LES of the spatially developing Sc to Cu cloud transition

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Introduction

- Motivation
  - What is the marine boundary layer cloud response to climate change?
  - The stratocumulus to cumulus cloud transition ("the transition") as a means to help answer a key question about cloud–climate feedback
- Large-eddy simulation of idealized cases (i.e., theoretical investigation)
  - Idealization in the sense that only a limited range of scales is simulated
  - Small-scale boundary layer view of the transition (no feedbacks with large-scale)
- This presentation discusses modeling approaches and boundary layer physics for spatially developing LES of the Cu to Sc transition
- Continuation of previous work
  - Horizontally-homogeneous steady-state simulations at different stages of the transition
    - Chung et al. (2012)
  - Boundary conditions for LES of spatially developing boundary layer
    - Inoue et al. (2014)
  - Investigation of the spatially developing transition
    - Inoue et al. (in preparation)
- Model is JPL's LES (Matheou & Chung 2014)

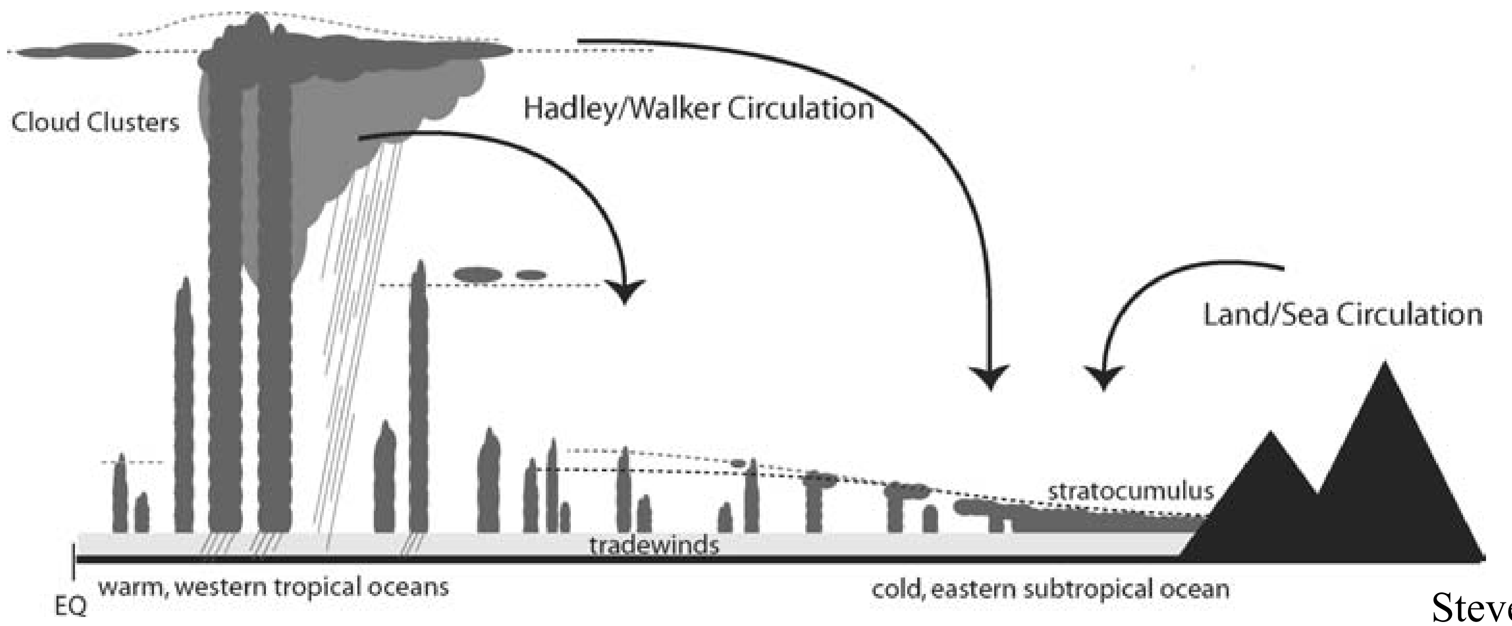
The transition and mean circulation

- All transition simulations employ a significant degree of idealization

Mean circulation

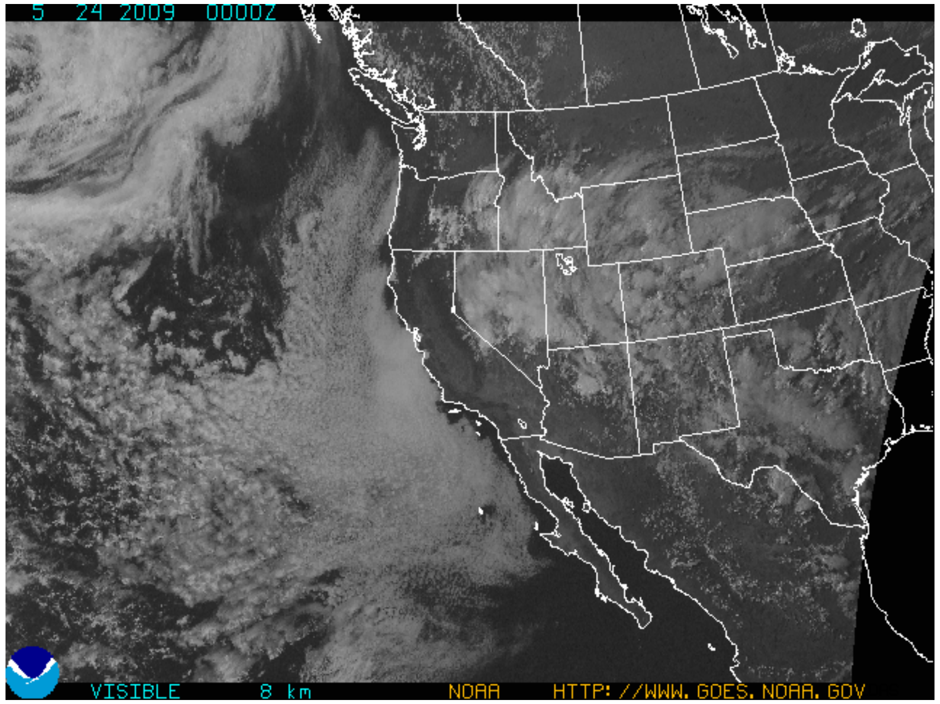
also see,

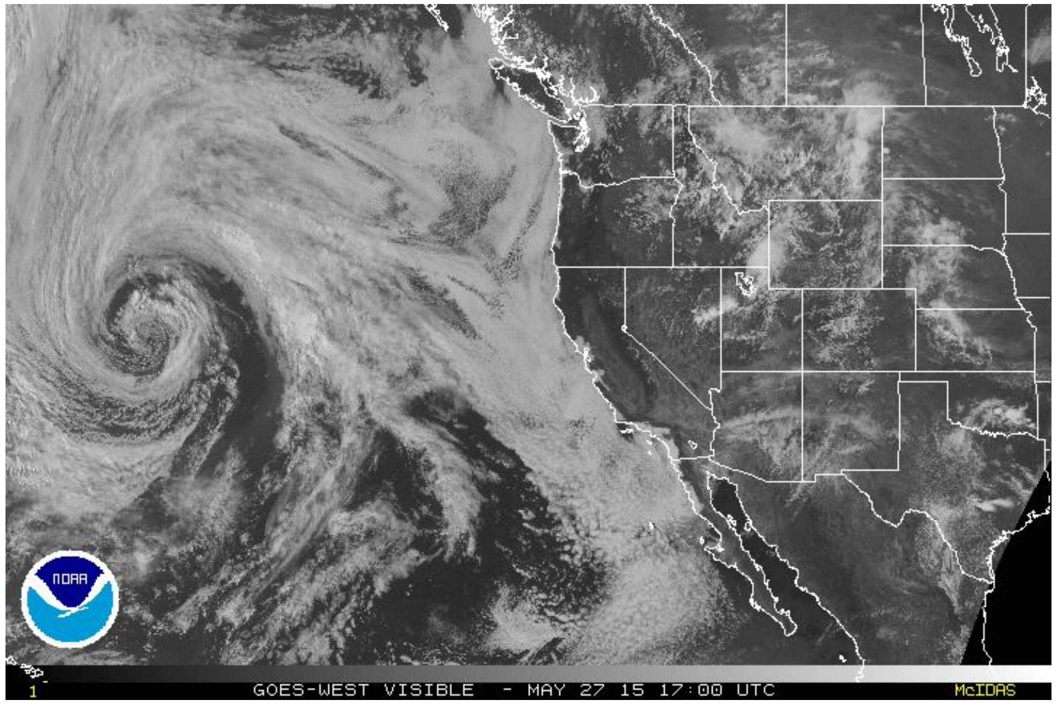
- Karlsson et al. (2010)
- Teixeira et al., GPCI (2011)



Stevens (2005)

Instantaneous realizations





GOES NOAA

Why a spatially developing case?

