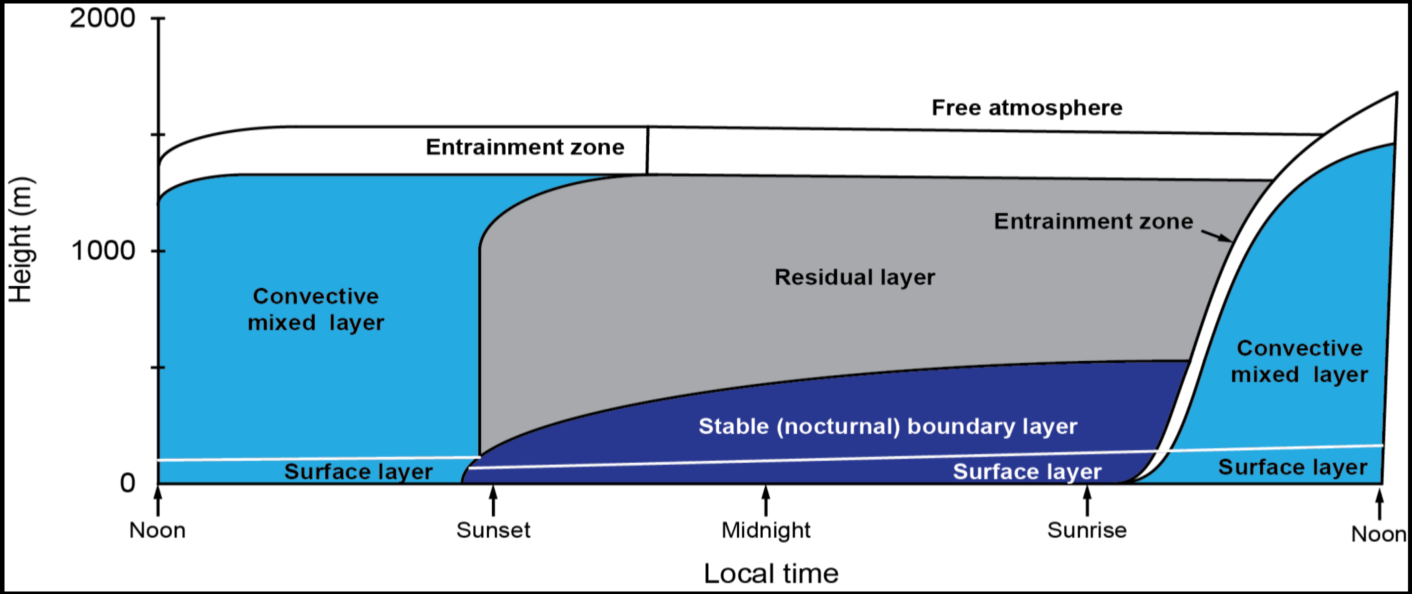
Examination of turbulence decay and the role of mechanical and buoyant forcing over a forest during the Boundary Layer Late Afternoon and Sunset (BLLAST) Experiment

Alexander, D., Hang ,C. , Pardyjak, E.R., Lothon, M., Lohou, F., Derrien, S., de Coster, O., Pietersen, H., and Pique, E.

Motivation



- Gaining an improved understanding of the various transitory processes associated with the afternoon transition

Figure adapted from Stull by Dan Nadeau

Outline

- Brief review of evening decay hypotheses in current literature
- Description of the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) experiment and setup
- Comparison of BLLAST TKE decay results to Nadeau (2011)model, Goulart (2010) LES, and Sorbjan (1997) LES
- Discussion of the competing buoyancy and mechanical TKE production processes during the decay

Outline (cont.)

- Brief review of the potential temperature variance budget in current literature

- Method of calculating molecular dissipation using the third order longitudinal structure function

- Plot of the potential temperature variance budget with residual

Authors	Method of Study	Region of Interest	Key Findings
Caughey et al. (1979)	Field Obs., Minnesota	Entire ABL	Top down heat flux
Nieuwstadt & Brost (1986)	LES, Ug = 0; inst. rem. flux	Integral quantities entire ABL	See H1, t^{-n}
Beyrich & Klose 1988	Field Obs., Wangara	Entire ABL	t* ~ u*/h
Sorbjan (1997)	LES, Ug = 0;	Integral quantities entire ABL	See H1, H2
Grant (1997)	Field Obs. Cardington, UK	Entire ABL	heat flux profiles strong cooling near the surface, t* ~ u*/h
Cole & Fernando (1998)	Laboratory	Entire boundary layer	σ_T & σ_w decay t ~ DT/(dTs/dt)
Acevado & Fitzgerald (2001)	Field	Surface Layer	Spatial Heterogienity
Pardyjak 2001	Field Obs., Phoenix	Surface Layer	Simple decay model σ_T & σ_w decay at different rates

Authors	Method of Study	Region of Interest	Key Findings
Shaw & Bernard (2002)	DNS		Delay of decay due to shear
Grimsdell & Angeine 2002	Field Obs., Urbana-Champaign	Entire ABL	inversion layer separation (ILS), descent, demixing
Goulart et al 2003	Theoretical Spectral form of tke equation	Integral quantities entire ABL	
Riley 2003	Laboratory Measurement, overlying stratification	Entire ABL	Overlying stratification effects u'^2 more than w'^2
Pino et al 2006	LES, shear and overlying stratification	Entire ABL	Decay length scales, scaling exponents
Kumar et al. 2006	LES, diurnal cycle	Entire ABL	
Pardyjak et al. 2008	Field Observations Phoenix, AZ	Surface Layer	Spatial Heterogeneity of decay
Goulart et al. 2010	LES, contribution of shear production term to TKE	Entire ABL	Shear production dominates buoyant production in lower CBL

Authors	Method of Study	Region of Interest	Key Findings
Nadeau et al. 2011	Model for afternoon and early evening decay of CBL	Surface Layer	Erfc fit to sensible heat flux along with H1

Hypotheses from the Literature

- H1 – Surface Heat Flux "instantly set to zero". The volume integrated turbulence quantities are only a function of the initial CBL state and t/t* (Nieuwstadt & Brost)

- H2 – Gradually Decaying Surface Heat Flux. Turbulent decay is dependent on 2 time scales t* and t_f (Sorbjan)
  - H2* – Limiting Cases (Sorbjan):

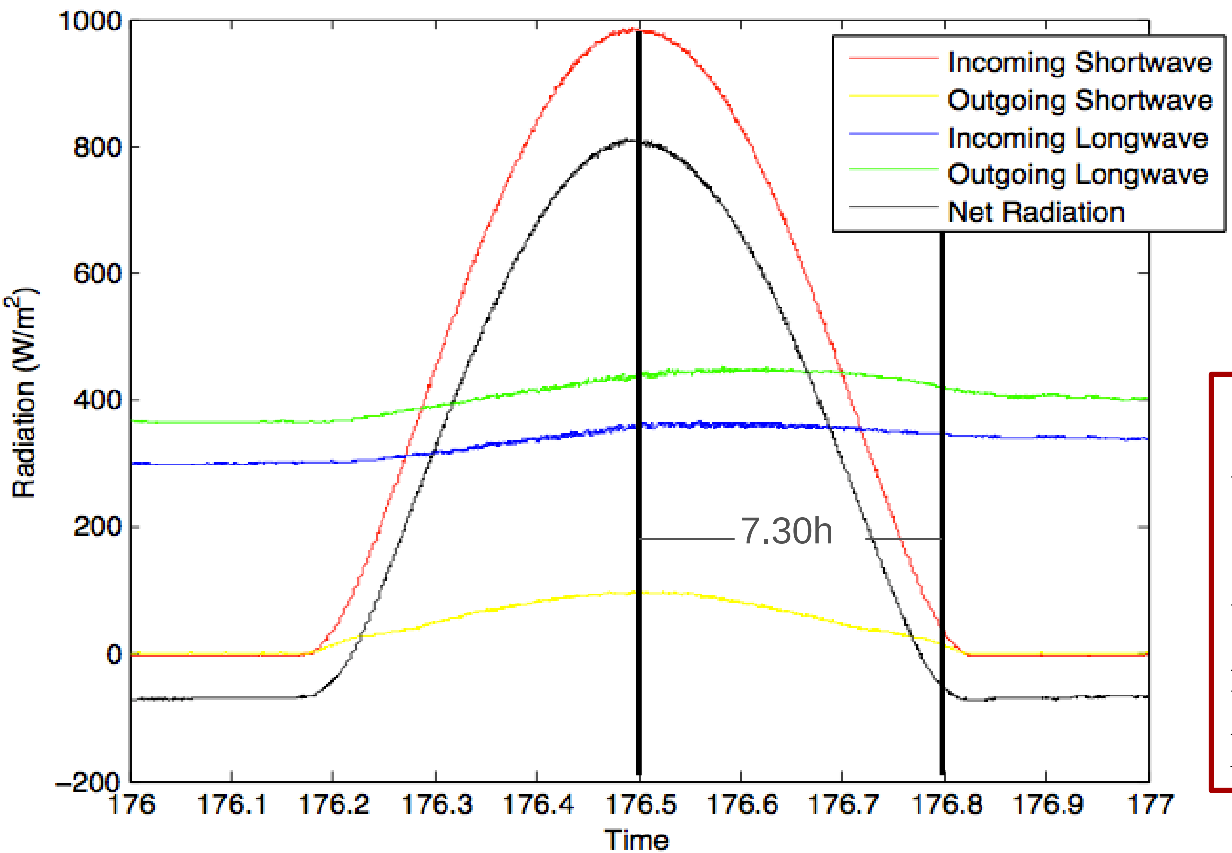
$t_f / t^* \rightarrow 0$ Hs=0 @ t_f=0

$t_f / t^* \rightarrow \infty$ Constant Hs

Hypotheses (cont.)

