Marine Stratocumulus

Indirect effects in a single-column model

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AOS

Marine (subtropical) stratocumulus

- **West coasts**

→ Upwelling

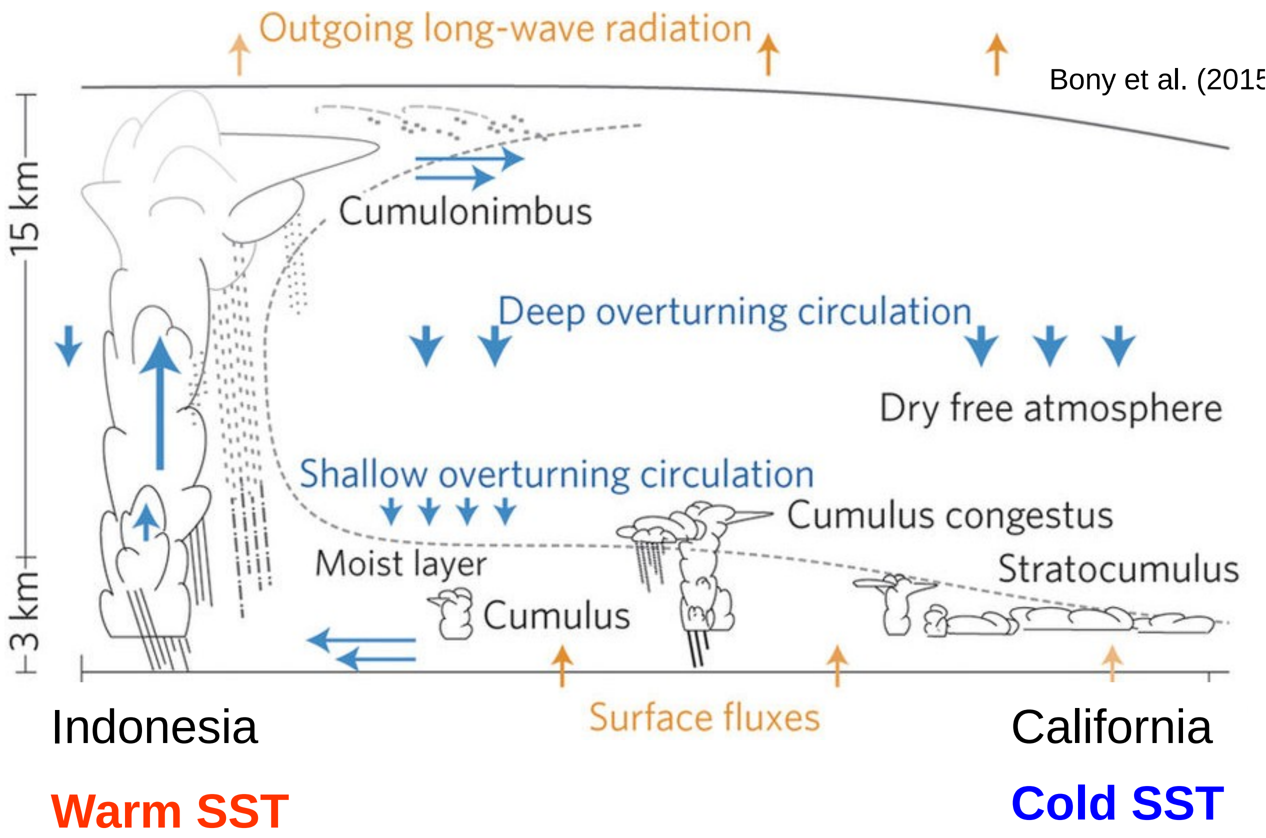
→ Cold SST

→ Strong inversion

→ Only shallow convection

→ Low-level stratocumulus

- **SW effects**
  - Most uncertain cloud feedback (Vial et al., 2013)



Examples

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Stratocumulus Perlucidus

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Stratocumulus Undulatus

Indirect effects

- **First indirect effect (e.g. Twomey, 1974)**
- **Constant LWC:**

CCN⬆

→ More smaller drops

→ Higher optical depth

→ Brighter clouds

Indirect effects

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- Second indirect effect (e.g. Albrecht, 1989)
- More drops:

→ Coalescence⬇

→ Precipitation⬇

→ LWP⬆

→ Brighter clouds

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→ Precipitation⬇

→ LWP⬆

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Which one drives changes in optical depth?

Experiments: 1. Observed aerosol distribution (387 cm^{-3})
2. Doubled number concentration (2*387 cm^{-3})

Total energy-mass flux scheme (TEMF)

Equations:

$$\frac{\partial \bar{v}}{\partial t} = -\bar{w}\frac{\partial \bar{v}}{\partial z} - f(\bar{u} - u_g) - \frac{\partial \overline{v'w'}}{\partial z} \quad (5.2)$$

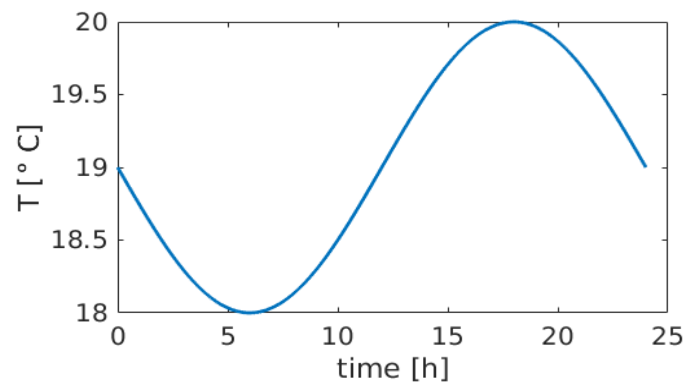
$$\frac{\partial \bar{\theta}}{\partial t} = -\bar{w}\frac{\partial \bar{\theta}}{\partial z} - \frac{\partial \overline{\theta'w'}}{\partial z} - Q_{newt} \quad (5.3)$$

$$\frac{\partial \bar{q}}{\partial t} = -\bar{w}\frac{\partial \bar{q}}{\partial z} - \frac{\partial \overline{q'w'}}{\partial z} + (E - C)_{micro}$$

$$\overline{w'\psi'} = -K\frac{d\psi}{dz} + M(\psi_u - \psi)$$

No latent heating or radiation!