- Lateral periodicity imposes significant restrictions on solution
  - E.g., all x-means of x-derivatives must vanish $\left\langle \frac{\partial \bullet}{\partial x} \right\rangle_x = 0$
- Subtle differences between temporally and spatially developing turbulent flows
  - Entrainment ratio in free shear layers (Dimotakis 1986)
  - Homogeneous grid turbulence (Danaila et al. 1999)
  - Effects of initial conditions in neutrally stratified boundary layers (Kozul & Chung 2014)
- "Lagrangian" transition simulations
  - Difficult to track fluid columns because of atmospheric turbulence
    - shear, stretching, 3D dispersion
  - Additional source terms are required to account for lateral advection and mixing
- A spatially developing case is promising in coupling boundary layer dynamics with large-scale circulation
  - E.g., Hartmann & Michelsen (1993), Bony and Dufresne (2005), et al.

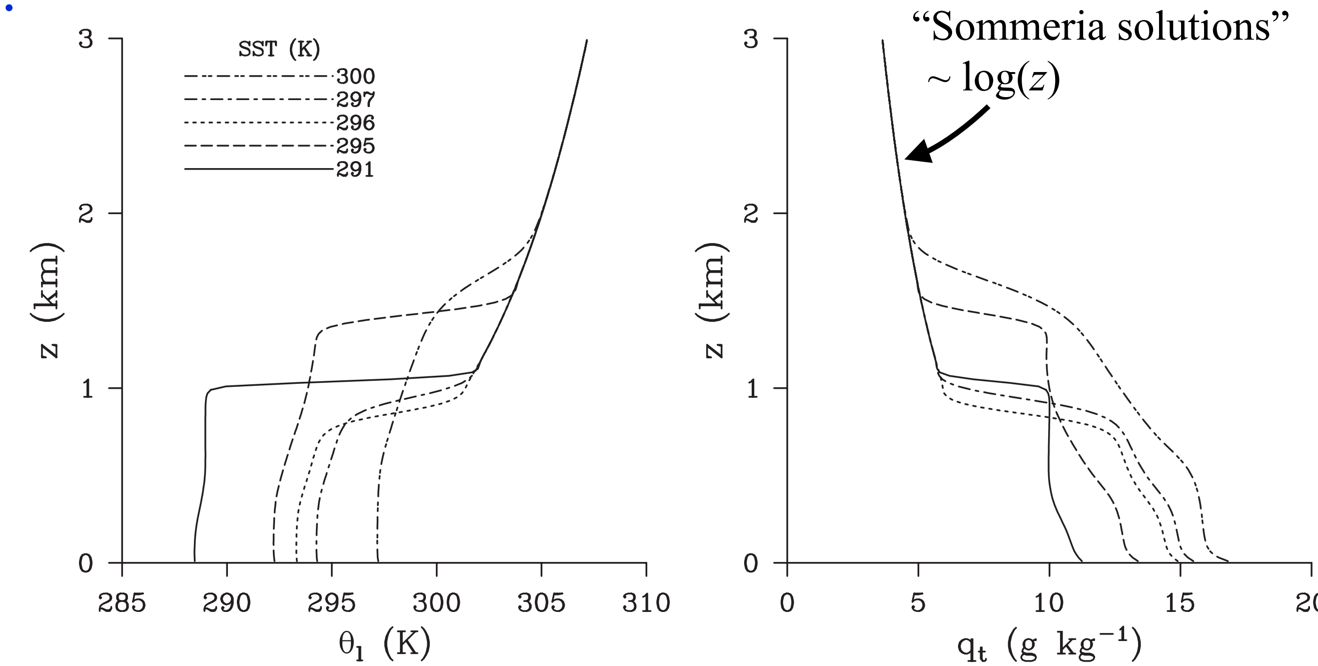
Inflow boundary condition

- Goal is to perform an LES without "buffer regions," nudging at boundaries etc…
- Use an "auxiliary" LES to supply inflow boundary conditions
  - Steady-state horizontally-homogeneous boundary layers (Sommeria 1976, Chung et al. 2012)

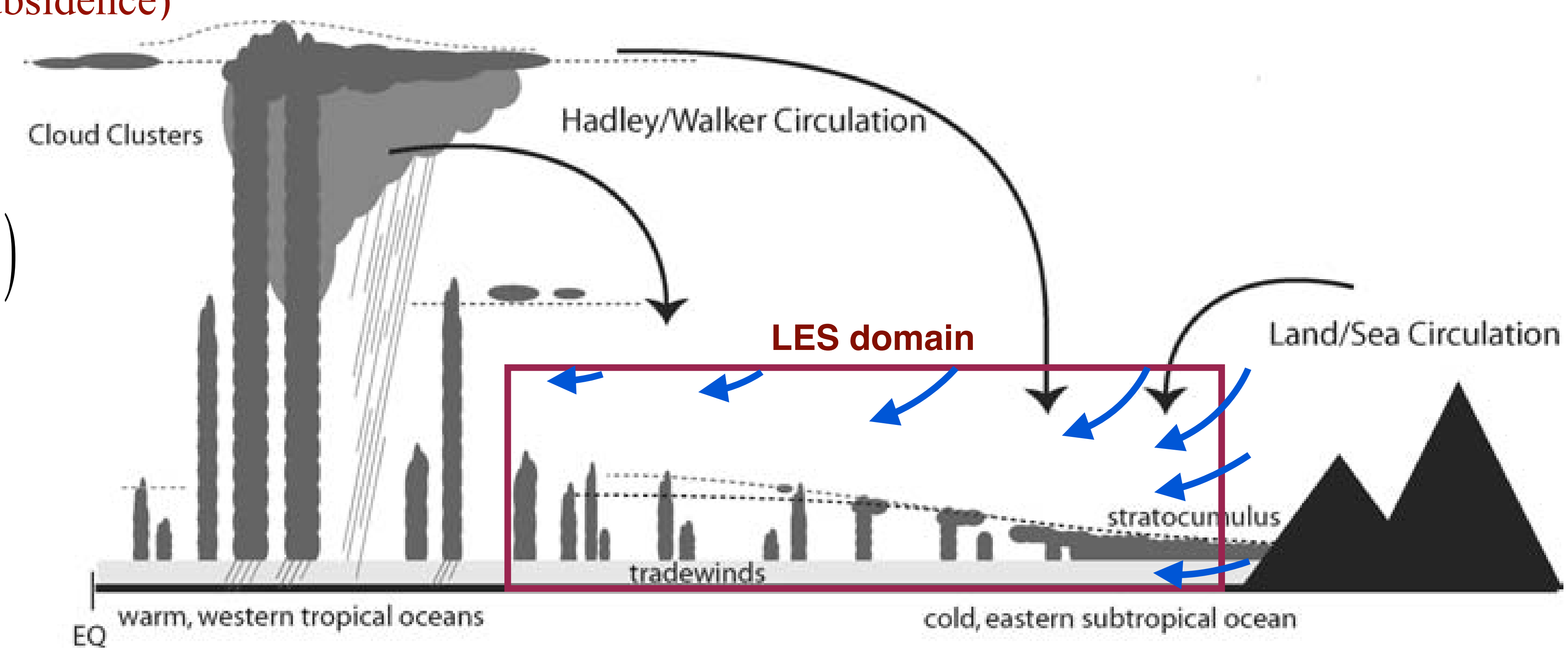
$$\frac{\partial\langle\theta_l\rangle}{\partial t} = -\frac{\partial\langle w'\theta_l'\rangle}{\partial z} + zD\frac{\partial\langle\theta_l\rangle}{\partial z} - \langle u_H\rangle\bullet\nabla_H\Theta_l - C - \frac{1}{\rho c_p}\frac{\partial\langle F_{\mathrm{cld}}\rangle}{\partial z}$$

