Turbulent transport of the energy in the entrainment interface layer

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Outline

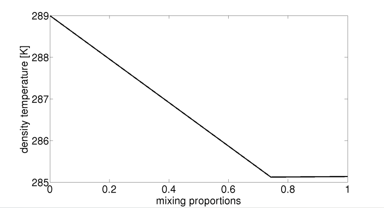
Outline

Physics of Stratocumulus Top (POST)

- POST (Physics of Stratocumulus Top) - aircraft field study off the California Coast in 2008.
- Single aircraft investigating unbroken stratocumulus clouds (Sc) near cloud top
- Aircraft instrumented with a full suite of probes for measuring state parameters of the atmosphere, drop spectra, CCN, irradiances, wind velocity and turbulence

Flight TO13

- date: 09-08-2008
- evening flight
- weak inversion
- small surface fluxes:
  5 W/m^2 (sensible heat) and
  10 W/m^2 (latent heat)
- no bouayancy reversal due to entrainment/mixing



Outline

Physics of Stratocumulus Top (POST)

Setup

Results

Summary

LES setup

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- EULAG model - anelastic equations
- domain size: $4\times4\times1.2$ km
- grid: $20\times20\times2.5$ m
- time step: 0.3 s
- simulated time: 4 h
- 4 simulations

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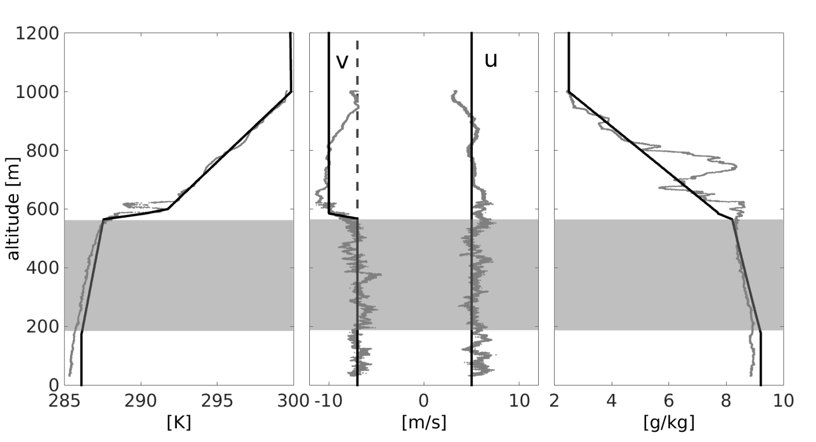
  - "shrc" - with wind shear and radiative cooling.

LES initial profiles



potential temperature, velocity components and water vapour mixing ratio

LES radiative cooling

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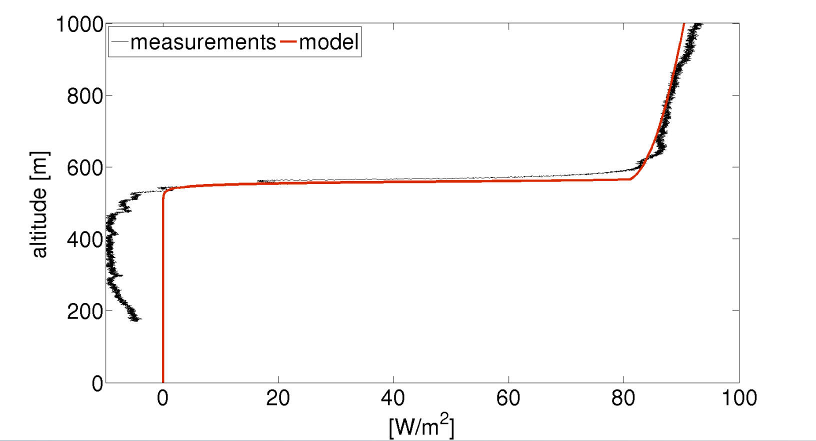
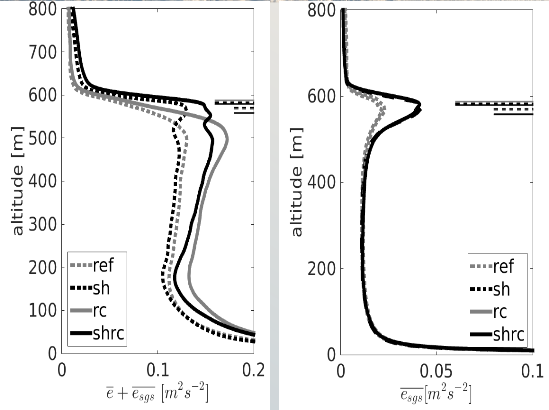


