Constant Flux Layers with Gravitational Settling: deposition to an underlying surface and links to fog.

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The turbulent boundary layer concepts of constant flux layers (CFL) and surface roughness lengths are extended to include gravitational settling (GS) and surface deposition of fog or cloud droplets in neutrally stratified atmospheric surface boundary layers (CFLGS). Investigating details of how fog/cloud droplet water content is treated within the surface boundary layer of models such as WRF leads one to look at deposition of fog droplets towards underlying ground/water surfaces. This can be a mix of gravitational settling and turbulence causing droplets to impact the surface. WRF can include turbulent deposition for vegetation but, until we added it, was not representing turbulent deposition velocities for water surfaces.

Photo: Jason Surette, Parks Canada

Radiation fog on Sable Island – typically shallow and short lived (3-4 hrs).

Marine fog advected in over Sable Island, 31 May 2021. Picture by Zoe Lucas.

Marine advection fog, warm, moist air advected over cold water. Once fog has formed radiative cooling at fog top becomes important and main source of fog water can be from the top. Water surface can be a sink.

Marine Fog - Advection of warm moist air over cold water
Heat and water vapour diffuse to/from lower boundary
Cooling can lead to condensation and droplet formation.
Droplets emit more LW radiation than water vapor (per kg)
Fog top cools, and becomes a source of more fog water
Fog droplets are subject to gravitational settling AND removal at the surface by turbulent impaction. collision and coalescence.

Idealised steady state case, uniform droplet size (in range 1-50 µm).
Most of the air column is at 100% Relative Humidity, no droplet growth or evaporation.
Fog droplets and liquid water (Qc) are being created by cooling in upper part of fog layer,
the lower part has a constant downward flux of fog water (Qc) which is finally deposited to the water surface, by gravitational settling + turbulence

One could then model the constant downward flux of fog, F_{Qc}, as

$$w_s Qc + ku^*(z + z_{0c})\, dQc/dz = F_{Qc} = u^* q_c^* \quad (3)$$

Gravitational Turbulent flux Total, assumed constant

where w_s represents the gravitational settling velocity and u^* is the friction velocity. The eddy diffusivity K_{qc} is assumed to be

$$K_{qc} = ku^*(z + z_{0c})$$

Here z_{0c} is a roughness length specific to water droplets and different from z_{0m} and z_{0h} or z_{0q}, for momentum, hear and water vapour transfers. There are different transfer mechanisms at the surface. MOST background, Buckingham pi theorem, matched asymptotic expansions → log profiles.

Assuming constant values for z_{0c} , u^* and w_s one can then solve Eq (3), by integrating factor techniques, multiplying (3) by $(z+z_{0c})^{S-1}/(ku^*)$ where $S = w_s/(ku^*)$, to give,

$$(d/dz)[(z+z_{0c})^S Qc] = (qc^*/k)(z+z_{0c})^{S-1}$$

and, **with Qc(0) = 0** the solution is,

$$Qc(z) = (qc^*/(kS)) [1- ((z+z_{0c})/z_{0c})^{-S}].$$

In terms of **$\zeta = \ln((z+z_{0c})/z_{0c})$,** we can write,

$$Qc(\zeta) = (qc^*/(kS)) [1-e^{-S\zeta}].$$

These can be referred to as **Constant Flux Layer with Gravitational Settling or CFLGS, profiles.** In the limit as w_s and $S \rightarrow 0$, as $\zeta \rightarrow 0$, this would give $Qc(\zeta) = (q_c^*/k)\,\zeta$, a standard log profile.

a) b)