  - Parameters:
    - SST
    - Divergence (subsidence)
    - large-scale advection

$$F_{\mathrm{cld}} = F_0\exp\left(-\alpha\int_z^\infty \rho l\,\mathrm{d}z'\right)$$



Chung et al. (2012)



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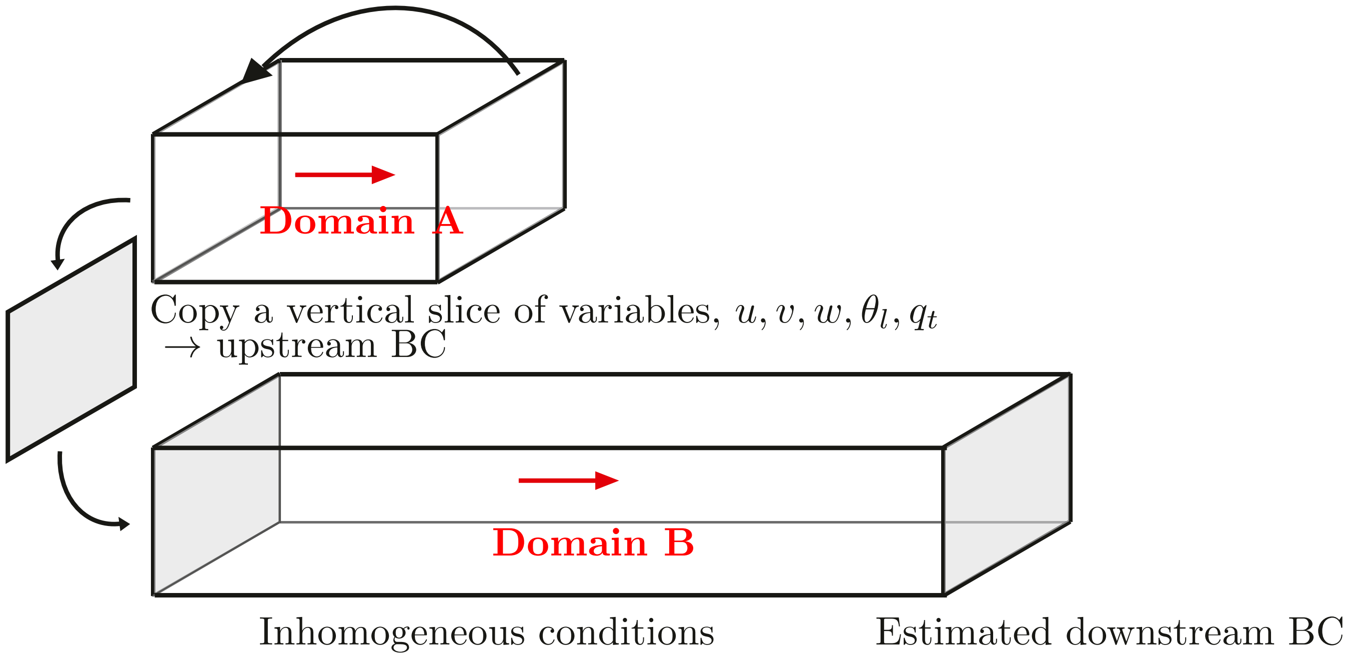
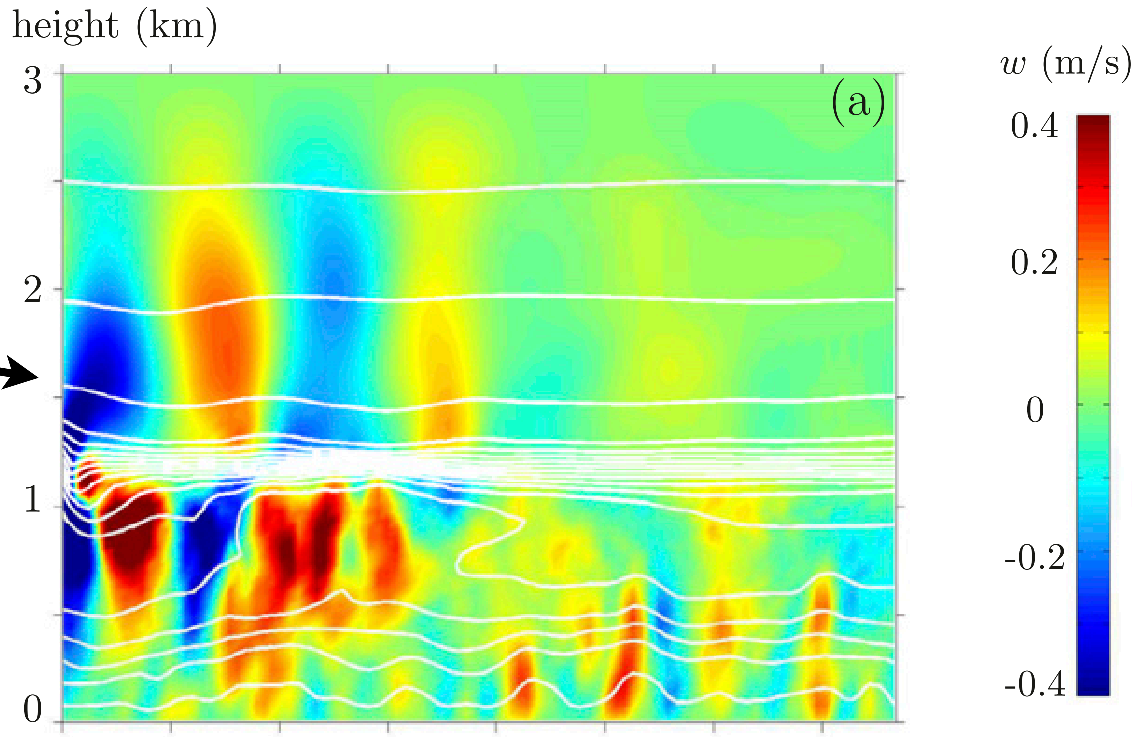
The AB method

- Often used in neutrally-stratified flows (e.g., Mayor et al. 2002)
- Does not perform well for stratified flows
  - Mismatch of buoyancy at boundaries
  - Excessive gravity waves in domain



