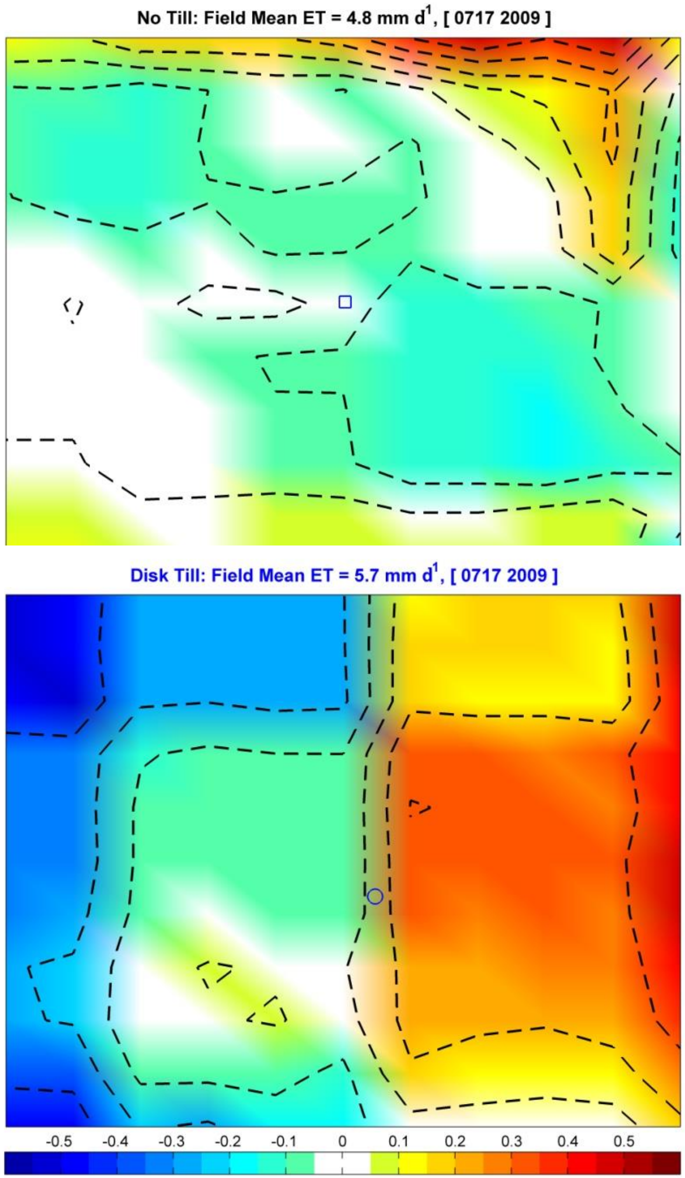
Variations from the Field Mean (mm d $^{-1}$)

[0701 2009]

Observed ET $_{\text{NO Till}}$ and ET $_{\text{Disk Till}}$



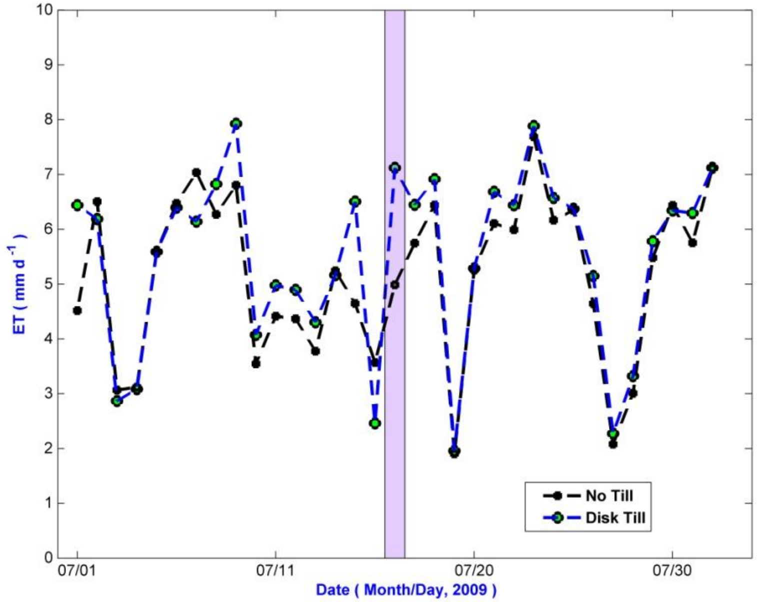
Validation: Daily ET [300 x 300m] for No Till vs. Disk Till



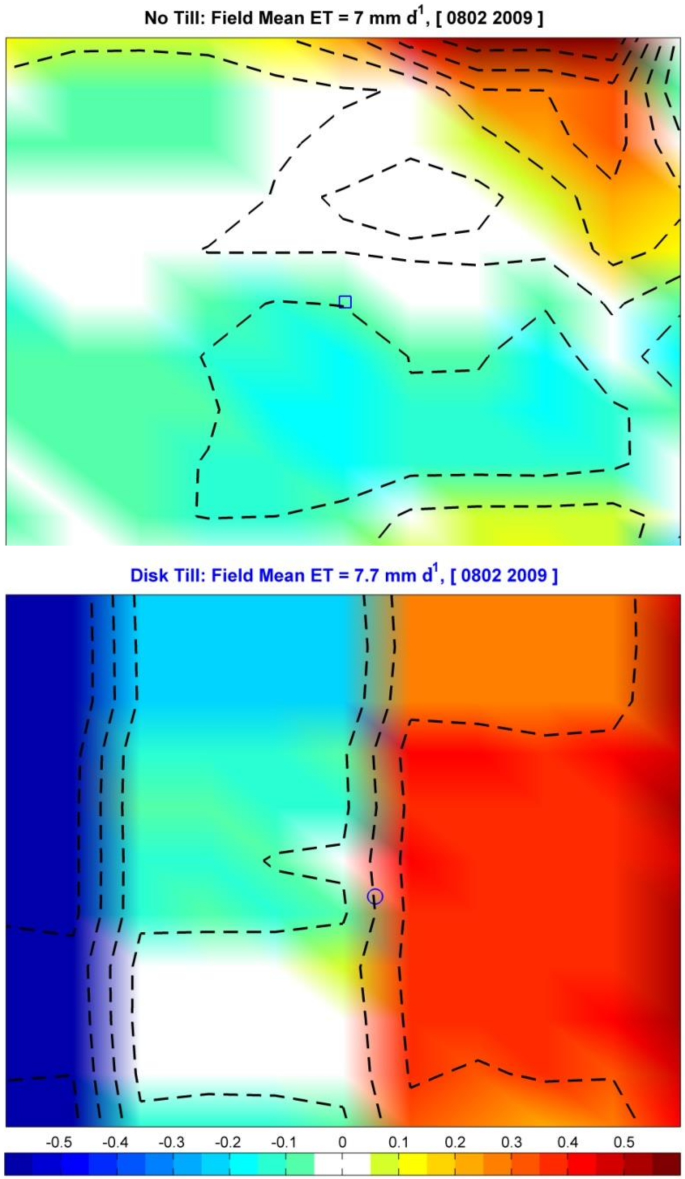
Variations from the Field Mean (mm d $^{-1}$)

[0717 2009]

Observed ET $_{\text{NO Till}}$ and ET $_{\text{Disk Till}}$



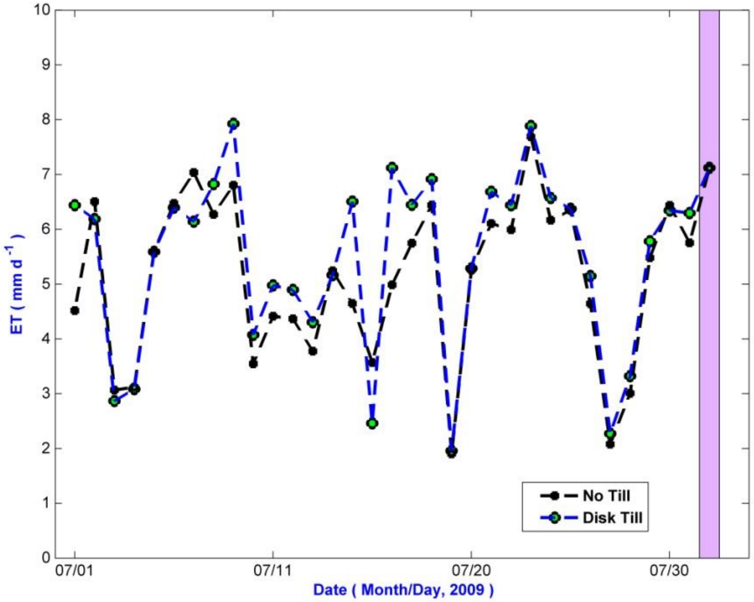
Validation: Daily ET [300 x 300m] for No Till vs. Disk Till



Variations from the Field Mean (mm d $^{-1}$)

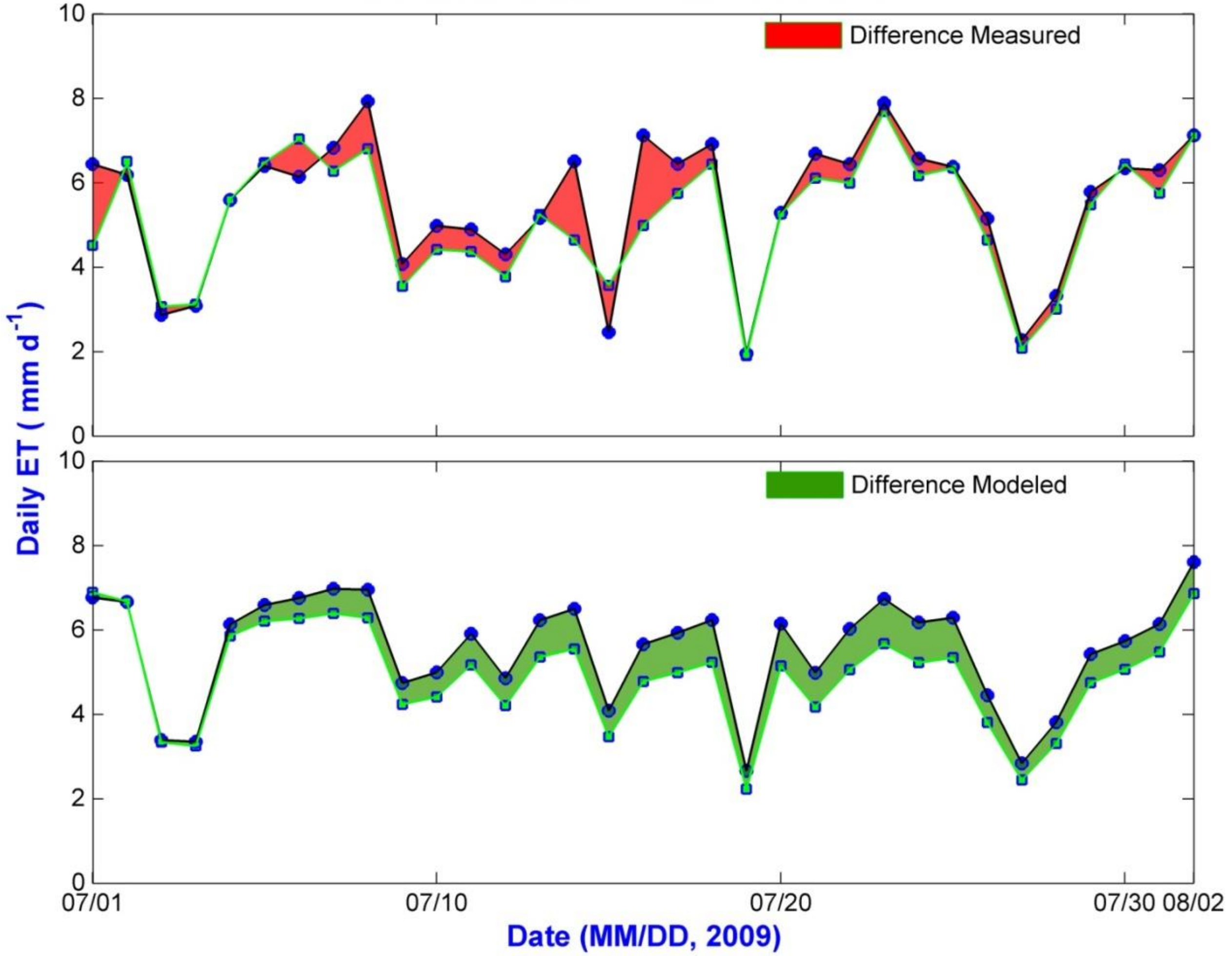
[0802 2009]