- H3 –Mechanical effects in the boundary layer increase with decreasing z/L to the extent that in the lower part of the convective boundary layer, the mechanical term is dominant (Goulart)

Definition of Solar Forcing Time



τ_f is a solar forcing time defined as the length of time between the peak of solar radiation and when it passes zero

Illustration Depicting TKE Decay Limiting Cases

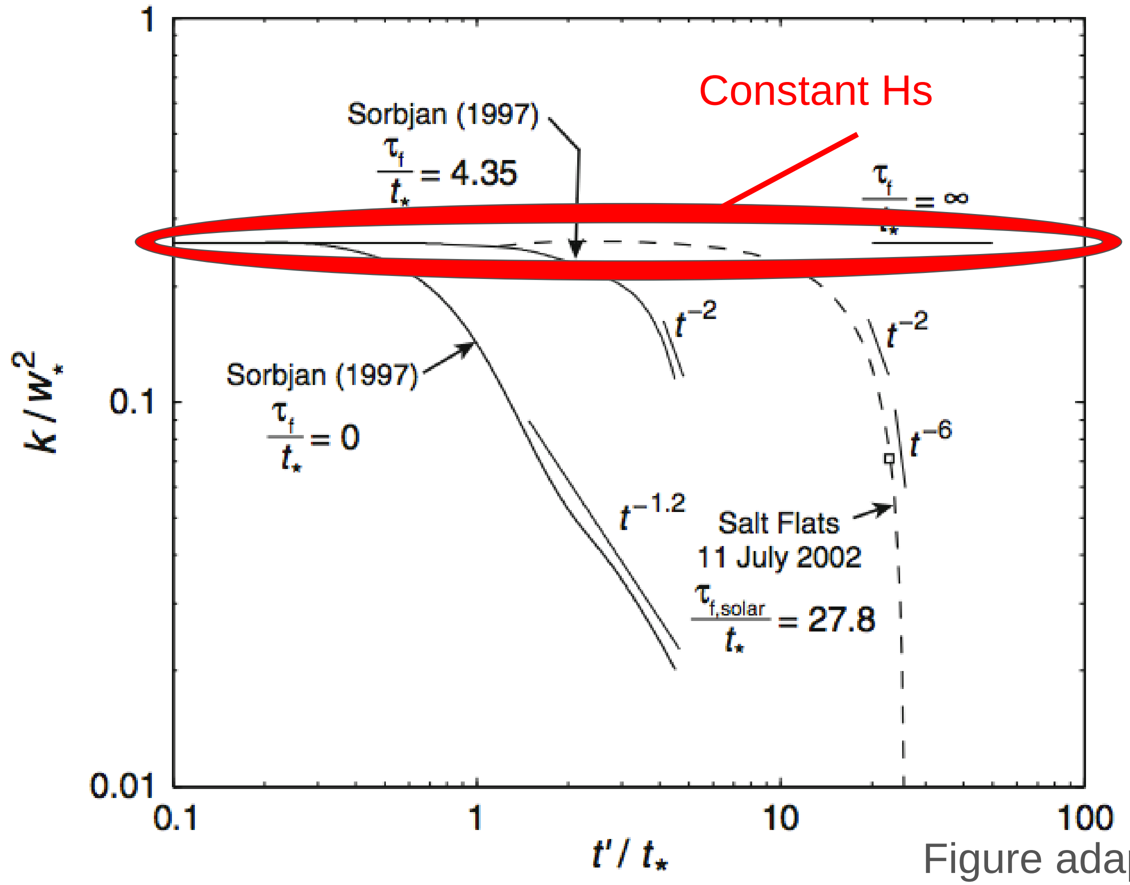
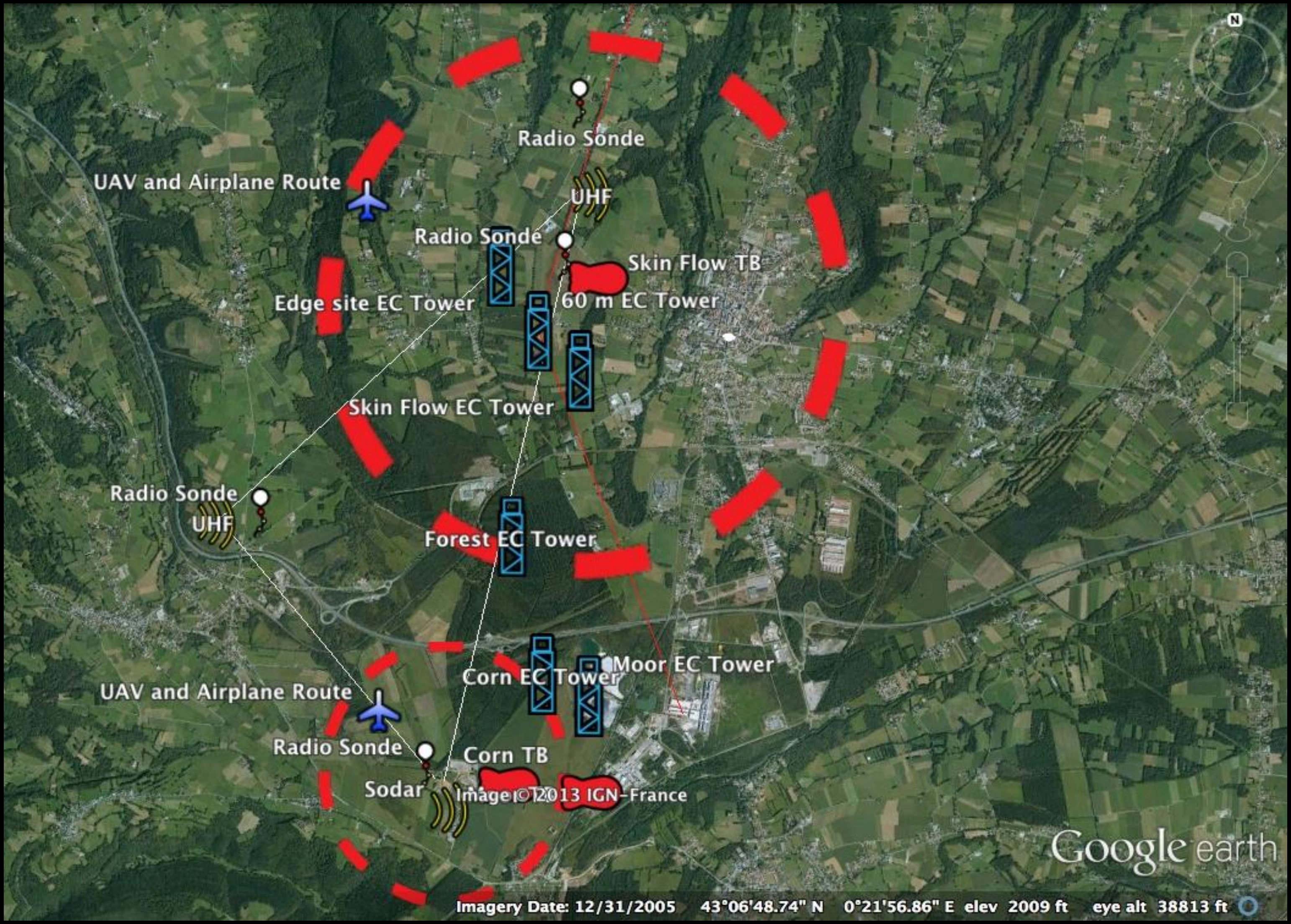


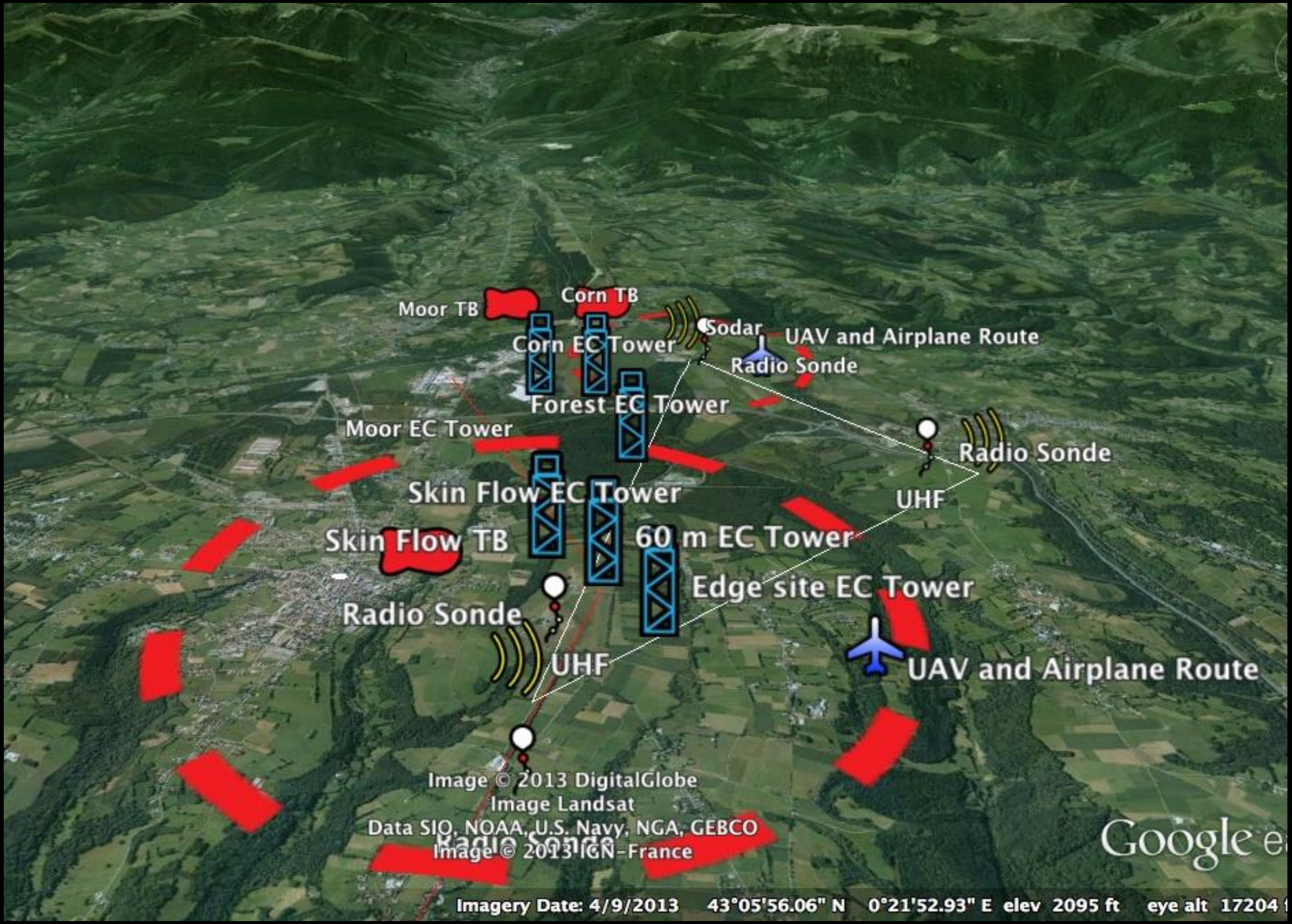
Figure adapted from Sorbjan by Dan Nadeau

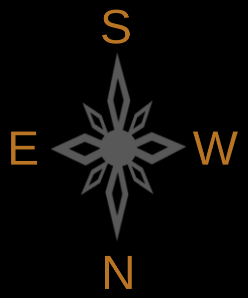
Experimental Setup


Carnac
Loire Valley
France
Basle
St Nazaire
Tours
Dijon
Nantes
Bern
Switzerland
Lausanne
Geneva
La Rochelle
Atlantic Ocean
Chamonix
Aiguille du Midi
Clermont-Ferrand
Sariat-La-Caneda
Annecy
Lyon
Val d'Isere
Meribel
Grenoble
Alps
Italy
Bordeaux
Massif Central
Alpes de Haute Provence
Bay of Biscay
Monaco Principality
Avignon
Les Baux de Provence
Nimes
Arles
Nice
Bayonne
Biarritz
Toulouse
Montpelier
Bilbao
Cannes
Aix-en-Provence
San Sebastien
Carcassonne
Marseilles
St Tropez
Lourdes
Narbonne
Toulon
Gulf of Lion
Cote d'Azur
Pamplona
Pyrenees
Andorra Principality
Perpignan
Corsica island
Spain