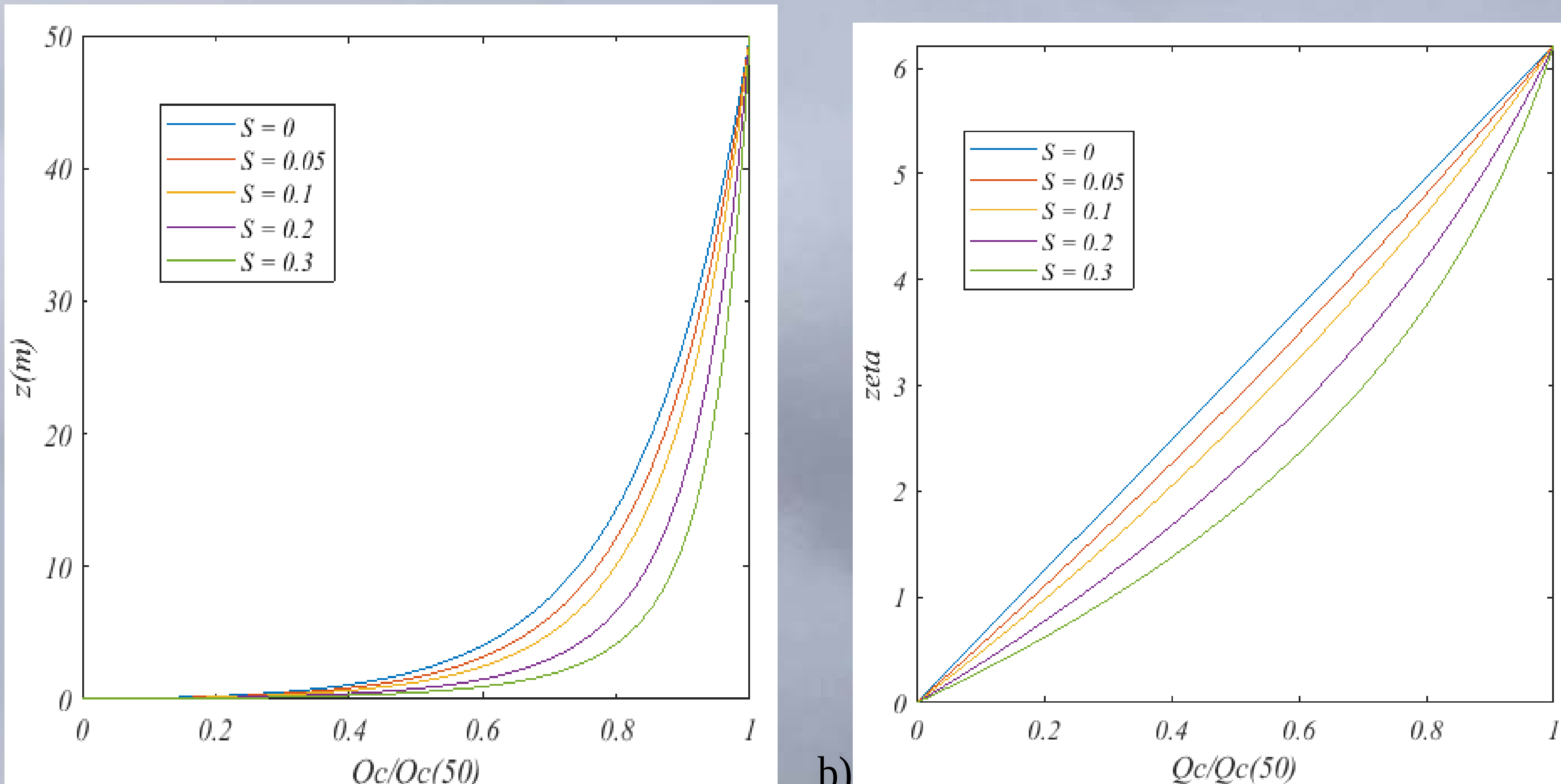


Fig. 1 *Qc* profiles, scaled by 50 m value, from surface to z = 50 m in constant flux layers with gravitational settling and surface roughness length for water droplet removal, z_{0c} = 0.1 m. Linear (a) and logarithmic (b) height scales.