Observed ET $_{\text{NO Till}}$ and ET $_{\text{Disk Till}}$

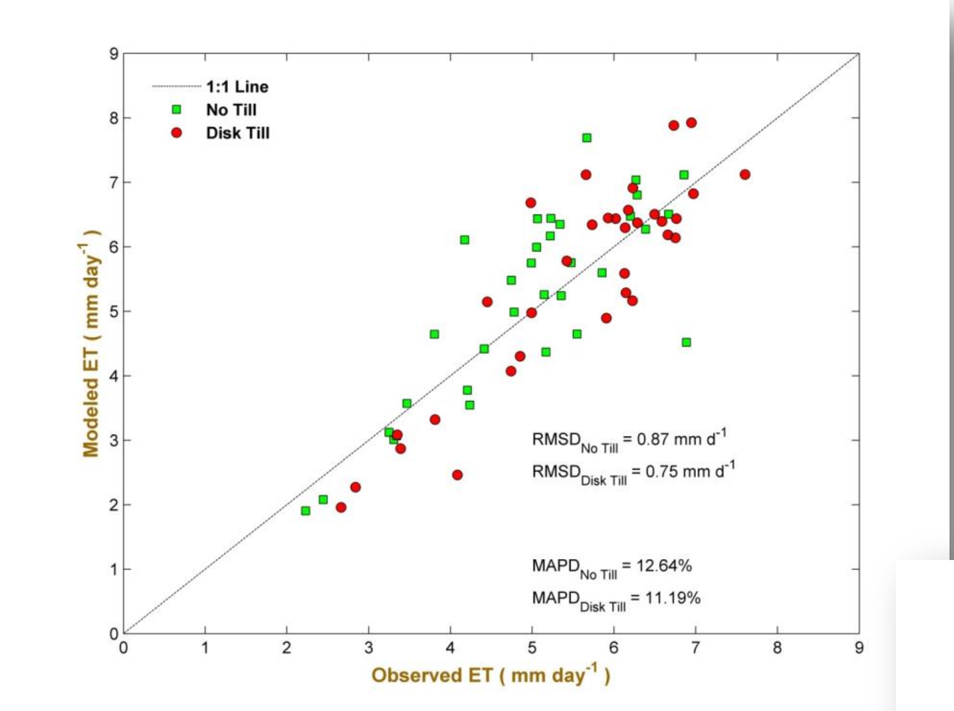


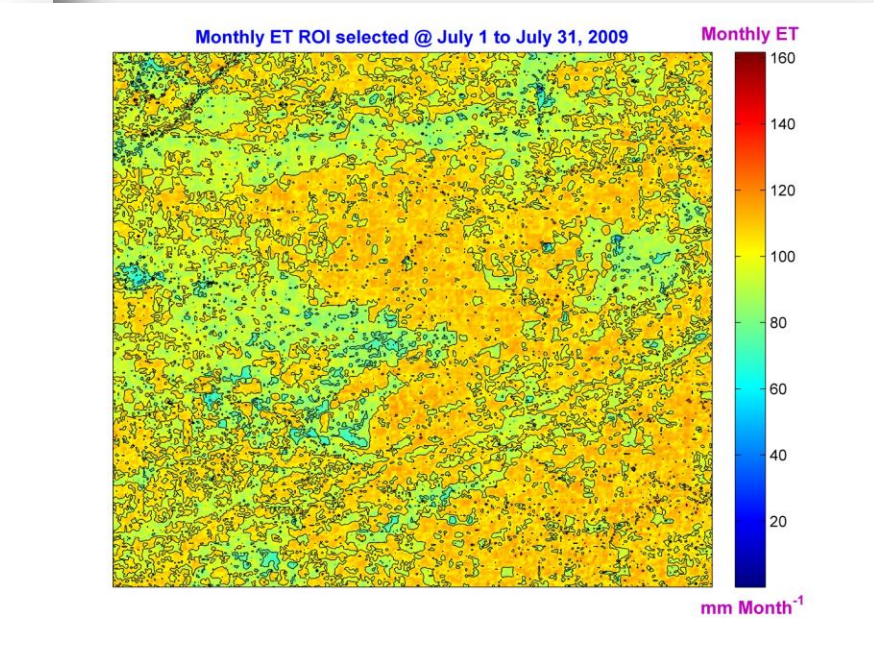
Comparison of Daily ET

Measured Difference (top) and Modeled Difference (Bottom) between No Till ( )and Disk Till ( ) Field



Modeling Performance and Monthly Spatial ET Estimate





Summary: ET Modeling

A modified surface energy balance model was developed. Models were performed well under both large scale [100 x 100 Km] and field scale --- R_{EX} and LU data Introduced.

Automated searching, locating, and estimating the endpoints of the hot and cold pixels made selection objective with less assumptions --- Automatic & Robust.

The models used have been designed to be robust to expected errors (around 12%) for daily ET validated by the point-measurements from Bowen ratio systems.

The field scale ET variations presented here suggest that disk till corn field had significantly and consistently larger ET than the no till corn fields in July 2009.

Mapping Tool: only four inputs

```
% OSM modeling and mapping ET
%
% This program is a research code for calculating ET by using satellites of
% Landsat 5 and 7 as well as local whether station information. It is
% workable under current condition when your selected ROI is apopporiate
% but WITHOUT ANY WARRANTY for your application purposes.
%
% Time:     Jan. 2007 started up and continuted in July 2009 at the UNL
% Status:   Workable
% Author:   Xiaomao Lin @ UNL
% Revision: 07_27_2009: it was working
%           08_03_2009: Optimalized pixel selection algorithm (Dry and Wet)
%           08_03_2009: Fixed dT algorithm
%           08_2009:    Added the landuse and DEM
%           08_2009:    Comparison confirmed with Ian
%           09_2009:    Final comparison done
%           09_2009:    Optimized the codes
%           01_2010:    Comparison re-confirmed with Towers
%           02_2010:    OK_status with
clear all; clc; close all;
% ****************************************
% Step 1:  INPUTS for OSM: 4 input groups
% ****************************************
% Weather data is the mat format already inclduing HD st ed lat lon ele
% HD contains 9 variables (see STNbasicINFO.m) inside
%  1.1 Weather station Info
STNPATHandName = 'd:\mat\et_pm\matdata\Claycenter2005_9hr';
% *****************************************************************
%  1.2 Input sat image file
% *****************************************************************
SATimPATHandName= 'd:\sat_data_center\L5029032_03220090701_B';
%SATimPATHandName = 'd:\sat_data_center\L5029032_03220090717_B';
%SATimPATHandName= 'd:\sat_data_center\L5029032_03220090802_B';
%  1.3 Input landuse and land cover info
LULCimPATHandName = 'd:\sat_data_center\Landuse_p29r32_2005.tif';
DEMimPATHandName = 'd:\sat_data_center\dem_30m_p29r32_float.tif';
%  1.4 Input soil property info
%DEMimPATHandName = 'd:\sat_data_center\dem_30m_p29r32.tif';
SOILfcPATHandName = 'd:\sat_data_center\fc_fraction_p29r32_30m.tif';
SOILwpPATHandName = 'd:\sat_data_center\wp_fraction_p29r32_30m.tif';
%LULCimPATHandName = 'd:\sat_data_center\jly2009\landuse_2005_pwgs84.tif';
%DEMimPATHandName = 'd:\sat_data_center\jly2009\p29r32_051905_dem_30m_wgs84_float.tif';
%SOILfcPATHandName = 'd:\sat_data_center\jly2009\fc_fraction_p29r32_30m.tif';
%SOILwpPATHandName = 'd:\sat_data_center\jly2009\wp_fraction_p29r32_30m.tif';
```

Input I

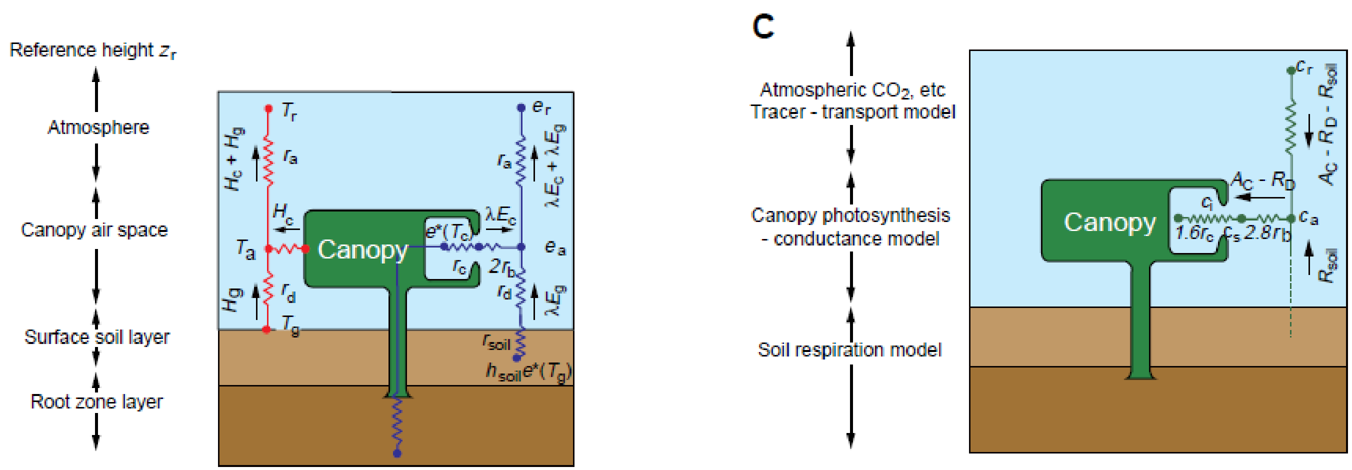
Input II

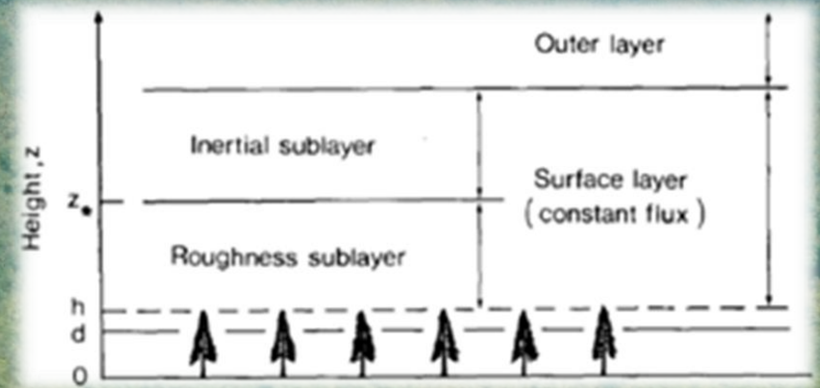
Input III

Input IV

References

1. P. J. Sellers et al, 1995, Science
2. John Norman et al, 1995, AFM
3. James Wallance, 1995, AFM
4. Shuttleworth and Wallace, 1985

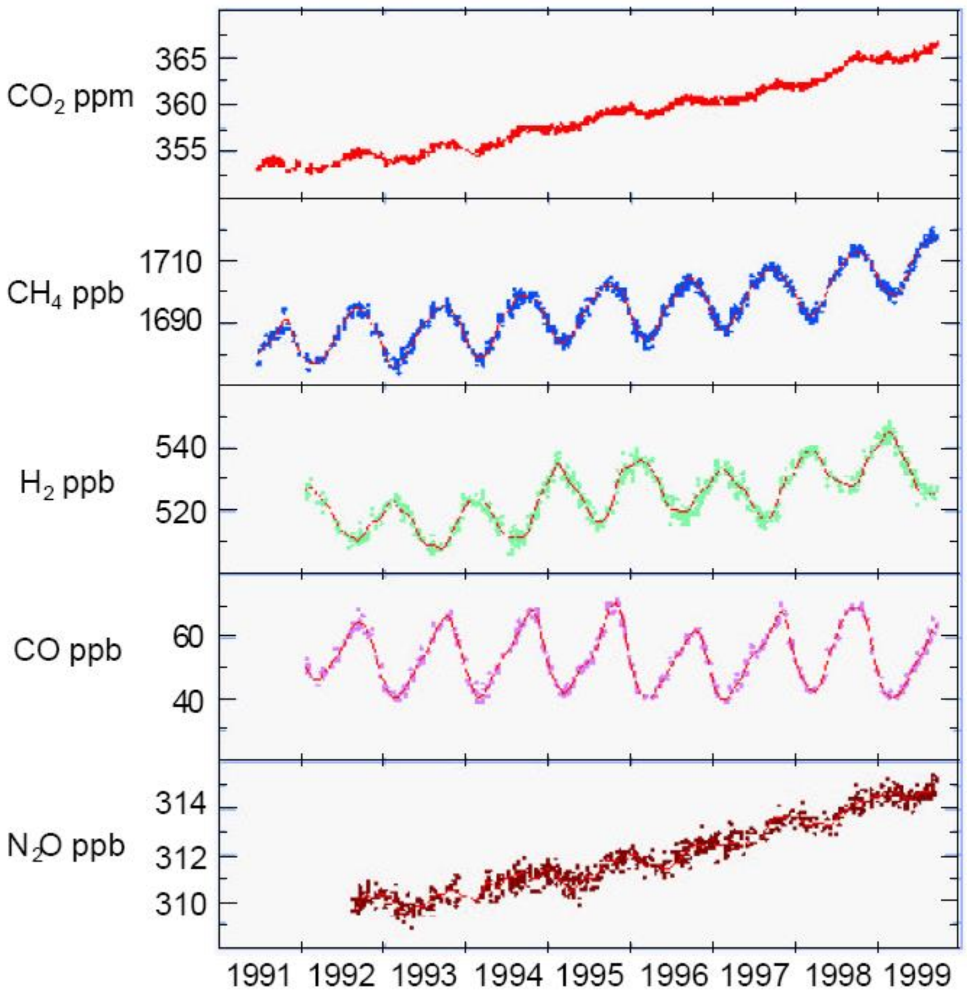




II: Uncertainties in Eddy Covariance Flux Estimate

1. Spatial Context of Flux vs. Sensor Heights
2. High Frequency Loss vs. Sensor Heights
3. Low frequency Loss vs. Sensor Heights.

Why EC Fluxes of Trace Gas are Important ?