Radio Sonde
UAV and Airplane Route
UHF
Radio Sonde
Skin Flow TB
Edge site EC Tower
60 m EC Tower
Skin Flow EC Tower
Radio Sonde
UHF
Forest EC Tower
Moor EC Tower
Corn EC Tower
UAV and Airplane Route
Radio Sonde
Corn TB
Sodar
Image © 2013 IGN-France
Google earth
Imagery Date: 12/31/2005 43°06'48.74" N 0°21'56.86" E elev 2009 ft eye alt 38813 ft

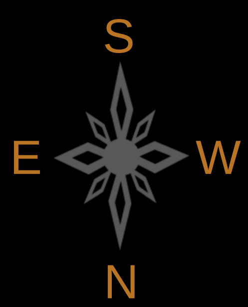

N
W
E
S

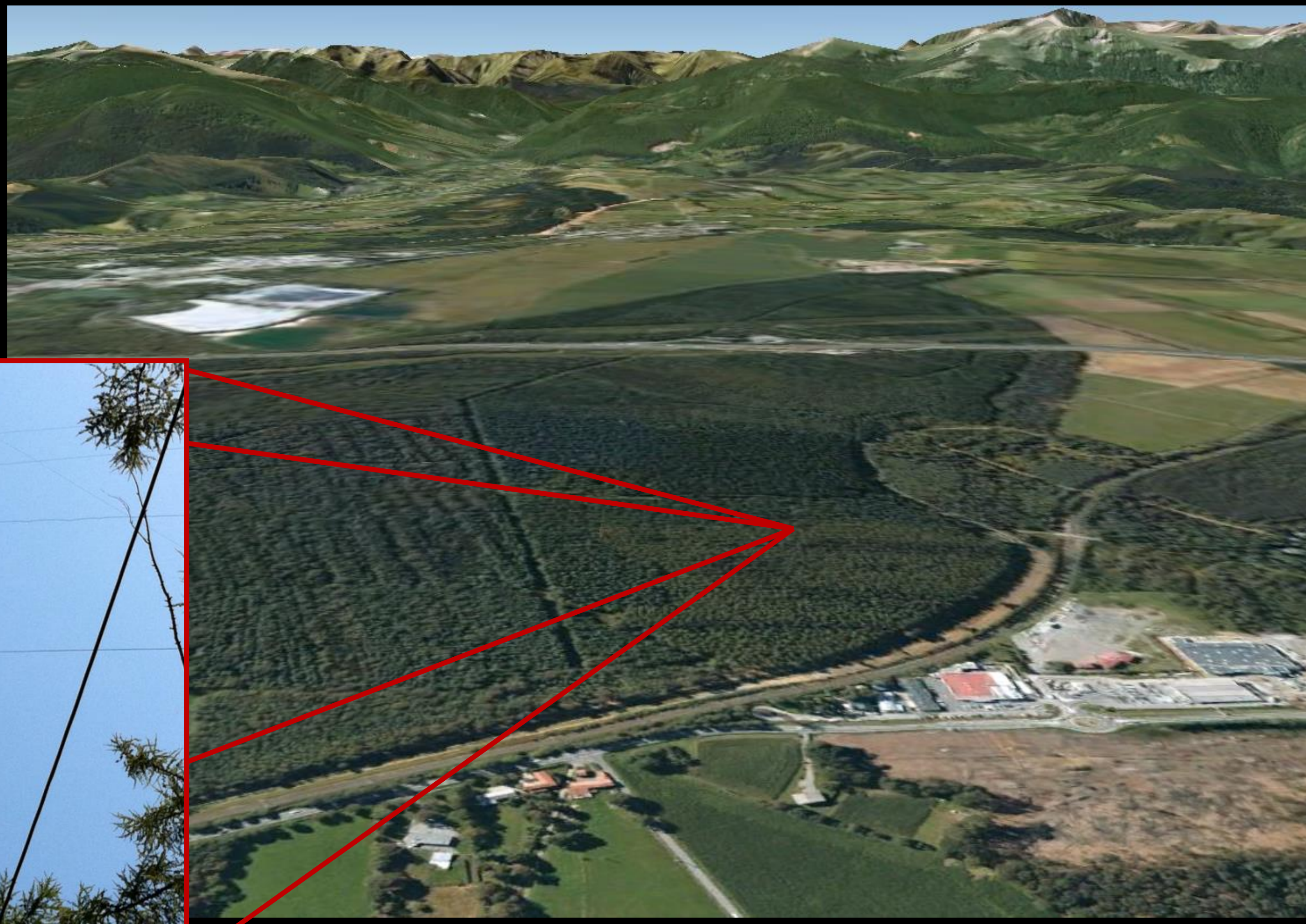

Moor TB
Corn TB
Sodar
Corn EC Tower
UAV and Airplane Route
Radio Sonde
Forest EC Tower
Moor EC Tower
Radio Sonde
Skin Flow EC Tower
UHF
Skin Flow TB
60 m EC Tower
Edge site EC Tower
Radio Sonde
UHF
UAV and Airplane Route
Image © 2013 DigitalGlobe
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2013 IGN-France
Imagery Date: 4/9/2013 43°05'56.06" N 0°21'52.93" E elev 2095 ft eye alt 17204


S
E
W
N

IOPs

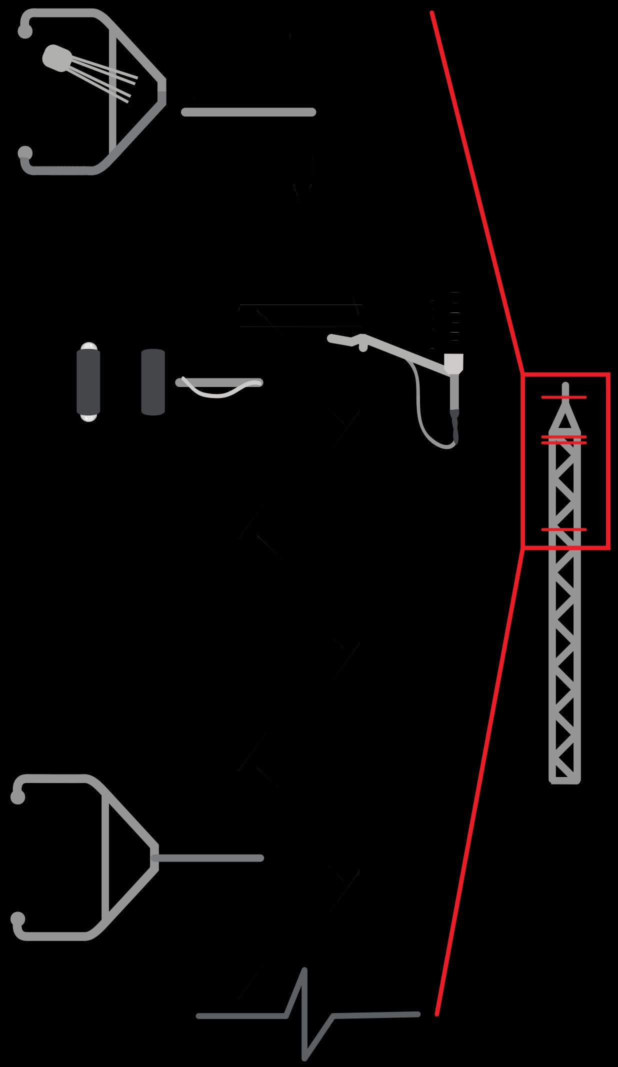
- IOP 1 – 15 June 2011
- IOP 2 – 19 June 2011
- IOP 3 – 20 June 2011
- IOP 4 – 24 June 2011
- IOP 5 – 25 June 2011
- IOP 6 – 26 June 2011
- IOP 7 – 27 June 2011
- IOP 8 – 30 June 2011
- IOP 9 – 01 July 2011
- IOP 10 – 02 July 2011
- IOP 11 – 05 July 2011





Forest Eddy Covariance Tower


Forest Eddy Covariance Tower



CSAT3: 31.55 m
u velocity component
v velocity component
w velocity component
sonic temperature

Finewire TC: 31.55 m
temperature

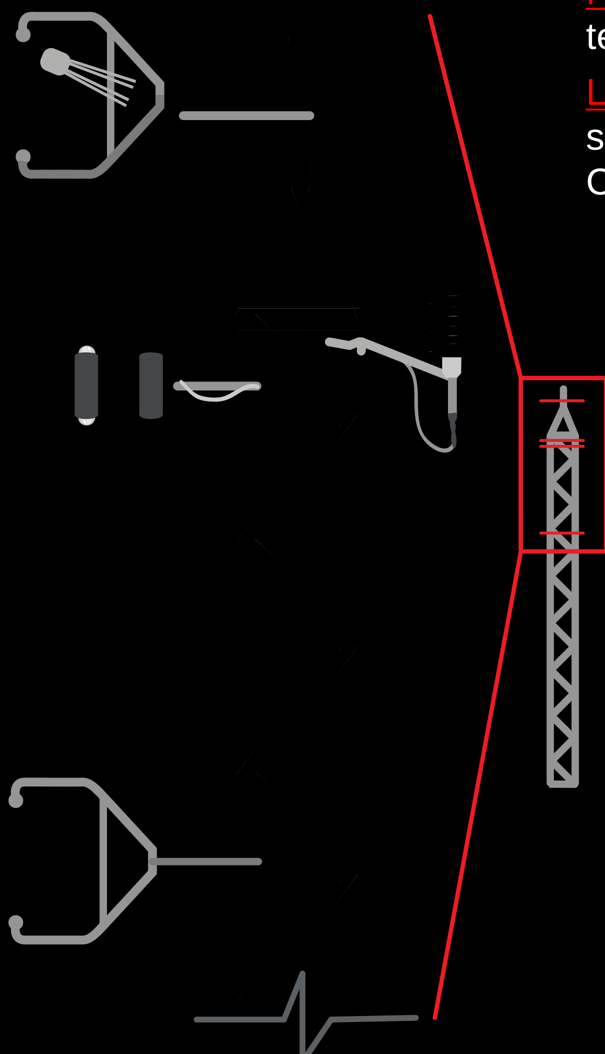
LICOR: 31.55 m
specific humidity
C02 concentration

