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Aircraft Flux during FIFE and BOREAS

R. Desjardins, I. MacPherson, P. Schuepp, D. Worth, E. Pattey et al.

Canada

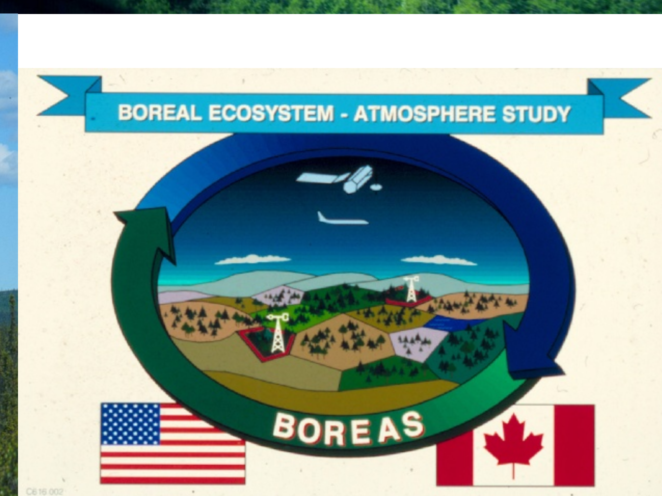
Co-investigators

B. Amiro, D. Baldocchi, A. Barr, M. Bastian, A. Betts, P. Caramori, T. Crawford, J. Chen, J. Cihlar, G. den Hartog, R. Dobosy, E. Eloranta, D. Fitzgerald, R. Grossman, F. Hall, R. Hart, D. Joiner, S. Kaharabata, R. Kelly, M. Leclerc, L. Mahrt, D. Manak, M. Mauder, S. Metzger, H. McCaughey, C. Mitic, H. Neumann, S. Ogunjemiyo, P. Sellers, R. Srinivasan, J. Sun, S. Verma, M. Wesely, S. Wofsy, et al.

FIFE and BOREAS

FIFE 1987-89

BOREAS 1994-96



Flight patterns during FIFE

AC/AC inter comparisons	10
L & T patterns- 2 to 4 levels	109
Budget studies (double stacks)	3
Grid flights 100 m (16 lines)	12
Night flight (100 m)	1
Regional run altitude 150m (77 km)	47
Lidar inter comparisons	8
Soundings	62

Aircraft intercomparison

Comparison of aircraft EC flux measuring systems

Heat Fluxes

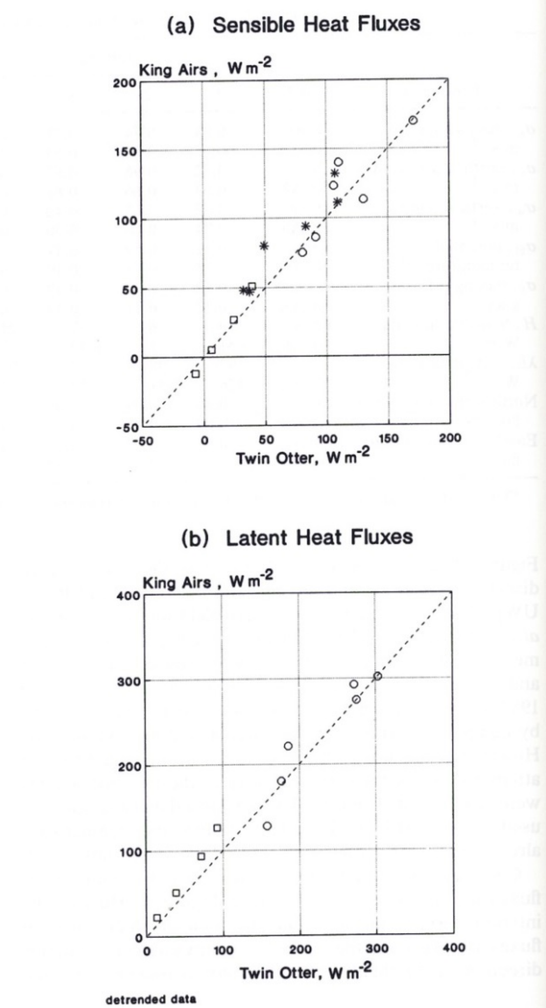


Fig. 4. Comparison of fluxes from detrended data: (*a*) sensible heat fluxes and (*b*) latent heat fluxes. NCAR 1987 is shown by squares, NCAR 1989 by circles, and the University of Wyoming 1987 by asterisks. The dashed line indicates the 1:1 ratio.

In 1989, the agreement between the flux measurements of sensible and latent heat and carbon dioxide by the various aircraft was excellent.

Cospectra

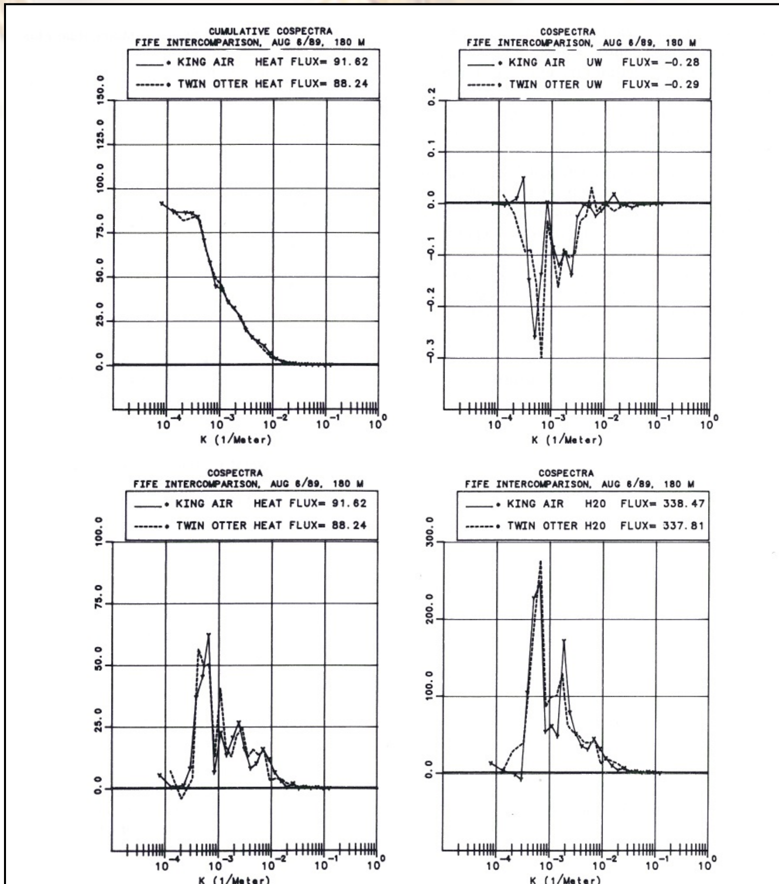


Fig. 7*a*. Cospectra from NCAR King Air (solid curve) and NRC Twin Otter (dashed curve) for 15-km run over FIFE site on August 6, 1989, at 180 m. Sensible heat (bottom left panel), latent heat (bottom right panel), and momentum (top right panel) fluxes as well as cumulative cospectrum for sensible heat flux (top left panel) are shown.

Comparison of flux measurements from aircraft L and T flight patterns and tower-based systems during FIFE

Sensible Heat flux

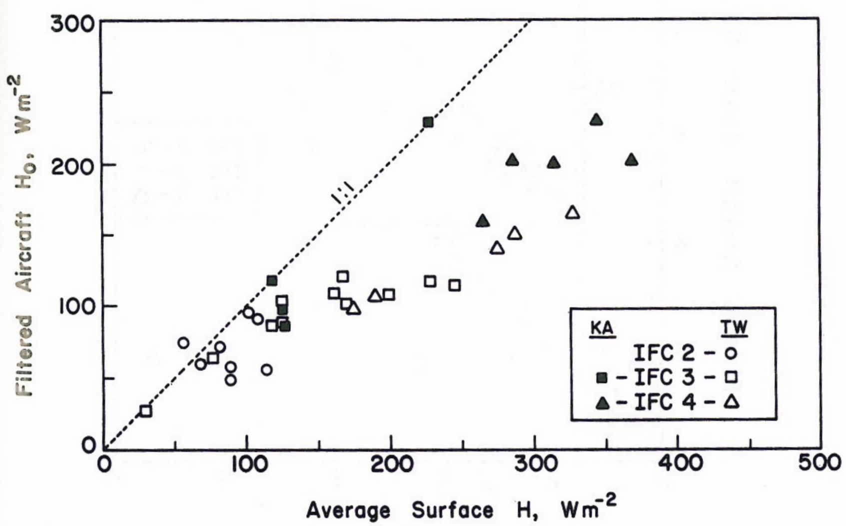


Fig. 6. Same as Figure 5, for aircraft sensible fluxes from filtered data versus surface average fluxes.

Latent Heat flux

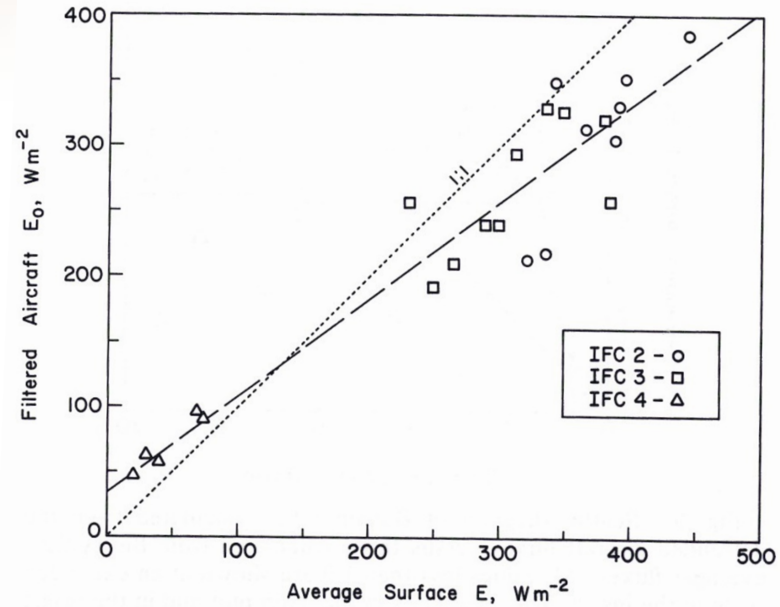
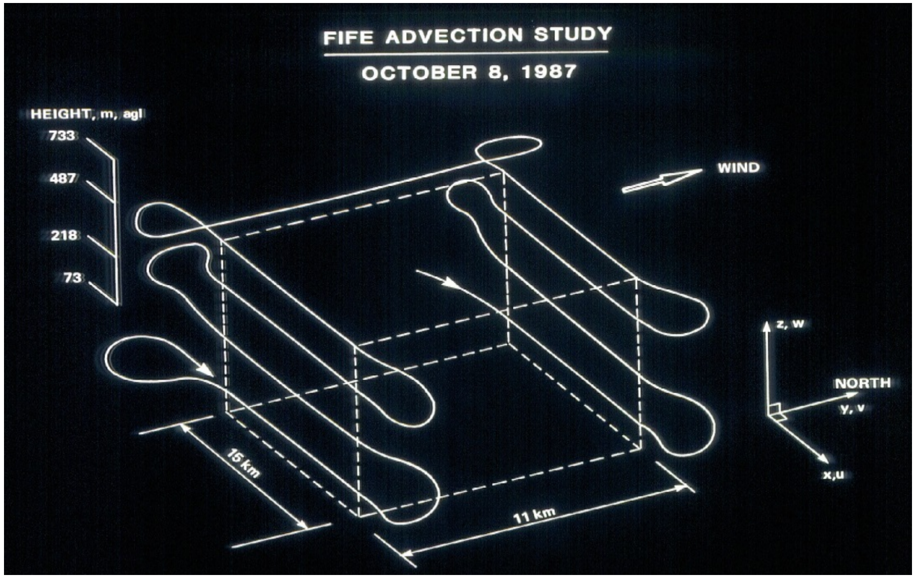


Fig. 8. Same as Figure 5, for aircraft latent heat fluxes from filtered data versus surface average fluxes.

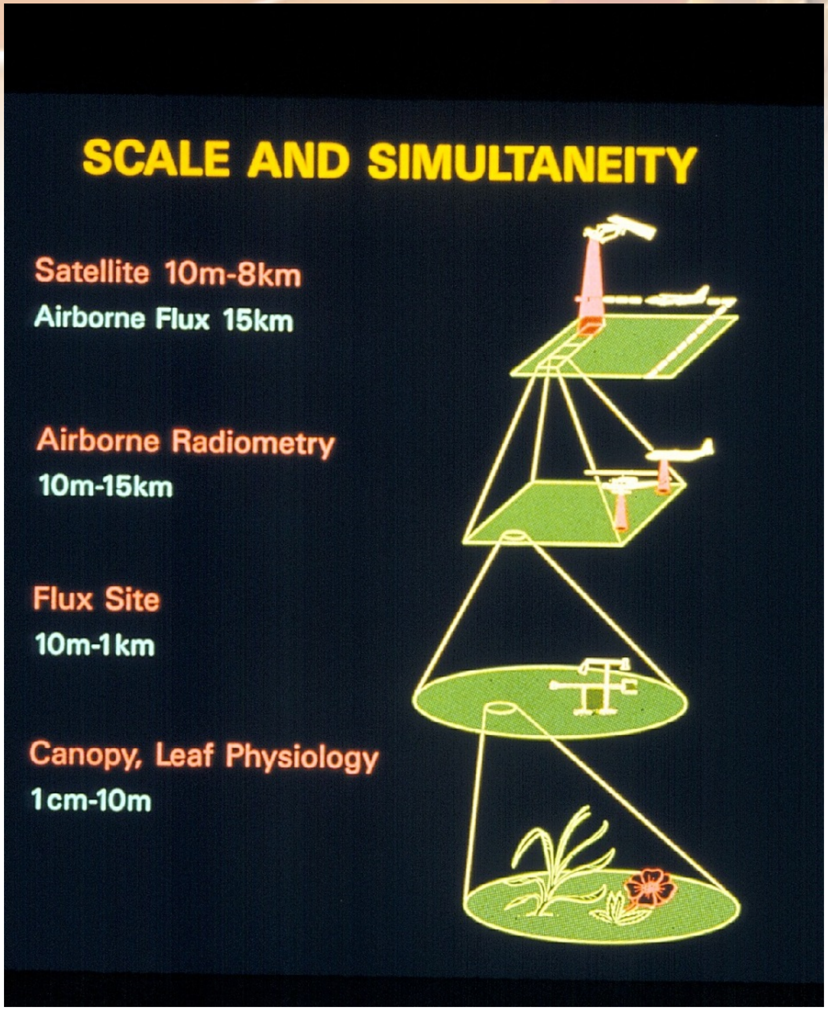
The sum of sensible and latent heat fluxes from the aircraft-based systems were smaller than from the tower-based flux systems because of flux divergence with height (100m), short transects (15 km) and high-pass filtering (5 km) of the data.