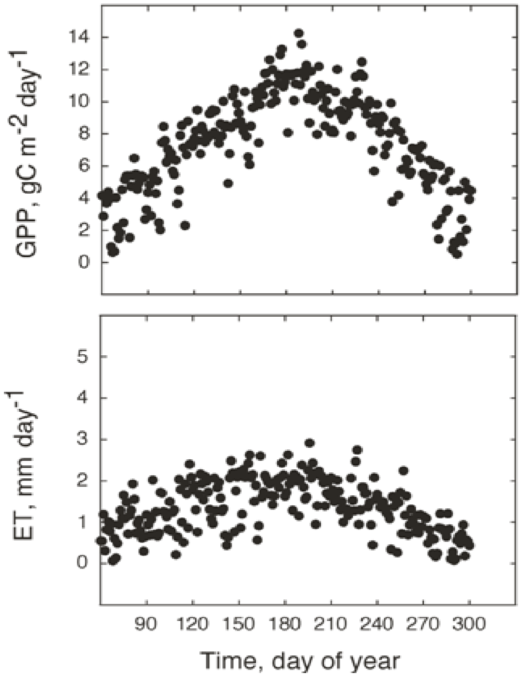


Eddy Covariance: From Measurements to Fluxes

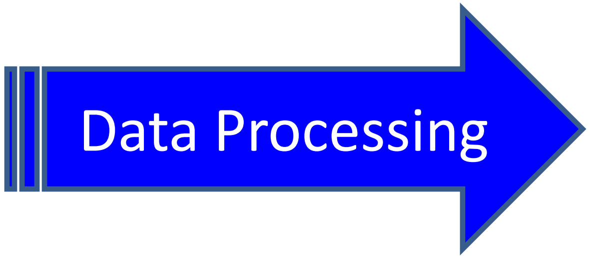
$$H = \rho\, c_p\, \overline{w'T'}$$

$$LE = \lambda\, \overline{w'q'}$$

$$F_c = \overline{w'c'}$$



- u v w, and T_{sonic}
- H_2O and CO_2 (IRGA)
- Pressure
- Mean T_a and RH_a
- Diagnostic Status



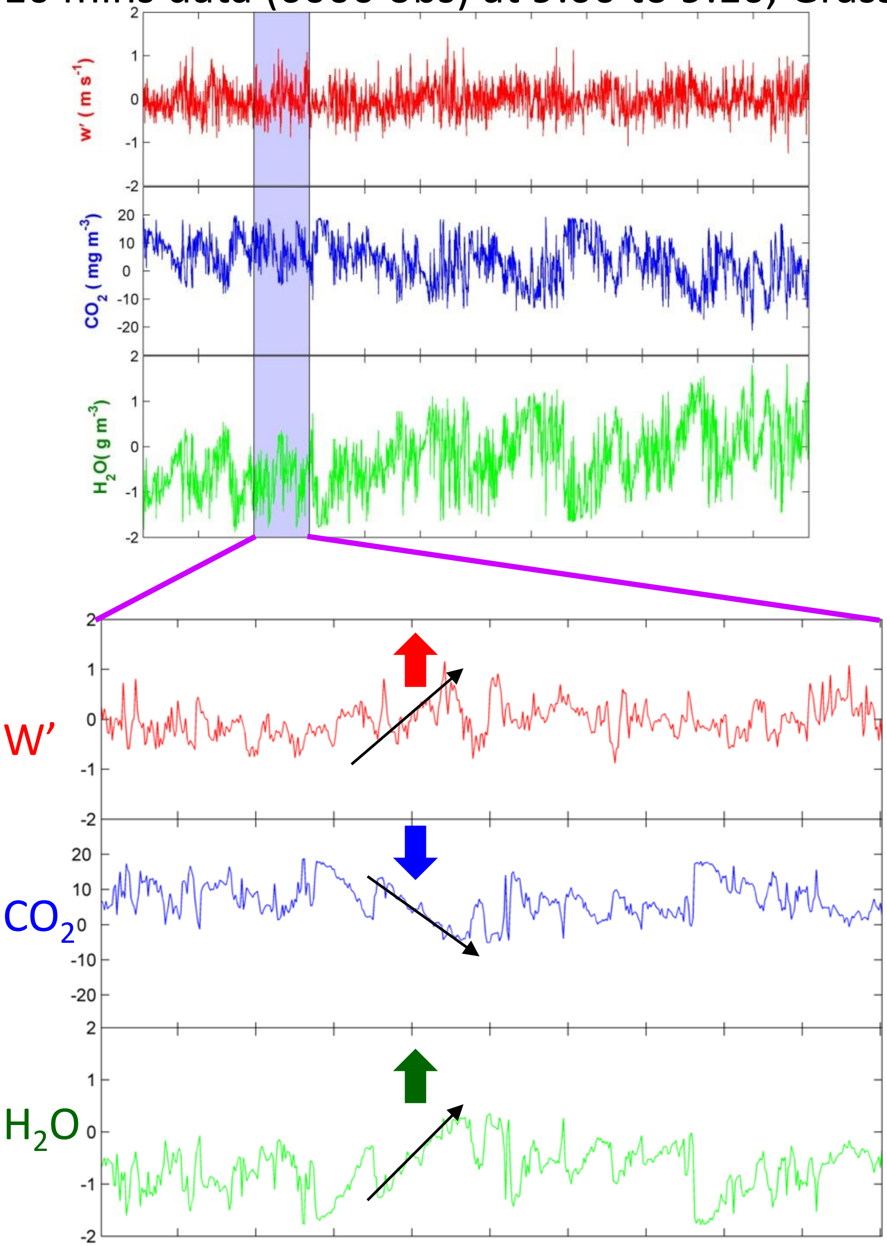
- Fc (carbon flux)
- LE (water flux)
- Hs (sensible heat flux)

Eddy Size (Limited Bandwidth)

10Hz ⟷ 0.000556 Hz (30 mins)

What is the Eddy Covariance in a simple way?

10 mins data (6000 obs) at 9:00 to 9:10, Grassland



$$Cov(w,c) = E[(w-\overline{w})(c-\overline{c})] = E[w'c']$$

```
>> CO2=cov(w,c)

CO2 =

    0.0952   -0.8467
   -0.8467   56.2482

>> H2O=cov(w,q)

H2O =

    0.0952    0.0742
    0.0742    0.4750
```

CO_2 Flux

Var. of w

Var. of CO_2

H_2O Flux

Var. of H_2O

So, we have

CO_2 Flux = -0.8467 m s^{-1} mg m^{-3}
= -0.8467 mg m^{-2} s^{-1}

H_2O Flux = 0.0742 m s^{-1} g m^{-3}
= 0.0742 g m^{-2} s^{-1}
= 176.4 W m^{-2}

The Juice of the Eddy Covariance

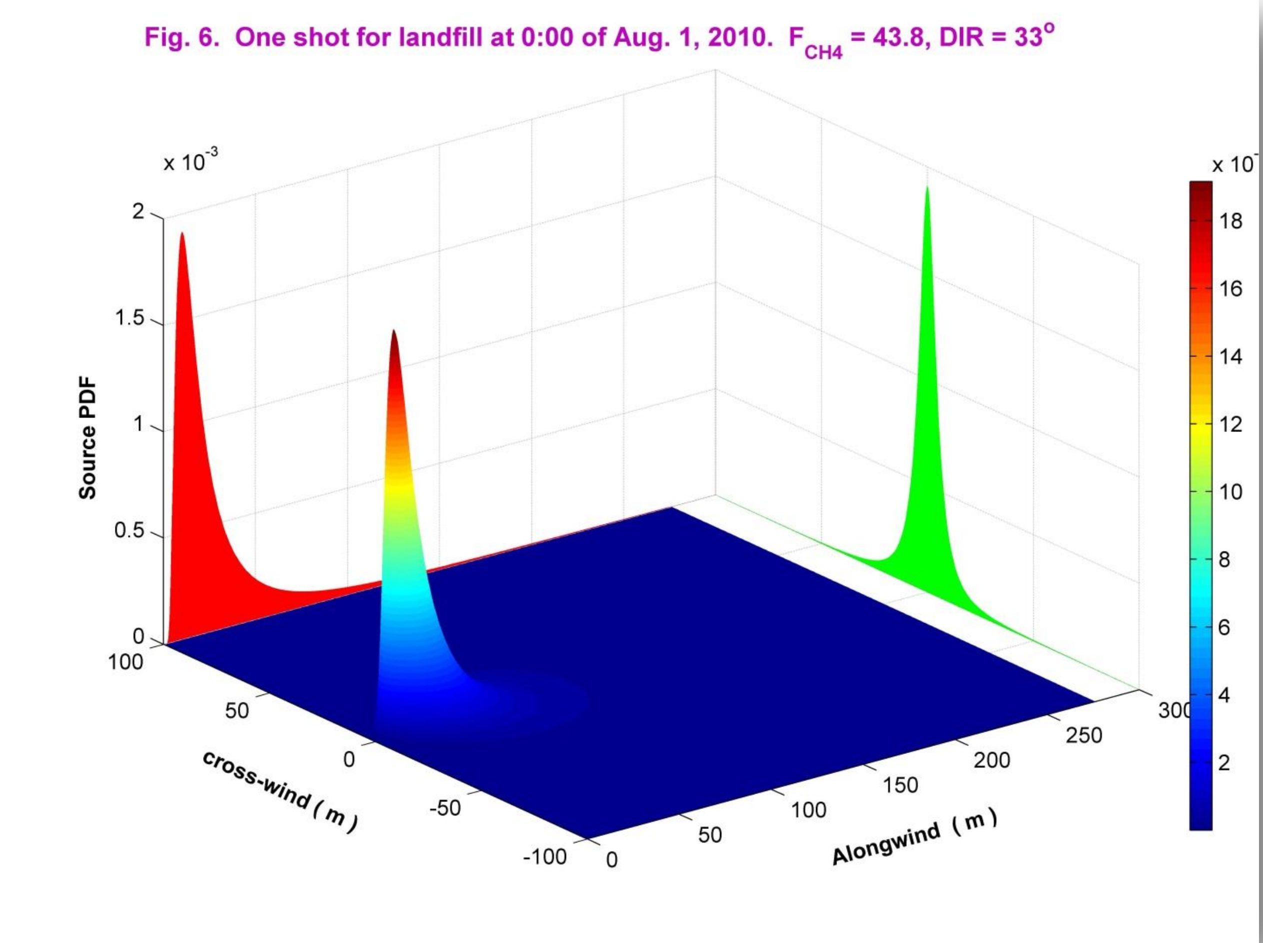
Start from mass conservation equation (CO2, or H2O) or Navier-Stokes equation, then, apply Reynolds decomposition and averaging, along with the turbulent continuity equation in the x-z planes, it will lead to:

$$\underbrace{F_v}_{Total\ Flux} - \underbrace{L_v \overline{w'\rho_v'}\Big|_{h_m}}_{F_v^{EC}:\ Eddy\ Cov.}$$

$$= \underbrace{\int_0^{h_m} L_v \frac{\partial \overline{\rho_v}}{\partial t} dz}_{F_v^{ST}:\ Storage} + \underbrace{\int_0^{h_m} L_v \left(\bar{u} \frac{\partial \overline{\rho_v}}{\partial \mathrm{x}} \right) dz}_{F_v^{HA}:\ Hori.\ Adv} + \underbrace{\int_0^{h_m} L_v \left(\bar{w} \frac{\partial \overline{\rho_v}}{\partial \mathrm{z}} \right) dz}_{F_v^{VA}:\ Vert.\ Adv}$$

An Example of Scalar Footprint Analysis

Footprint Context



Spectral Attenuation of Scalar Flux

$$\langle w'c' \rangle = \int_0^\infty Co_{wc}(f)df$$

$$\langle w'c' \rangle_m = \int_0^\infty H_c(f)Co_{wc}(f)df$$

Cospectrum model:

$$\frac{fCo_{wc}(f)}{\langle w'c' \rangle} = \frac{2}{\pi}\frac{f/f_m}{(1+(f/f_m)^{\mu})^{\alpha}}$$

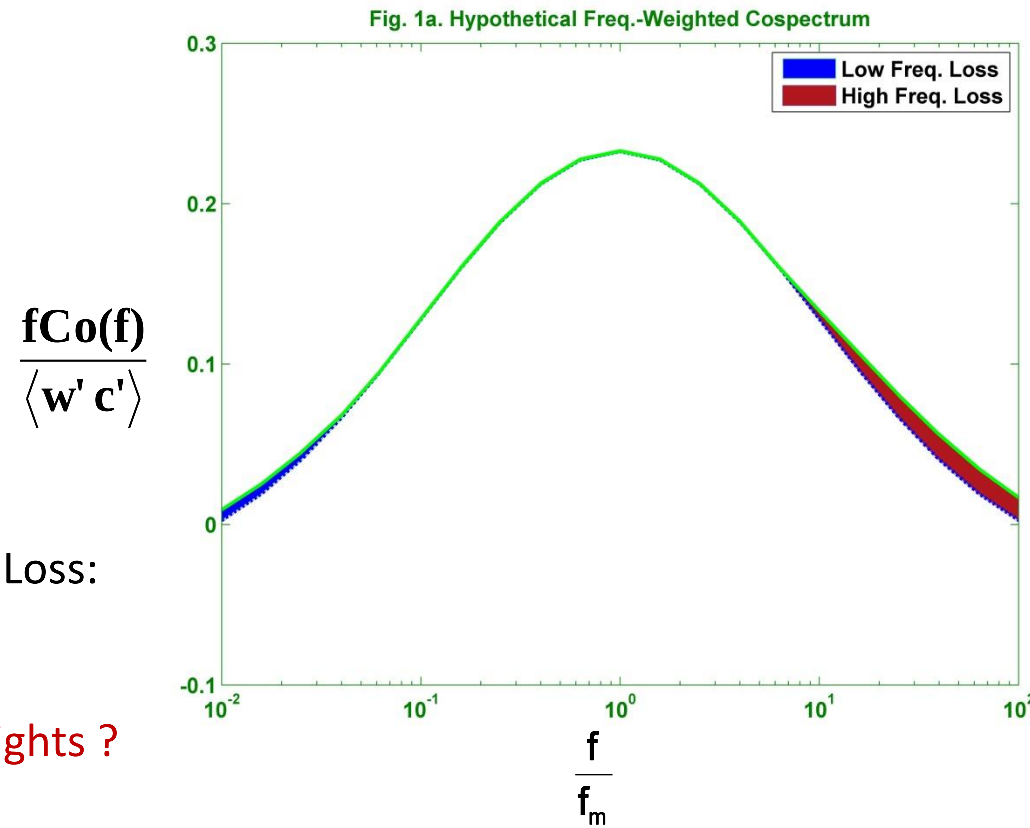
Spectral correction:

$$\frac{\langle w'c' \rangle_m}{\langle w'c' \rangle} = \underbrace{\frac{1}{1+(2\pi f_m \tau_c)^{\alpha}}}_{\text{I}} \underbrace{\frac{(2\pi f_m \tau_b)^{\alpha}}{1+(2\pi f_m \tau_b)^{\alpha}}}_{\text{II}}$$

I: a single-pole, low-pass RC filter for all path average, displacement, and other high-freq.

II: block average considered as a high-pass filter if assume the $\tau_b = T_B / 2.8$ (Kaimal, 1989).