meridionally-averaged vertical velocity

inflow plane



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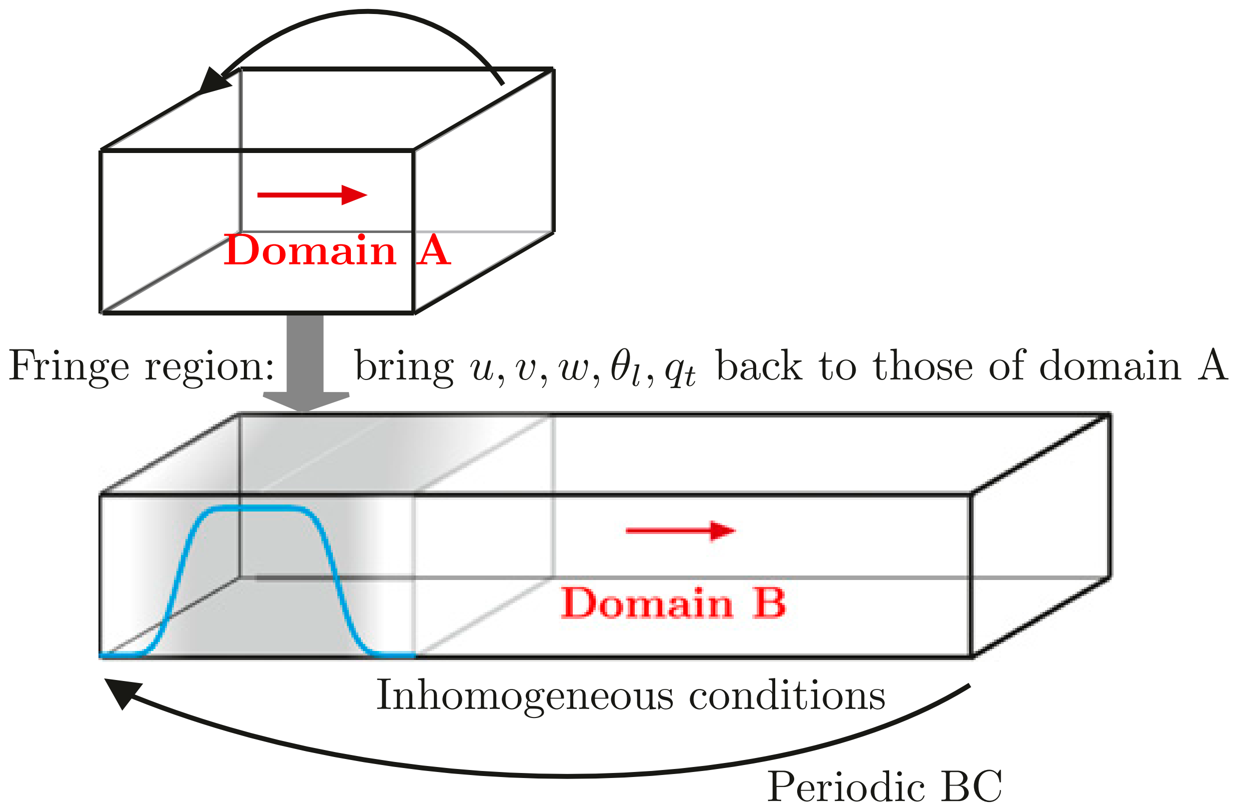
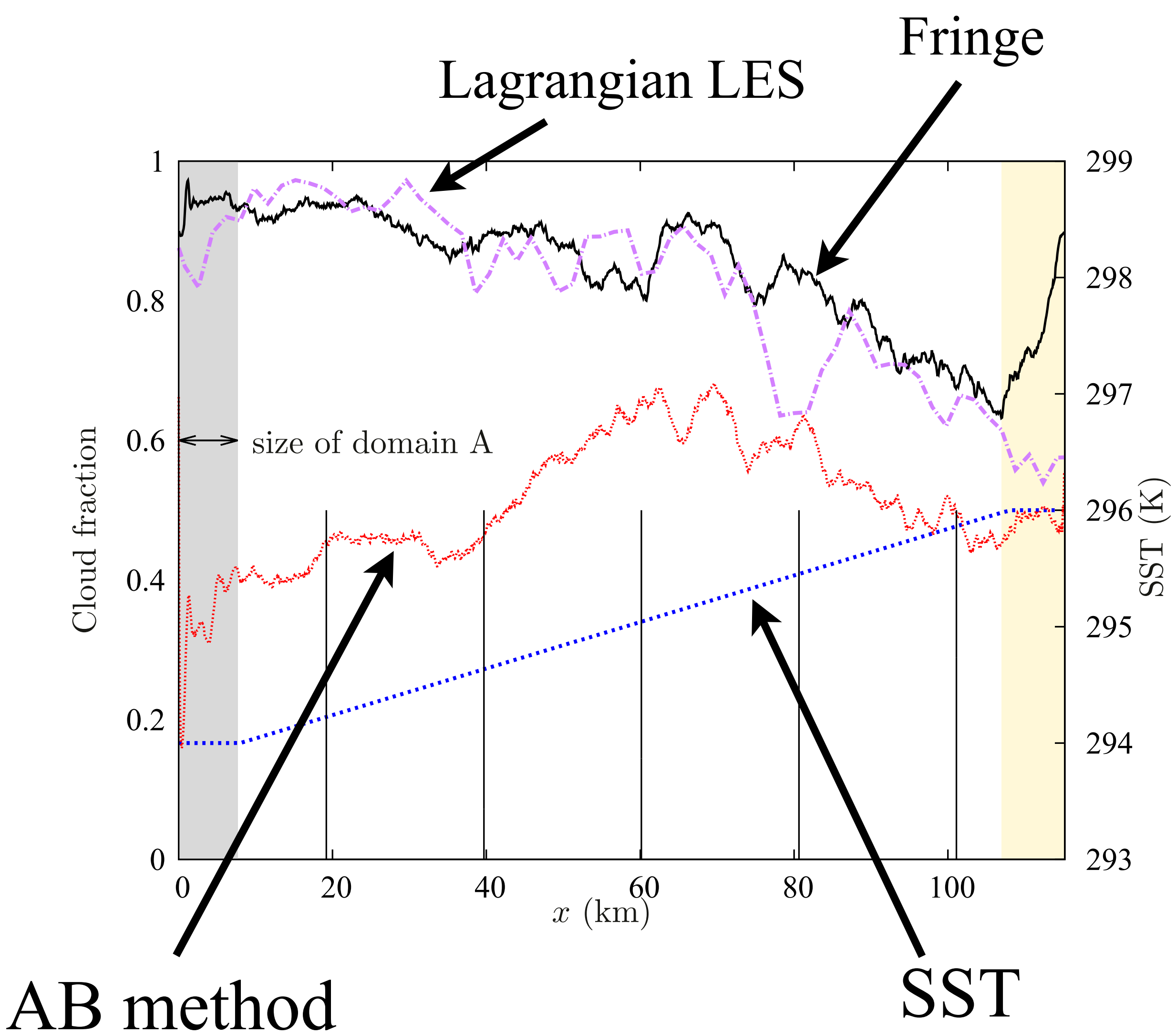
The fringe method