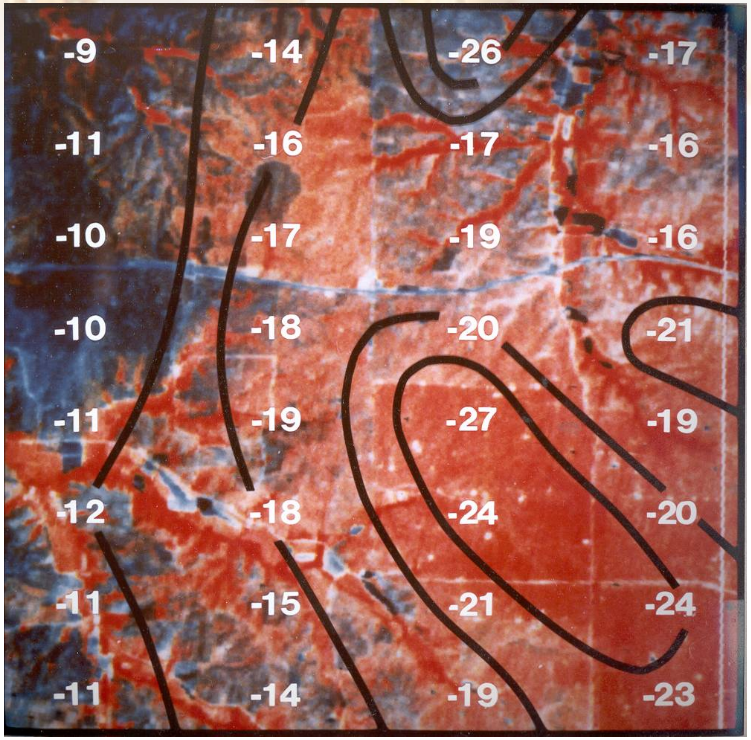
Budget studies

Based on a budget study during FIFE, Betts et al. (1992) found flux underestimations of about 20% using aircraft-based flux measurements. They concluded that high-pass filtering of the data at 5 km and the relatively short runs of about 15 km were the main reasons for the difference. The total flux of a scalar includes a storage term, flux divergence and advection.



CO_2 fluxes measured on July 28 during FIFE using the Canadian Twin Otter (block averaging)

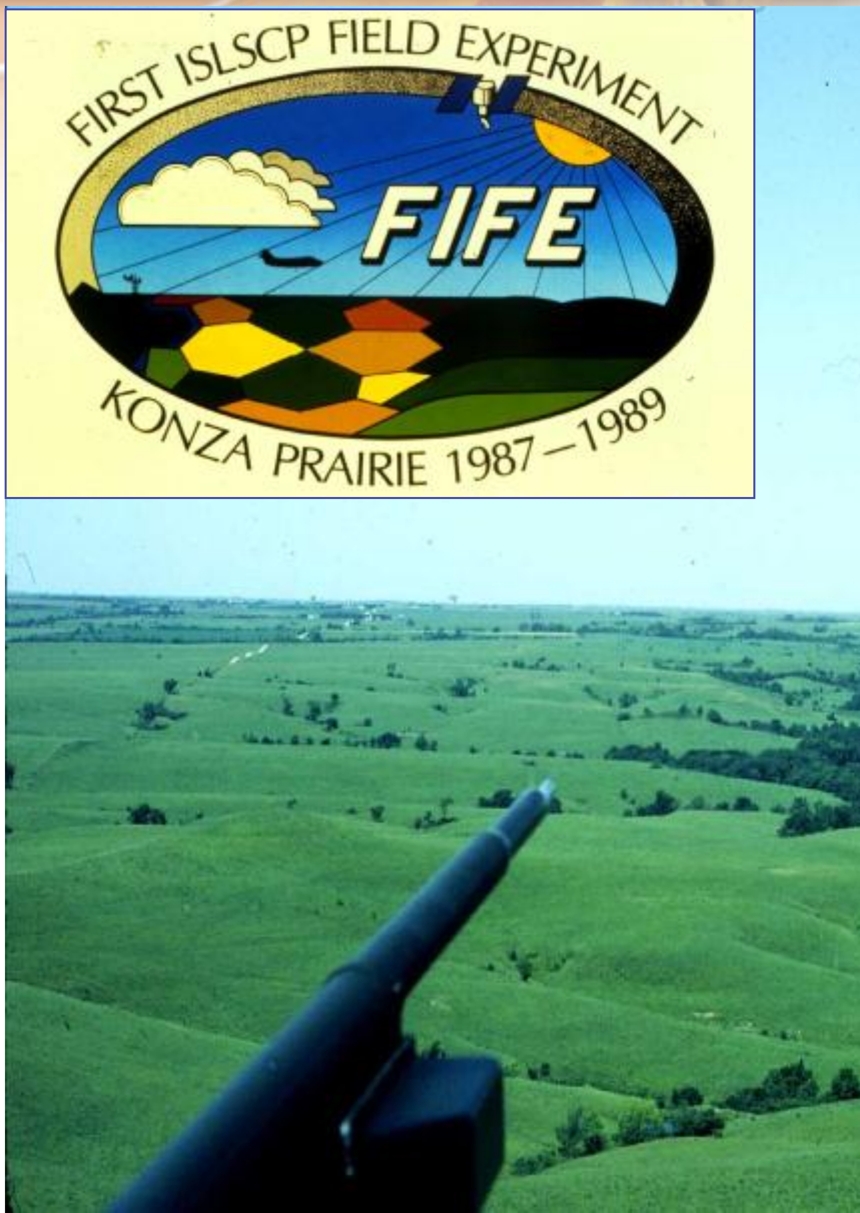


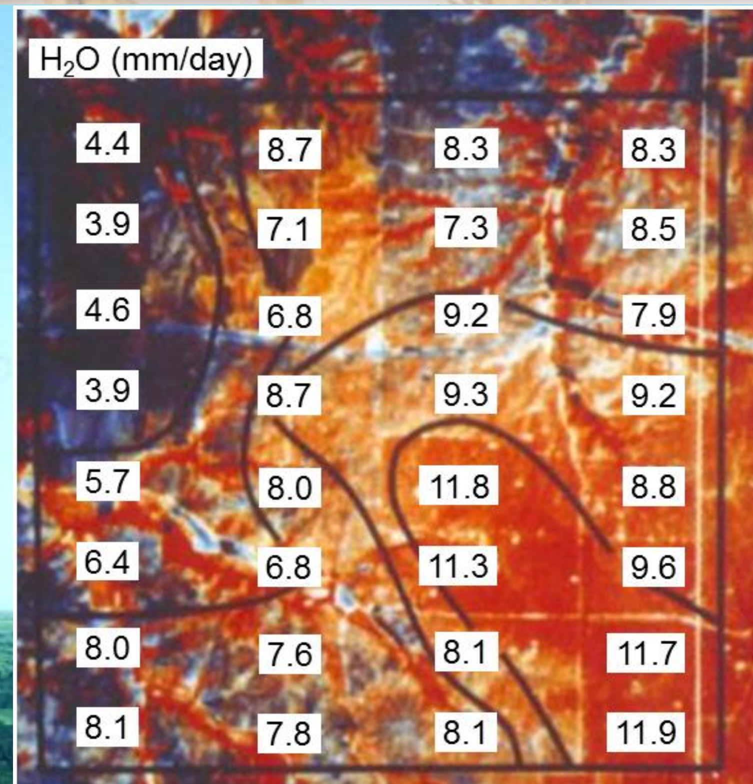


CO_2 Fluxes (kg CO_2 ha^{-1} h^{-1})

Carbon dioxide exchange measured over a 15 x 15 km grassland site using the Canadian aircraft, flying a grid pattern at 100 m above the surface. The data is superimposed on a satellite image.

Latent heat fluxes measured using the Twin Otter aircraft over the Konza Prairies on July 28 during FIFE (block averaging)



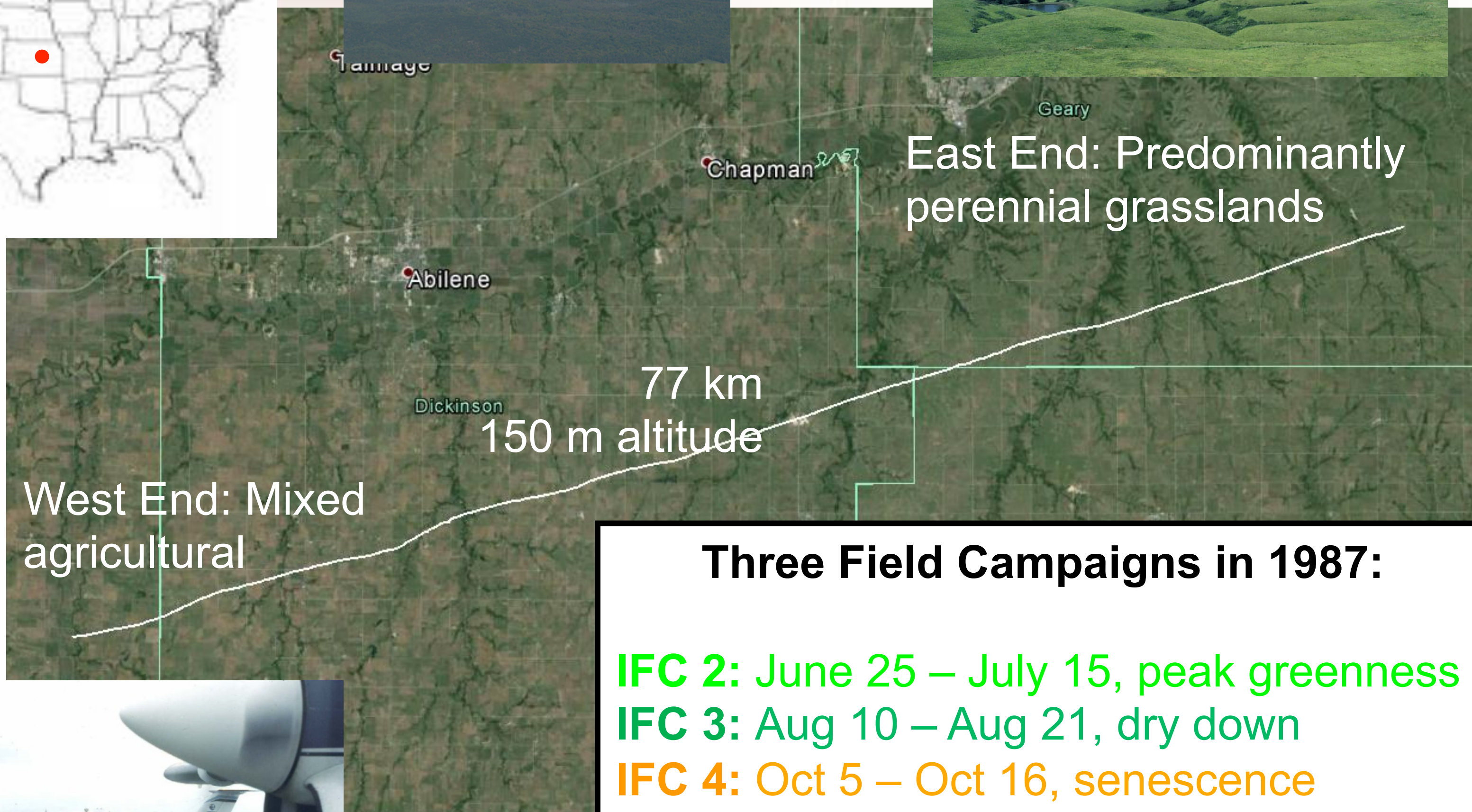


Daytime and nighttime fluxes at an altitude of 100 m over the Konza during FIFE (Aug 10, 1989)

Time of the day EDT	Distance (km)	Altitude (m)	Radiation ($W\ m^{-2}$)	Latent heat ($W\ m^{-2}$)	Sensible heat ($W\ m^{-2}$)	CO_2 flux ($mg\ m^{-2}\ s^{-1}$)	Z/L
	Verma line						
1152	15.5	106	764	131	157	-0.23	-0.8
2118 2215	16.0	98	0	-1	3	0.002	6
	Wesely line						
1206	16.1	101	666	125	205	-0.32	-0.6
2139 2239	16	107	0	-1	2	-0.002	2