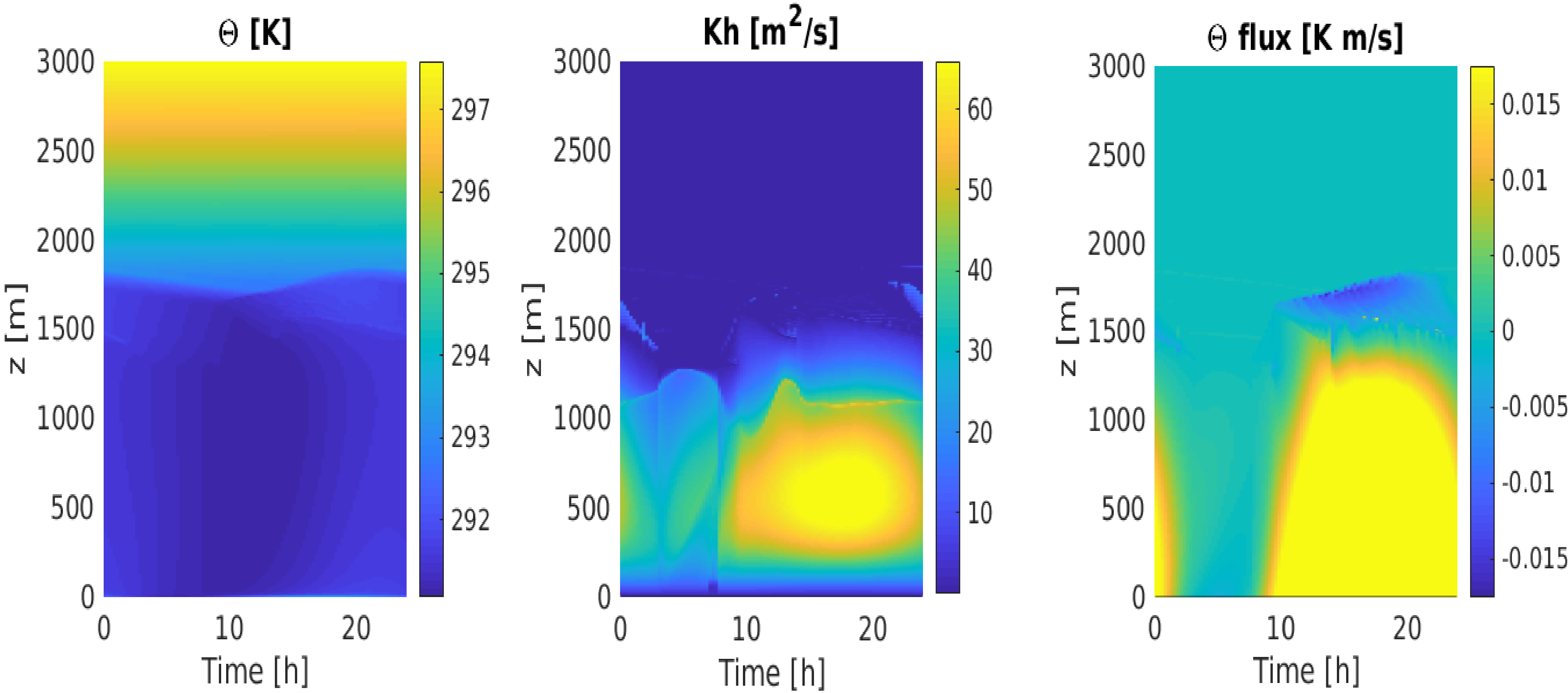
Surface temperature:



Lower boundary:

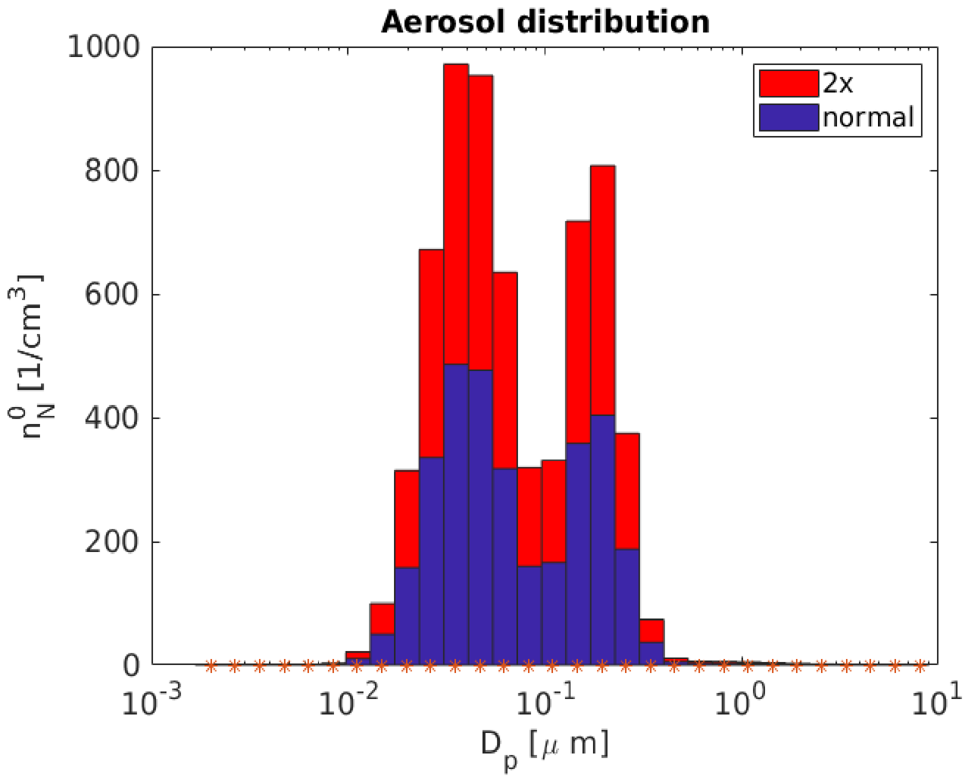
$q(z=0) = q_{sat}(T_{surf})$

TEMF Outputs



Warm Microphysics

- **Spectral (bin) method (e.g. Kogan, 1991)**
- **Processes:**
  - Drop activation
  - Condensation
  - Coalescence
  - Breakup
  - Sedimentation
  - Eddy fluxes (TEMF)



Koponen et al. (2002)

Warm Microphysics

- **Aerosols**
    - Assumed sea salt
    - $S > S_{crit} \rightarrow$ Activate

$$S - \frac{2\sigma}{\rho_w R_v T r} + \frac{2\rho_n M_w r_n^{\,3}}{\rho_w M_n r^3} = 0$$

- Surface distribution outside cloud
    - Even in free troposphere
- TEMF vertical advection

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- **Condensation**

$$\frac{dr}{dt} = \frac{D_v E_S F_v}{\rho_w R_v T} \frac{\left(S - \frac{2\sigma}{\rho_w R_v T r} + \frac{2\rho_n M_w r_n{}^3}{\rho_w M_n r^3}\right)}{(r + r^*)\left(1 + \frac{D_v L^2 E_S}{K R_v{}^2 T^3}\right)}$$

- **D_v: H_2O(g) diffusivity**
- **E_s: Sat. vapor pressure**
- **F_v: Ventilation coefficient**
- **K: Thermal cond. of air**
- **r^*: Kinetic correction**
- **r_n: Volume mean dry diam of recently activated drops**

Warm Microphysics

- **Coalescence**
  - Collection of smaller drops

$$\frac{dV_i}{dt}=\sum_{k=1}^{i} V_k N_k K_{k,i}$$

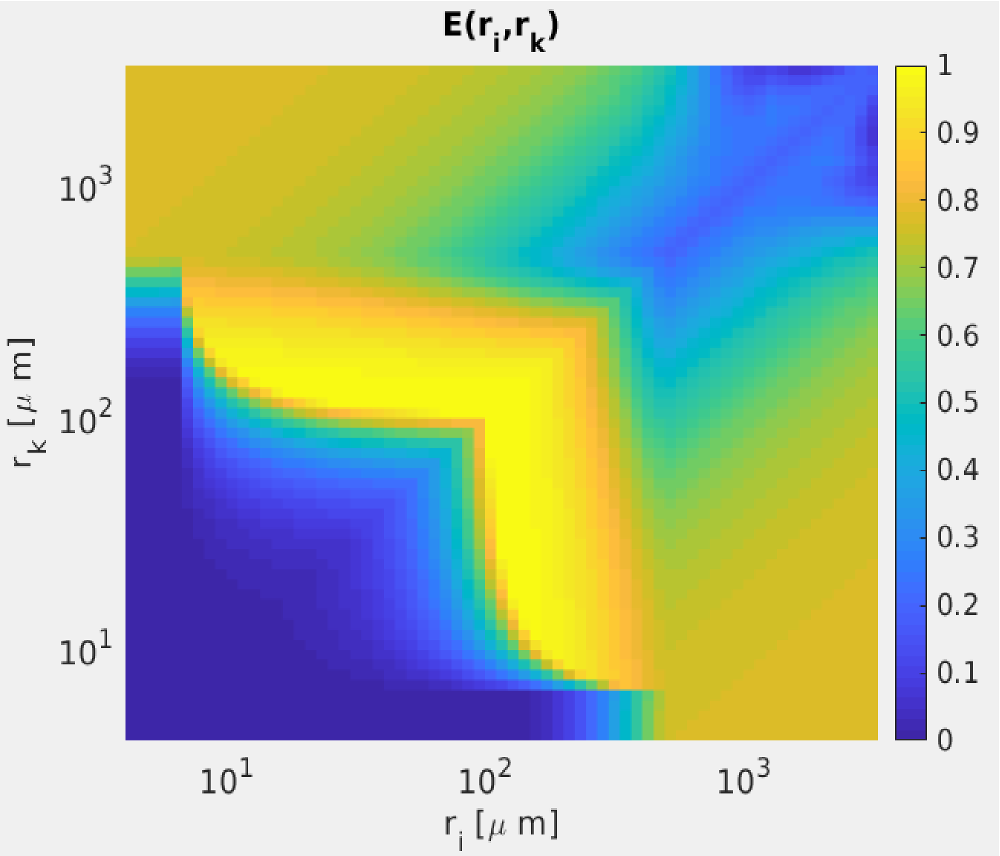
  - Collection by larger drops

$$\frac{dN_i}{dt}=-N_i\sum_{k=i+1}^{k_{max}} N_k K_{k,i}$$

  - Collision kernel (probability)