CNR1: 28.69 m
outgoing shortwave radiation
Incoming shortwave radiation
outgoing longwave radiation
incoming longwave radiation

HMP 45: 29.02 m
relative humidity
temperature

Finewire TC: 21.84 m
temperature

CSAT3: 21.84 m
u velocity component
v velocity component
w velocity component
sonic temperature



Forest Eddy Covariance Tower

Turbulence Kinetic Energy (k) Budget

$$\underbrace{\frac{\partial \overline{k}}{\partial t}}_{\text{term I}} + \underbrace{\overline{u_j}\frac{\partial \overline{k}}{\partial x_j}}_{\text{term II}} = \underbrace{\delta_{i3}\frac{g}{\overline{\theta_v}}(\overline{\theta_v' u_i'})}_{\text{term III}} - \underbrace{(\overline{u_i' u_j'})\frac{\partial \overline{u_i}}{\partial x_j}}_{\text{term IV}} - \underbrace{\frac{\partial \overline{u_j' k}}{\partial x_j}}_{\text{term V}} - \underbrace{\frac{1}{\overline{\rho}}\frac{\partial (\overline{u_i' p'})}{\partial x_i}}_{\text{term VI}} - \underbrace{\epsilon}_{\text{term VII}}$$

- term I: Local Storage term
- term II: Advection by Mean Wind
- term III: Buoyant Production/ Consumption
- term IV: Mechanical Production/ Loss
- term V: Turbulent Transport of k
- term VI: Pressure Correlation Term
- term VII: Viscous Dissipation of k into heat

Assuming a coordinate system aligned with the mean wind, horizontal homogeneity, and neglecting subsidence:

$$\underbrace{\frac{\partial \overline{k}}{\partial t}}_{\text{term I}} = \underbrace{\frac{g}{\overline{\theta_v}}(\overline{\theta_v' w'})}_{\text{term III}} - \underbrace{(\overline{u' w'})\frac{\partial \overline{u}}{\partial z}}_{\text{term IV}} - \underbrace{\frac{\partial \overline{w' k}}{\partial z}}_{\text{term V}} - \underbrace{\frac{1}{\overline{\rho}}\frac{\partial (\overline{w' p'})}{\partial z}}_{\text{term VI}} - \underbrace{\epsilon}_{\text{term VII}}$$

Additional Definitions

k as a function of velocity perturbations:

$$\overline{k} = .5\left[\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2}\right]$$

Deardorff Velocity:

$$w_* = \left[\frac{g}{\theta_v} z_i (\overline{w'\theta_v'})\right]^{\frac{1}{3}}$$

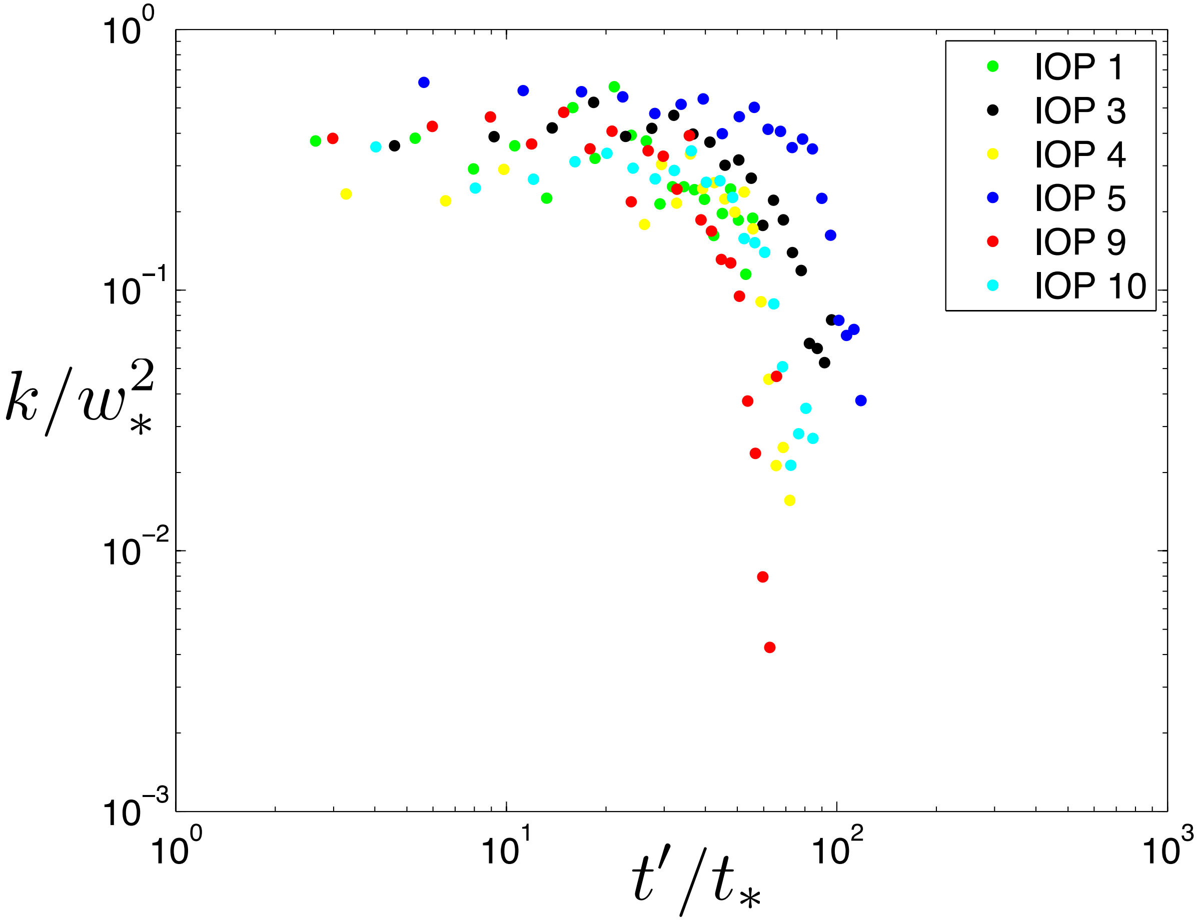
Notation:

t' = Time from start of Decay
z_i = Depth of Boundary Layer at t' = 0
g = Acceleration due to gravity
u' = Perturbation from mean velocity

Eddy Turnover Time:

$$t_* = \frac{w_*}{z_i}$$

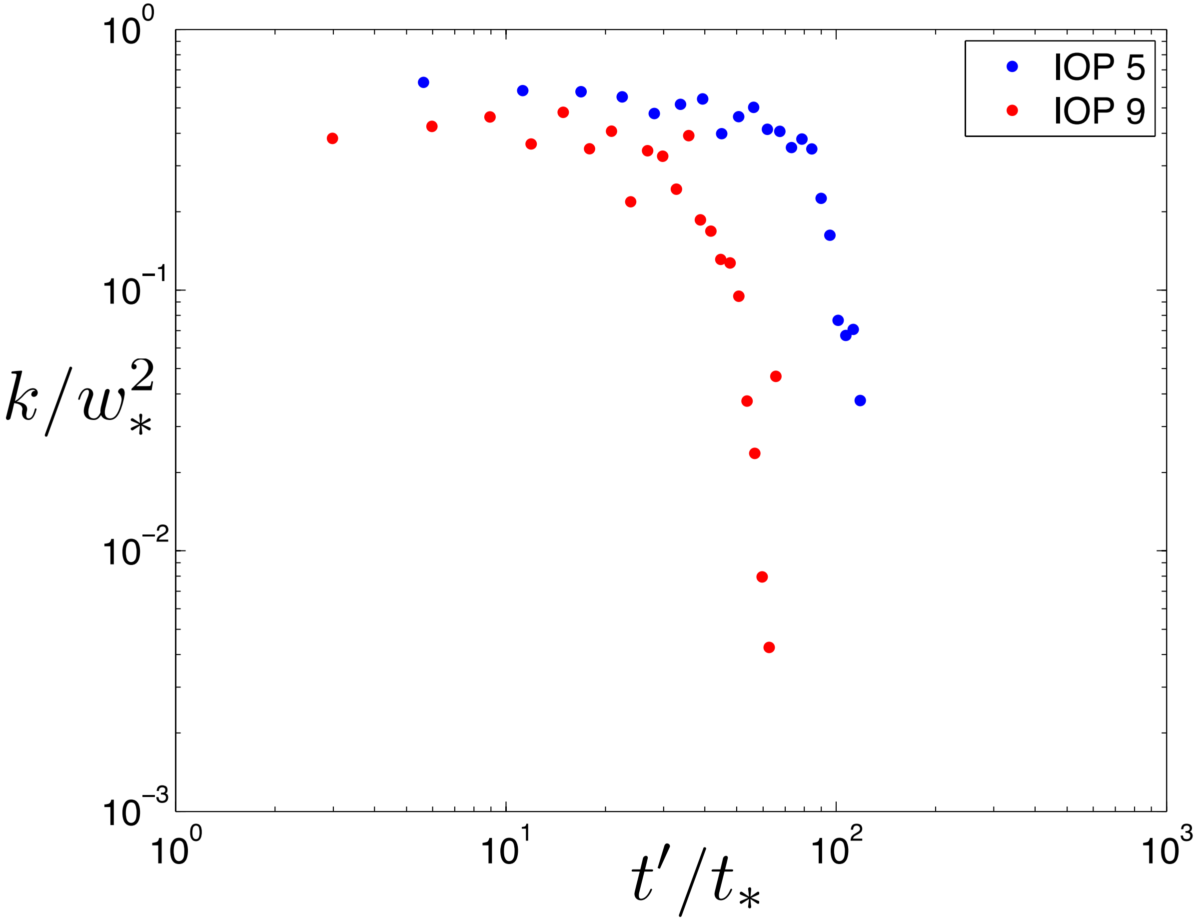
Normalized TKE as a function of Time from Start of Decay



Forest Eddy Covariance Tower

Measurement Height:	$.02z_i$
Roughness Height:	~21 m
Ground Covering:	Forest
Instruments used:	CSAT3