Tower-based systems were measuring a daytime CO_2 flux of -.027mg m^{-2} s^{-1} and a nighttime respiration of about 0.09 mg m^{-2} s^{-1}

Regional run between FIFE site and Salina



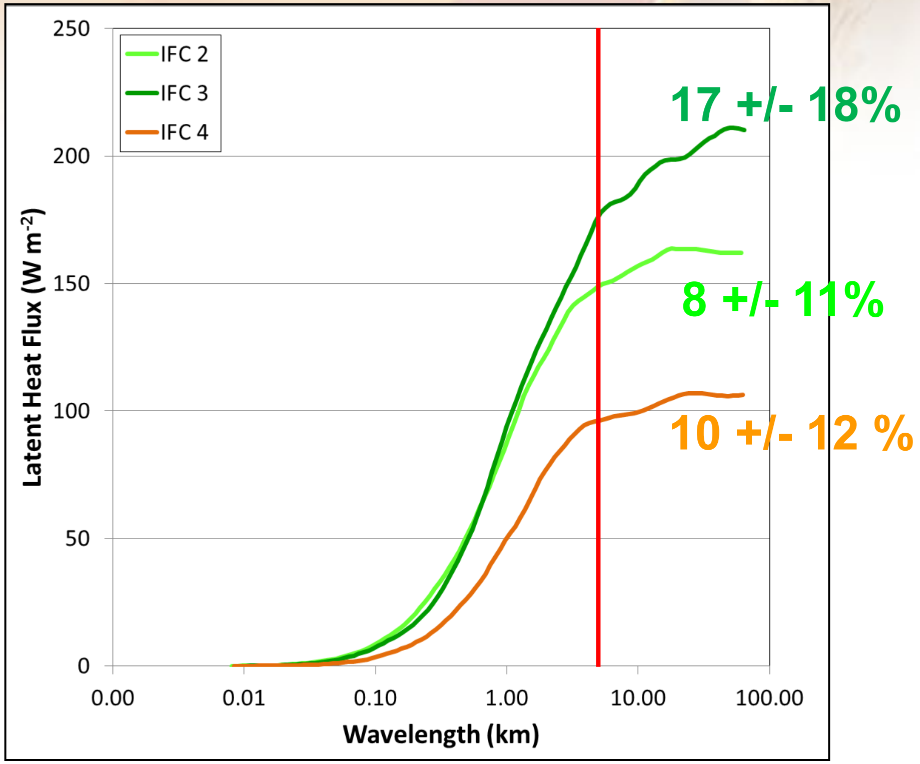
Three Field Campaigns in 1987:

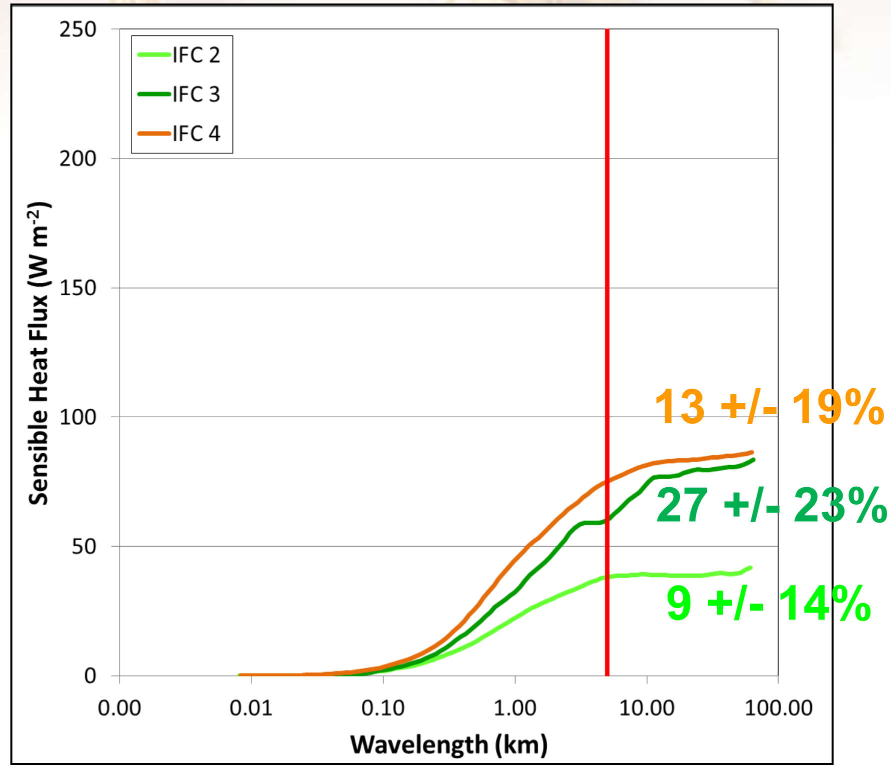
IFC 2: June 25 – July 15, peak greenness
IFC 3: Aug 10 – Aug 21, dry down
IFC 4: Oct 5 – Oct 16, senescence

FIFE Regional Runs

(Flight altitude 150 m) n=29

Flux contributions for wavelengths > 5 km



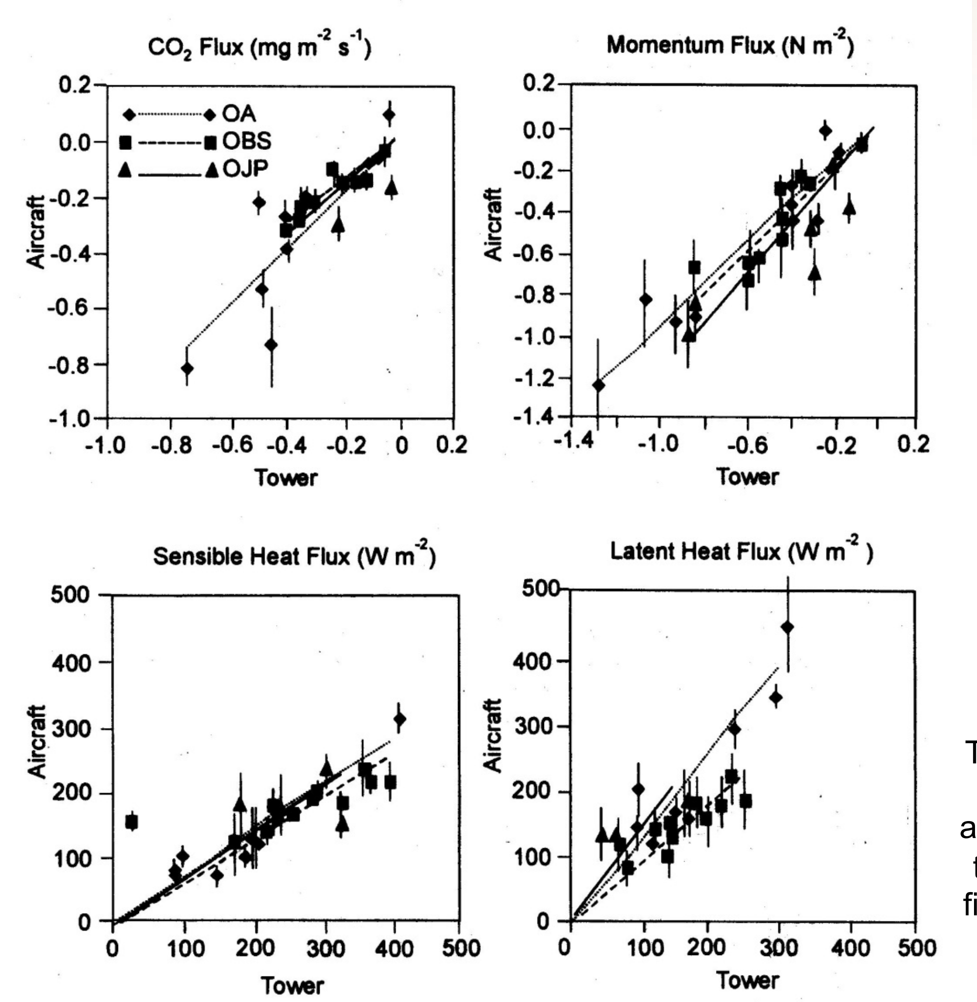


At 150 m, long wavelength flux contributions > 5 km are significant and vary substantially.

Flight patterns during BOREAS

AC/AC inter comparisons	16
AC/ tower inter comparisons (30–40 m)	86
Grid flights 35 m (18 lines)	32
Candle Lake runs 40m (115 km)	20
L's flights 40 m & 95 m (80 km)- budget study	3
Flight at dawn- CO_2 study over Candle Lake	1
Transects SSA-NSA 40 m (500 km)	5
Agricultural runs 30 m (20 km)	64

Comparison between Aircraft (30 m) and Tower-based Flux Measurements over the Boreal Forest



Slope

CO_2 ~ 0.88 $\pm$ 0.17

WU ~ 1.05 $\pm$ 0.11

LE ~ 1.16 $\pm$ 0.16

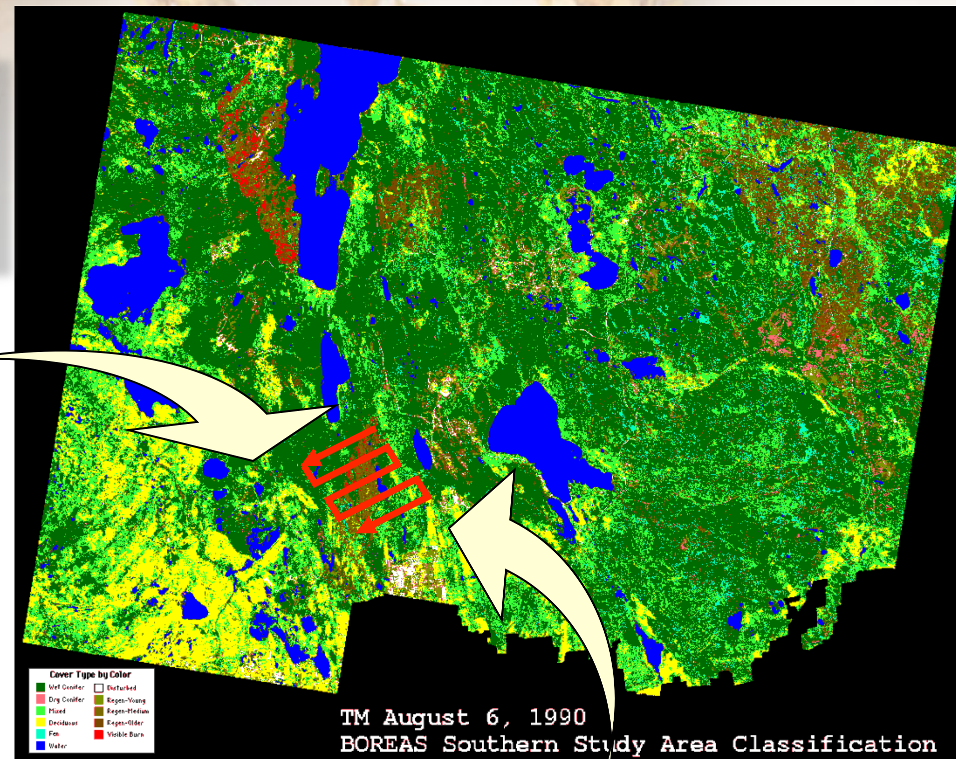
SH ~ 0.67 $\pm$ 0.06

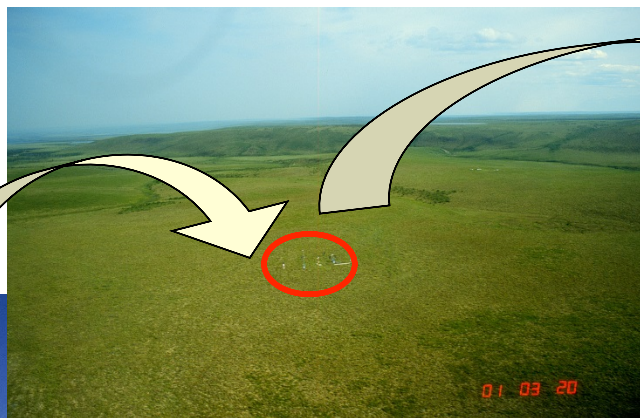
Towers were located in areas that were slightly dryer than the landscape type they were designed to represent and the aircraft flux measurements were underestimated as compared to the tower-based measurements because of the high-pass filter, short transects (5-6 km) and flux divergence with height.

Desjardins et al., 1997, J. Geophys. Res., 102D24, 29125-29133.