$$K_{k,i}=\pi(r_i-r_k)^2\left|V_i^{term}-V_k^{term}\right|E_{k,i}$$

- **Breakup**
  - Large droplets disintegrate due to aerodynamic forces

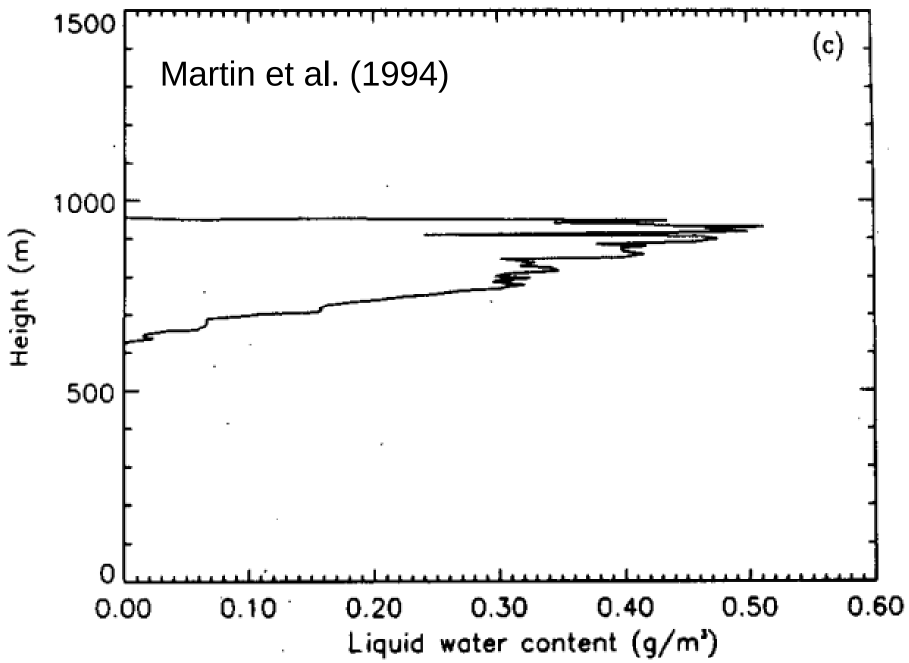


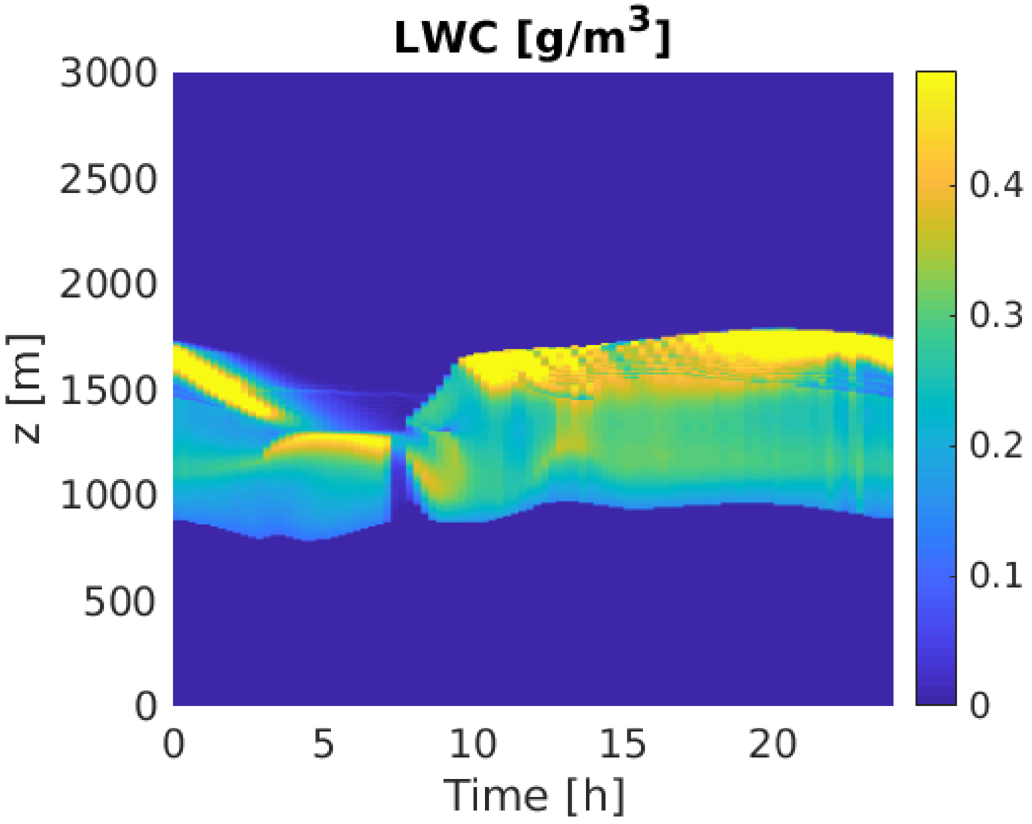
Small r: Long (1974)

Large r: Seifert et al. (2005)