$$F_{rad} = \begin{cases} F_0 e^{-\int_z^{\infty} k q_c dz} & z < z_i \\ F_0 e^{-\int_z^{\infty} k q_c dz} + C(z-z_i)^{1/2} & z \geq z_i \end{cases}$$

Outline

Turbulent kinetic energy (TKE)

$$\overline{e} = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$



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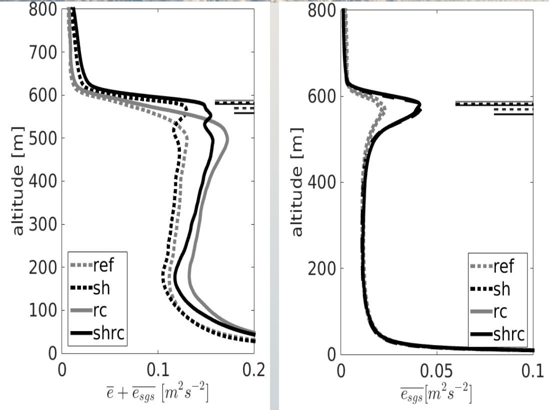

- TKE is larger in cases with radiative cooling.

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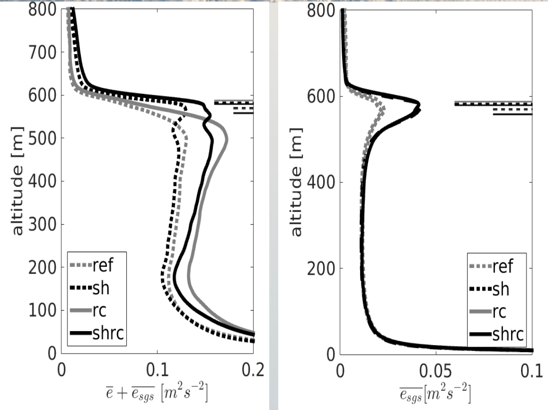

- TKE is larger in cases with radiative cooling.
- TKE profile has two local maximum near cloud top in wind shear cases.

TKE budget

$$\frac{\partial \overline{e}}{\partial t} + \overline{w}\frac{\partial \overline{e}}{\partial z} = \frac{g}{\overline{\theta_v}}\overline{w'\theta_v'} - \left(\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}\right) - \frac{\partial \overline{w'e}}{\partial z} + -\frac{1}{\overline{\rho}}\frac{\partial \overline{w'p'}}{\partial z} - \epsilon.$$

TKE budget

tendency

$$\frac{\partial \overline{e}}{\partial t} + \overline{w}\frac{\partial \overline{e}}{\partial z} = \frac{g}{\overline{\theta_v}}\overline{w'\theta_v'} - \left(\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}\right) - \frac{\partial \overline{w'e}}{\partial z} + -\frac{1}{\overline{\rho}}\frac{\partial \overline{w'p'}}{\partial z} - \epsilon.$$

TKE budget

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tendency — advection

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TKE budget

tendency advection

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buoyant production/
consumption