Obtaining regional estimates of surface fluxes

Verification of scaling up of tower-based flux measurements using aircraft-based grid flight results

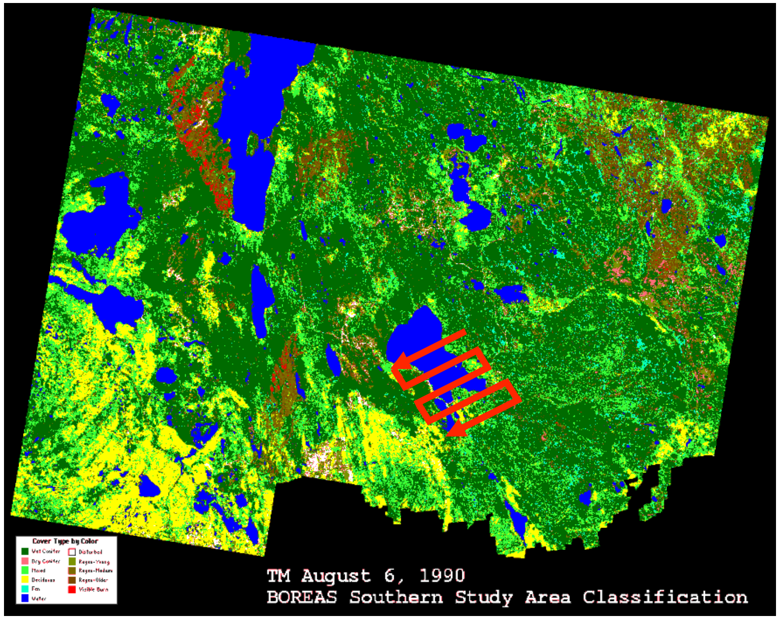




Regional flux estimates during BOREAS

Land Cover within a 15 x 15 km grid in the BOREAS SSA

Lakes	Black Spruce	Rock	Jack Pine	Aspen	Fen
0.2%	57.6%	1.2%	18.5%	15.4%	6.4%

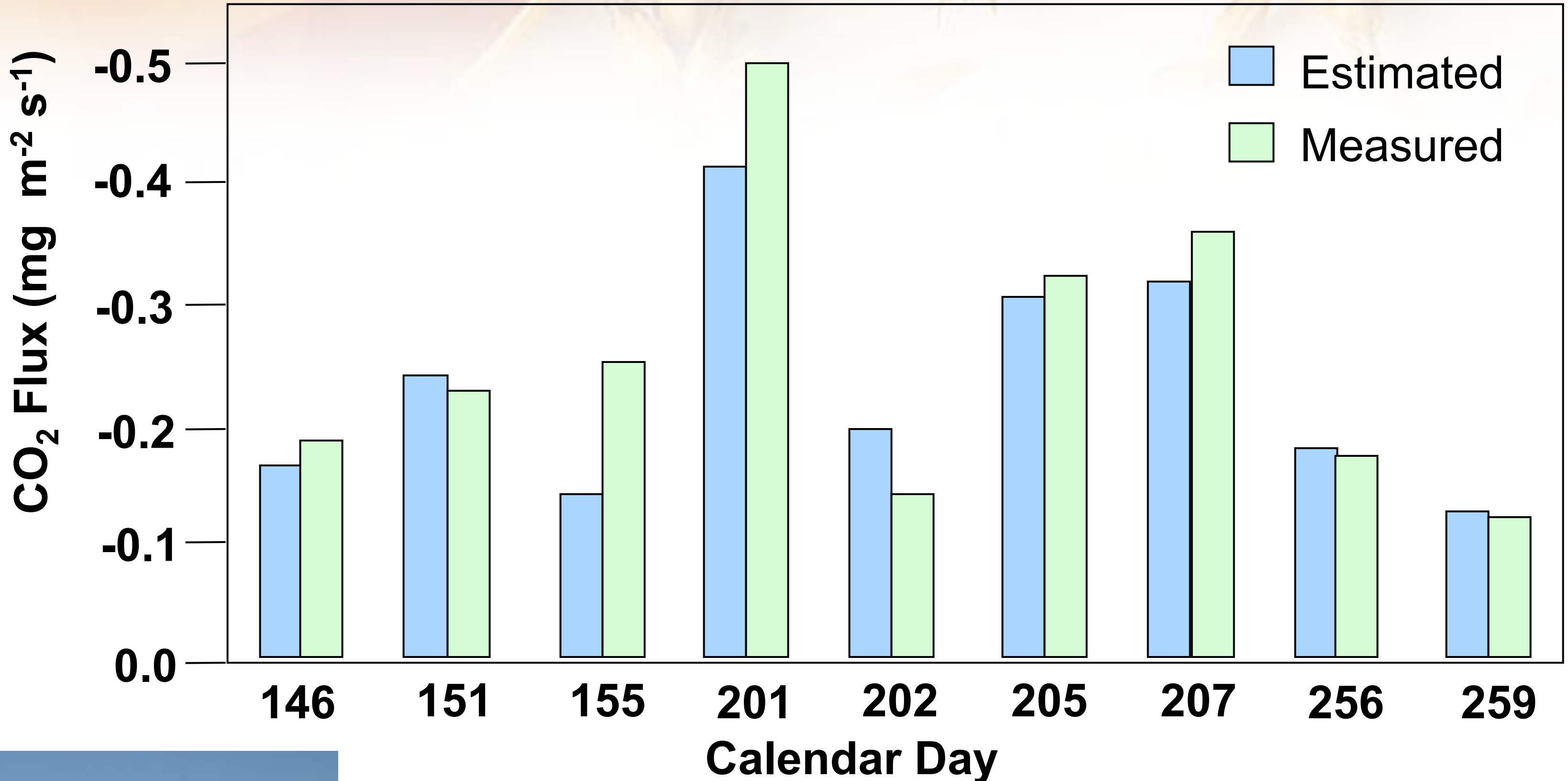


Desjardins et al. 1997. J. Geophys. Res., 102, 29125-29133.

Sellers et al. 1997. J. of Hydrology 190: 269-301.

Chen et al. 1999, J. Geophys. Res. 104: 16859-16877.

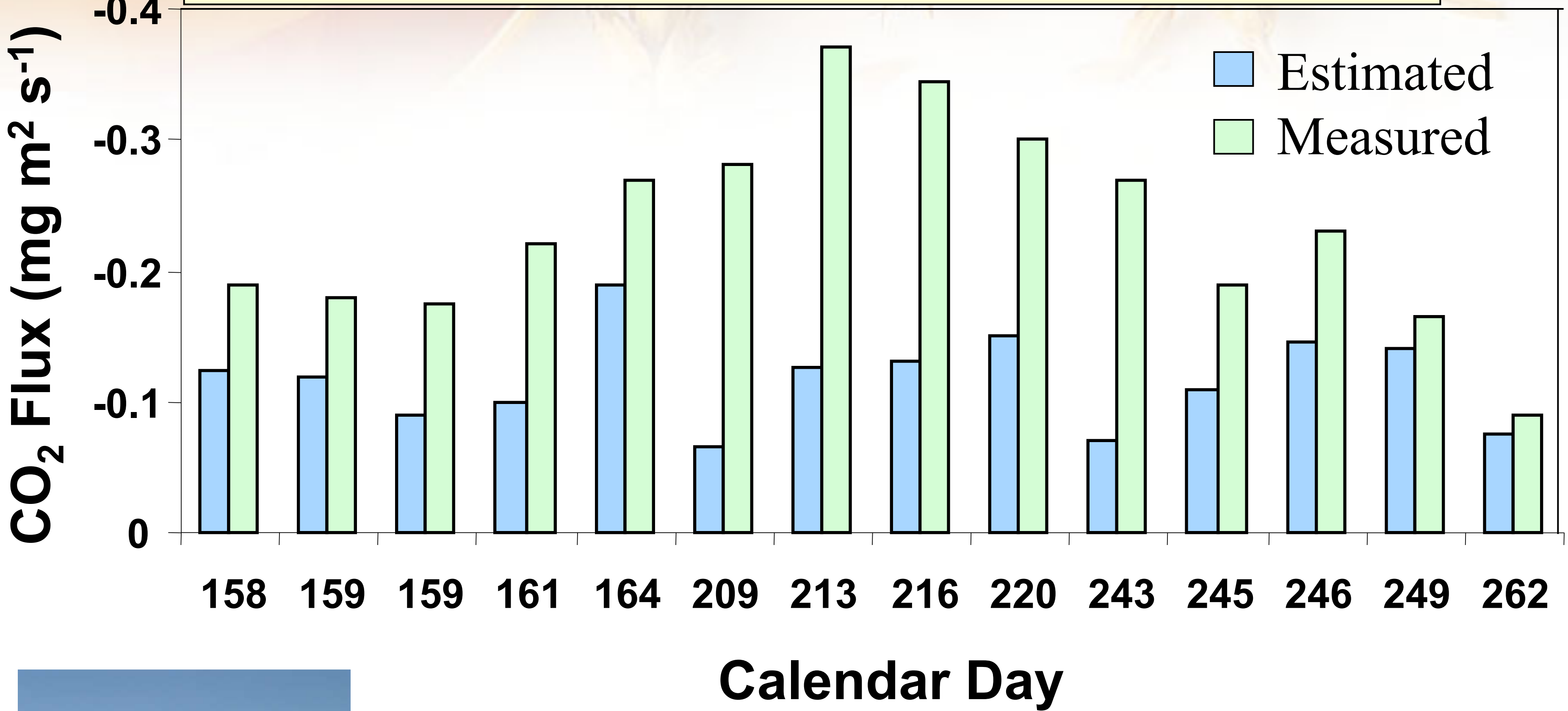
Regional flux estimates during BOREAS SSA using the results from four towers and aircraft grid flights



Desjardins et al. 1997. J. Geophys. Res., 102D24, 29125-29133
Chen et al. 1999. J. Geophys. Res. 104: 18,859-16,877.

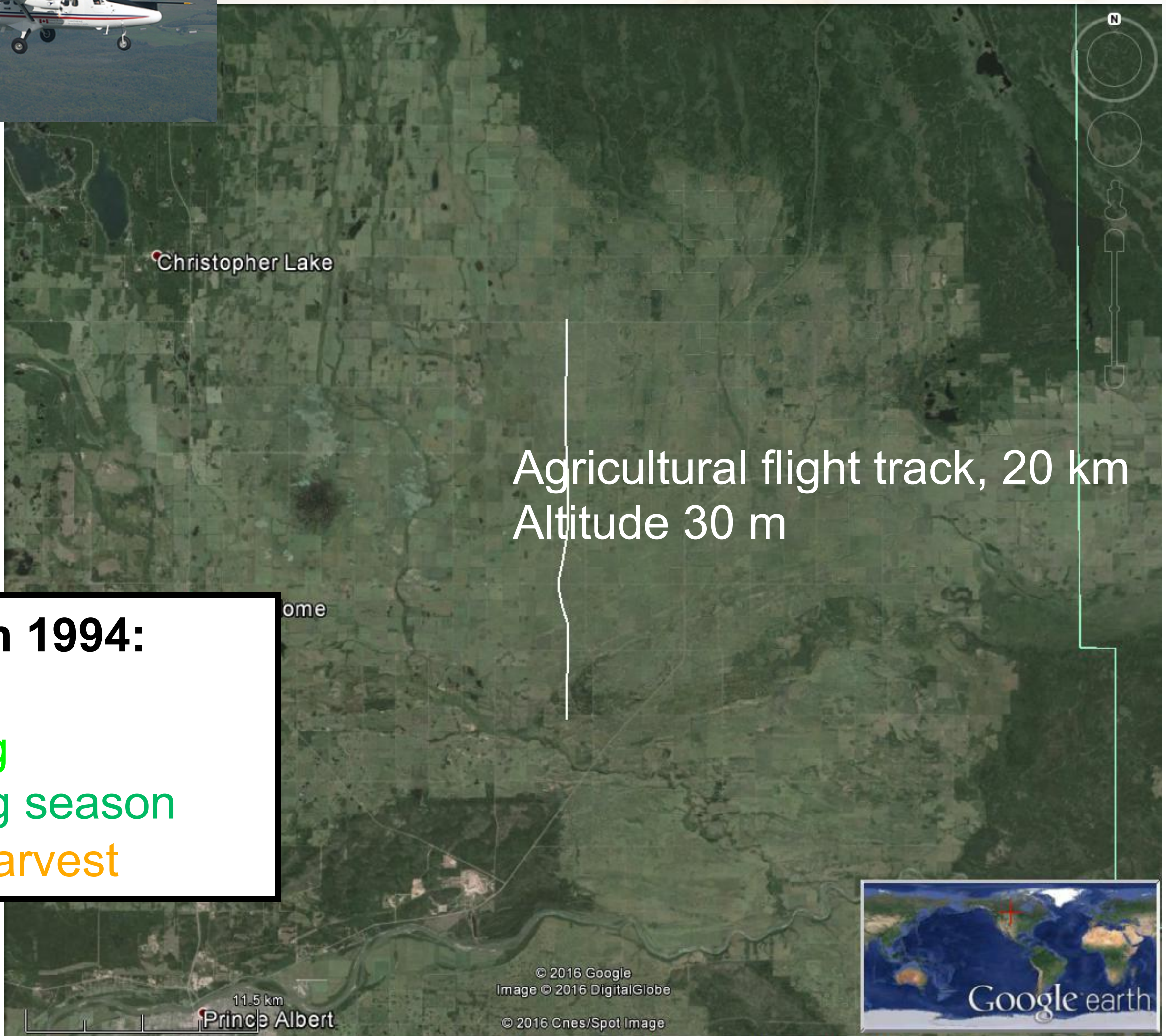
Regional flux estimates during BOREAS, NSA using the results of four towers and aircraft grid flights

Discrepancy between estimated and measured is probably due to lack of data for aspen, which represented 20% of the grid area



Desjardins et al. 1997. J. Geophys. Res., 102D24, 29125-29133.