Examples – LWC

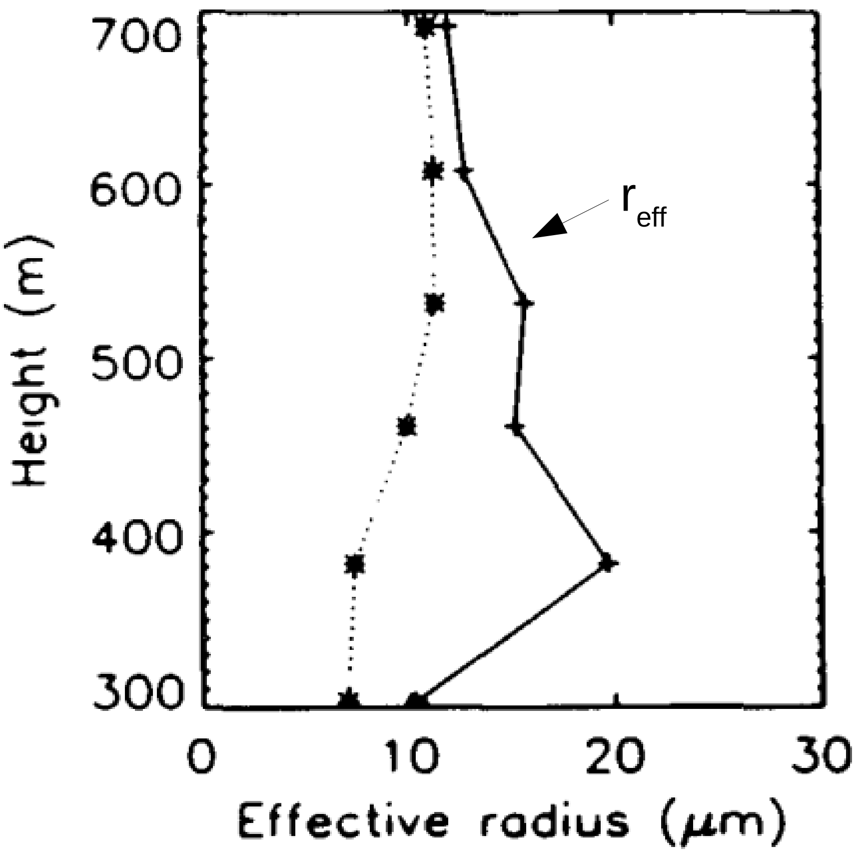
Observations – Californian coast



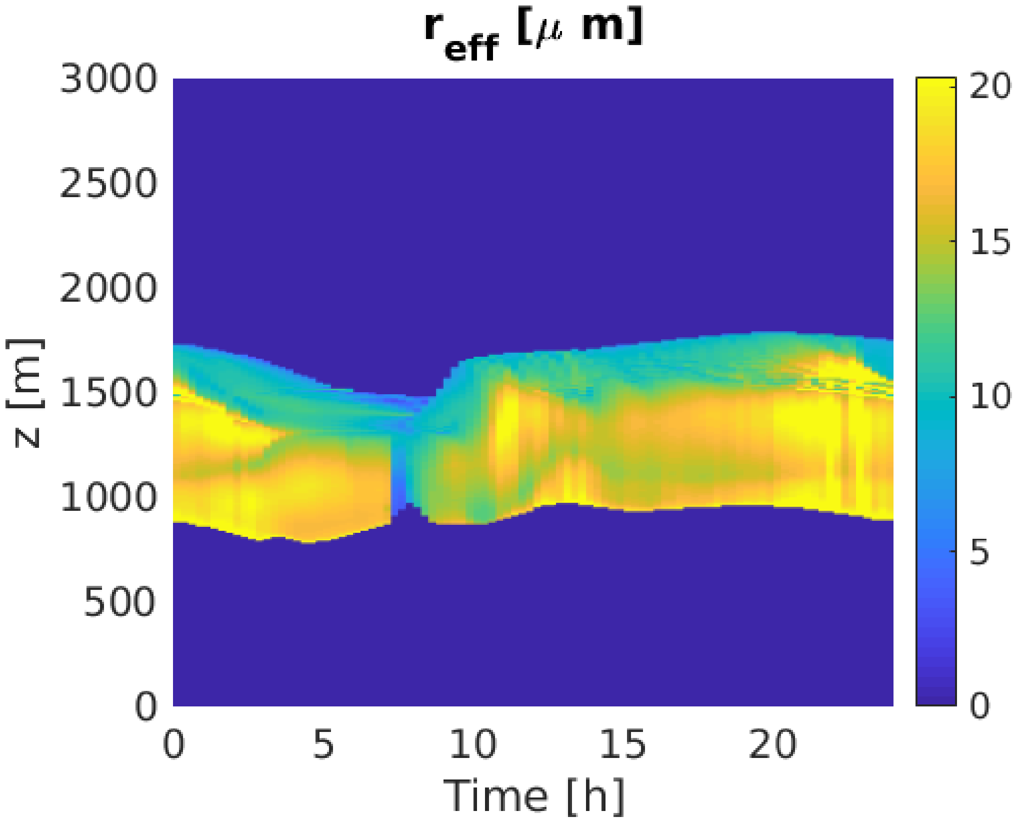


Examples – r_{eff}

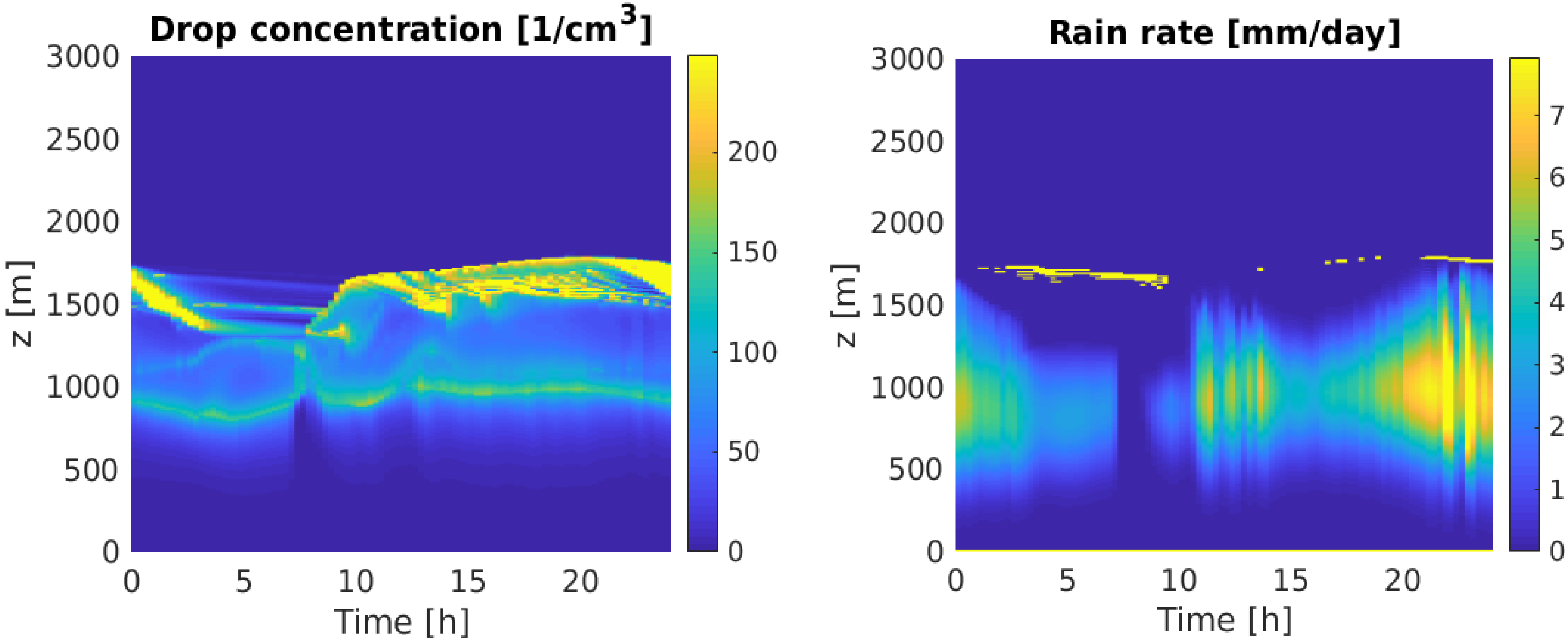
Observations – Atlantic



Martin et al. (1994)