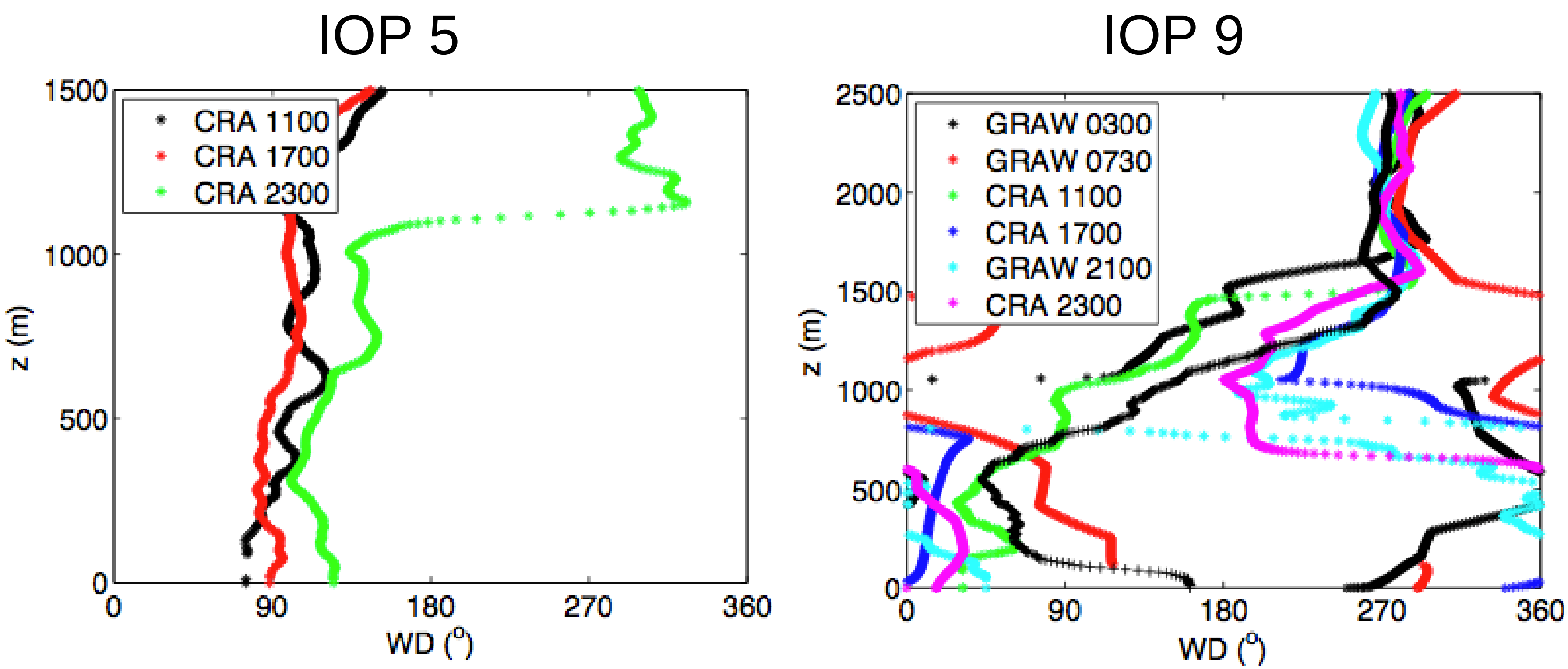
Normalized TKE as a function of Time from Start of Decay



Forest Eddy Covariance Tower

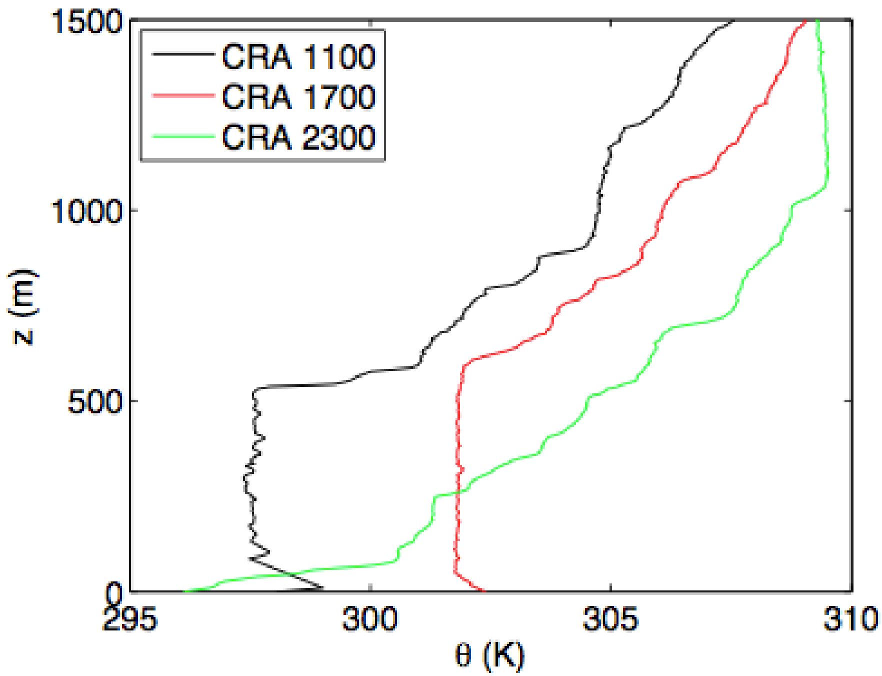
Measurement Height:	$.02z_i$
Roughness Height:	~21 m
Ground Covering:	Forest
Instruments used:	CSAT3