TKE budget

tendency — advection

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buoyant production/
consumption

shear production/
loss

TKE budget

tendency advection

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turbulent transport

buoyant production/ consumption

shear production/ loss

TKE budget

$$\frac{\partial \overline{e}}{\partial t} + \overline{w}\frac{\partial \overline{e}}{\partial z} = \frac{g}{\overline{\theta}_v}\overline{w'\theta'_v} - \left(\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}\right) - \frac{\partial \overline{w'e}}{\partial z} + -\frac{1}{\overline{\rho}}\frac{\partial \overline{w'p'}}{\partial z} - \epsilon.$$

- tendency
- advection
- buoyant production/ consumption
- shear production/ loss
- turbulent transport
- pressure correlation

TKE budget

tendency advection

$$\frac{\partial \overline{e}}{\partial t} + \overline{w}\frac{\partial \overline{e}}{\partial z} = \frac{g}{\overline{\theta}_v}\overline{w'\theta'_v} - \left(\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}\right) - \frac{\partial \overline{w'e}}{\partial z} + - \frac{1}{\overline{\rho}}\frac{\partial \overline{w'p'}}{\partial z} - \epsilon.$$

turbulent transport

buoyant production/ consumption

dissipation

shear production/ loss

pressure correlation

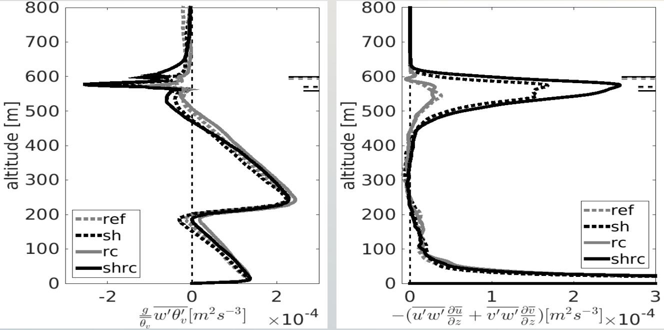
TKE budget

$$\frac{\partial \overline{e}}{\partial t} + \overline{w}\frac{\partial \overline{e}}{\partial z} = \frac{g}{\overline{\theta_v}}\overline{w'\theta_v'} - \left(\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}\right) - \frac{\partial \overline{w'e}}{\partial z} + -\frac{1}{\overline{\rho}}\frac{\partial \overline{w'p'}}{\partial z} - \epsilon.$$

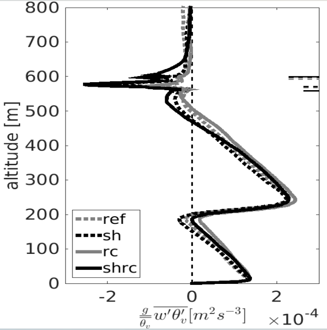
buoyant production/
consumption

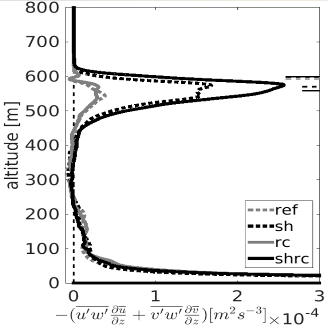
shear production/
loss

TKE budget - buoyant and shear production



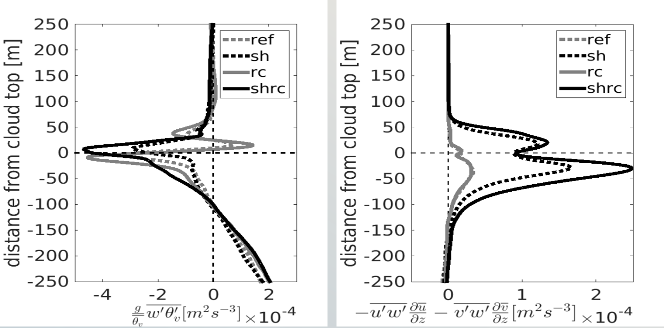
TKE budget - buoyant and shear production





- Radiative cooling prevents decoupling.