Long wavelength contributions to fluxes over an agricultural region during BOREAS (30 m)

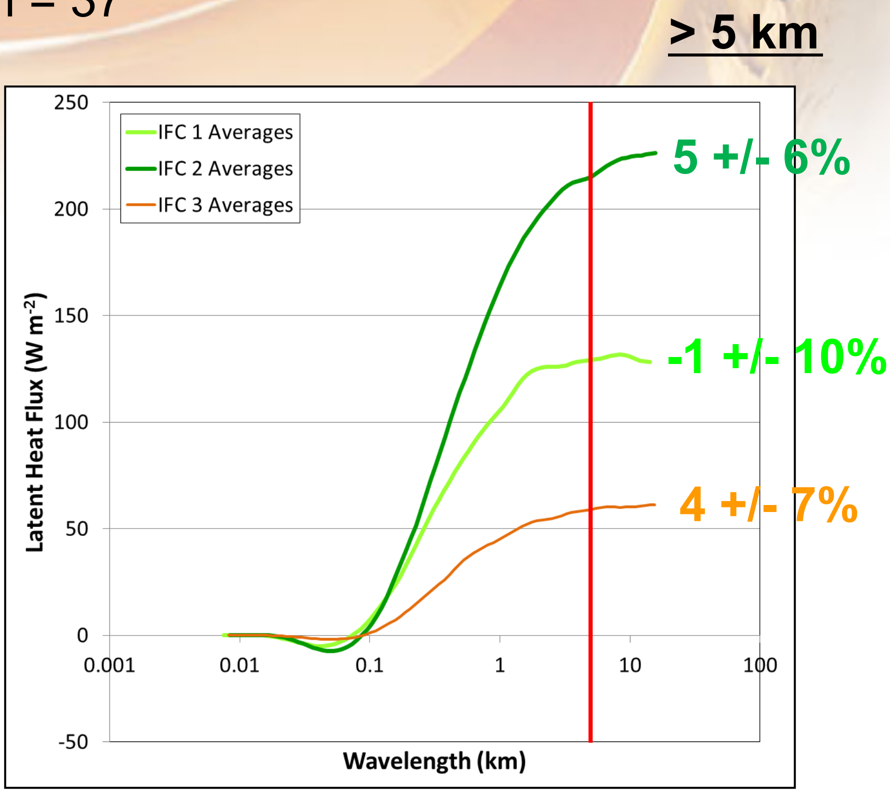


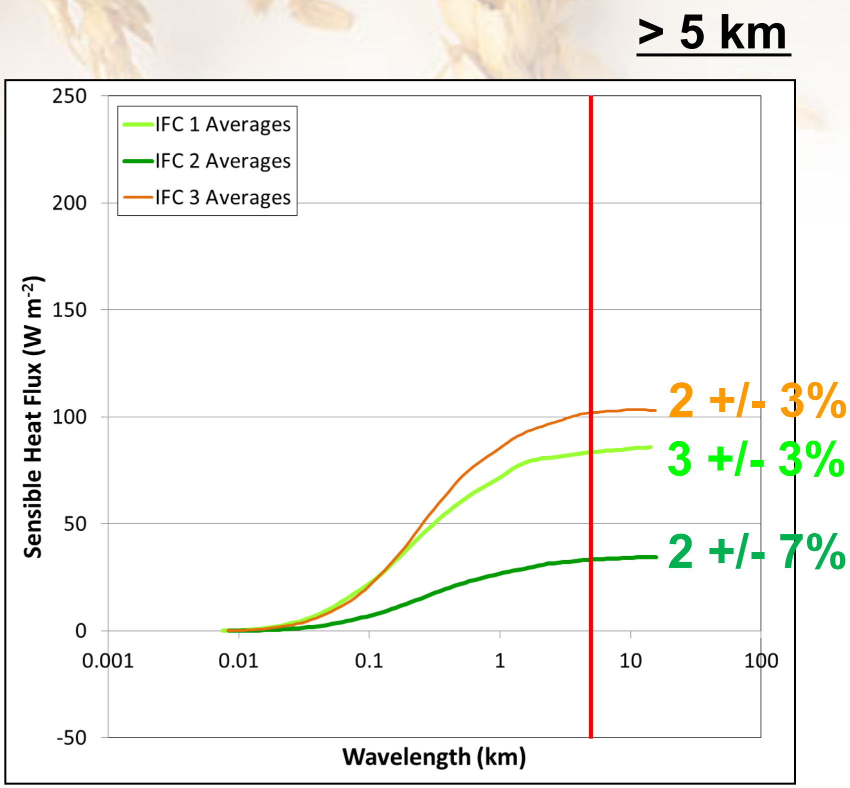
Three Field Campaigns in 1994:

IFC 1: May 23 – June 6, planting
IFC 2: July 20 – July 27, growing season
IFC 3: Sept. 8 – Sept.18, post-harvest

Long wavelength contributions (> 5km) to fluxes over an agricultural region in the Canadian Prairies at 30 m agl

n = 37



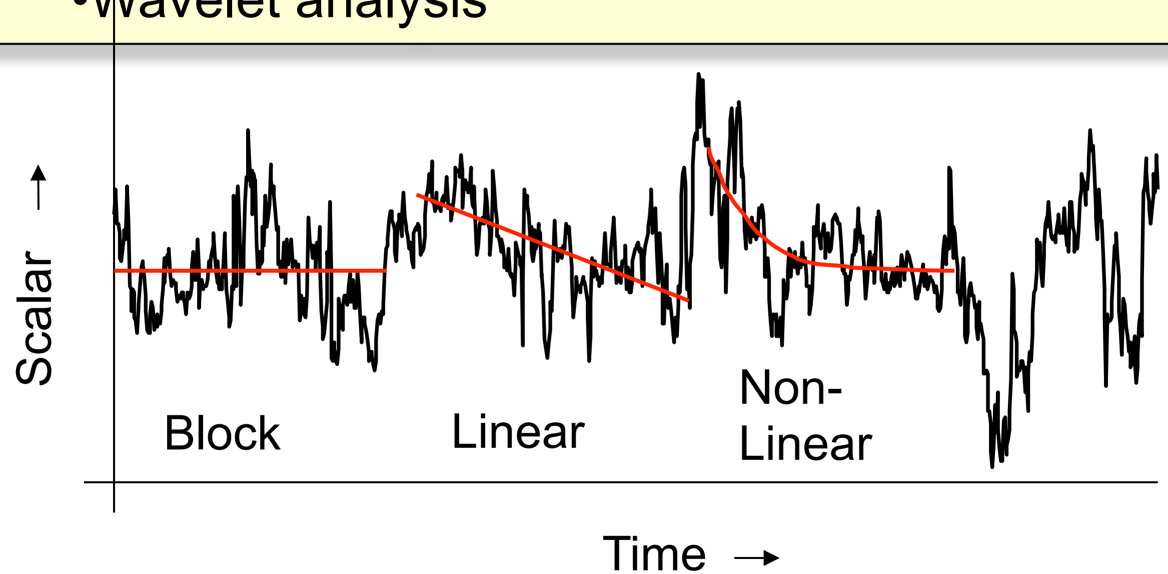


At 30 m, long wavelength flux contributions > 5 km are small.

There are many ways to calculate eddy fluxes

In order to calculate the flux using the eddy covariance technique the mean value of the scalar being measured must be subtracted from the instantaneous value. The fluxes can be calculated using:

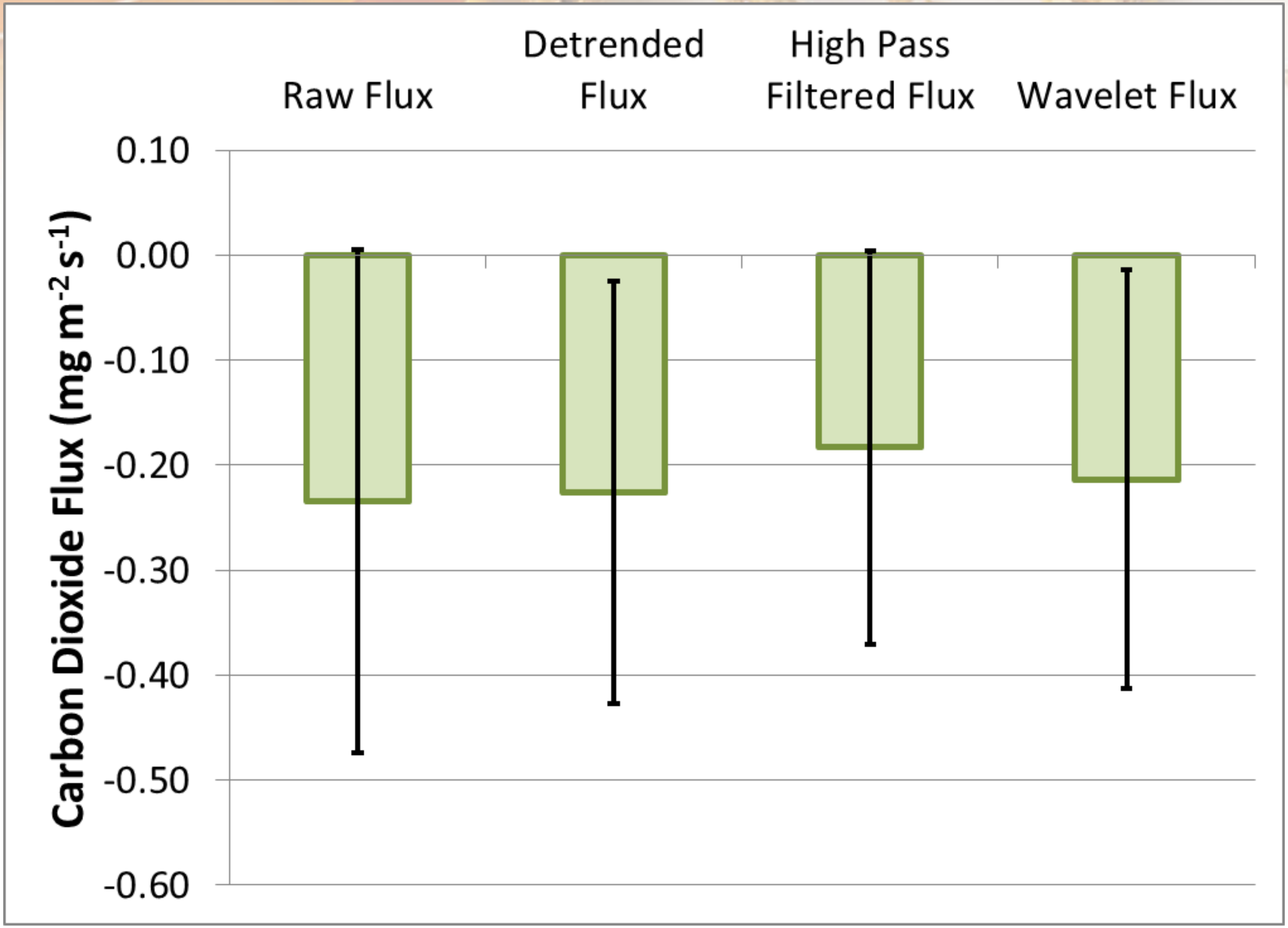
- Block averaging
- Linear detrending
- Non-linear detrending (high-pass filtering)
- Wavelet analysis



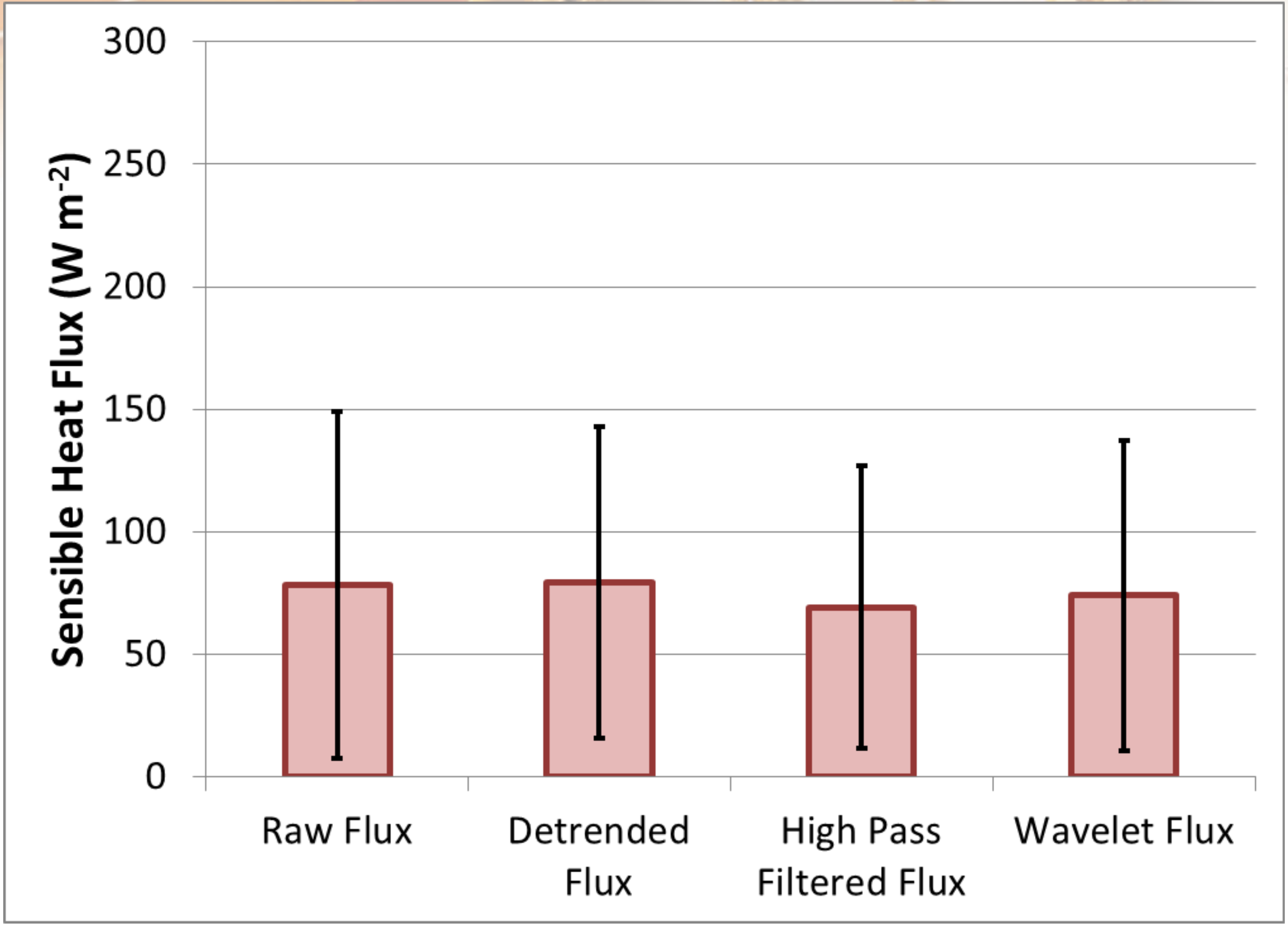
Why wavelet analysis?