- Fringe method produces a smooth inflow condition





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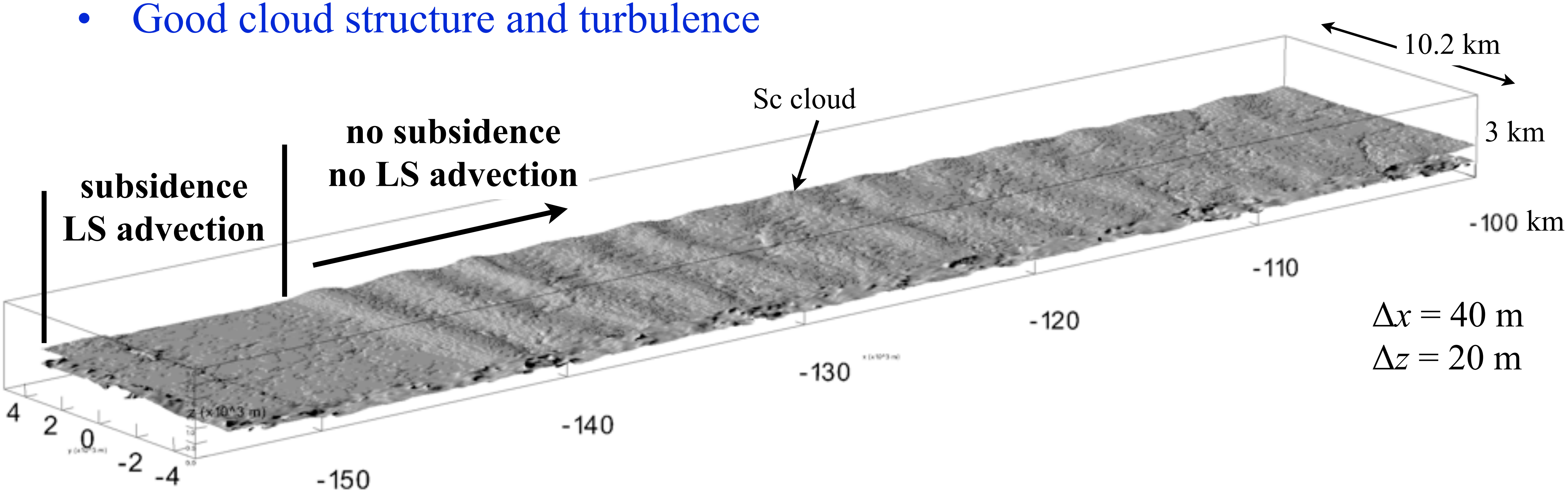
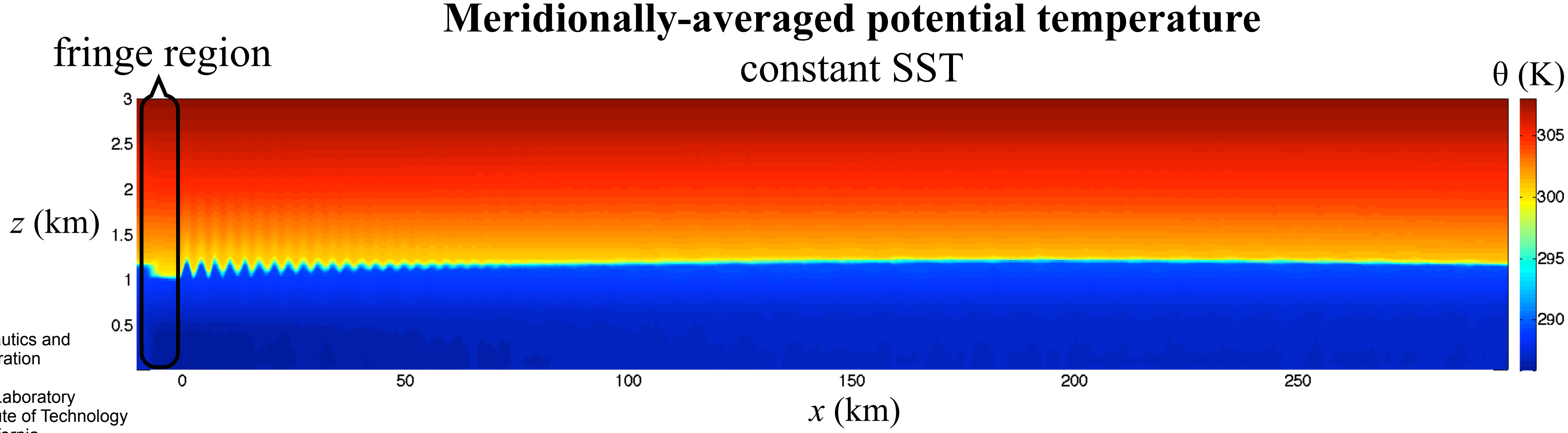
Boundary conditions in stratified flows are challenging

- Mismatch and incompatibilities at the boundary can excite gravity waves
  - Strong inversion and very weak coupling with free troposphere in Sc-topped BL
- Good cloud structure and turbulence



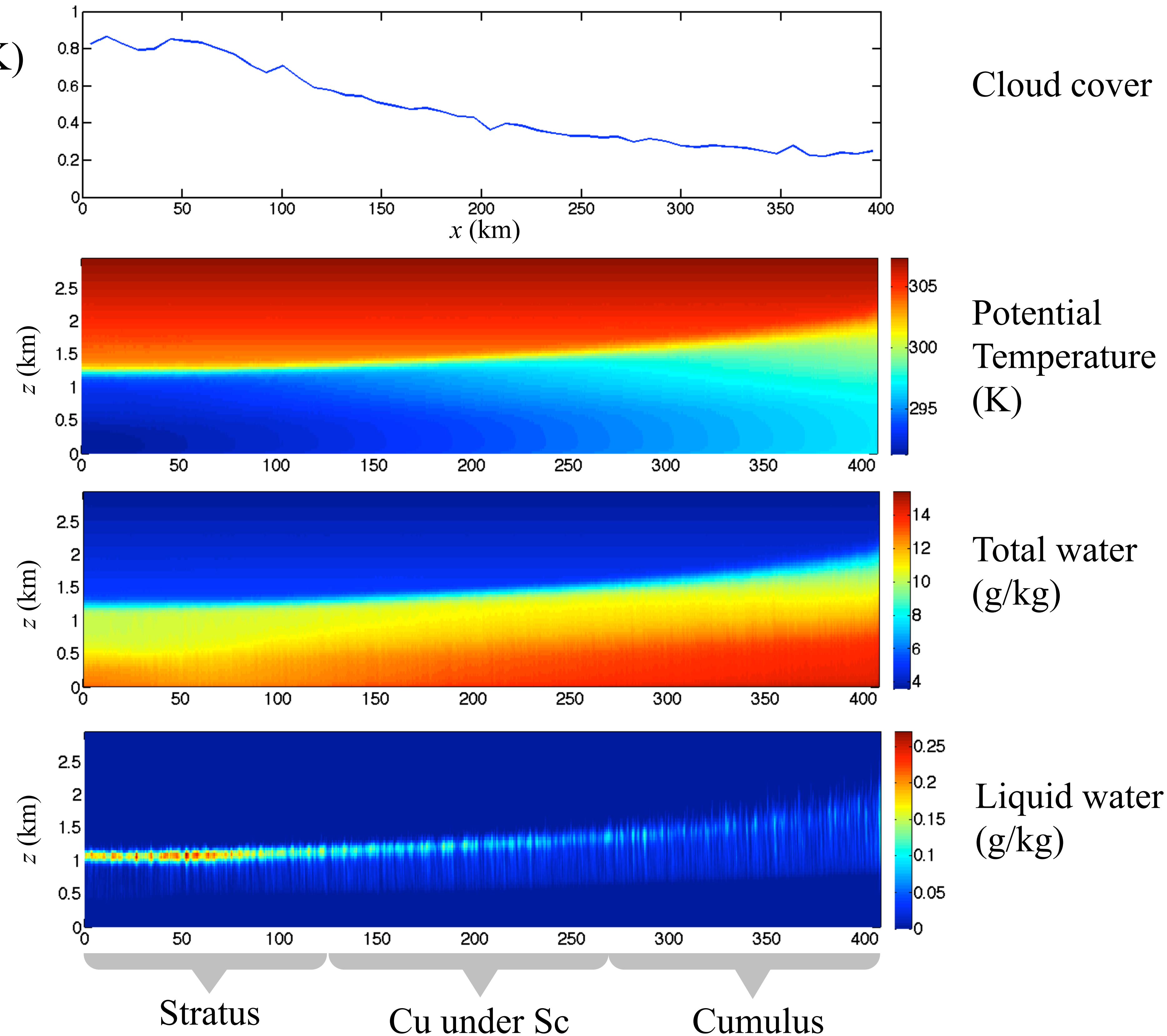
Meridionally-averaged potential temperature

constant SST



Transition in a 400 km-long domain

SST = $294 + 2 \times 10^{-5}\, x$ (K)
$D = 9 \times 10^{-6}$ (1/s)
No precipitation allowed