Vertical Wind Direction Profile

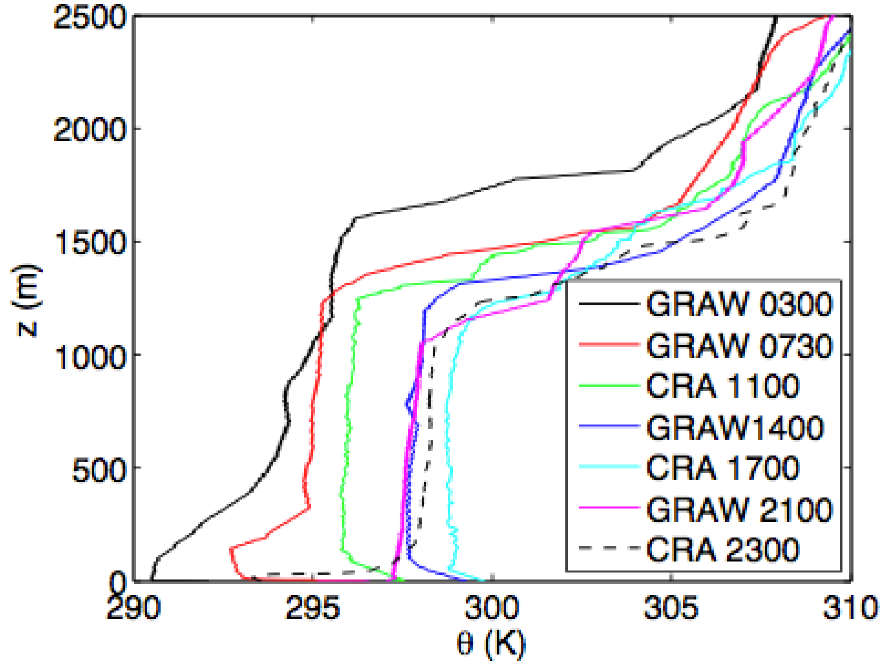


Vertical Wind Temperature Profile

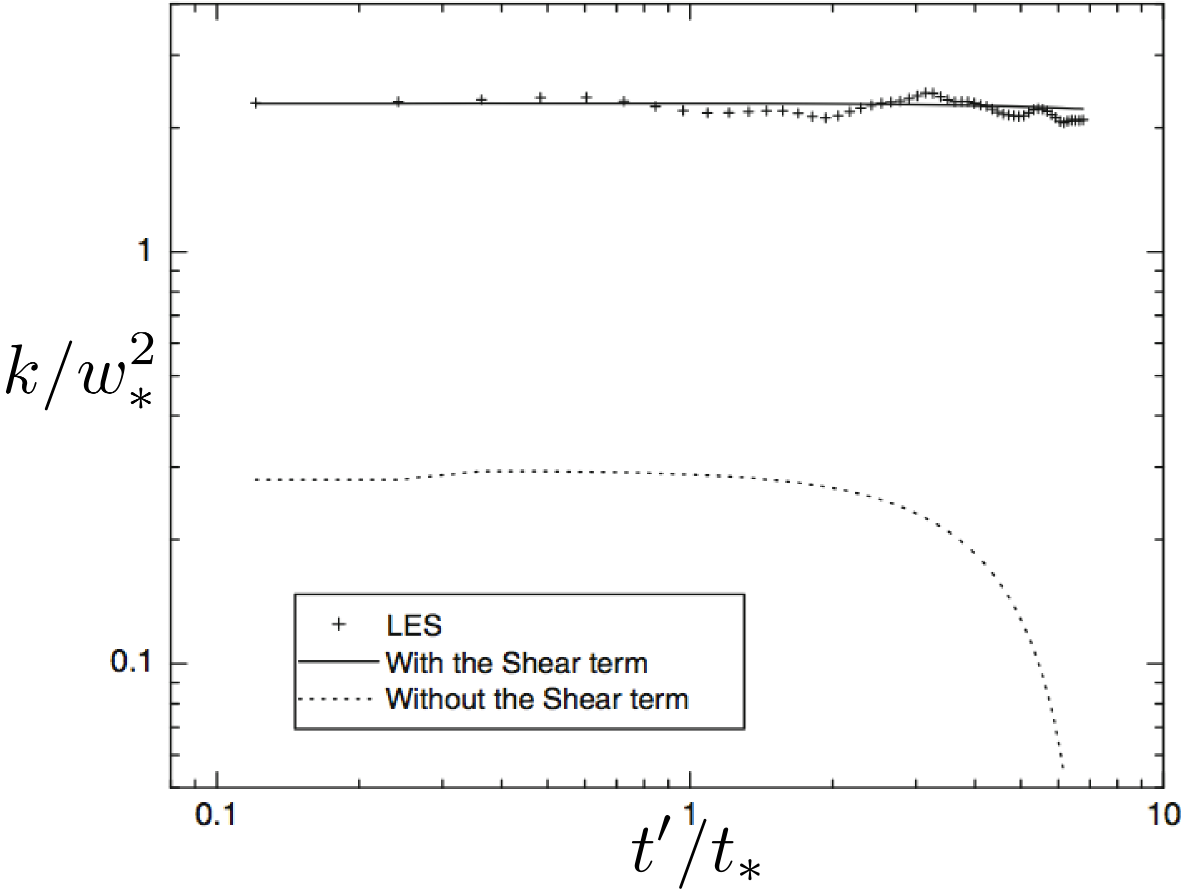
IOP 5



IOP 9



Goulart (2010) Model for the Decay of TKE at .05z_i

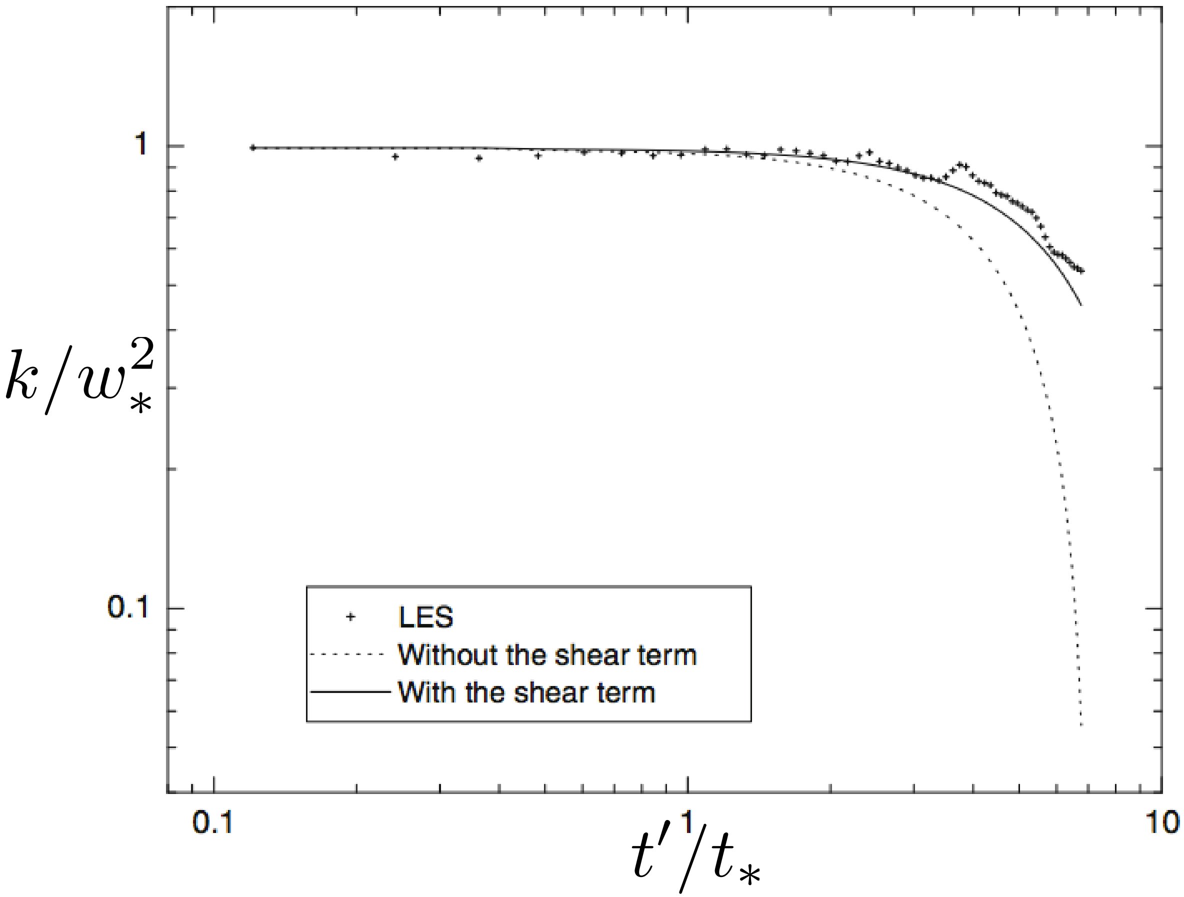


LES Model shown both with and without shear

Measurement Height:	.05z_i
Roughness Height:	N/A
Ground Covering:	N/A
Instruments used:	LES

Goulart (2010)

Goulart (2010) Model for the Decay of TKE at .5z_i

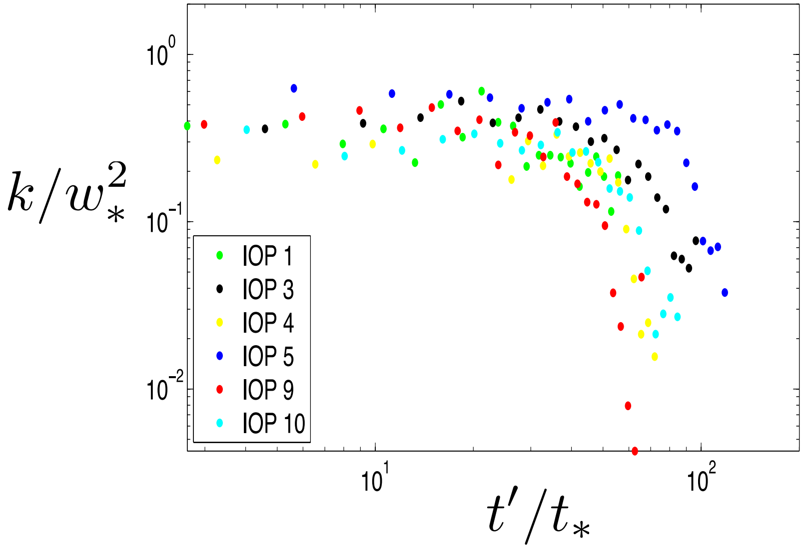


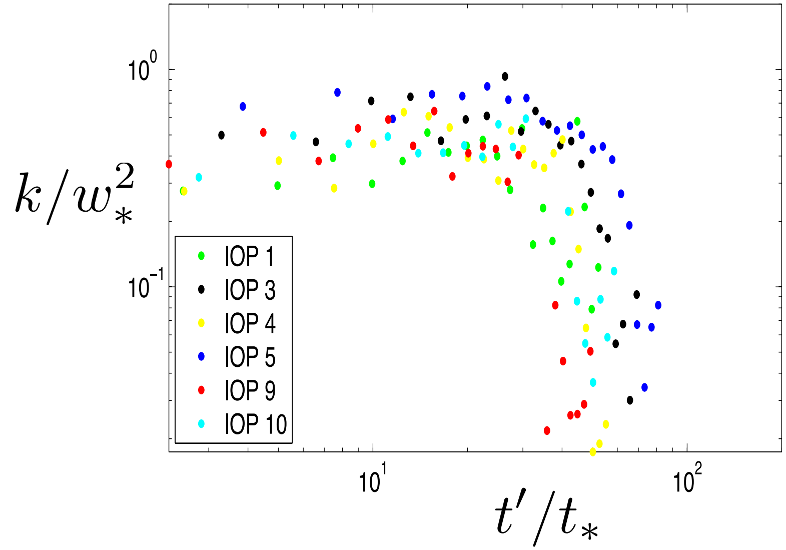
LES Model shown both with and without shear

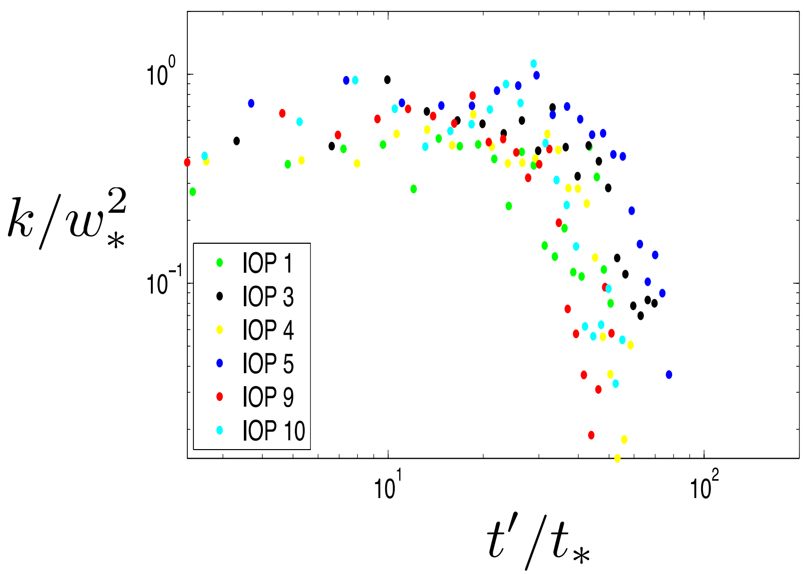
Measurement Height:	.5z_i
Roughness Height:	N/A
Ground Covering:	N/A
Instruments used:	LES

Goulart (2010)

TKE Decay Comparison Between Forest, Corn, and Moor Sites







Forest Eddy Covariance Tower

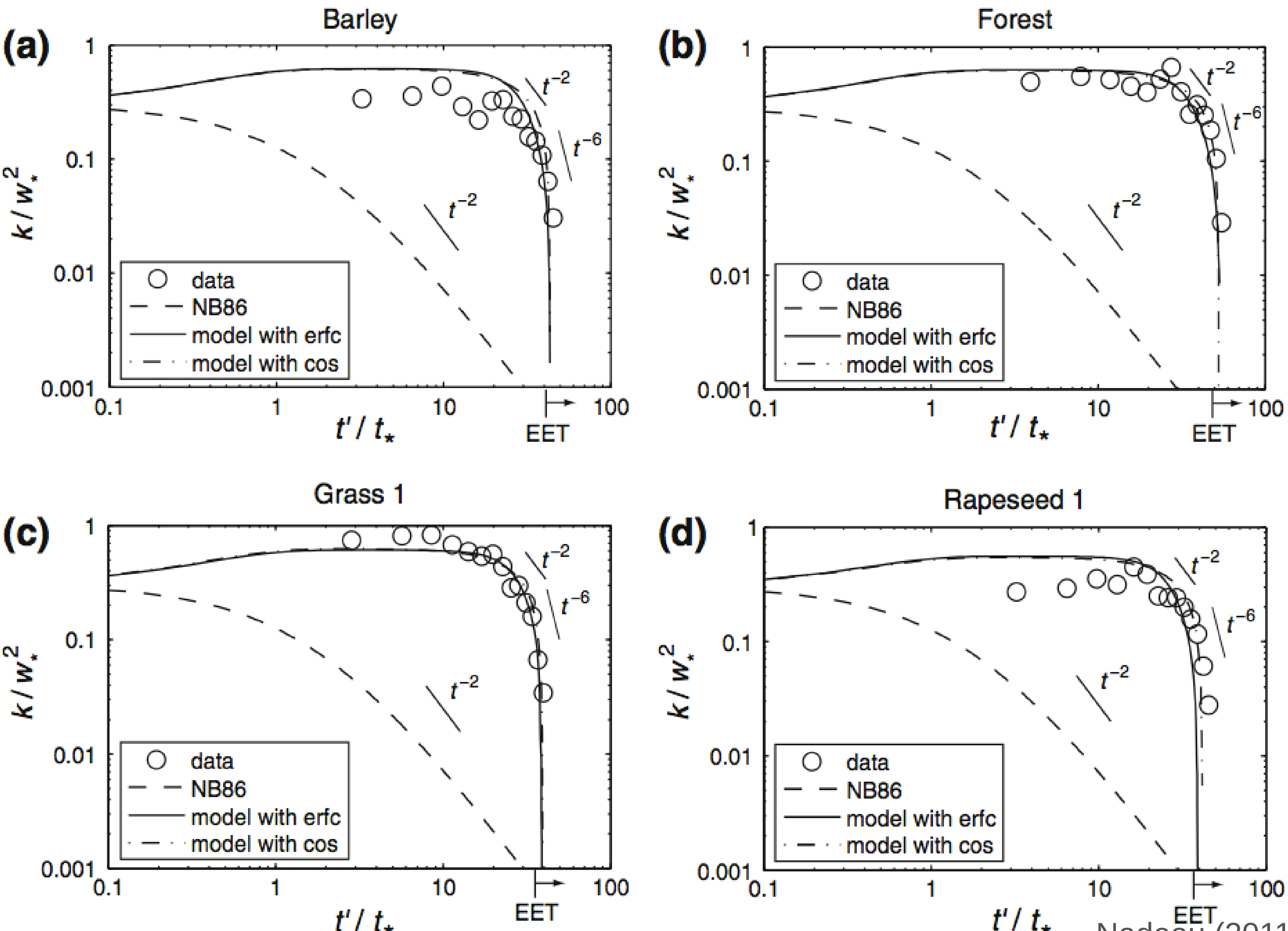
Measurement Height:	$.02z_i$
Roughness Height:	~21 m
Ground Covering:	Forest
Instruments used:	CSAT3