1. Theoretical assumptions of the EC method are not always met
2. Wavelet analysis does not require stationarity and homogeneity assumption (in contrast to Fourier analysis)
3. Gives quantitative information, where in space and on what wavelength flux contributions occur
4. Allows to distinguish between small-scale turbulence (i.e., 10-100 m) and larger scales fluxes (i.e., 1-10 km)
5. Allows to compute fluxes at a relatively small spatial resolution ($\approx$ 0.1 km) without neglecting flux contributions from longer wavelengths

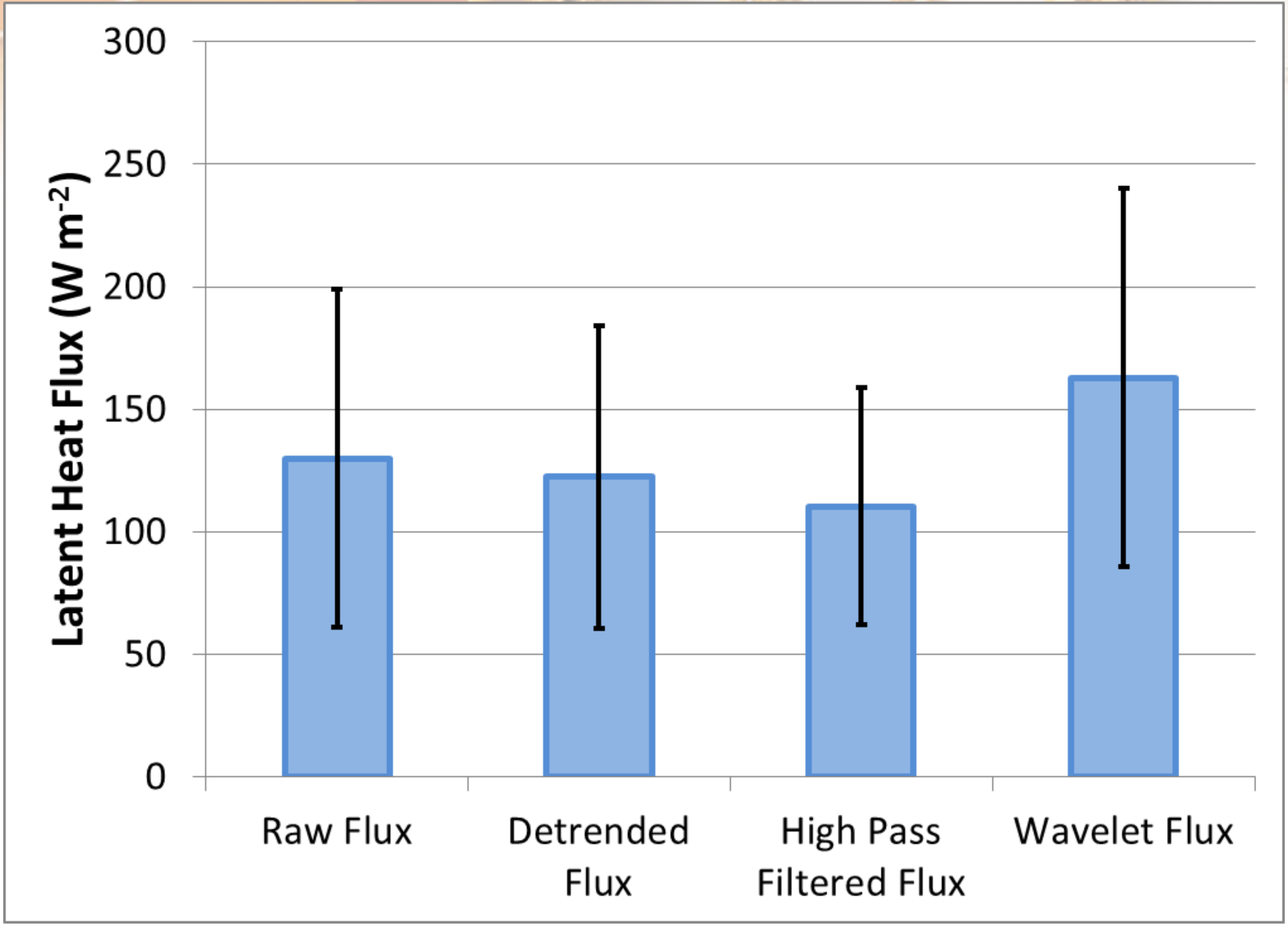
Carbon dioxide flux for the FIFE regional runs



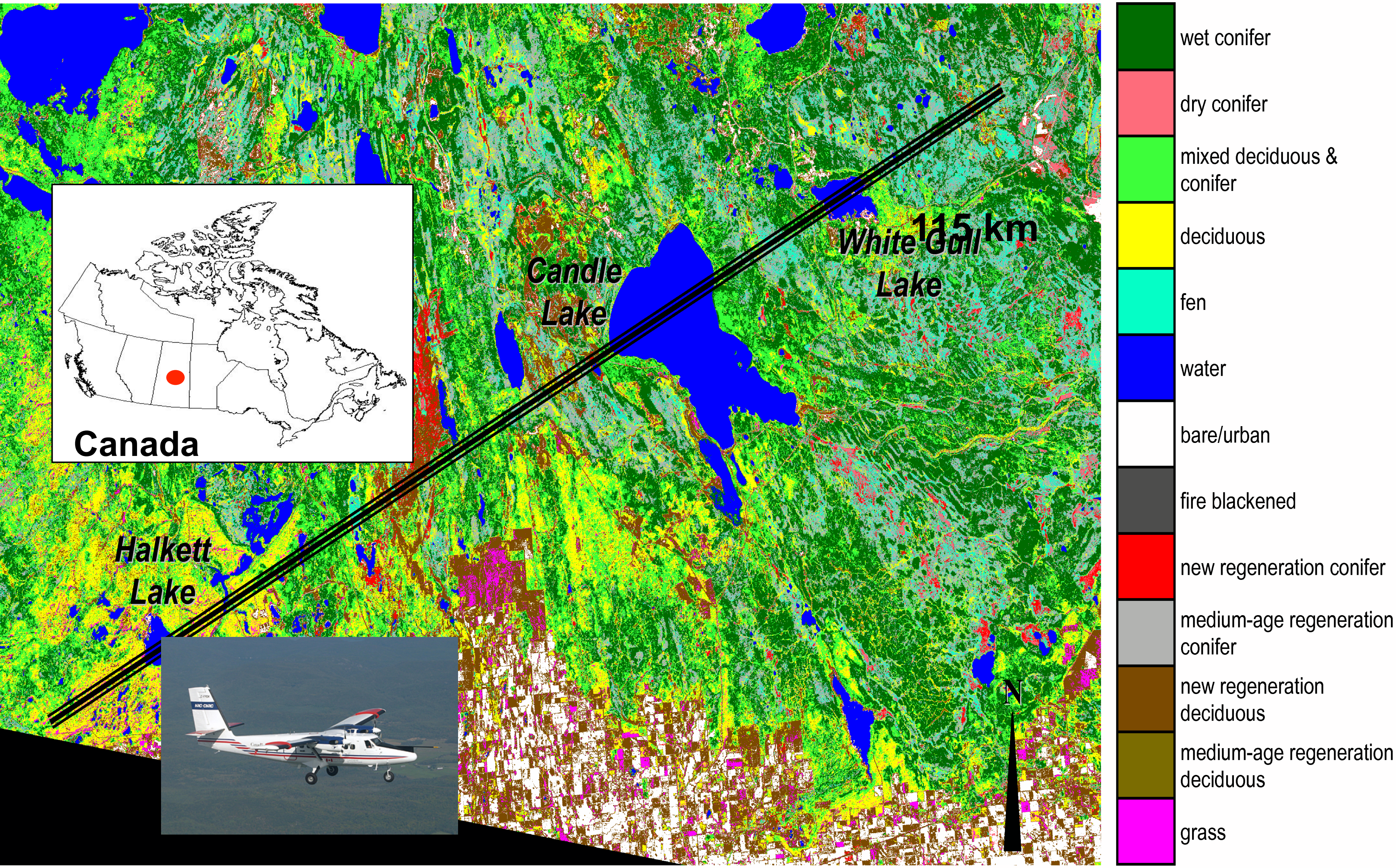
Sensible heat fluxes for the FIFE regional runs



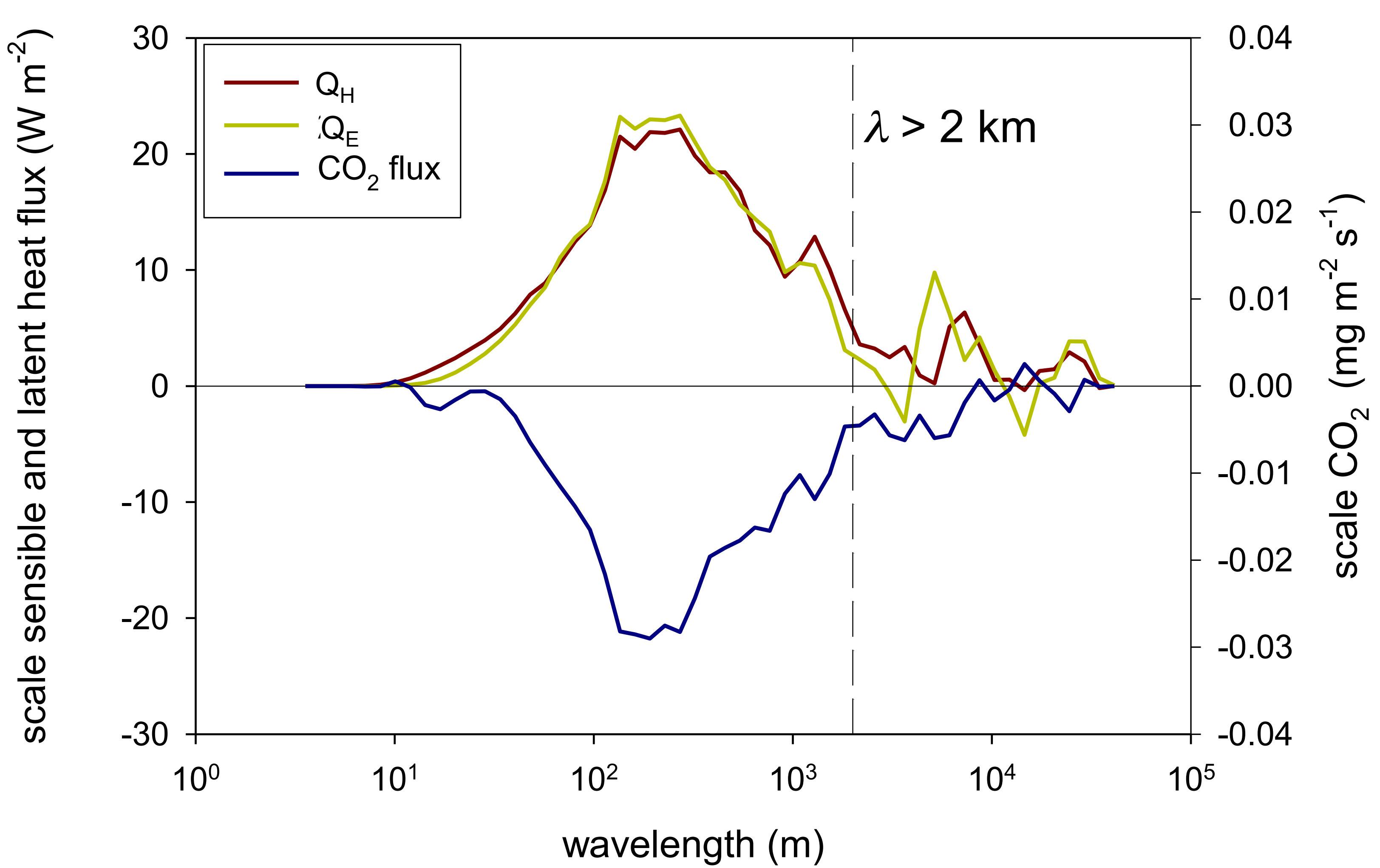
Latent heat fluxes for the FIFE regional runs



Candle Lake flight track (30- 40 m)