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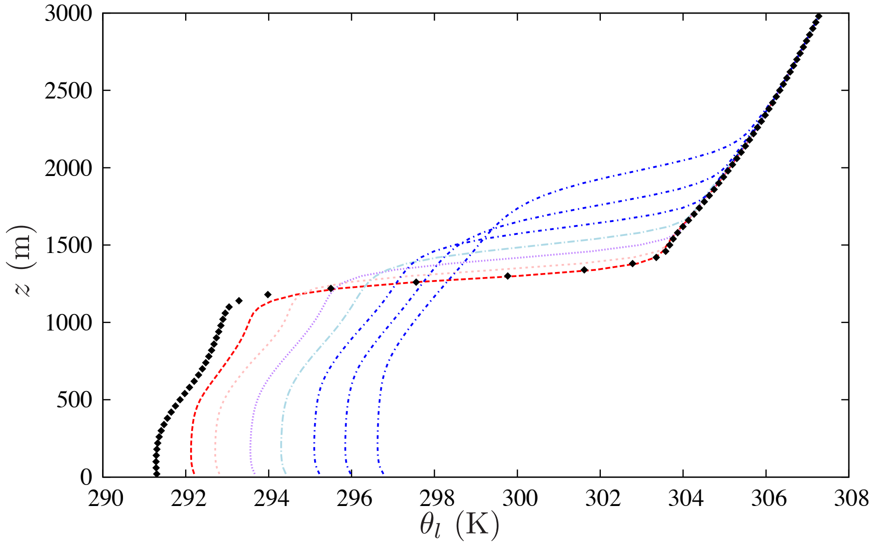
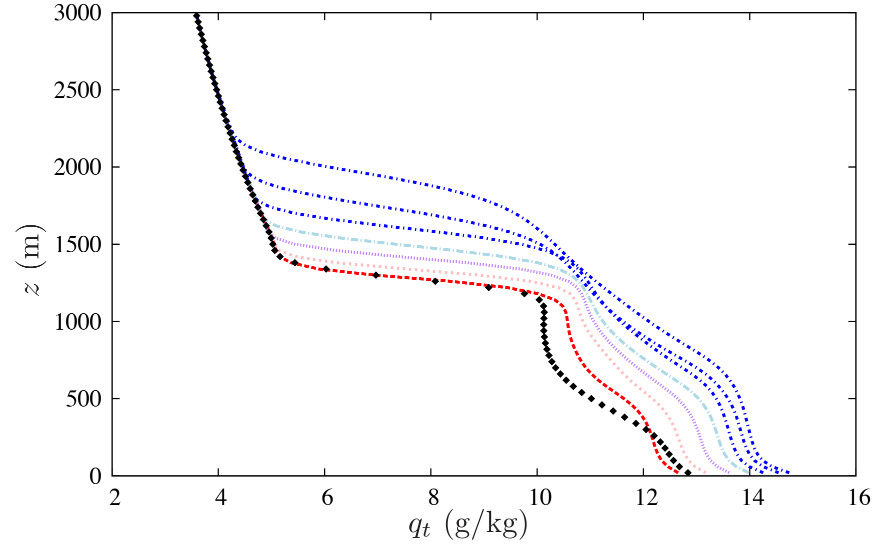
400 km-long domain – profiles

- 8 profiles at:
  - 50 km x-increments, or
  - 0.5 K SST-increments (294 – 298 K)

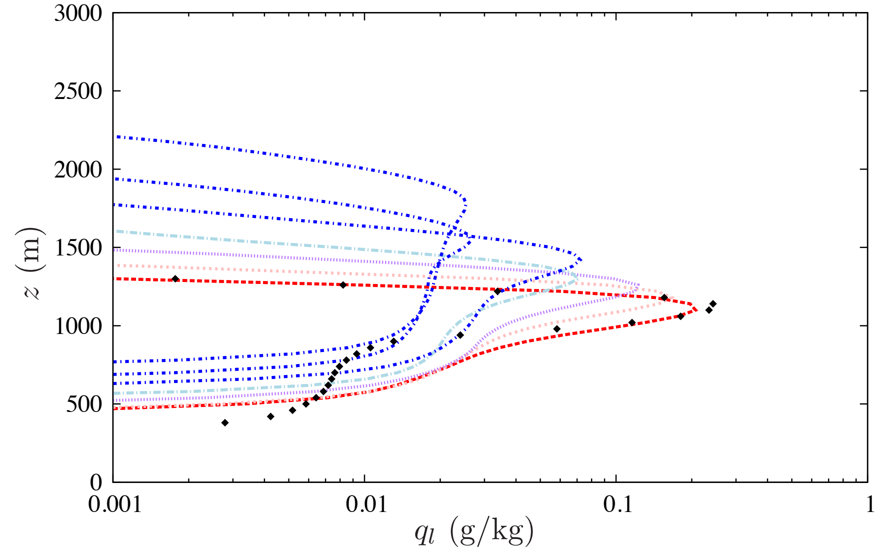
Liquid water potential temperature



Total water mixing ratio



Liquid water mixing ratio



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Energy budget

- Following Chung et al. (2012): horizontally-homogeneous steady-state LES
- Horizontally-averaged energy equation:

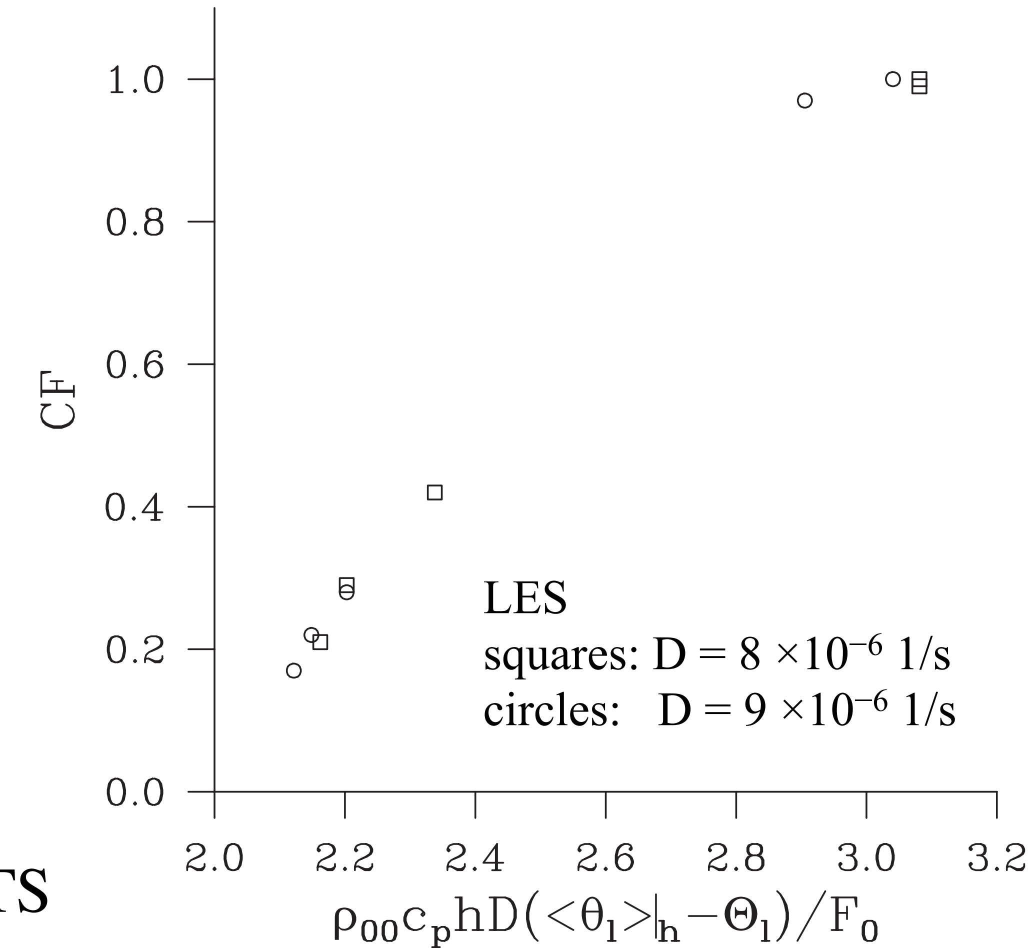
$$\frac{\partial\langle\theta_l\rangle}{\partial t} = -\frac{\partial\langle w'\theta_l'\rangle}{\partial z} + zD\frac{\partial\langle\theta_l\rangle}{\partial z} - \langle u_H\rangle \bullet \nabla_H \Theta_l - C - \frac{1}{\rho c_p \pi}\frac{\partial\langle F_{\mathrm{cld}}\rangle}{\partial z}$$

- Integrate from 0 to h (h > boundary layer)

$$\rho_{00} c_p h \frac{\mathrm{d}\Theta_l}{\mathrm{d}t} = \mathrm{SHF} + \rho_{00} c_p h D(\langle\theta_l\rangle_h - \Theta_l) - \rho_{00} c_p h \langle u_H\rangle \bullet \nabla_H \Theta_l - \rho_{00} c_p h C - \langle F_{\mathrm{cld}}\rangle_h$$