Cospectra Models for EC Flux Corrections



Low Freq. Flux Loss:

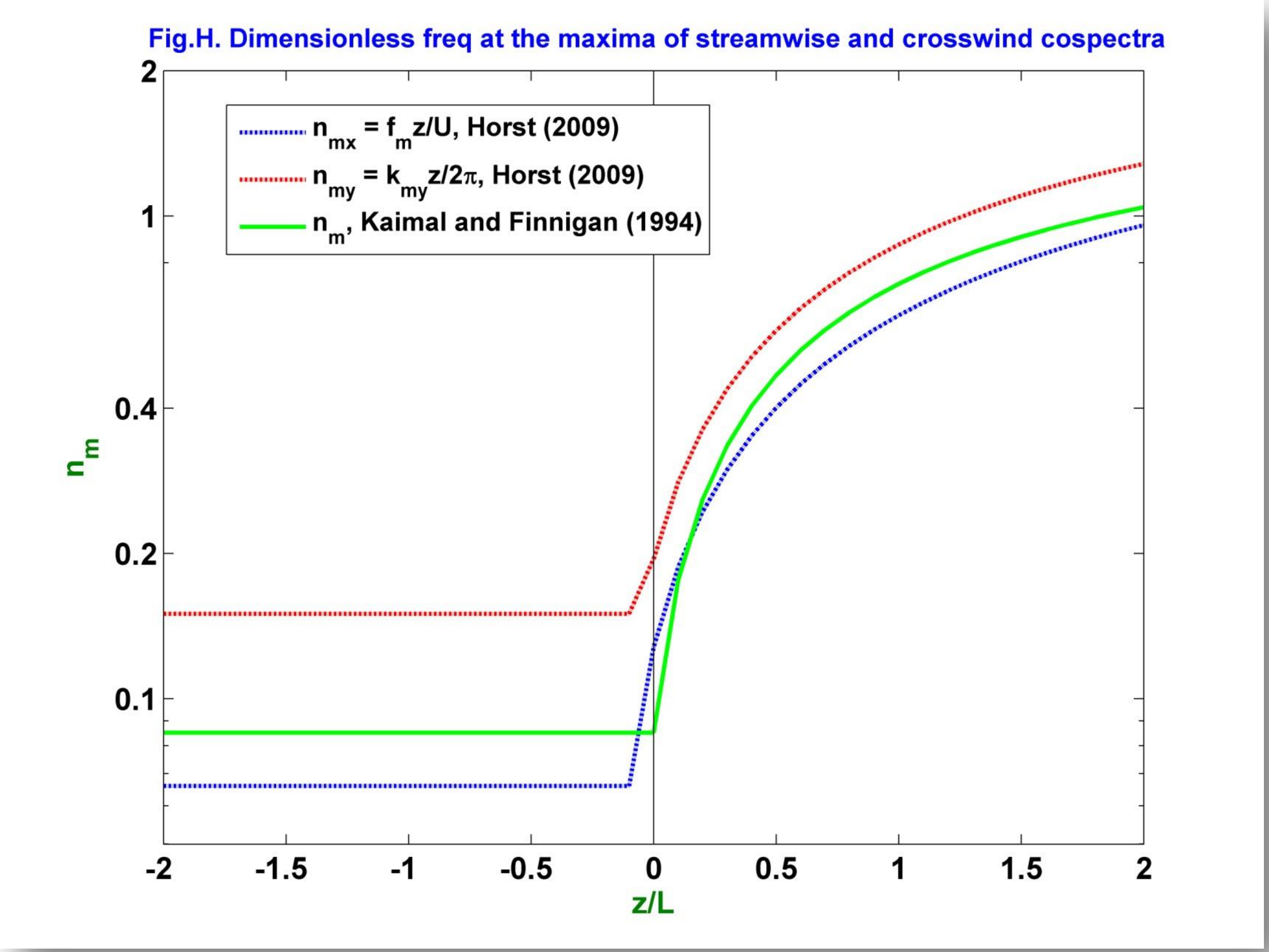
Block Average
30 mins vs. Heights ?

High Freq. Flux Loss:

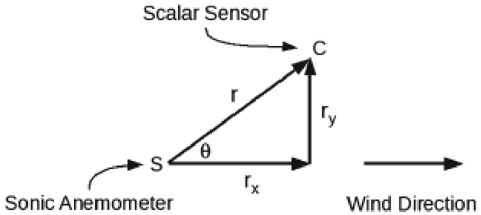
- Path average?
- Time Response?
- Tube attenuation (if CP)?

- Sensor Displacement?

A Key in Spectral Models: Maxima (f_m or n_m) of Cospectra



Sensor Displacement: High Freq. Flux Loss Vs. Heights

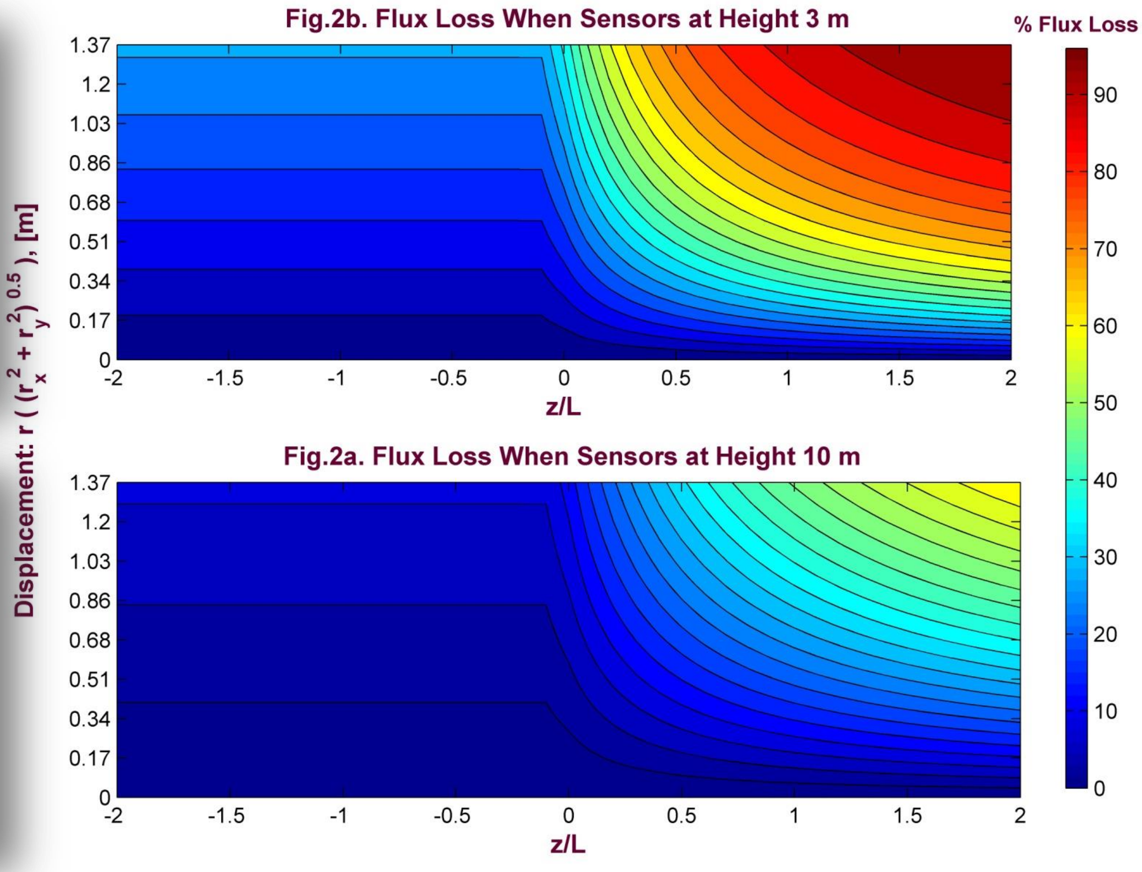


$$\frac{F(r_x, r_y)}{F_0} = \exp[-(\ln^2 Ax + \ln^2 Ay)^{1/2}]$$

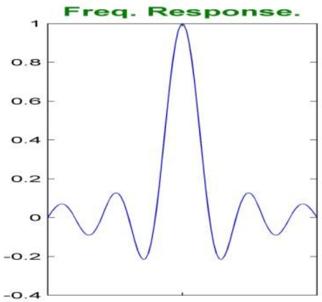
$$Ax = \exp(-\frac{2\pi}{z} n_{mx})$$

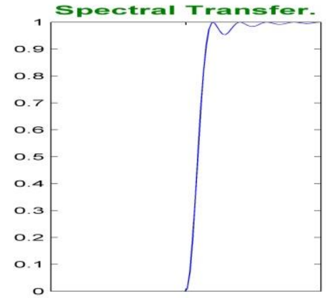
$$Ay = \exp(-\frac{2\pi}{z} n_{my})$$

- Horst and Lenschow, 2009. BLM



Block Average: Low Freq. Flux Loss vs. Heights



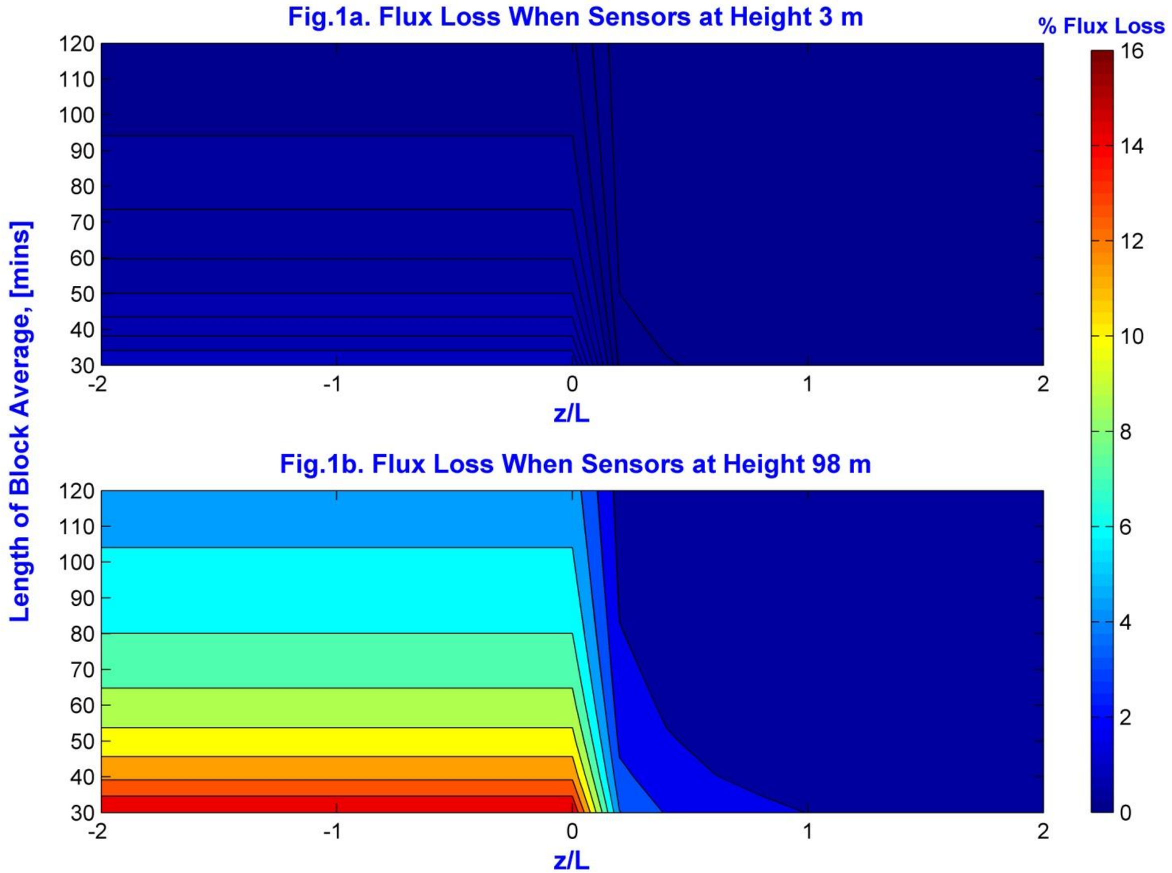


Approximate Model

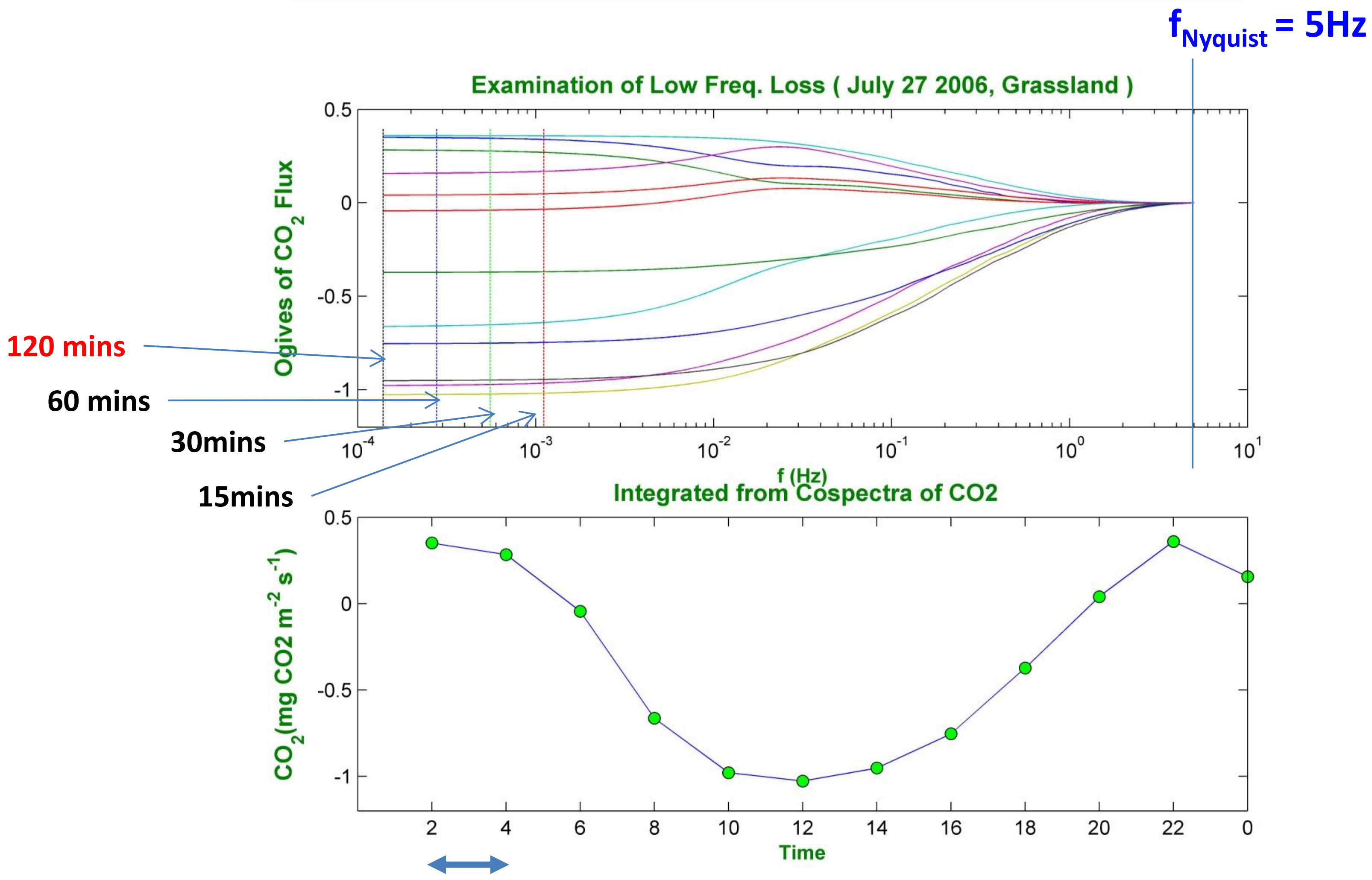
$$\frac{F}{F_0} = \frac{(2\pi n_m \tau_b \frac{u}{z_d})^{\alpha}}{1+(2\pi n_m \tau_b \frac{u}{z_d})^{\alpha}}$$

$$\tau_b = \frac{T_B}{2.8}$$

- Modified from Massman 2000 . AFM.