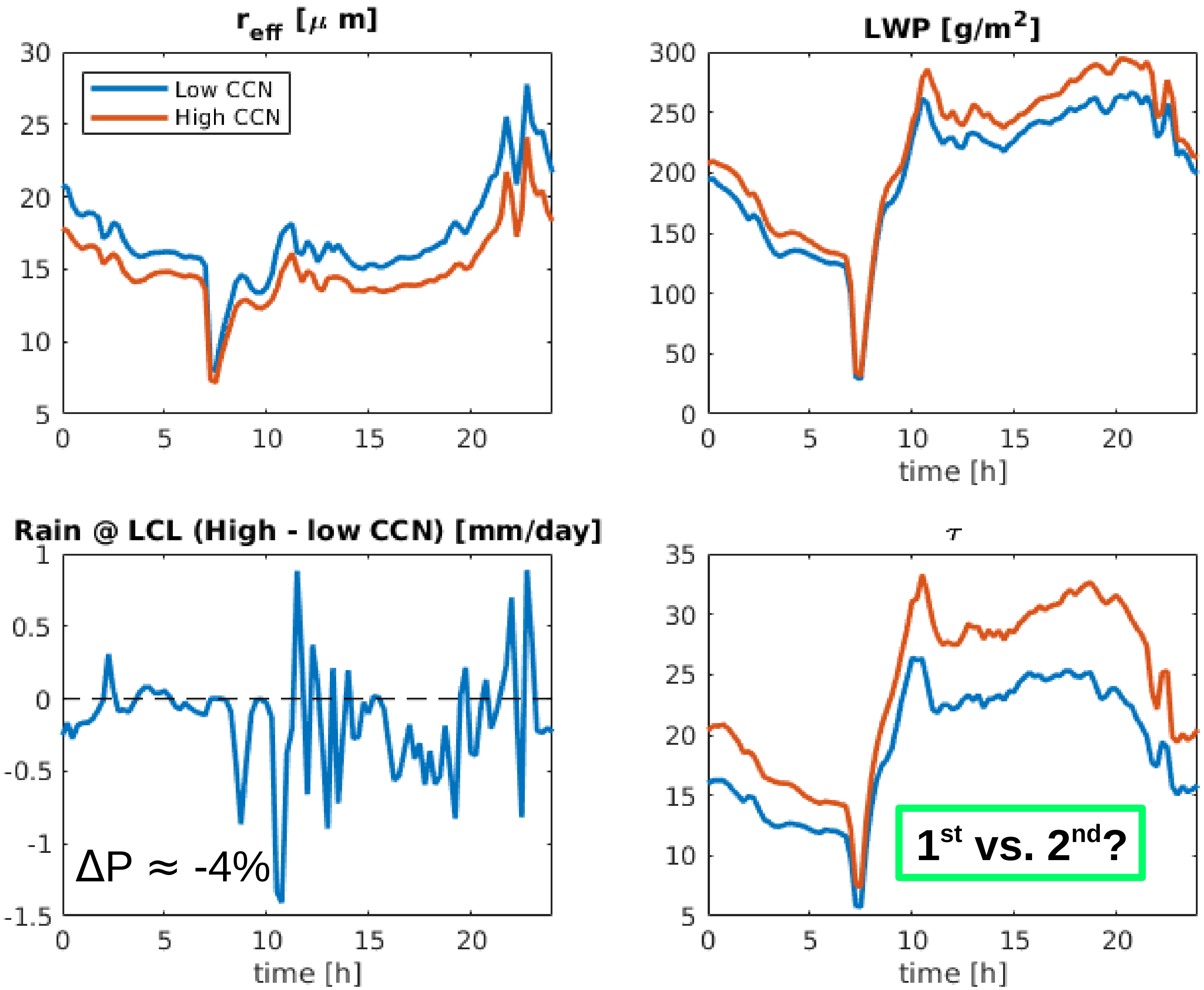
Examples



Drop concentration [1/cm³]
3000
2500
2000
1500
1000
500
0
z [m]
0
5
10
15
20
Time [h]
200
150
100
50
0
Rain rate [mm/day]
3000
2500
2000
1500
1000
500
0
z [m]
0
5
10
15
20
Time [h]
7
6
5
4
3
2
1
0

Doubled aerosol experiment

Observations (e.g. Twohy et al., 2005) **and models** (e.g. Khain et al., 2008; Zhang et al., 2006) **agree.**



Mathematically

Wood (2007): $$\frac{d\ln\tau}{d\ln N_d}=\left(\frac{\partial\ln\tau}{\partial\ln N_d}\right)_{LWP}+\left(\frac{\partial\ln\tau}{\partial\ln LWP}\right)_{N_d}\left(\frac{\partial\ln LWP}{\partial\ln N_d}\right)$$

Twomey!

Albrecht!

Mathematically

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Twomey! **Albrecht!**