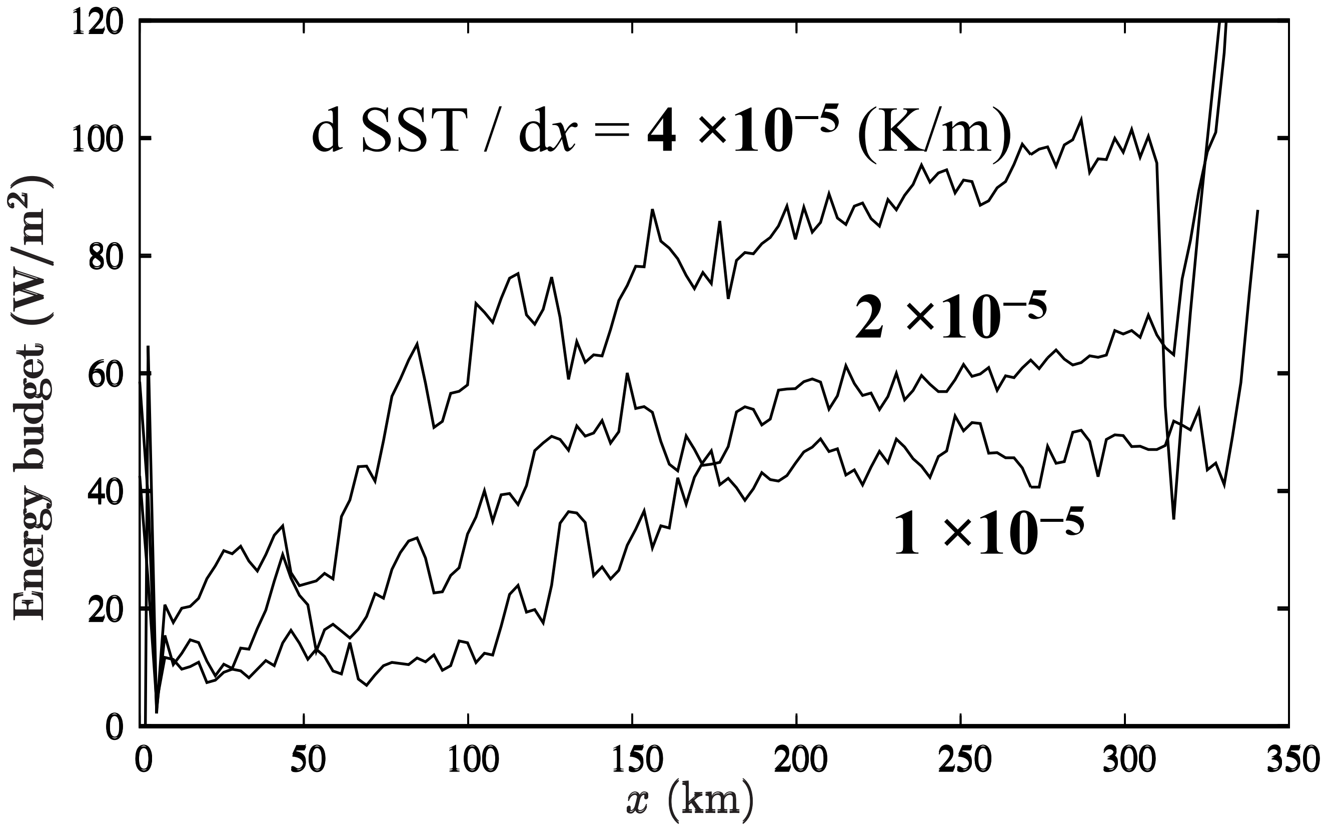
- Radiative cooling $\langle F_{\mathrm{cld}}\rangle_h = F_0\langle 1 - e^{-\alpha \mathrm{LWP}}\rangle \approx F_0\,\mathrm{CF}$
- Dominant balance $\mathrm{CF} \sim \rho_{00} c_p h D(\langle\theta_l\rangle_h - \Theta_l)/F_0$
- Relation to lower tropospheric stability (LTS)

$$\langle\theta_l\rangle_h - \Theta_l \sim \langle\theta_l\rangle_h - (\langle\theta_l\rangle_h + \mathrm{SST})/2 \sim \langle\theta_l\rangle_h - \mathrm{SST} \equiv \mathrm{LTS}$$



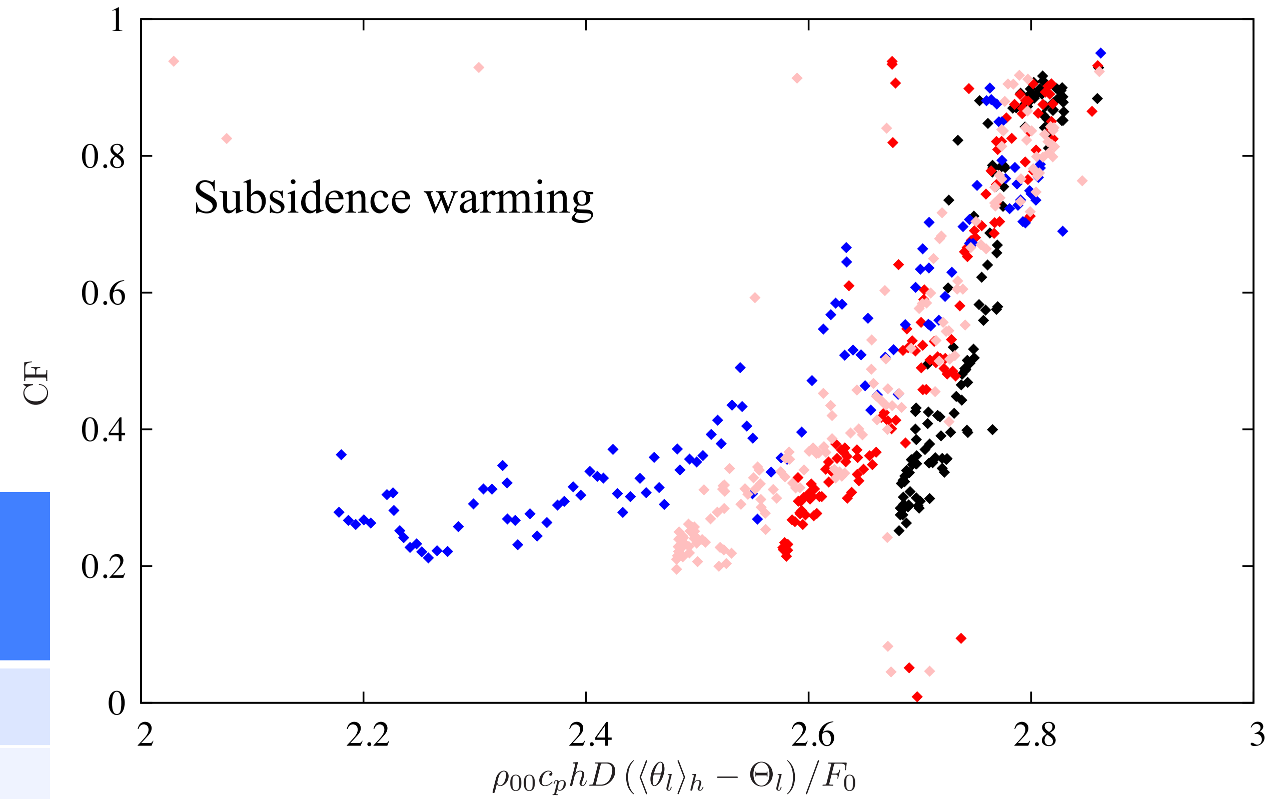
Storage term for spatially developing LES