TKE budget - buoyant and shear production



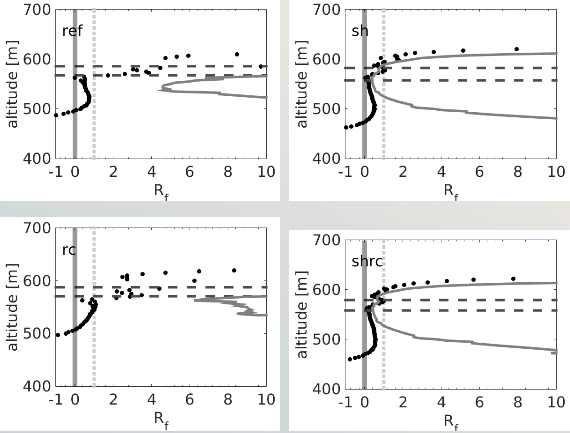
Richardson number

Flux Richardson number (dots)

$$R_f = \frac{\frac{g}{\theta_v}\overline{w'\theta'_v}}{\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \overline{v'w'}\frac{\partial \overline{v}}{\partial z}}$$

Gradient Richardson number (grey solid lines)

$$Ri = \frac{\frac{g}{\theta_v}\frac{\partial \overline{\theta_v}}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$$



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turbulent transport

pressure correlation

TKE budget - turbulent transport and pressure correlation

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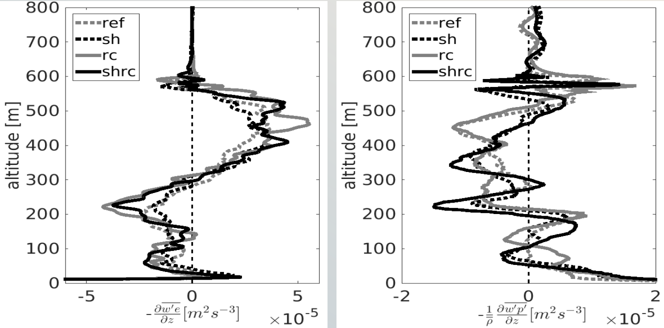

TKE budget - turbulent transport and pressure correlation

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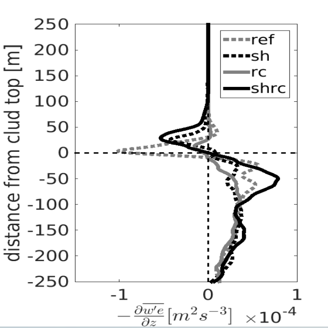
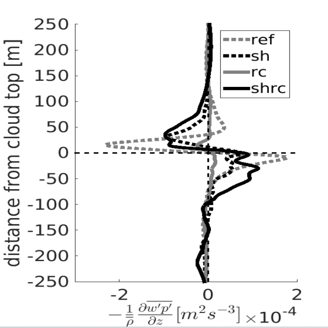
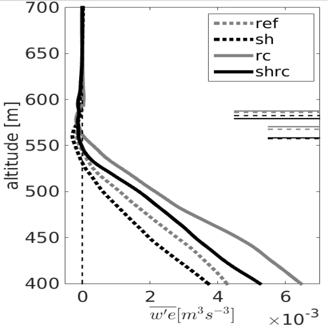
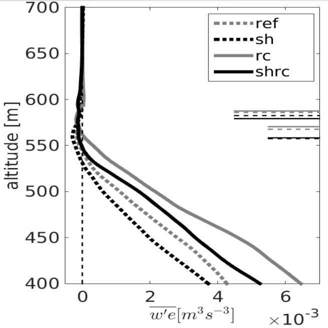