$$\tau\sim N_d^{1/3}\,LWP^{5/6}\longrightarrow\frac{d\ln\tau}{d\ln N_d}=\frac{1}{3}+\frac{5}{6}\left(\frac{\partial\ln LWP}{\partial\ln N_d}\right)\longrightarrow\frac{2^{nd}}{1^{st}}\equiv R_{2/1}=2.5\left(\frac{\partial\ln LWP}{\partial\ln N_d}\right)$$

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Wood (2007): $$\frac{d\ln\tau}{d\ln N_d} = \left(\frac{\partial \ln\tau}{\partial \ln N_d}\right)_{LWP} + \left(\frac{\partial \ln\tau}{\partial \ln LWP}\right)_{N_d}\left(\frac{\partial \ln LWP}{\partial \ln N_d}\right)$$

Twomey!

Albrecht!

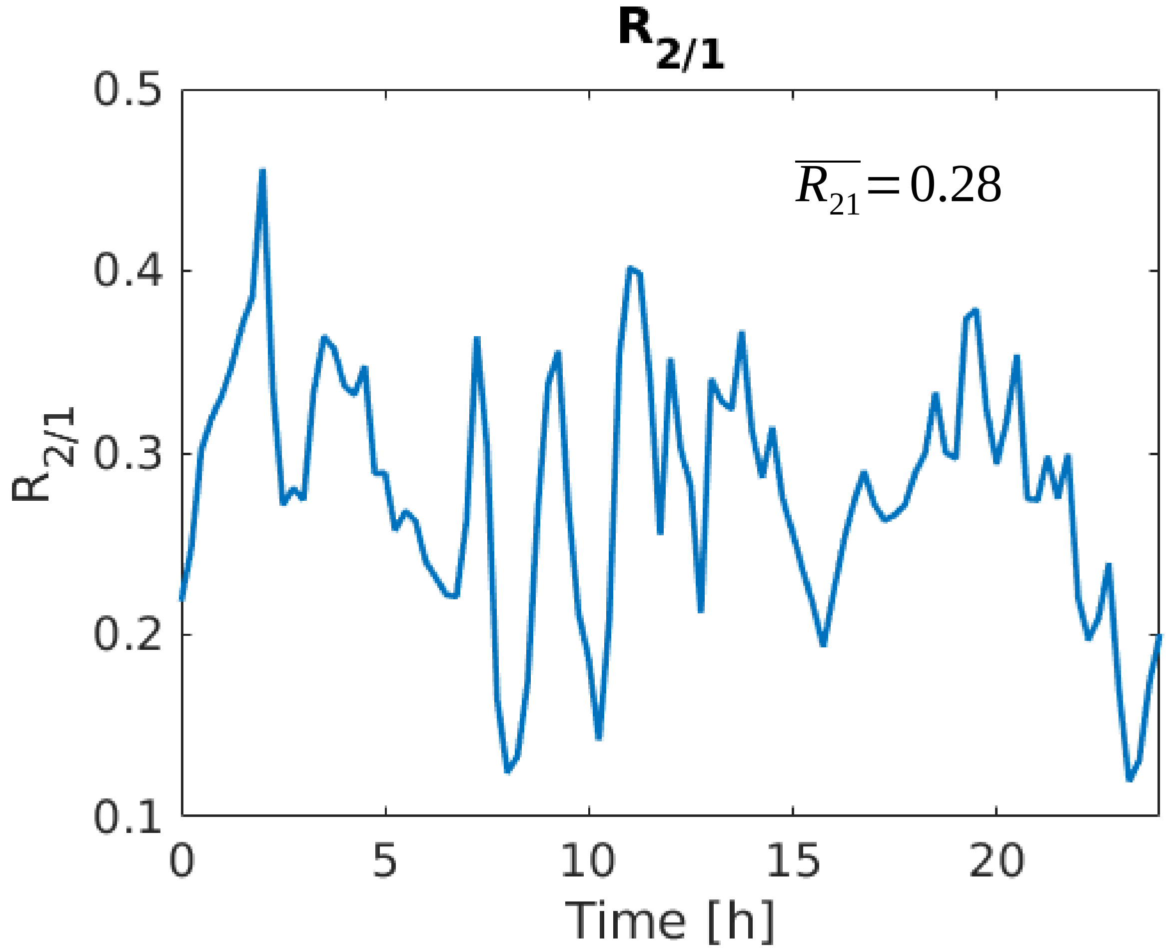
$$\tau \sim N_d^{1/3} LWP^{5/6} \longrightarrow \frac{d\ln\tau}{d\ln N_d} = \frac{1}{3} + \frac{5}{6}\left(\frac{\partial \ln LWP}{\partial \ln N_d}\right) \longrightarrow \frac{2^{nd}}{1^{st}} \equiv R_{2/1} = 2.5\left(\frac{\partial \ln LWP}{\partial \ln N_d}\right)$$