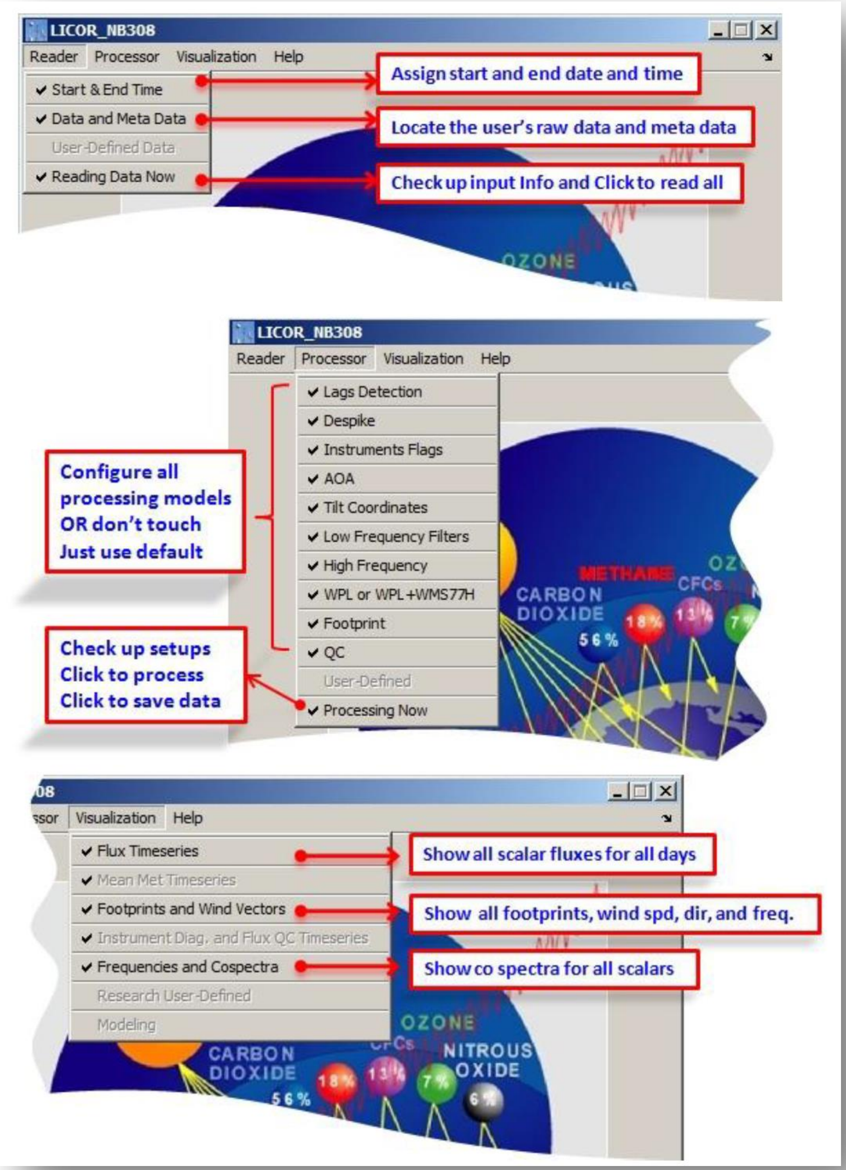


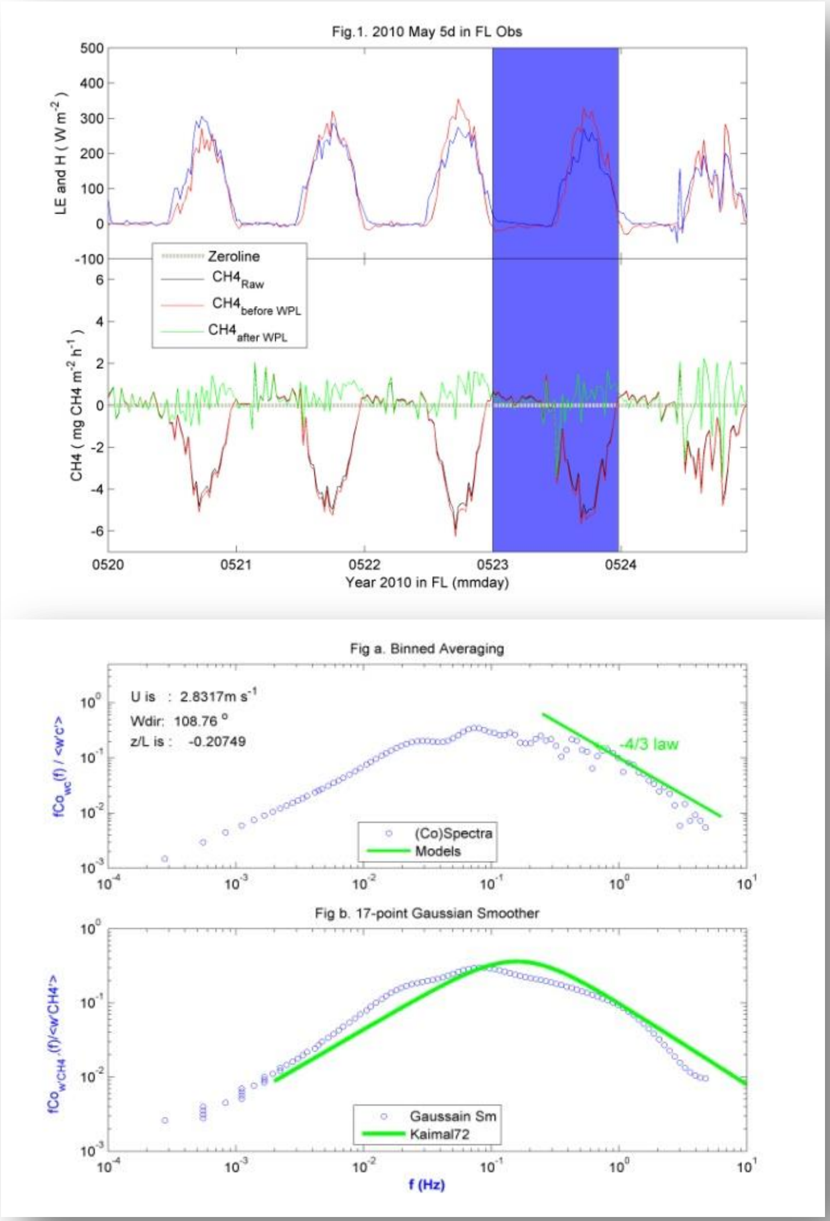
Visualization of Low Freq. Flux Loss



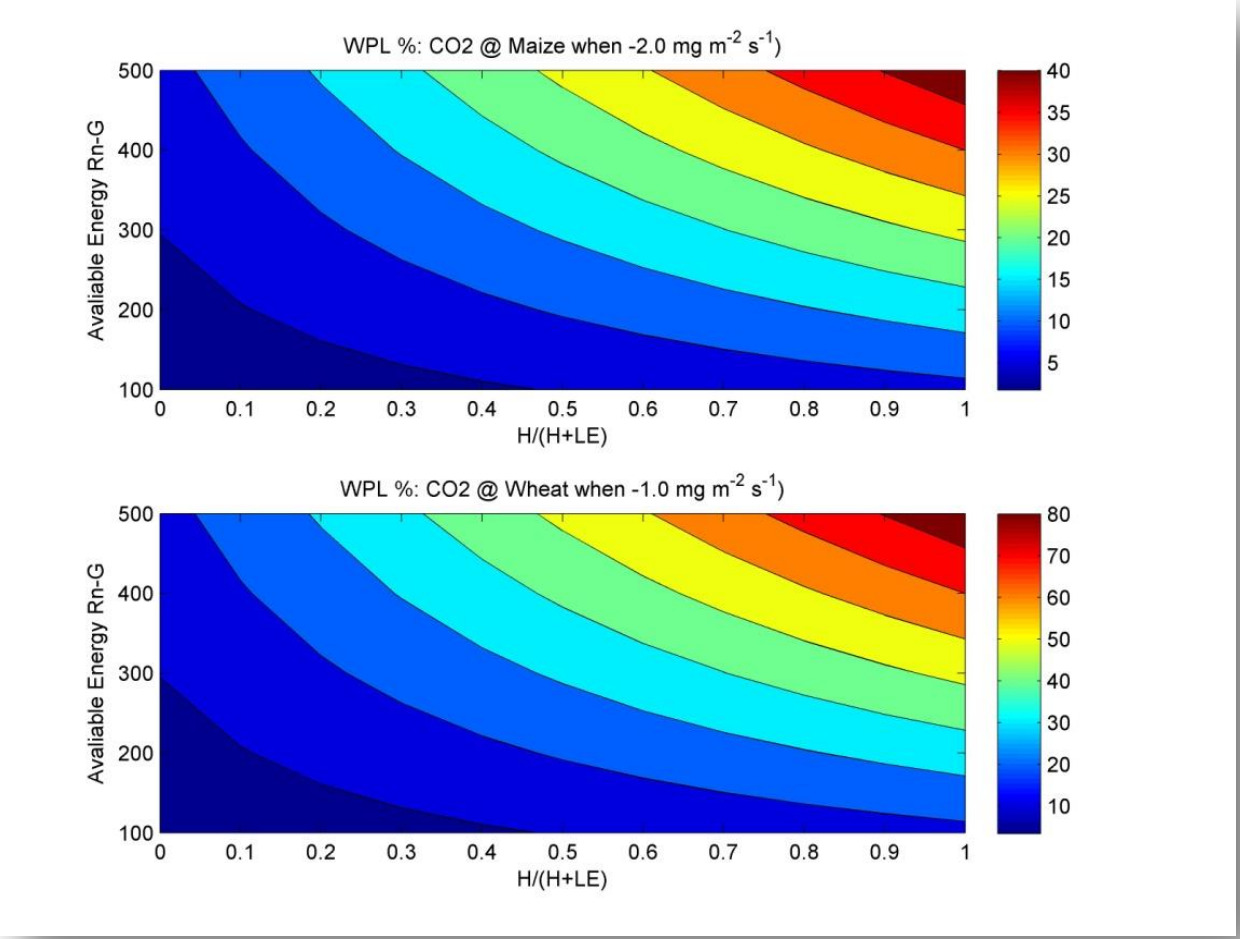
120 mins
=1.39×10^{-4} Hz

EC Software for Ecosystem Flux Computation, Analysis, and Visualization

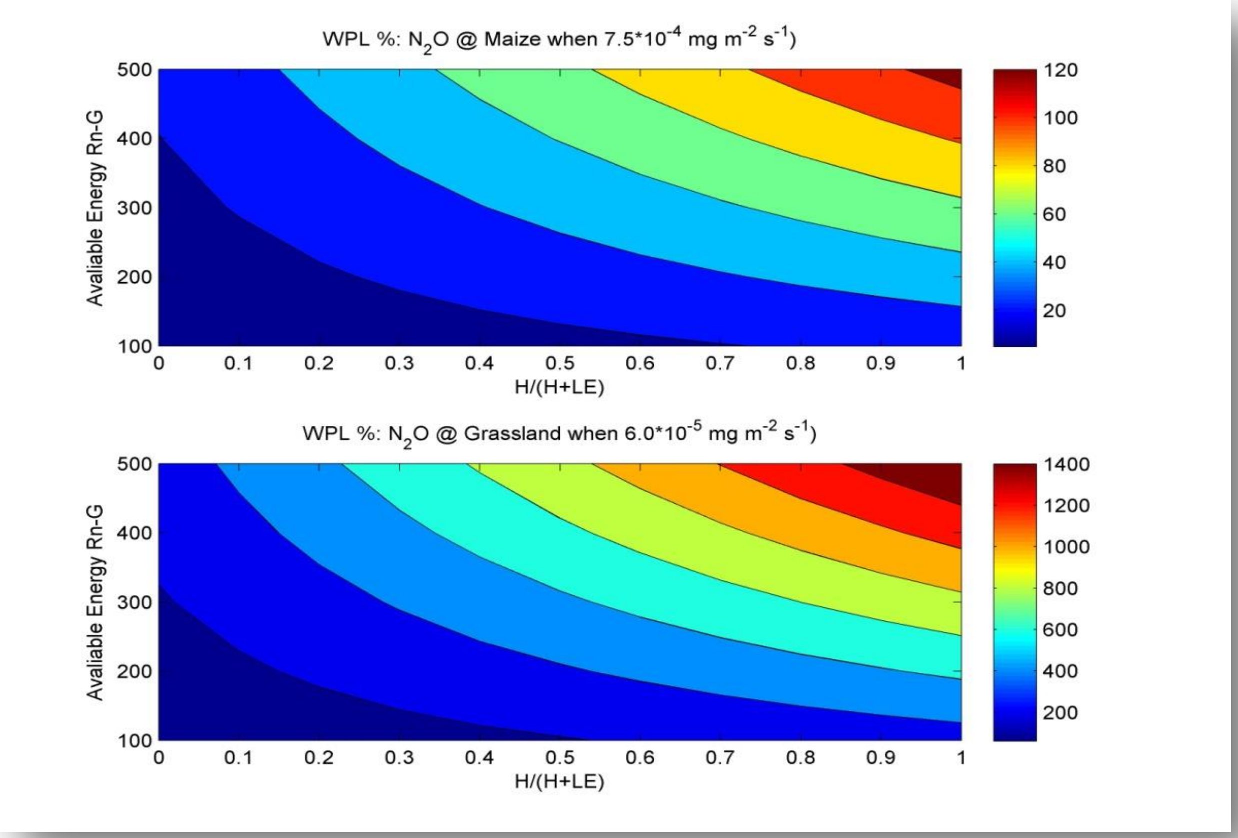




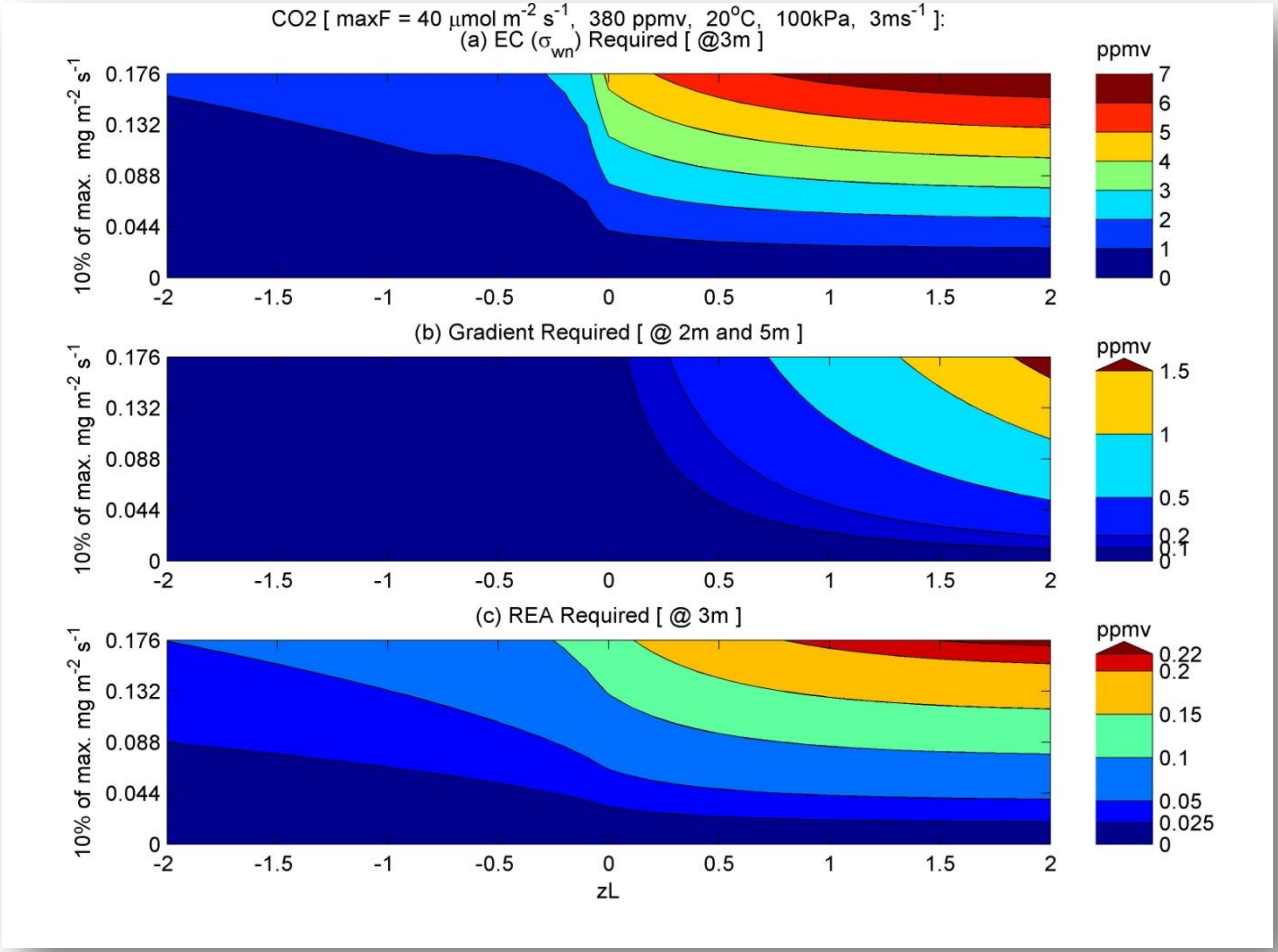
WPL for CO2 Flux



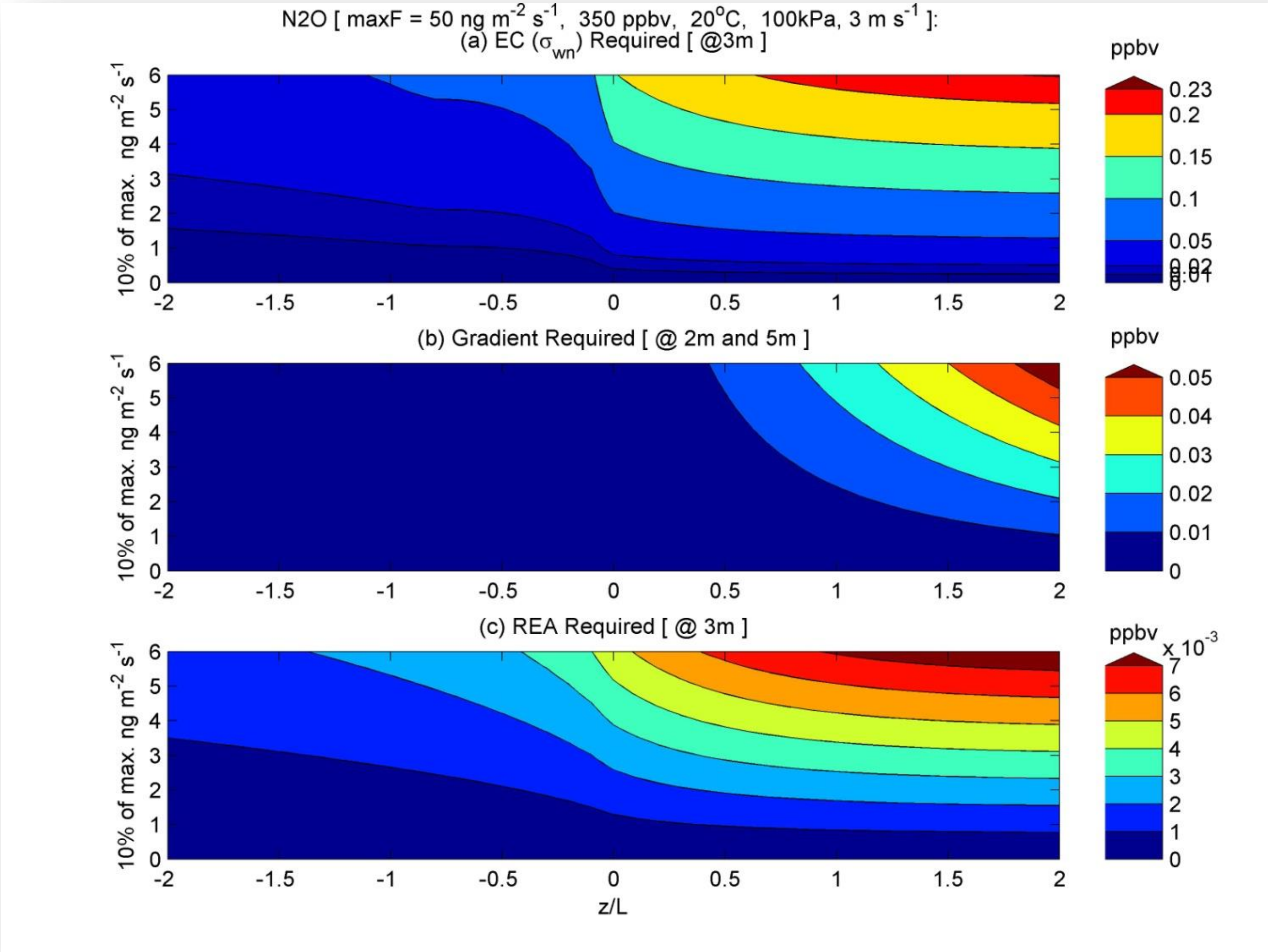
WPL for N2O Flux