Candle Lake – Wavelet cospectra

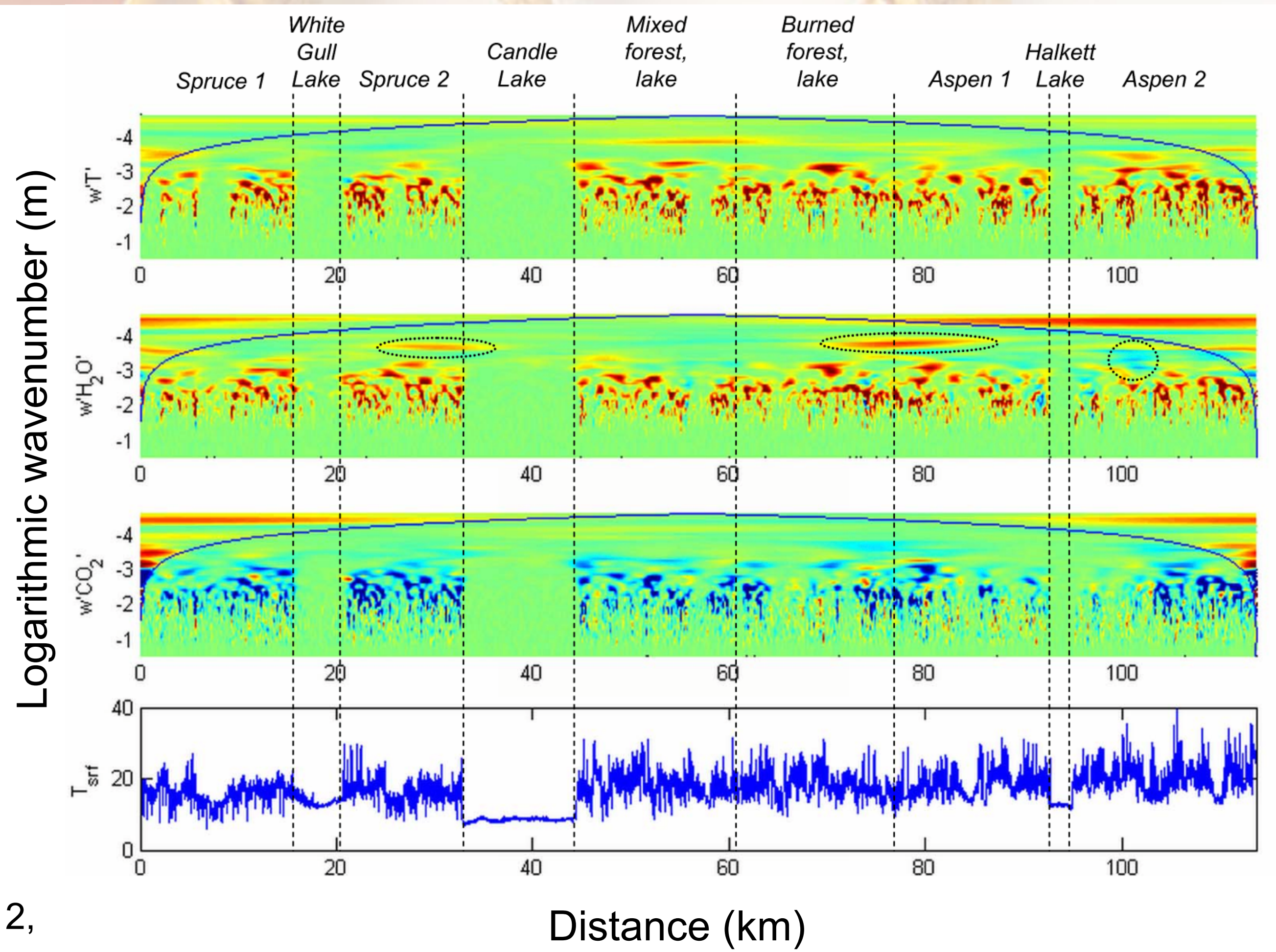


Flight BOREAS 1, 1041 – 1116 CST, 25 May 1994,
flight altitude: 30 m

Mauder et al. (2007b)

Candle Lake – Wavelet cross-scalogram

Flight 1 BOREAS
1041 – 1116 CST
25 May 1994



Legend

- Positive flux contribution
- Near zero flux
- Negative flux contribution

Mauder, M., R. L. Desjardins, an
I. MacPherson. 2007. Scale analysis of airborne flux measurements over
heterogeneous terrain in a bore ecosystem. *J. Geophys. Res.*, 112, D 13112, doi: 10.1029/2006JD008133.

Net mesoscale flux contributions (i.e. wavelength > 2 km) in % of the turbulent flux, averaged over the entire flight track

Date	time (CST)	H	λE	CO_2 flux
25-May-1994	1041 - 1116	11%	10%	10%
25-May-1994	1118 - 1152	15%	13%	11%
25-May-1994	1154 - 1228	17%	14%	9%
27-May-1994	1328 - 1403	−2%	5%	−5%
01-Jun-1994	1300 - 1333	12%	14%	14%
06-Jun-1994	1057 - 1130	15%	17%	12%
06-Jun-1994	1133 - 1211	8%	12%	9%
21-Jul-1994	1611 - 1646	13%	12%	11%
23-Jul-1994	1056 - 1126	6%	14%	9%
25-Jul-1994	1220 - 1251	10%	16%	17%
25-Jul-1994	1515 - 1548	11%	17%	17%
25-Jul-1994	1631 - 1702	11%	30%	19%
27-Jul-1994	1106 - 1136	23%	12%	11%
08-Sep-1994	1413 - 1444	8%	10%	2%

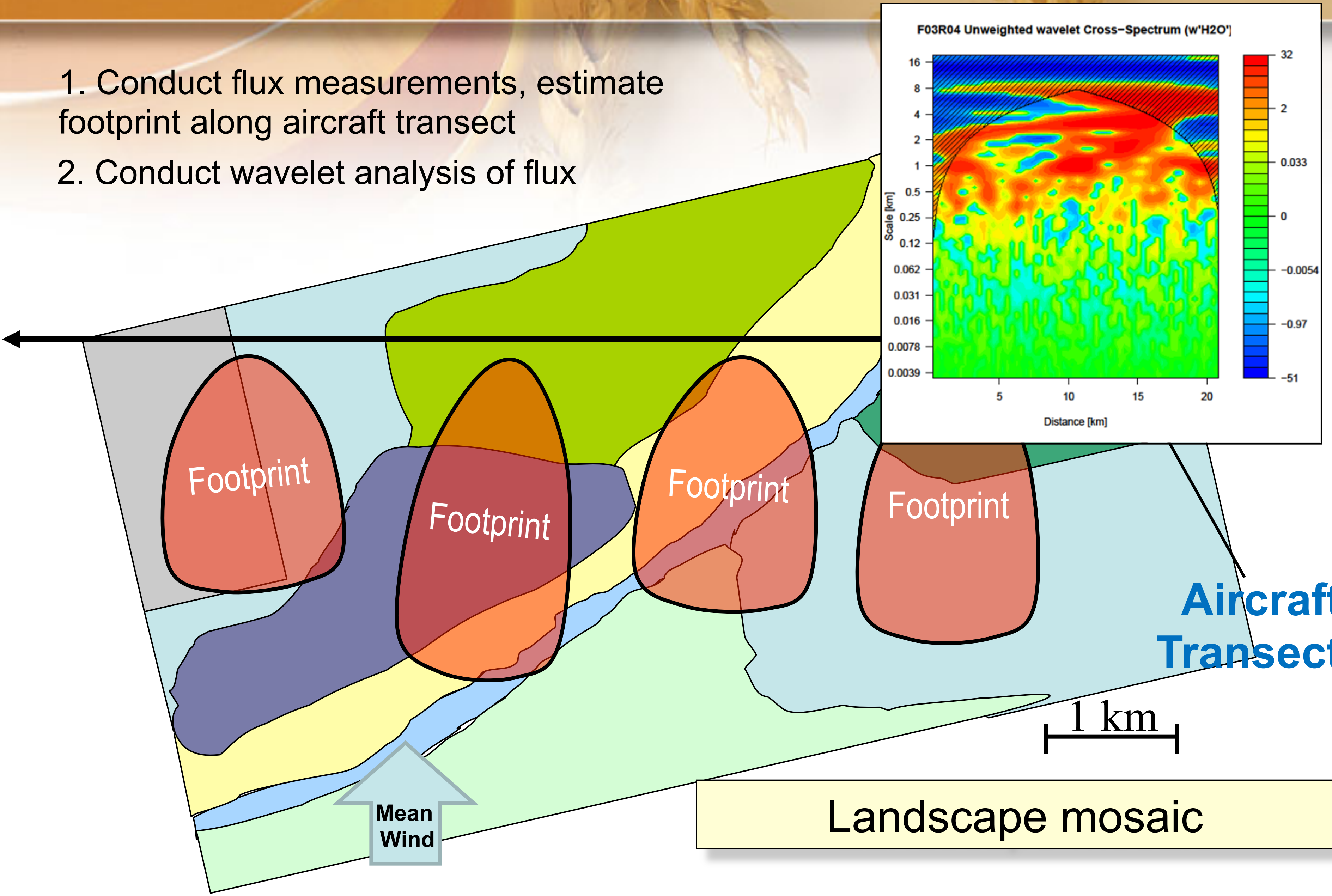
Mauder, M., R. L. Desjardins, and I. MacPherson. 2007. Scale analysis of airborne flux measurements over heterogeneous terrain in a boreal ecosystem. *J. Geophys. Res.*, 112, D 13112, doi: 10.1029/2006JD008133

What have we learned using wavelet analysis?

1. Mesoscale flux contributions between 10% – 30% were found.
2. This is on the order of the energy balance residuals that were measured at single-tower sites near the flight track.
3. The percentage of mesoscale flux contributions was different for each scalar and also for each flight.
4. Energy balance correction for the sensible and the latent heat flux according to the Bowen ratio cannot be justified.
5. Correcting CO_2 fluxes according to energy balance residual could lead to unrealistic results.
6. New approaches based on information about the spatial flux and spectral data are needed to obtain more realistic environmental response functions and to increase the value of satellite data.

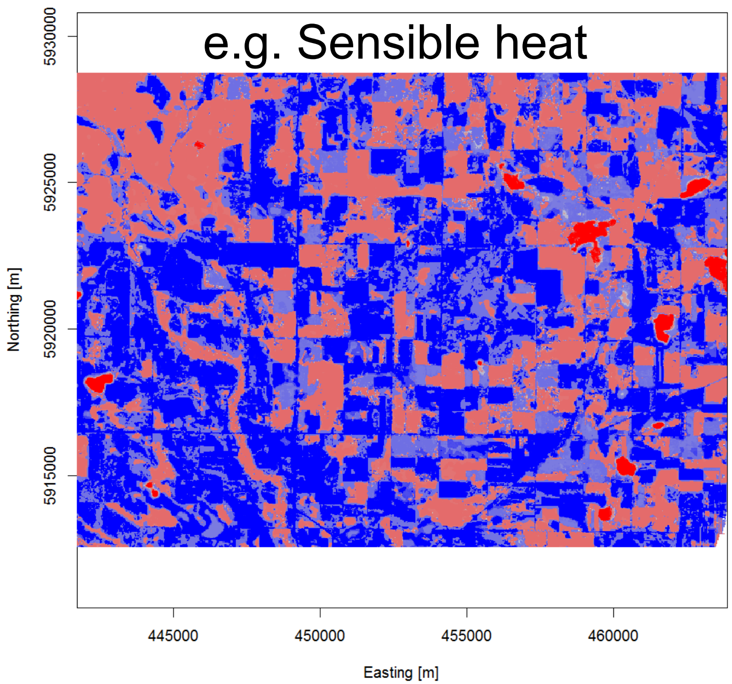
Developing Environmental Response Functions

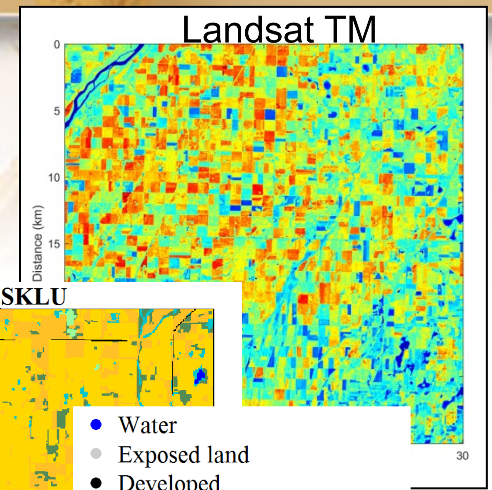
1. Conduct flux measurements, estimate footprint along aircraft transect
2. Conduct wavelet analysis of flux

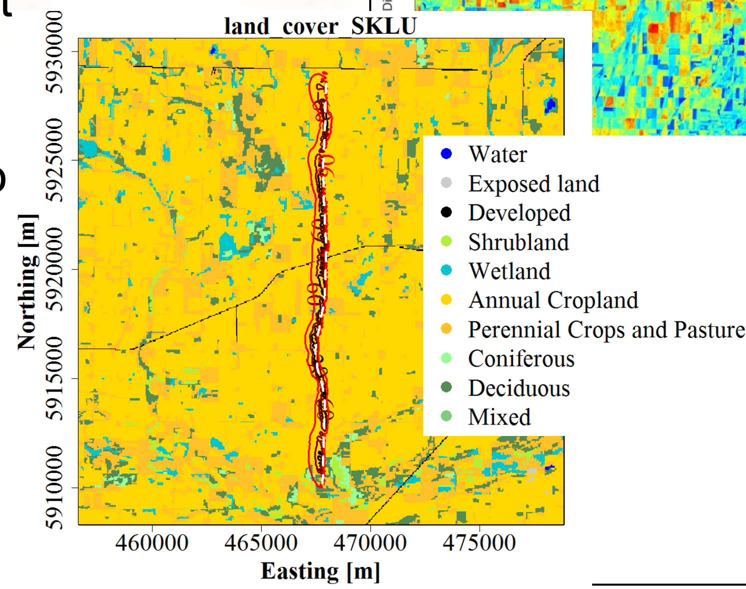


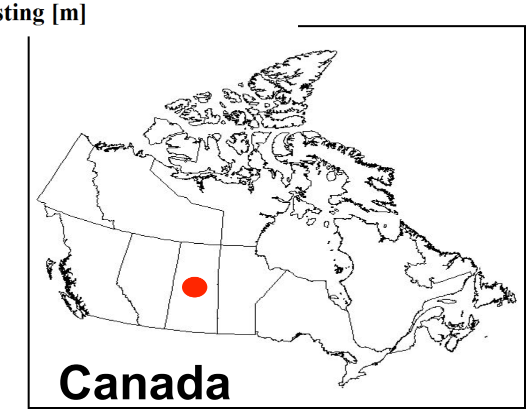
Developing Environmental Response Functions

3. Combine wavelet decomposition of flux with the footprint of remotely sensed/land use data
4. Develop and test Environmental Response Functions (ERFs) for the prediction of relevant variables (e.g. sensible heat flux, carbon dioxide flux)
5. Using remotely sensed data, apply ERFs to larger spatial area.

