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Mean inversion strength of the convective boundary layer over the oceans

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SUMMARY

An equilibrium energy budget for the oceanic convective boundary layer shows that the mean inversion strength in balance with a radiatively driven subsidence is typically ≈ 9 K, in agreement with the widely observed value.

1. INTRODUCTION

Kuo and Schubert (1988) (their Fig. 1) showed that for a wide range of data, including cumulus and stratocumulus boundary layers over the ocean, the inversion strength was roughly constant at $\Delta\theta \approx 9$ K. $\Delta\theta$ was defined as the difference $(\theta_t - \theta_m)$ between potential temperatures (θ_t) above the inversion and in the mixed subcloud layer, (θ_m). However, they did not provide an explanation. The reason appears to be that the convective boundary layer (CBL) over the ocean is not far from equilibrium with a radiatively driven subsidence field. Betts and Ridgway (1988) showed that the radiatively driven subsidence over the tropical oceans was $\approx 0{\cdot}042\,\mathrm{Pa\,s^{-1}}$ ($36\,\mathrm{mb\,d^{-1}}$). An equilibrium energy budget for the CBL readily shows that this gives an equilibrium inversion strength ≈ 9 K.

2. θ BUDGET FOR CBL

The one-dimensional potential temperature budget integrated from surface (subscript s) to CBL top (subscript t) for a horizontally homogeneous CBL in a steady state is

$$F_s + \int_s^t c_p(\omega/g)(\partial\theta_L/\partial p)dp - \int_s^t (\theta/T)(\partial N/\partial p)dp = 0 \tag{1}$$

where F_s is the surface flux of sensible heat (strictly a $c_p\theta$ flux); N is the (diurnally averaged) net radiative flux; and θ_L is the liquid water potential temperature. The adjustment time of the CBL is of order a day or two (Schubert *et al.* 1979) so we can integrate over a diurnal cycle for illustrative purposes. Equation (1) can be integrated in the form

$$F_s + (c_p\omega_t/g)(\theta_t - \overline{\theta}_L) - (\overline{\theta/T})\Delta N_{st} = 0 \tag{2}$$

where ω_t is the subsidence at CBL top, ΔN_{st} (defined positive) is the mean radiative cooling of the CBL, $\overline{\theta}_L$ is the divergence-weighted mean θ_L of the CBL and $(\overline{\theta/T})$ is a mean with respect to the radiative cooling. Approximating $(\overline{\theta/T}) \approx 1$ and $\overline{\theta}_L \approx \theta_m$, the subcloud layer mean, Eq. (2) can be simplified to

$$F_s + (c_p\omega_t/g)\Delta\theta - \Delta N_{st} = 0. \tag{3}$$

Equation (3) simply expresses the equilibrium balance of the surface heat flux, the subsidence warming and the radiative cooling for the CBL. Rearrangement gives the inversion strength, as defined by Kuo and Schubert (1988), as

$$\Delta\theta = g(\Delta N_{st} - F_s)/c_p\omega_t. \tag{4}$$

The terms on the right-hand side have quite characteristic values for equilibrium CBLs over the oceans (Betts and Ridgway 1988). The surface sensible heat flux, $F_s \approx 10\,\mathrm{W\,m^{-2}}$ associated with surface winds $\approx 7\,\mathrm{m\,s^{-1}}$ and sea–air temperature differences of order 1 K or less. The net radiative cooling of the moist CBL, $\Delta N_{st} \approx 50\,\mathrm{W\,m^{-2}}$. If we substitute these values in (4) and set $\omega_t = 0{\cdot}042\,\mathrm{Pa\,s^{-1}}$ ($36\,\mathrm{mb\,d^{-1}}$) (the mean value of the radiatively driven subsidence over the tropical oceans in Betts and Ridgway (1988)), we find

$$\Delta\theta = (9{\cdot}8 \times 40)/(1006 \times 0{\cdot}042) = 9{\cdot}3\,K. \tag{5}$$

The cooling of the troposphere above the CBL (and hence ω_t) is not very sensitive to CBL cloud fraction, nor is ΔN_{st}, the bulk cooling of the moist CBL. The equilibrium surface sensible heat flux is reduced to near zero beneath a fully cloudy CBL, because the net radiative cooling of the subcloud layer is removed; however, F_s is the smaller term in Eq. (4). As a result this budget is very similar for cumulus and stratocumulus boundary layers. The other main effect of 100% cloud cover is the reduction of the net incoming short-wave radiation at the ocean surface; however, this affects the sea surface temperature equilibrium, rather than the CBL budget directly.

3. Conclusion

Clearly some range of values can be expected for inversion strength, associated with variations in surface heat flux, the subsidence at CBL top, and the net radiative cooling (which depends somewhat on cloud fraction and CBL depth), but this mean value of $\Delta\theta \approx 9$ K is in close agreement with Kuo and Schubert (1988). Thus their results suggest that the CBL over the oceans is typically not far from equilibrium with a radiatively driven subsidence field.

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