Corn Covariance Tower

Measurement Height:	$.01z_i$
Roughness Height:	~1 m
Ground Covering:	Corn
Instruments used:	CSAT3

Moor Covariance Tower

Measurement Height:	$.005z_i$
Roughness Height:	~.10 m
Ground Covering:	Marsh
Instruments used:	CSAT3

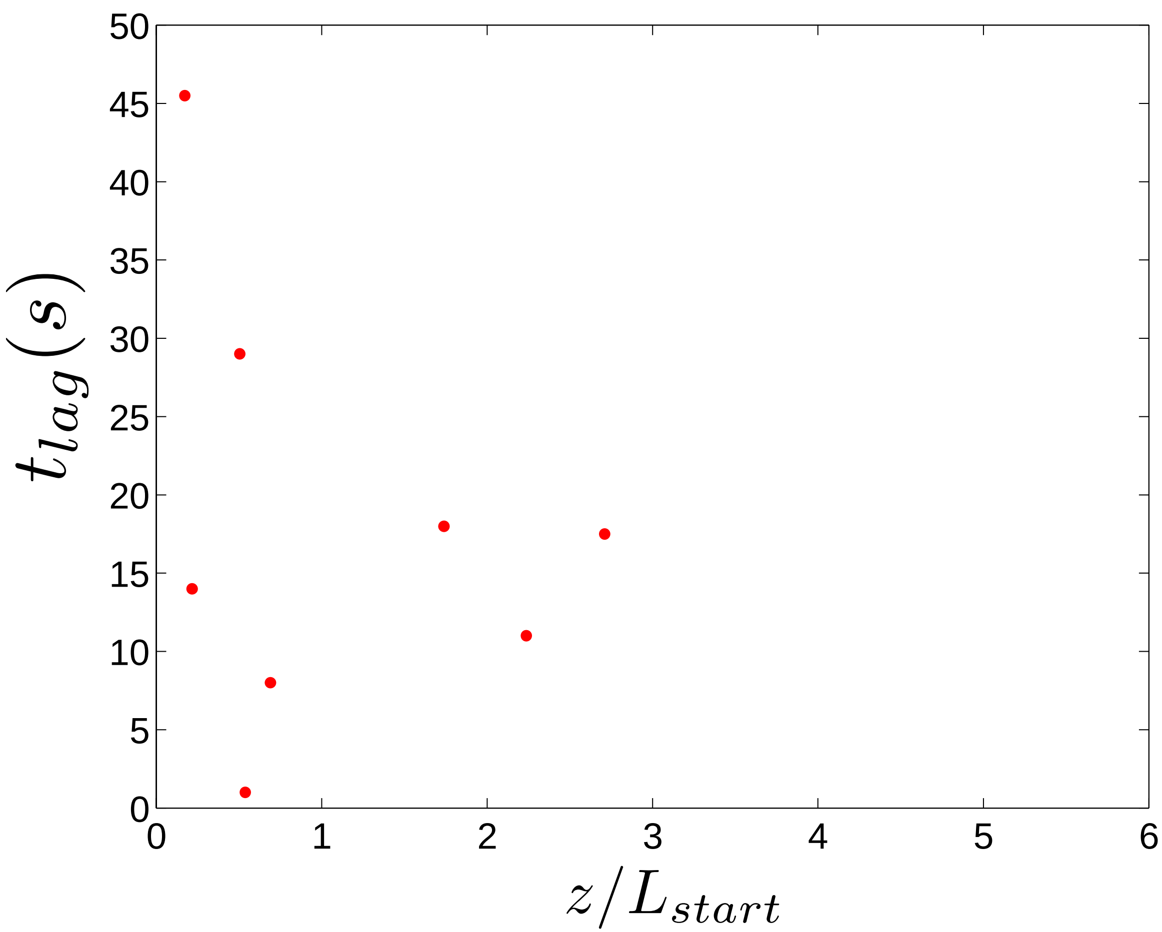

(a)
Barley
(b)
Forest
(c)
Grass 1
(d)
Rapeseed 1
k / w*²
t' / t*
EET
t⁻²
t⁻⁶
data
NB86
model with erfc
model with cos
1
0.1
0.01
0.001
0.1
1
10
100

Nadeau (2011)

Proposed Hypothesis

- H4 – There is a possible delay of the start of the rapid decay period with increased mechanical production of TKE

Lag of the Forest Rapid Decay Period as a Function of z/L

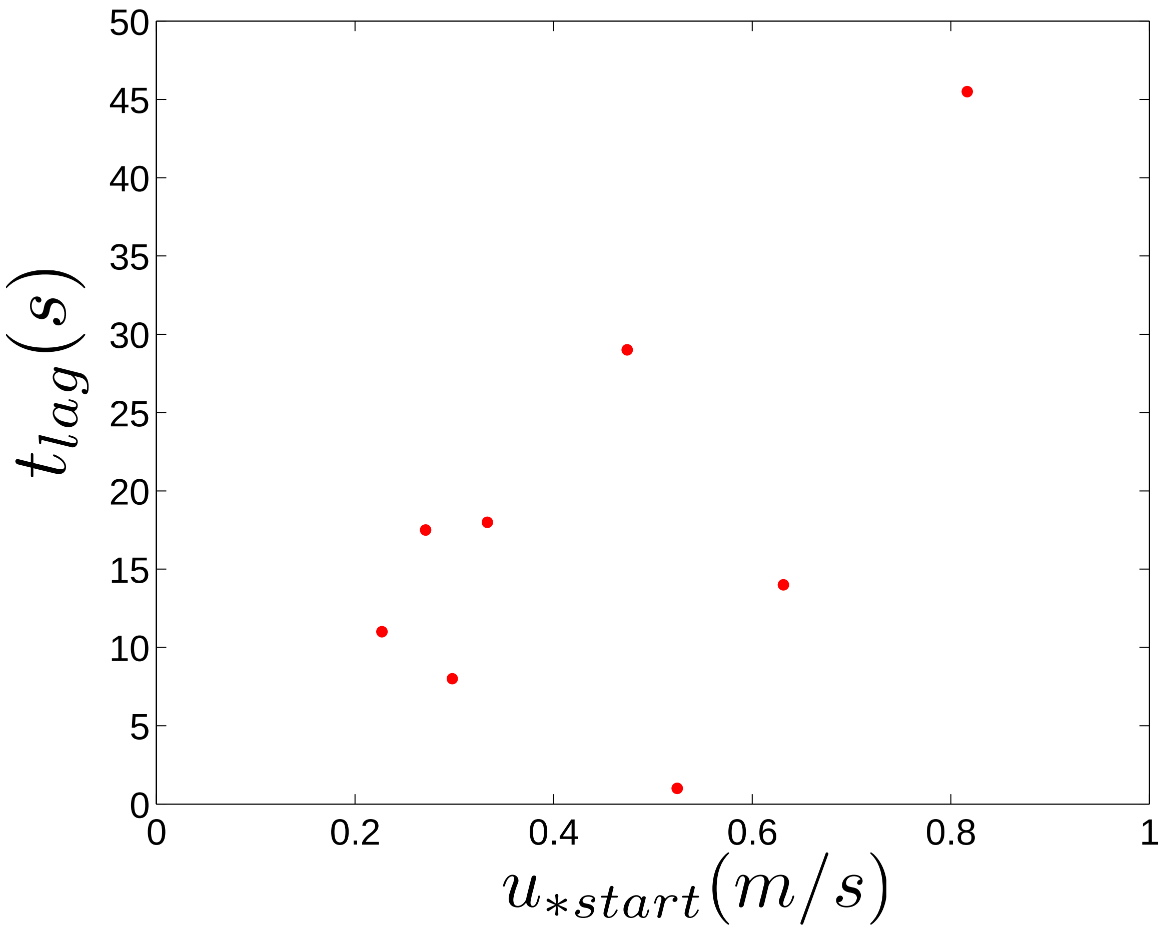


Forest Eddy Covariance Tower

Measurement Height:	$.02z_i$
Roughness Height:	~21 m
Ground Covering:	Forest
Instruments used:	CSAT3

$^*L_{start}$ = Monin-Obukhov length at the start of the decay period

Lag of the Forest Rapid Decay Period as a Function of u_{*start}



Forest Eddy Covariance Tower

Measurement Height:	$.02z_i$
Roughness Height:	~21 m
Ground Covering:	Forest
Instruments used:	CSAT3

$^*u_{*start}$ = Friction velocity at the start of the decay period

Potential Temperature Variance

- To better understand the decay of turbulence variables near the transition it may be useful to explore the potential temperature variance budget equation

- First, a brief literature review of work exploring the potential temperature variance budget and methods of calculating the various terms

Authors	Method of Study	Region of Interest	Key Findings
Wynguard and Coté (1970)			
Champagne et. al. (1976)	Field Obs., Minnesota	Unstable Surface Layer	Flux measurement and turbulence measurements
Antonia et al. (1979)	Field Obs., Bungendore	Entire ABL	
Pahlow et. al.(2000)	Multiple field experiments	Stable ABL	Support for M.O.S.T.
Grant (1997)	Field Obs. Cardington, UK	Entire ABL	heat flux profiles strong cooling near the surface, t* ~ u*/h
Cole & Fernando (1998)	Laboratory	Entire boundary layer	σ_T & σ_w decay t ~ DT/(dTs/dt)
Acevado & Fitzgerald (2001)	Field	Surface Layer	Spatial Heterogienity
Pardyjak 2001	Field Obs., Phoenix	Surface Layer	Simple decay model σ_T & σ_w decay at different rates