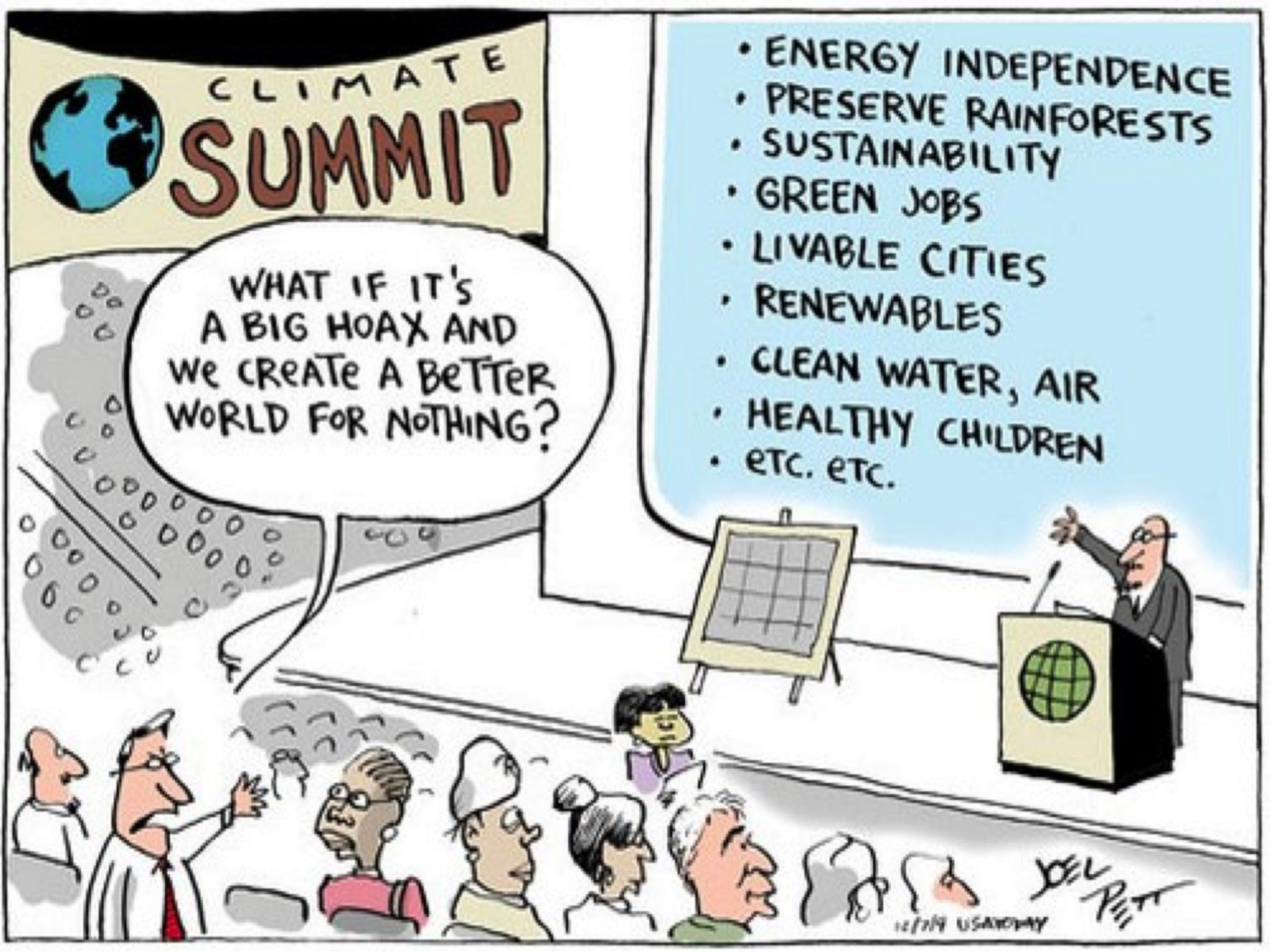
Analyzer's Requirement for CO2 Flux



Analyzer's Requirement for N2O Flux



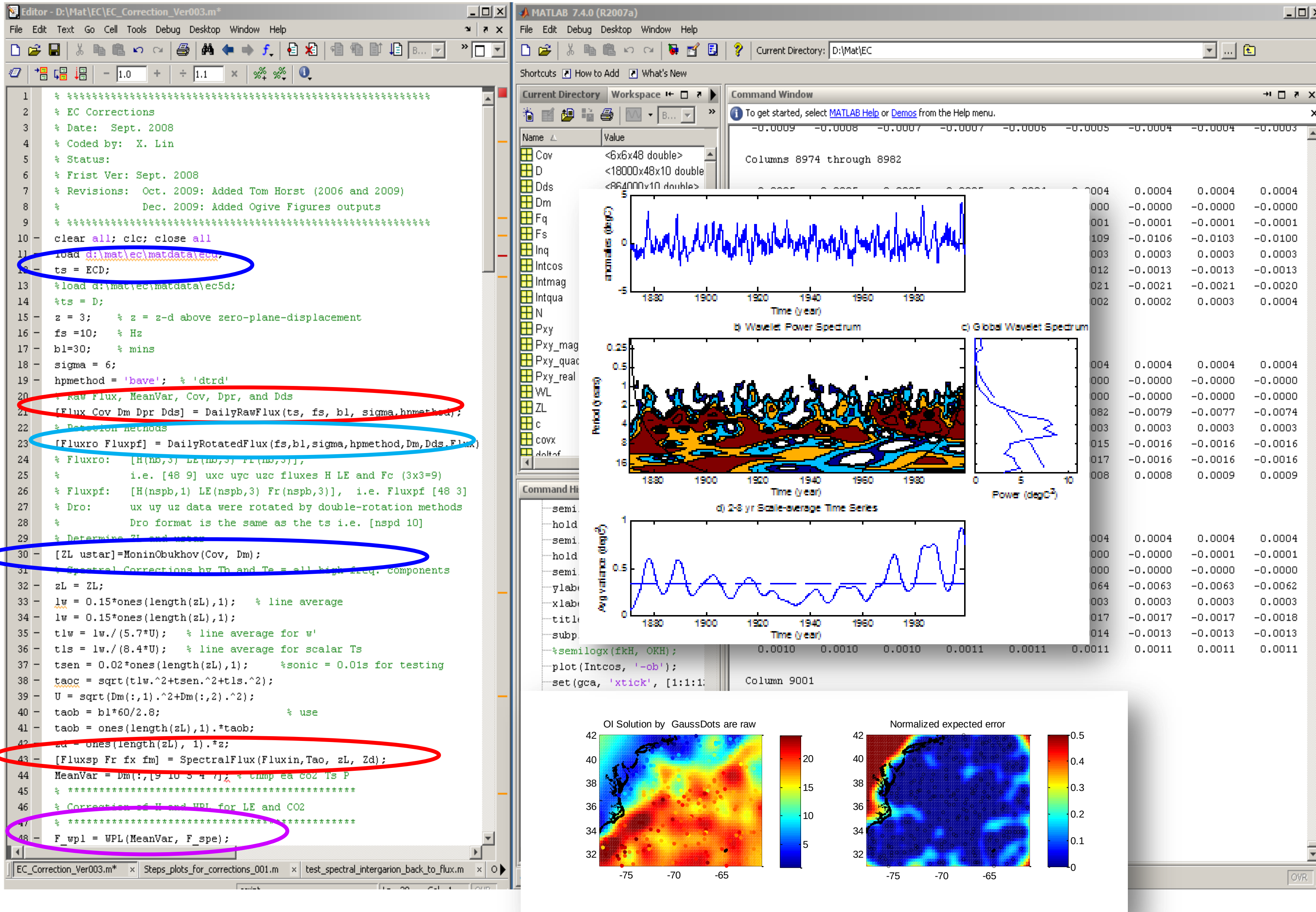
Recent Experiments from 2011 to 2013


CLIMATE SUMMIT
• ENERGY INDEPENDENCE
• PRESERVE RAINFORESTS
• SUSTAINABILITY
• GREEN JOBS
• LIVABLE CITIES
• RENEWABLES
• CLEAN WATER, AIR
• HEALTHY CHILDREN
• etc. etc.
WHAT IF IT'S A BIG HOAX AND WE CREATE A BETTER WORLD FOR NOTHING?
JOEL PETT
USA TODAY