TKE - vertical transport

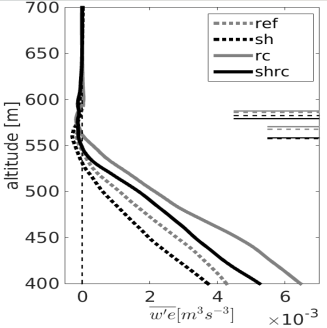


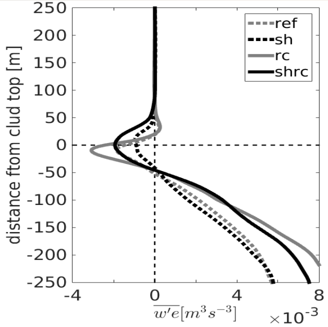
TKE - vertical transport



- Stronger vertical transport of TKE in radiative cooling cases.

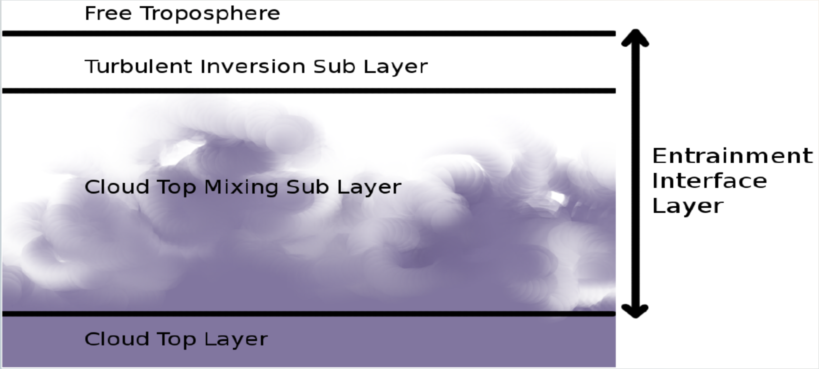
TKE - vertical transport





- Stronger vertical transport of TKE in radiative cooling cases.
- Upward transport of TKE ends $\sim 50\,m$ below cloud top.

Comparison with measurements - layers



Comparison with measurements

		Thickness [m]	TKE dissipation rate $[m^2 s^{-3} \cdot 10^{-3}]$	Shear $[s^{-1}]$	Corrsin scale [m]
TISL	m	14.3 ± 14.3	0.32 ± 0.92	0.11 ± 0.06	0.59 ± 0.45
	SHRC	19.7 ± 27.7	5.30 ± 0.33	0.070 ± 0.003	3.62 ± 0.06
CTMSL	m	74.2 ± 35.5	0.85 ± 0.45	0.05 ± 0.02	3.60 ± 1.72
	SHRC	54.3 ± 47.0	1.22 ± 1.22	0.03 ± 0.01	4.50 ± 0.01

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- Turbulence in both layers is anisotropic.

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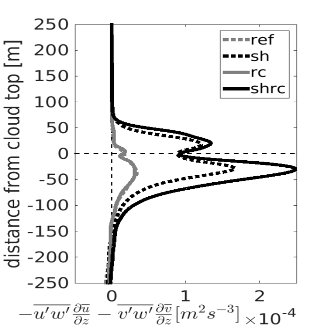
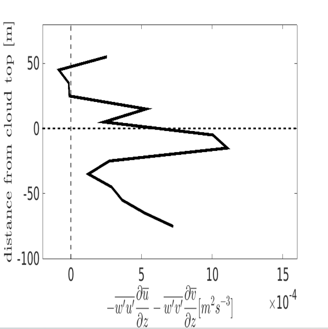
- Corsin scale in TISL in simulation was much larger than in the measurements, in CTMSL was comparable.

Comaprison with measurements





- TKE production by shear near cloud top has similar shape in measurements and in SHRC simulation.

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Physics of Stratocumulus Top (POST)

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- Two adjacent to cloud top layers were found (TISL and CTMSL).
- Both layers are turbulent.
- Turbulence in both layers is anisotropic.
- TKE transport in cloud top region is downward.
- TKE production by shear near cloud top has similar shape in measurements and in SHRC simulation.

Thank you for your attention.