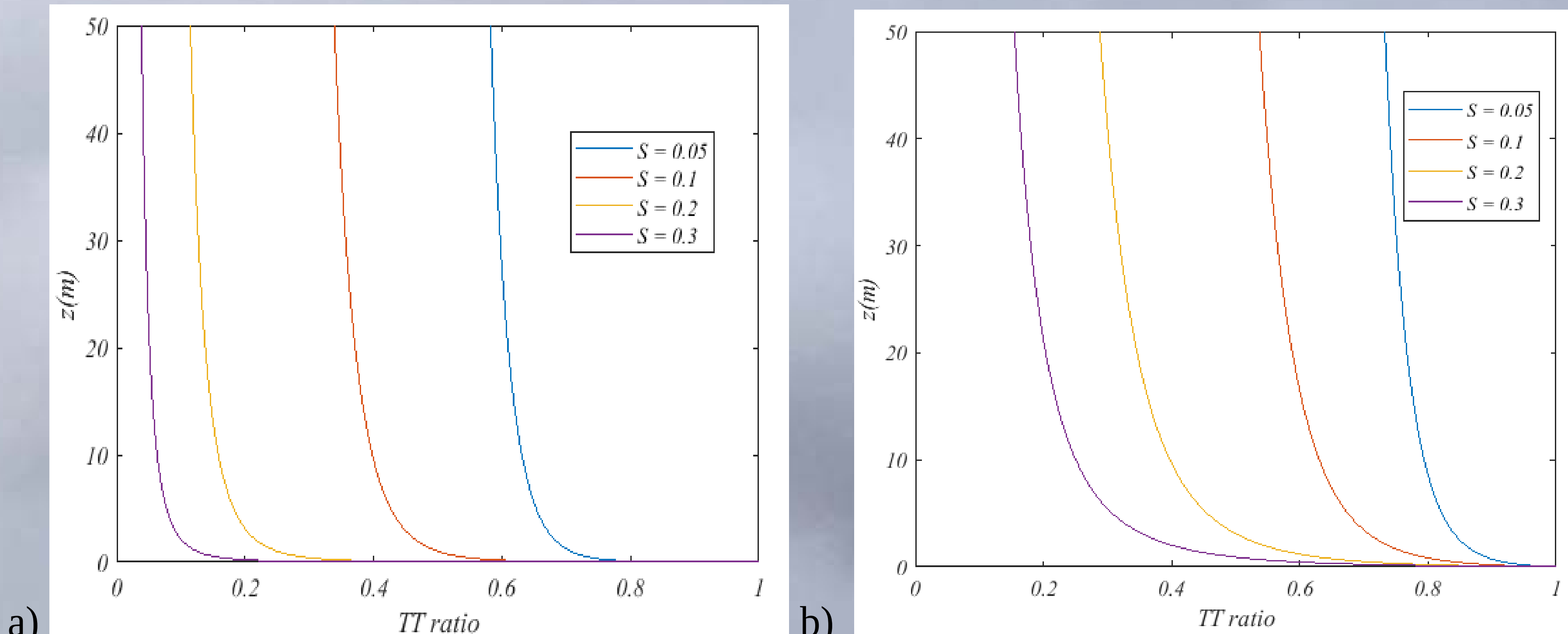
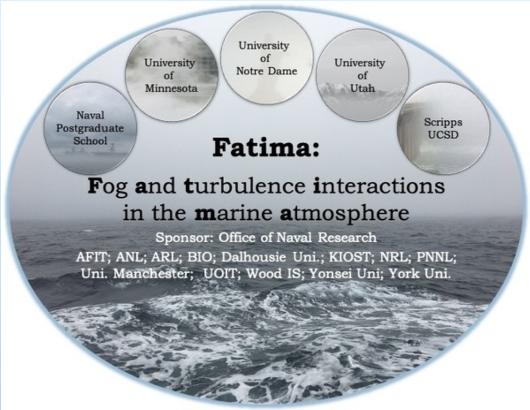


Fig. 2 Variation of the Turbulent Transfer fraction of the total *Qc* flux and its variation with *z* and *S*. Note that these *z* values are based on a) $z_{0c} = 0.001$ m and b) $z_{0c} = 0.1$ m

Gravitational settling dominates at top (50m) while turbulent transfer is responsible for more flux as z approaches 0. $S = w_s/(ku^*)$.