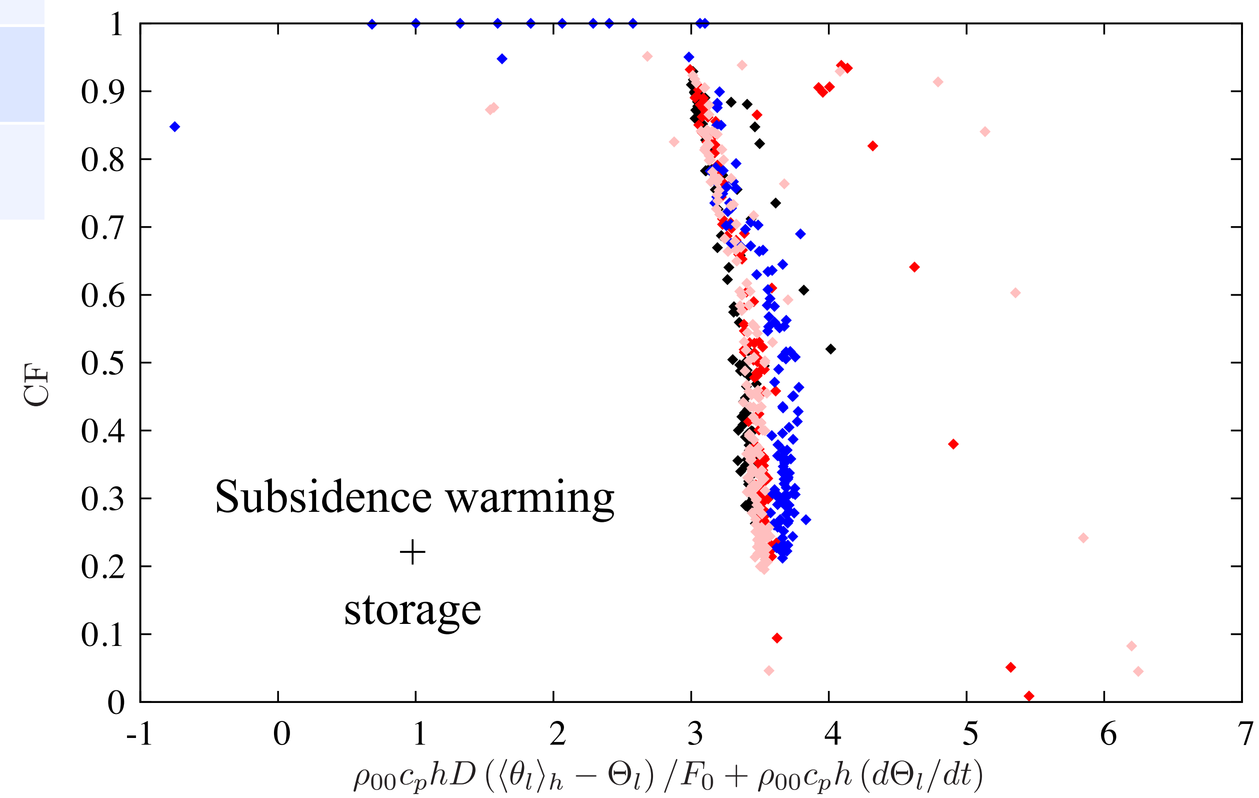
$$\rho\, c_p\, h \frac{\mathrm{d}\Theta_l}{\mathrm{d}t}$$



Cloud cover *vs* boundary layer warming

Key	d SST / dx (K/m)	L_x (km)
Black	1×10^{-5}	300
Red	2×10^{-5}	300
Pink	2×10^{-5}	400
Blue	4×10^{-5}	300





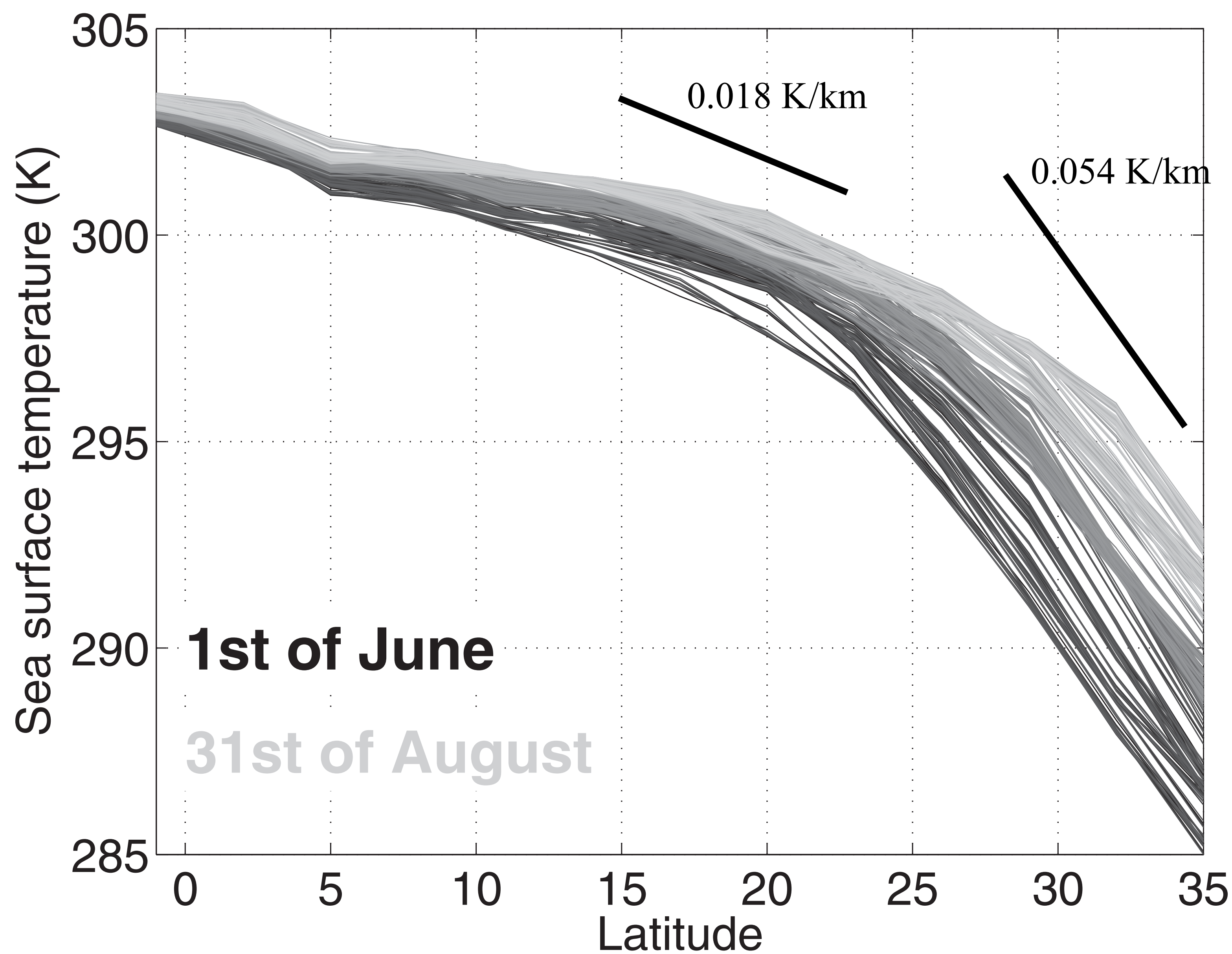
Summary and conclusions

- Implemented and verified a fringe method to allow for spatially developing large-eddy simulations of atmospheric boundary layers
  - Boundary conditions for stably stratified flows are challenging
- The Sc to Cu cloud transition was simulated in domains up to 400 km
- Simulations with variable SST increase rate
- Steady-state spatially developing LES reproduces observed and previously modeled Lagrangian transition characteristics
- Increase in SST is solely sufficient to cause the transition
  - Corroborates previous models and LES results, e.g., Sandu & Stevens (2011)
- Simulations show gradual decrease in cloud cover, rather than a sudden transition
- Simulations indicate the importance of the energy storage term
  - Spatially variable
  - Collapse of cloud cover data

Backup

SST increase along the GPCI cross section

- NCEP SSTs along the transect during JJA 2003 from Karlsson et al. (2010)



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