In this simulation: $$\tau \sim N_d^{0.38} LWP^{0.73} \longrightarrow \boxed{R_{2/1} = 1.92\left(\frac{\partial \ln LWP}{\partial \ln N_d}\right)}$$

R = 0.97!

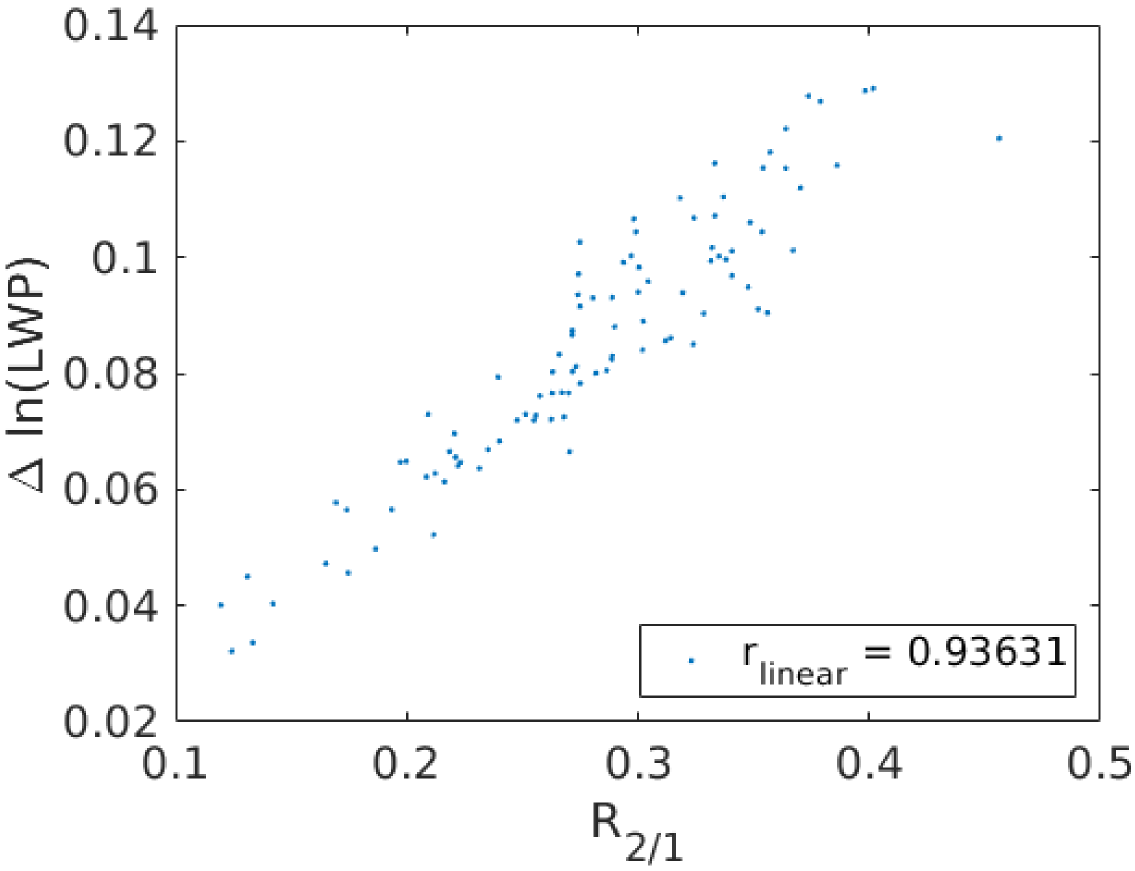
Twomey vs Albrecht

$$R_{2/1} = 1.92 \left(\frac{\partial \ln LWP}{\partial \ln N_d} \right)$$



Twomey vs Albrecht

$R_{2/1}$ driven by LWP changes



Conclusions

- **1D model with spectral microphysics**
  - reproduces aerosol indirect effects
- **2nd indirect**
  - 1/3 of Twomey effect
  - No diurnal cycle
  - Controlled by LWP changes

Conclusions

- **1D model with spectral microphysics**
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- **Future work**
  - What controls LWP? Condensation, precipitation (e.g. Khain et al., 2008)…?
  - Lu and Seinfeld (2005): 2nd ind. effect negative – N_d⬆→ More drying at the top
  - Radiation/latent heating: Change in turbulence → Cloud thickening (Wood, 2007)

Wood (2007) – Sc and TKE