The End


Enabling Technologies

Models Implemented and Improved: EC Corrections and Visualizations



How does Satellite Information do for ET ?

Satellite-Based Land Surface Energy Balance:

--- Thermal images provide T_R Information.

--- Visible and infrared images are used for calculating:

- Spectral radiances,
- Spectral reflectance and transmittance,
- NDVI, LAI, albedo, biomass, and
- Other biophysical variables.

Sensible Heat Flux:

$$H = \rho C_p \frac{T_{AC} - T_A}{R_A}$$

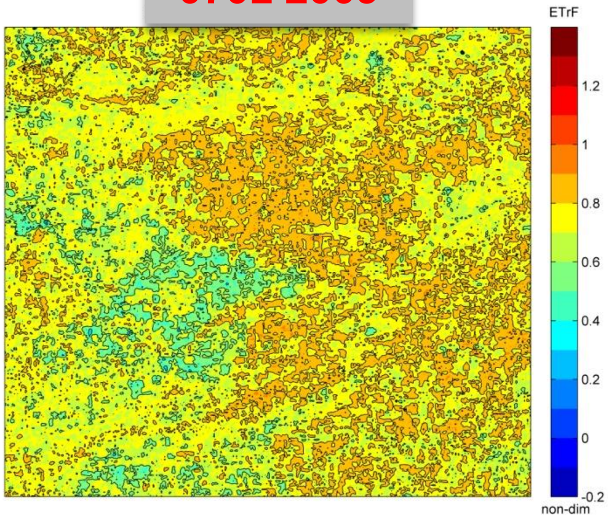
Aerodynamic and Radiometric Temperatures:

$$T_{AC} \propto T_R$$

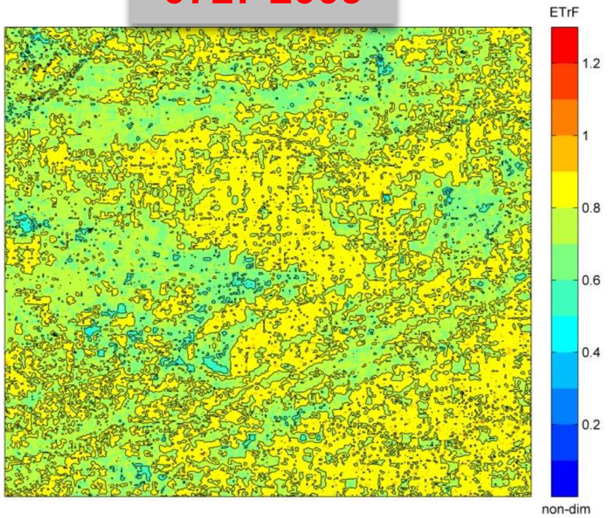
Fraction of Reference ET (ETrF)

$$\mathbf{ETrF} = \frac{\mathbf{ET_{INST}}}{\mathbf{ETr}}$$

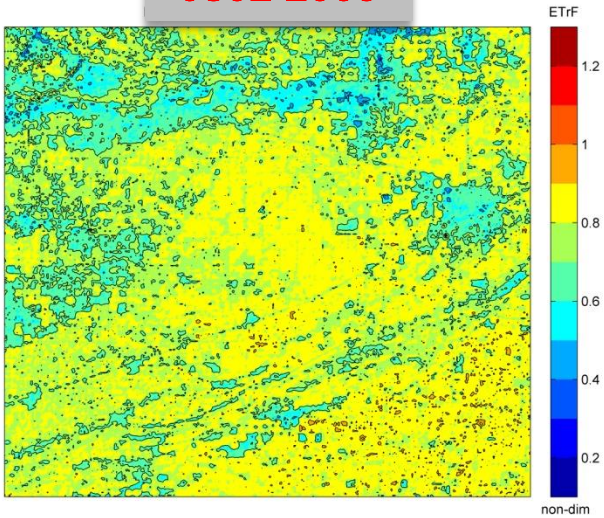
0701 2009



0717 2009

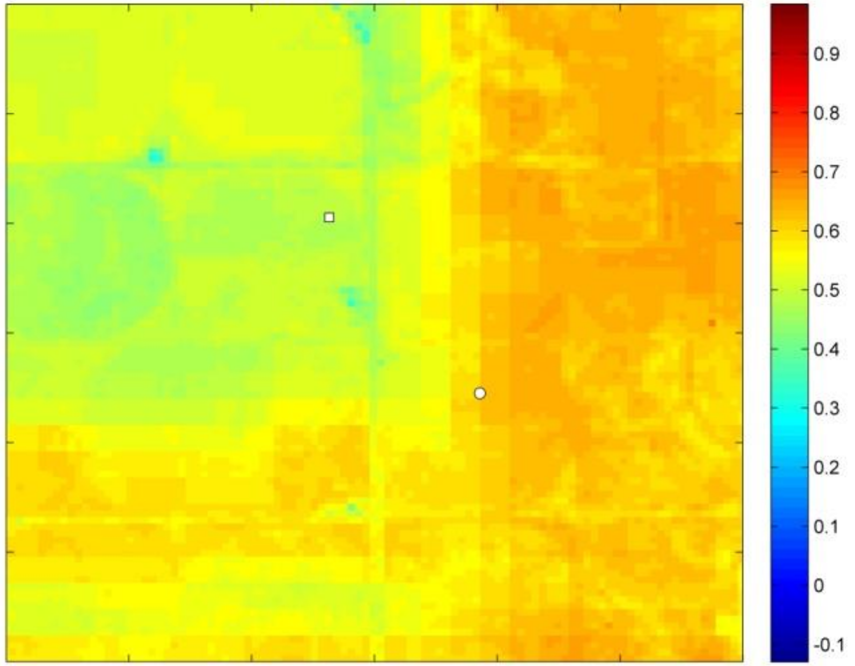


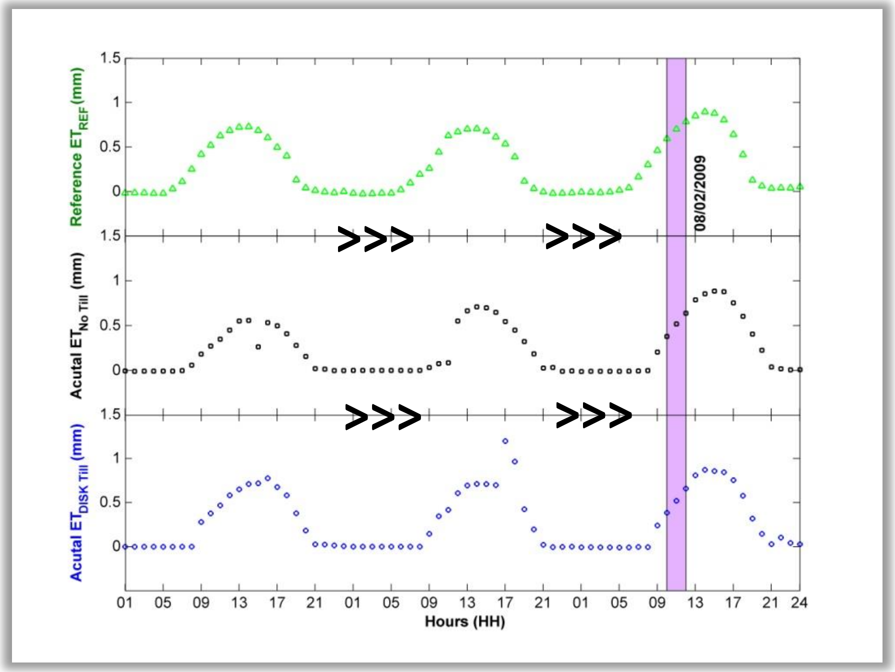
0802 2009



Hourly ET

[08 02 2009]





Modeled ET at Corn Fields

Observed ETr , $ET_{NO\ Till}$, $ET_{DISK\ Till}$

Key Parameterization

$$R_{EX} = \left[\sum_{i=1}^{6} a_i LAI^i\right] u_*^{-1}$$

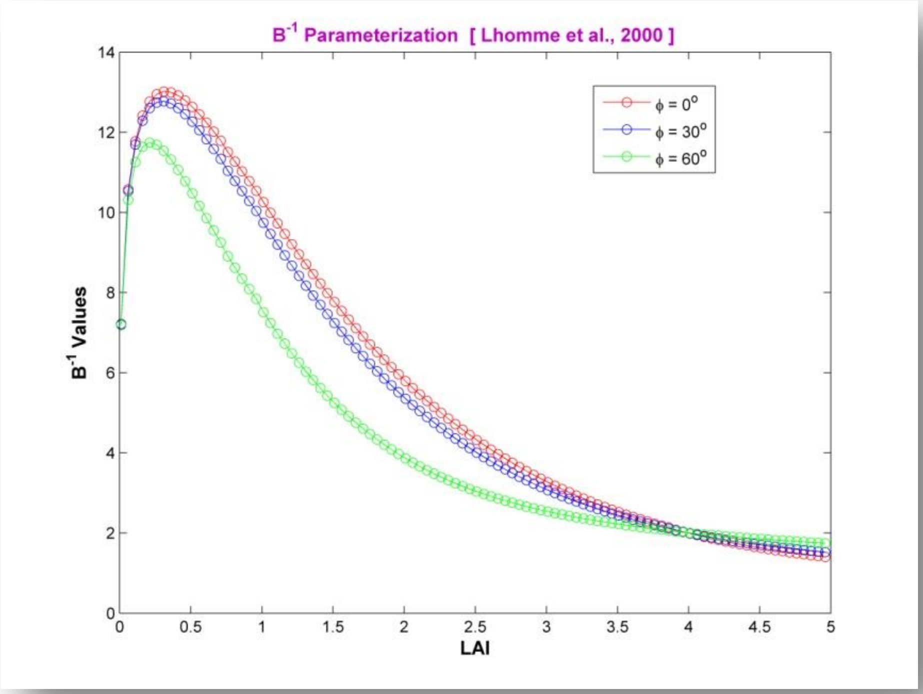
For major crop lands:

$$z_{OM} = \frac{h_c - d}{\exp\left(\frac{k u_{h_c}}{u_*} - \psi_H\right)}$$

$$z_{OH} = \frac{z_{OM}}{\exp\left(kB^{-1}\right)}$$

For non crop lands:

$$z_{OM} = \exp[a_1 NDVI + b_1]$$

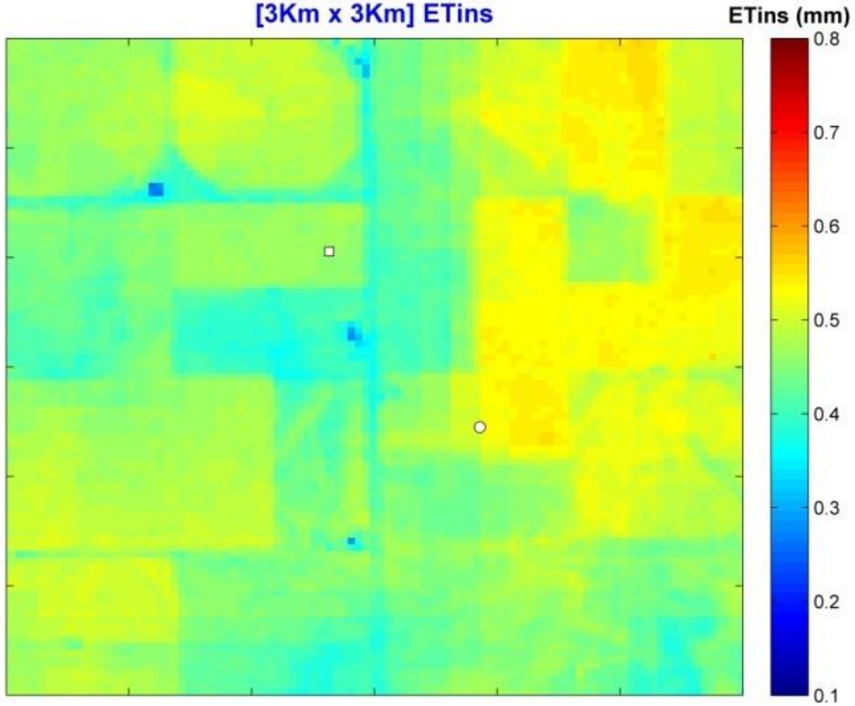


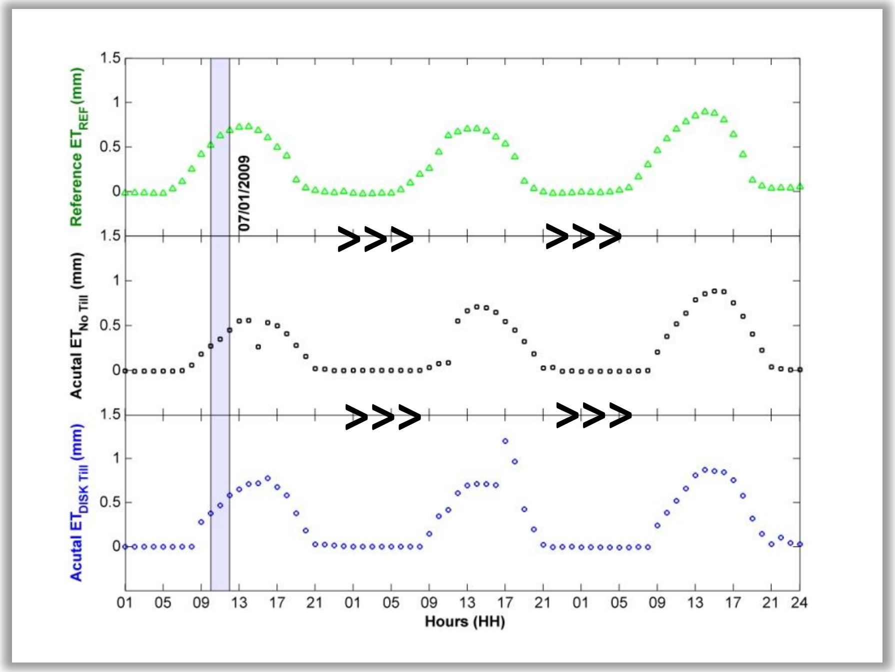
Lhomme et al. 2000

ϕ = 0 for Landsat TM sensors

Hourly ET

[07 01 2009]