Potential Temperature Variance Budget

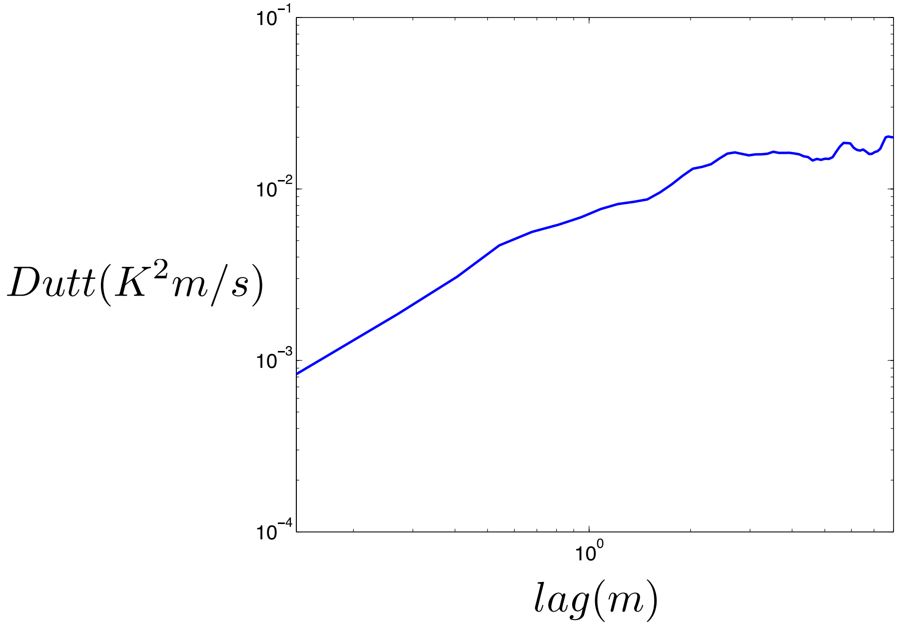
$$\underbrace{\frac{\partial\overline{\theta'^2}}{\partial t}}_{\text{term I}} + \underbrace{u_j\frac{\partial\overline{\theta'^2}}{\partial x_j}}_{\text{term II}} = -\underbrace{2\overline{\theta' u'_j}\frac{\partial\overline{\theta}}{\partial x_j}}_{\text{term III}} - \underbrace{\frac{\partial\overline{u'_j\theta'^2}}{\partial x_j}}_{\text{term IV}} - \underbrace{2\epsilon_\theta}_{\text{term V}} - \underbrace{\epsilon_R}_{\text{term VI}} - \underbrace{\mu\phi_v}_{\text{term III}}$$

- term I: Storage
- term II: Advection by Mean Wind
- term III: Production
- term IV: Turbulent Transport
- term V: Molecular Dissipation
- term VI: Radiation Destruction
- term III ($\mu\phi_v$): Viscous Dissipation

Assuming horizontal homogeneity, no subsidence, and neglecting molecular diffusion:

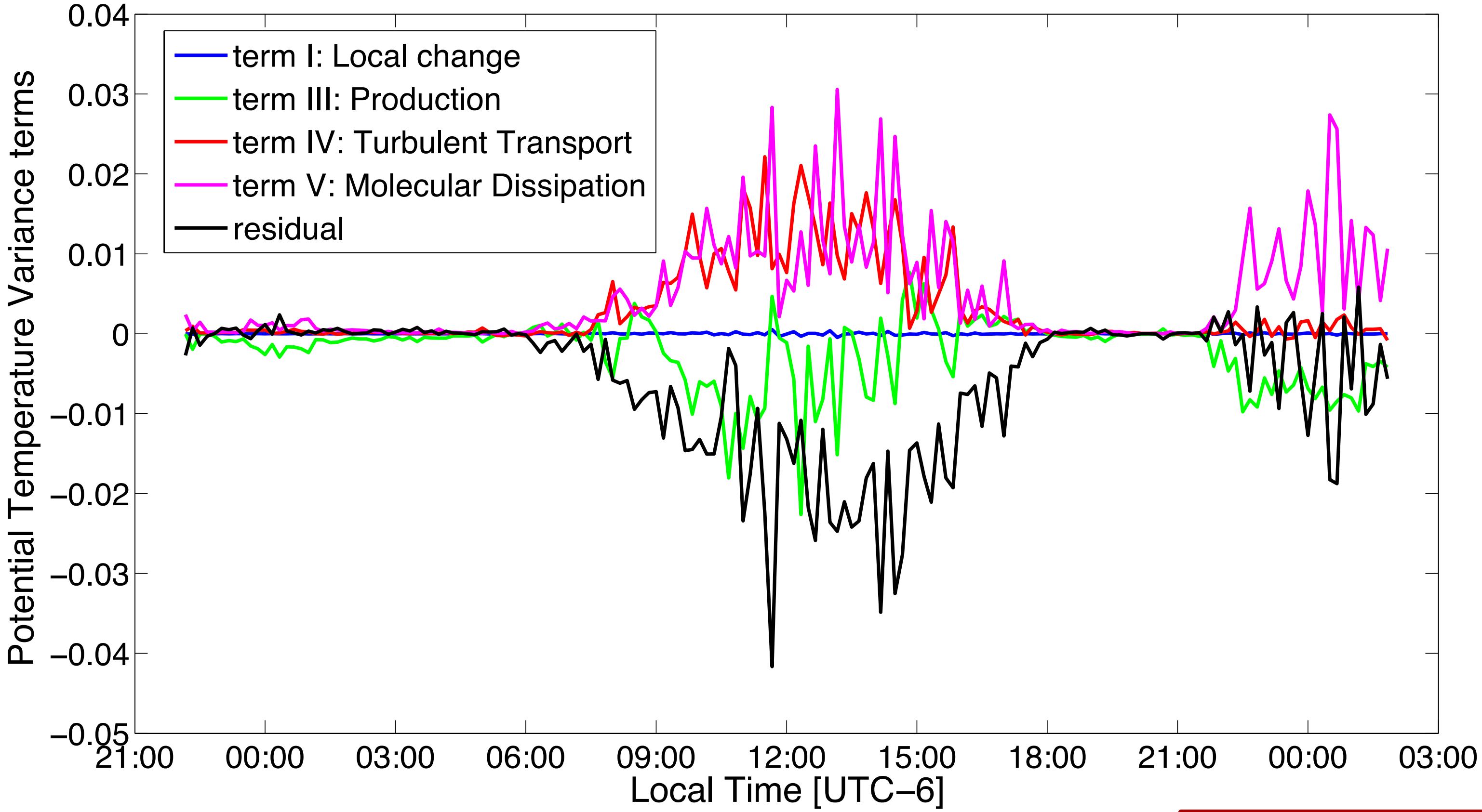
$$\underbrace{\frac{\partial\overline{\theta'^2}}{\partial t}}_{\text{term I}} = -\underbrace{2\overline{\theta' w'}\frac{\partial\overline{\theta}}{\partial z}}_{\text{term III}} - \underbrace{\frac{\partial\overline{w'\theta'^2}}{\partial z}}_{\text{term IV}} - \underbrace{2\epsilon_\theta}_{\text{term V}} - \underbrace{\epsilon_R}_{\text{term VI}}$$

Calculating Molecular Dissipation using the Third Order Longitudinal Structure Function



$$-\frac{4}{3}r\langle\epsilon_\theta\rangle = \left\langle (u(x+r)-u(x))(\theta(x+r)-\theta(x))^2 \right\rangle$$

Potential Temperature Variance Budget



Forest Eddy Covariance Tower

Measurement Height:	$.02z_i$
Roughness Height:	~21 m
Ground Covering:	Forest
Instruments used:	CSAT3

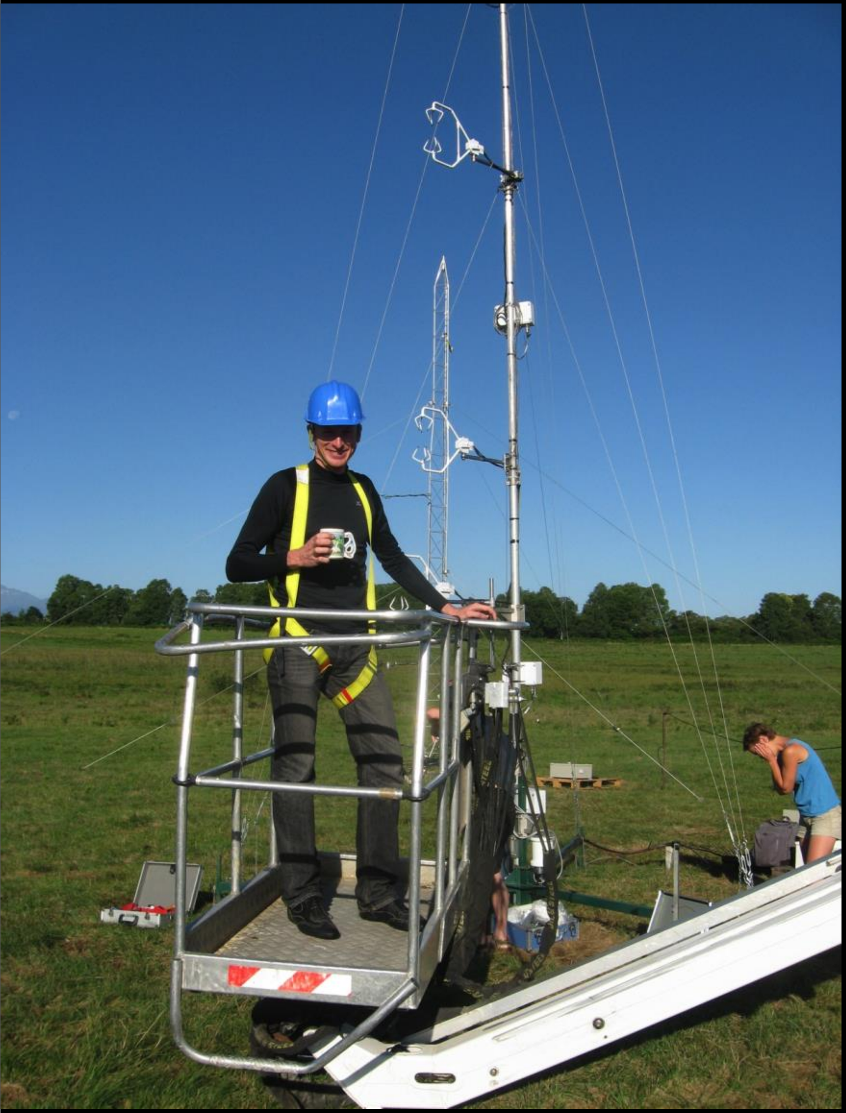
Summary

- Two TKE decay regimes are observed throughout the IOPs
- Mechanical Shear within the boundary layer varies as the transition nears, models need to take this into account to avoid over-predicting mechanical production of TKE
- There is a possible delay of the start of the rapid decay period observed with an increase in mechanical production of TKE
- The radiation destruction term of the potential temperature variance equation does not appear to always be negligible

Future Work

- Quantify the delay of TKE decay during periods of high synoptic forcing. Explore scaling by characteristic parameters.

- Further explore the potential temperature variance equation to better understand the decay of turbulence variables near the transition



Feedback and Questions