Summer 2022 – Sable Island component of Fatima: **Fog and turbulence interactions in the marine atmosphere**.
https://efmlab.nd.edu/research/Fatima/
Led by Joe Fernando, Notre Dame University.

Fog on Sable Island: Picture from Zoe Lucas,
Sable Island Institute (https://sableislandinstitute.org/

4. Stable Stratification Case

Over land radiation fog often occurs at low wind speeds with stable stratification. For constant flux boundary layers in these circumstances MOST has, for velocity, $K_m = k(z+z_{0m})/ \Phi_M(z/L)$ and

$$\Phi_M(\zeta) = 1 + \beta\ (z+z_{0m})/L : U = (u^*/k)\ (\ln ((z + z_{0m})/z_{0m}) + \beta\ z/L).$$

Observed profiles give $\beta = 5$ (Garratt 1992, p52). If we extend this idea to $K_{Qc} = k(z+z_{0c})/ \Phi_{Qc}(z/L)$ with a similar form for Φ_{Qc} we need to (and can) solve,

$$w_s Qc + [ku^*(z + z_{0c})/ \Phi_{Qc}(z/L)]\ dQc/dz = F_{Qc} = u^* q_c^*,$$ or

$$dQc/dz+S\{(1+\beta(z+z_{0c})/L)/(z+z_{0c})\}Qc=(q_c^*/k)(1+\beta(z+z_{0c})/L)/(z+z_{0c}); S=w_s/(ku^*$$

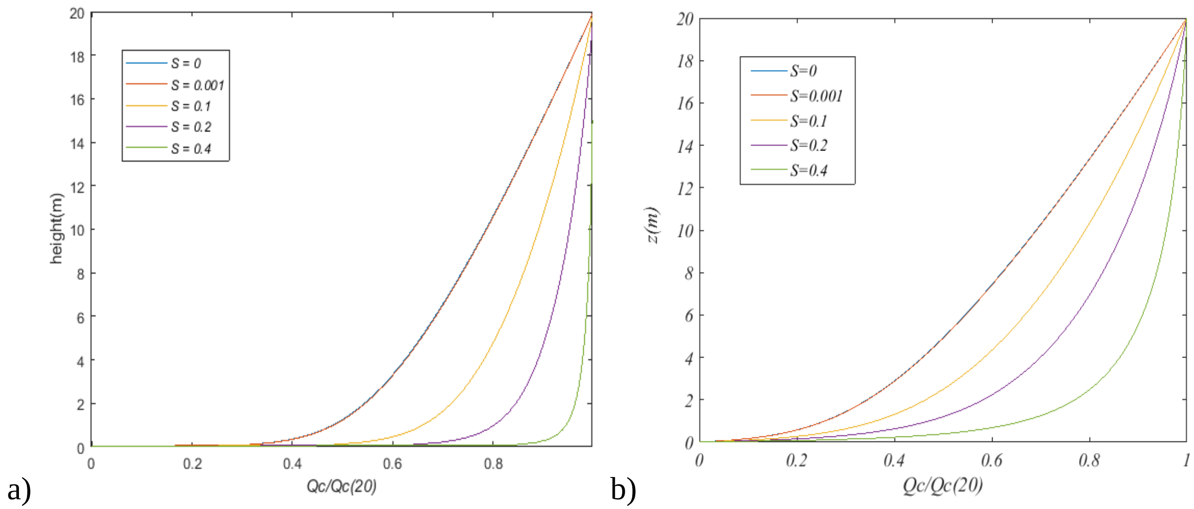


Fig 3. Profiles with stable stratification, $\Phi_{Qc}(\zeta) = 1 + \beta\ (z+z_{0c})/L$, $\beta = 5$, $L =$ 20m, S = 0 and 0.001 lines overlap as confirmation of our solution form. a) z_{0c} = 0.001m, b) z_{0c} = 0.1m.