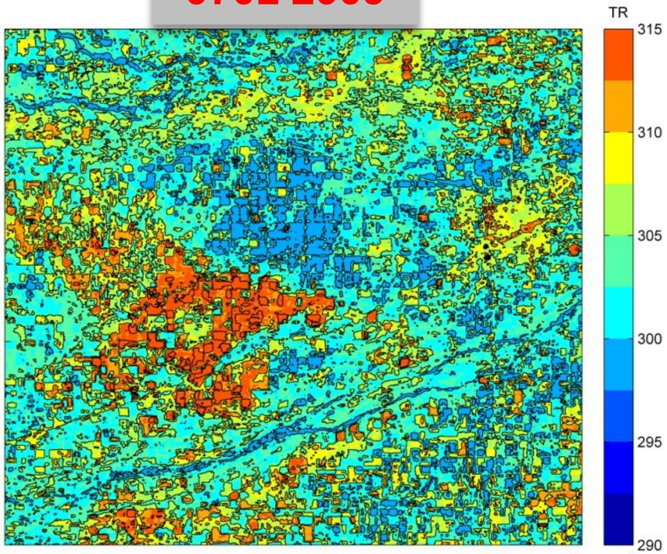


Modeled ET at Corn Fields

Observed ETr , $ET_{NO\ Till}$, $ET_{DISK\ Till}$

Scalar Outputs: T_R

0701 2009



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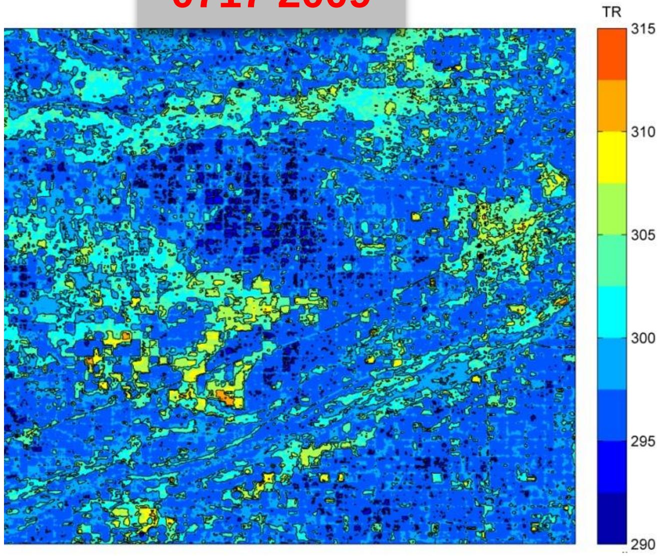
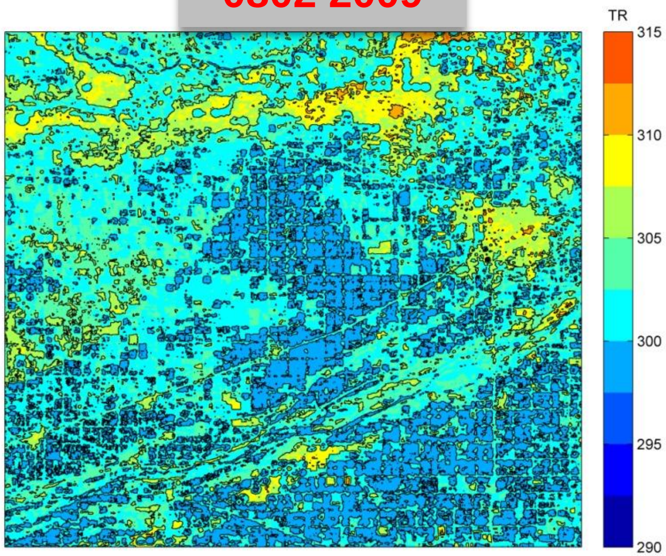
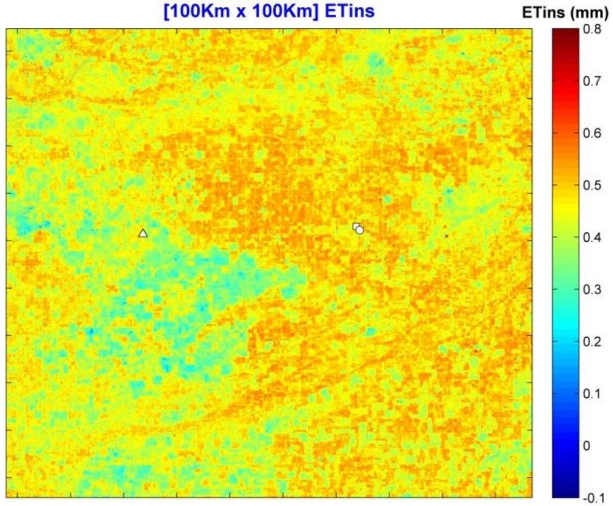


0802 2009

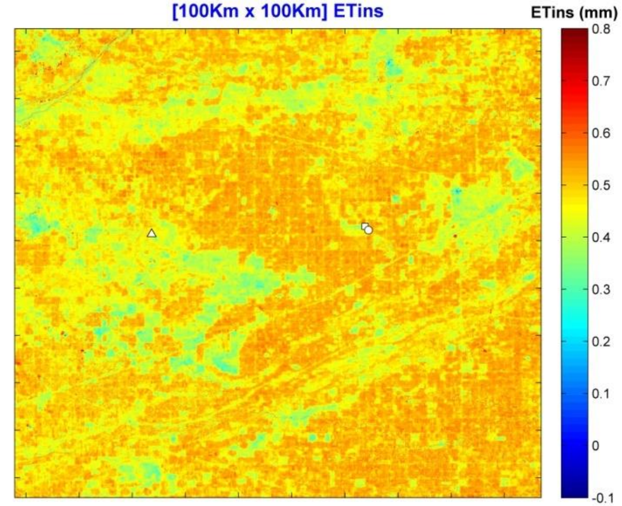


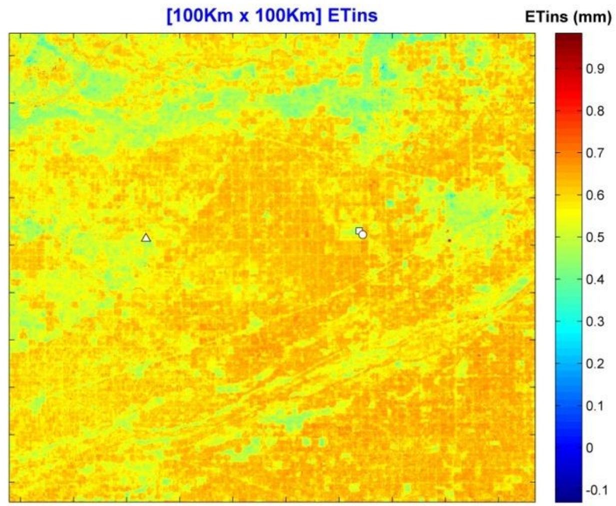
Midday Instantaneous ET as an Average of Daily ET

July 01 2009



July 17 2009

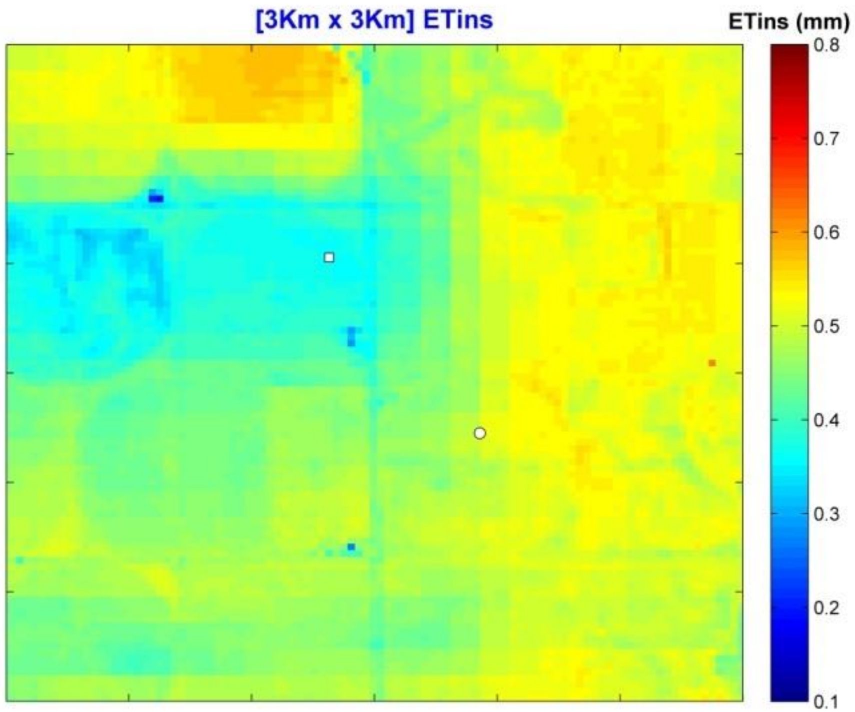


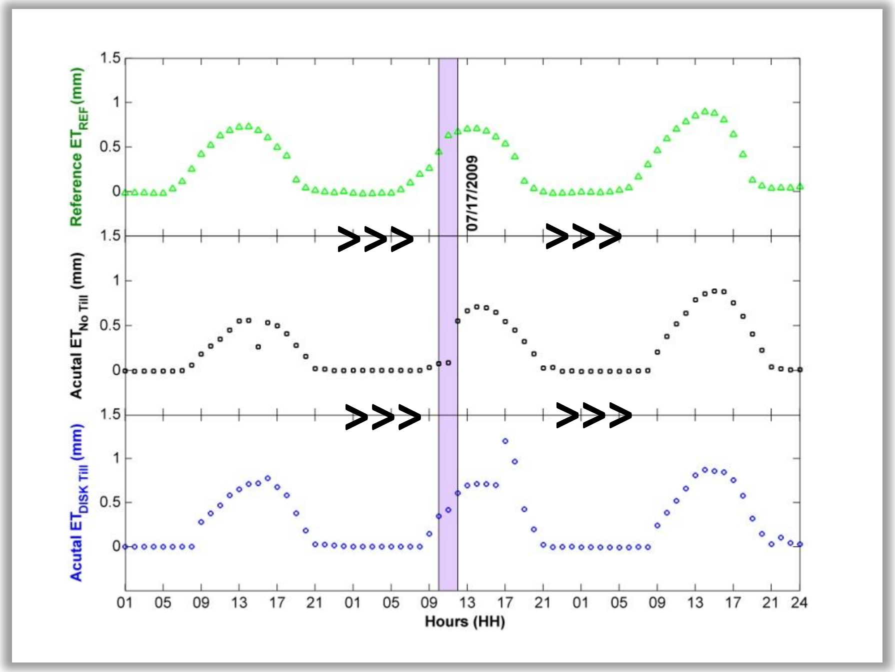


Aug. 02 2009

Hourly ET

[07 17 2009]



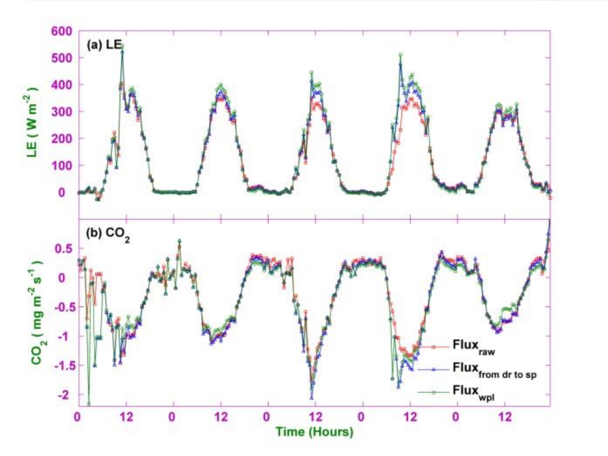


Modeled ET at Corn Fields

Observed ETr , $ET_{NO\ Till}$, $ET_{DISK\ Till}$

Uncertainty in EC Fluxes

raw: after despike (outlier removed).
dr: Double rotations (v_bar and w_bar = 0).
pf: Planar-fit method for rotation (5d).
spectral: low and high freq. loss.
wpl: Web correction (H and LE)
H_{le} : Corrected H only by the LE.



Aug. 1-5, 2006. Grassland