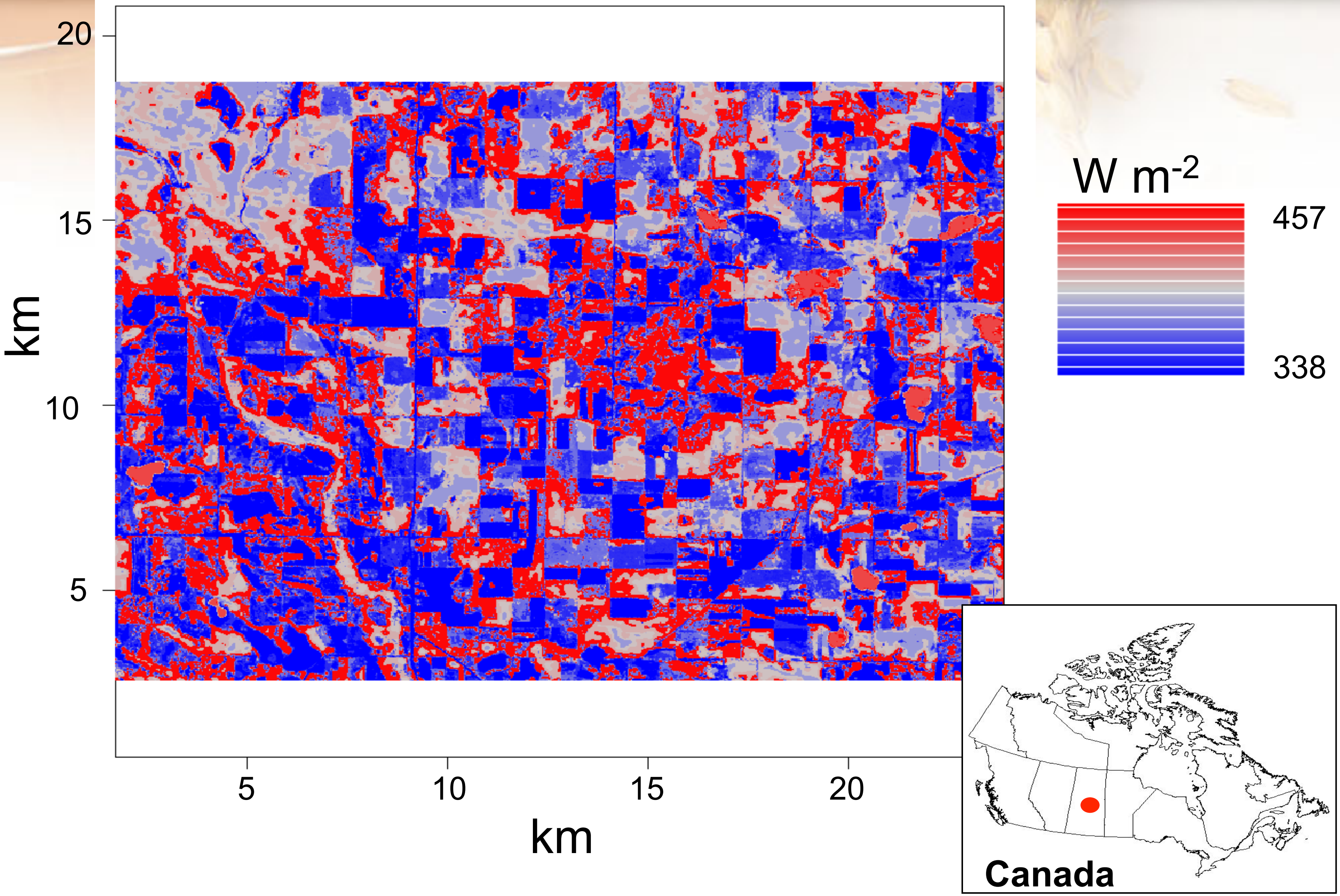




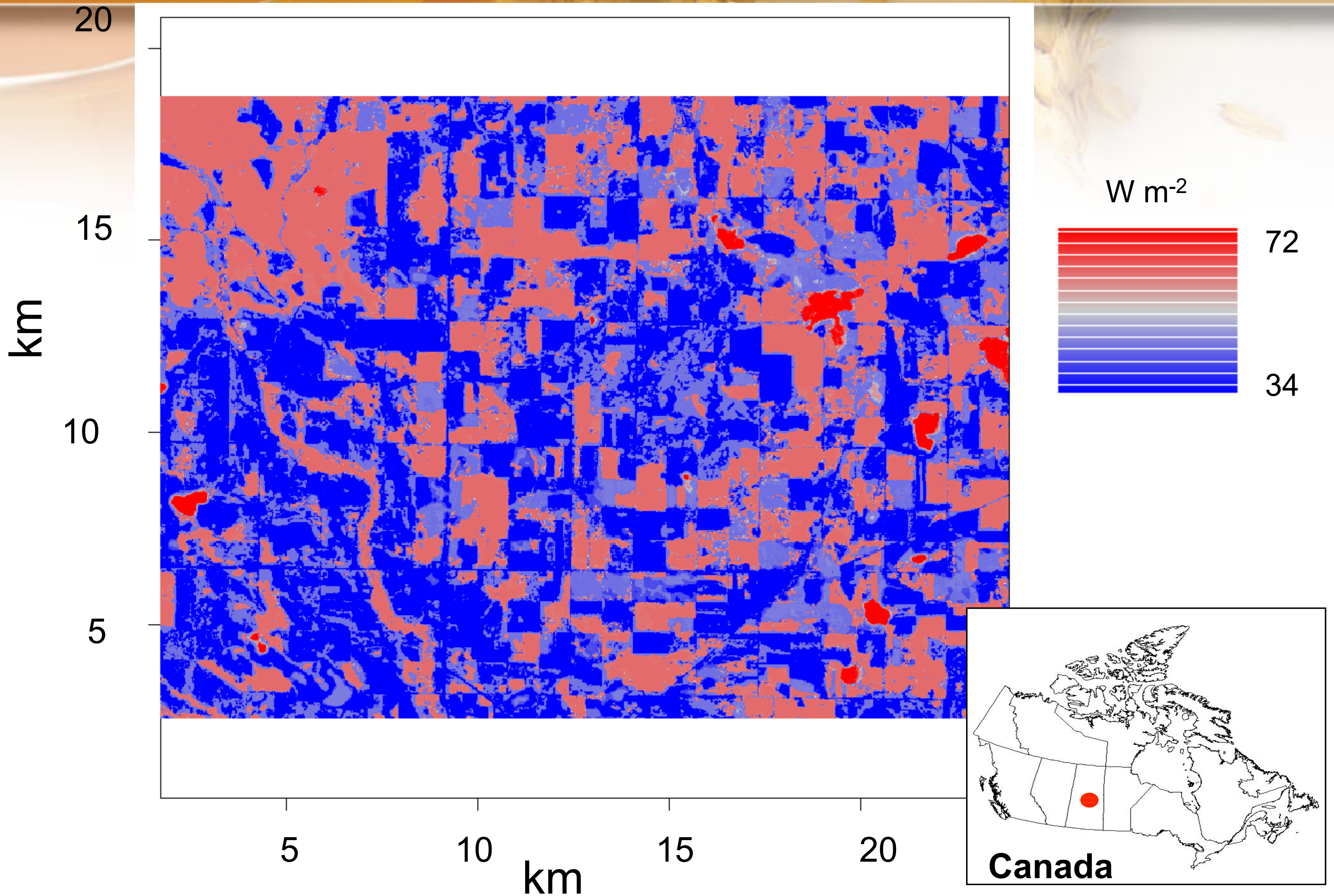




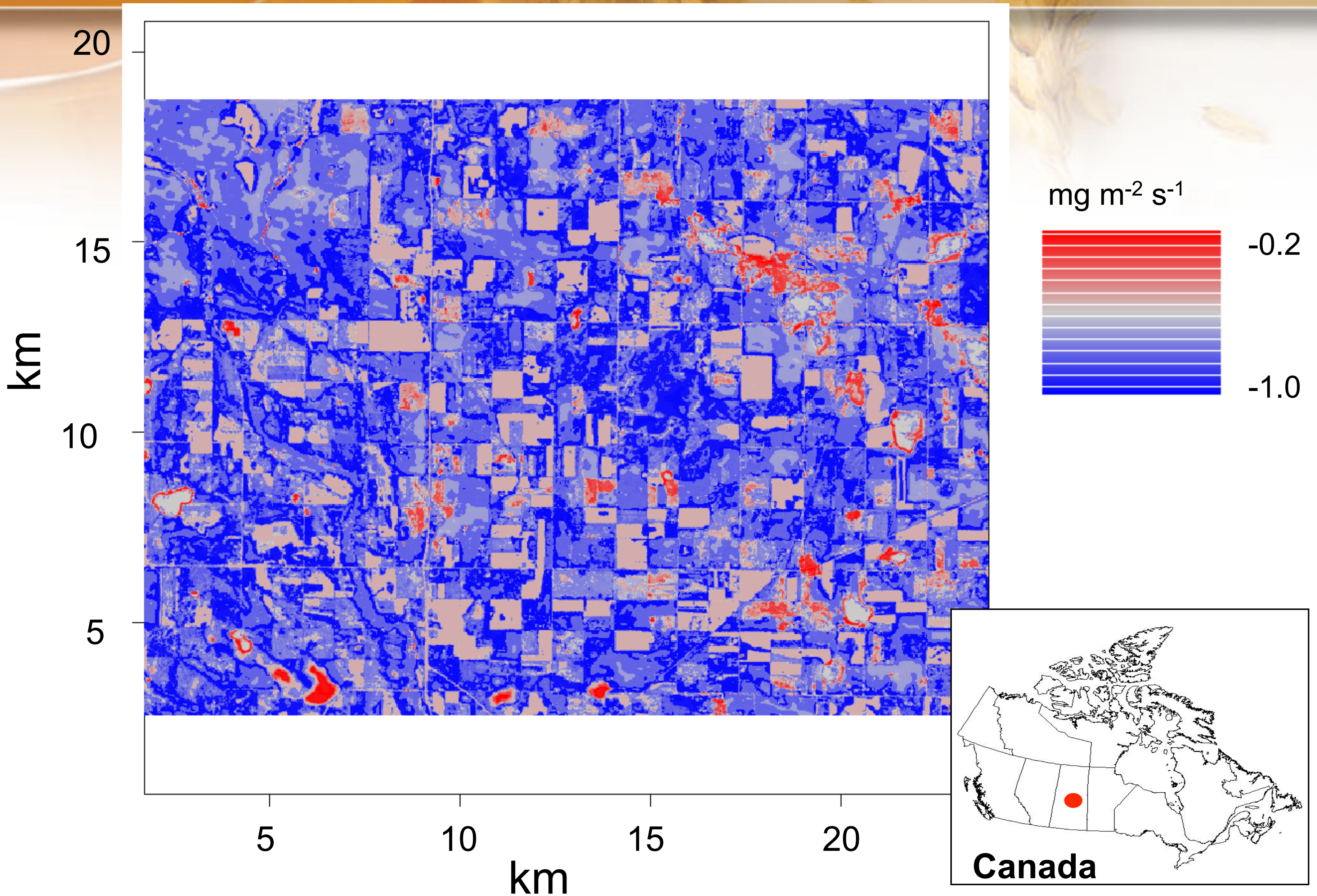
Predicted Latent Heat Flux



Predicted Sensible Heat Flux



Predicted Carbon Dioxide Flux



FIFE and BOREAS helped the aircraft team

- Aircraft/aircraft, aircraft/tower and aircraft/lidar comparisons, grid flights, budget studies, land-lake interface study, night flight all contributed to improving our understanding of flux measuring systems and flux measurements.
- FIFE and BOREAS increased our awareness of the importance of the footprint concept for relating fluxes of mass and energy to spectral information obtained from satellite (Schuepp et al. 1990).
- They also helped improve our understanding of the importance of the mesoscale contribution to the fluxes of various scalars; provided some insights on the impact of the lack of energy budget closure on the flux measurements of various scalars (Mauder et al. 2007).
- Most of all, FIFE and BOREAS provided data base of integrated observations which are essential for understanding land-atmosphere interactions.

Lessons learned

Flux measurements that meet theoretical assumptions are essential for model testing and for carrying out ecosystem studies

•Budget studies consisting of L flights at three levels with legs of 40 km synchronized so that the mean flux values for each level is taken at the same average time is probably the best way to test aircraft-based flux measurements. The test needs to be done under clear conditions.

•Aircraft –based flux measurements over long transects (> 100 km) in conjunction with spectral data from satellite should be used to develop environmental response functions that can then be used for testing and improving models.

Twin Otter data base collected during FIFE and BOREAS

Desjardins, R., D. Worth, I. MacPherson, M. Bastian and R. Srinivasan 2016. Flux measurements by the NRC Twin Otter research aircraft- 1987-2011. Advances in Science and

Research doi: 10.5194/asr-1-1-2016.

Thank you Piers and Forrest for all your efforts and fantastic leadership! It has been great!!!!!!!!