Simulating the Stratocumulus-to-Cumulus Transition Using a Quasi-third-order Closure Turbulence Parameterization

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Motivation

The character of turbulence in the planetary boundary layer varies significantly depending on the static stability and the presence of either cumulus or stratocumulus cloud cover. A successful turbulence parameterization should be able to produce accurate turbulent fluxes regardless of the planetary boundary layer's (PBL) state. Given the significant differences in the state of the PBL between cumulus and stratocumulus regimes, the ASTEX Lagrangian Transition Case provides a challenging test case for a new parameterization. A description of the new turbulence parameterization, results from the ASTEX case, and results from a large-scale subsidence sensitivity test are presented.

Parameterization Description

What is quasi-third-order closure?

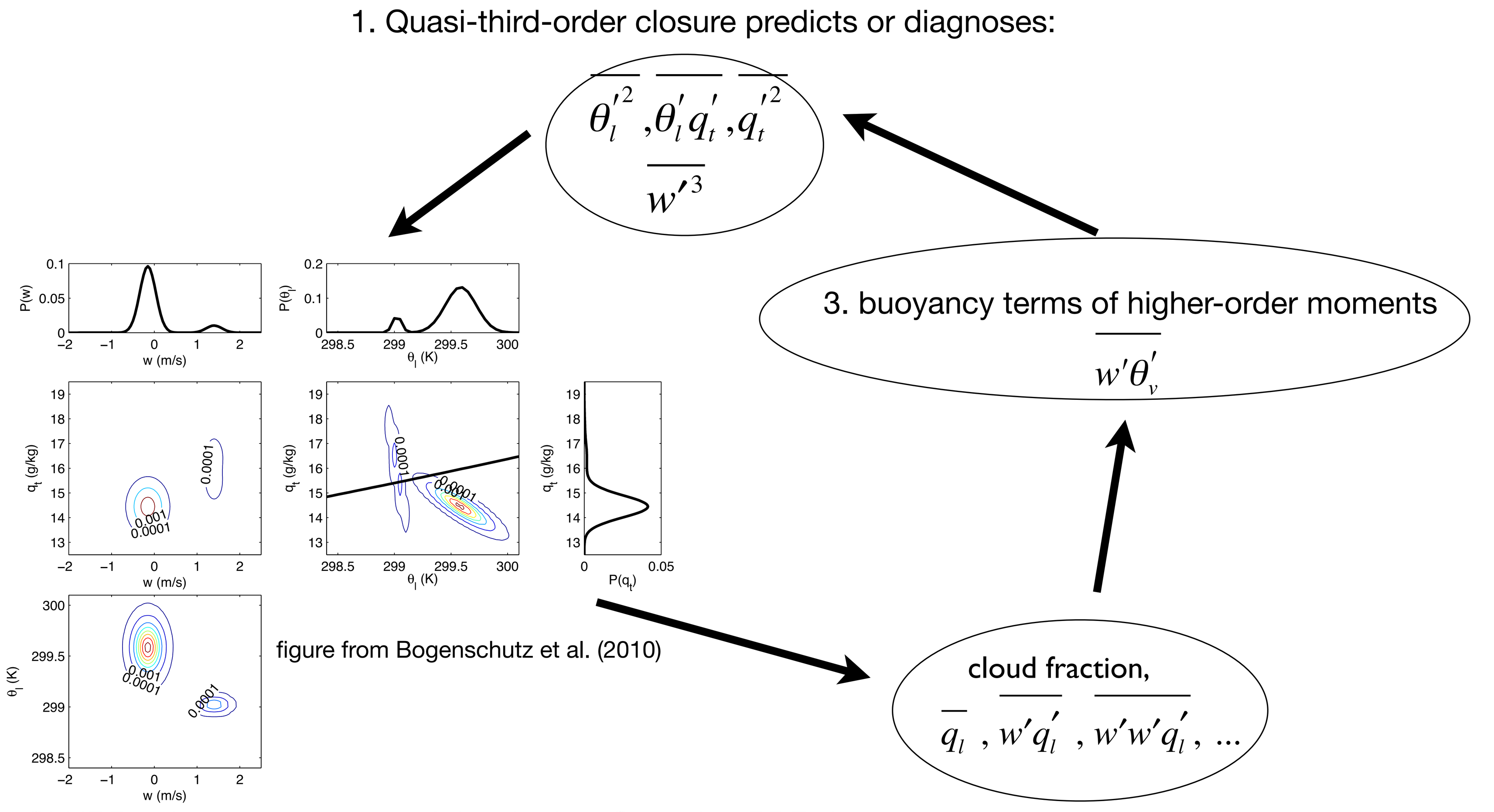
- Predicts 10 second-order moments (TKE components, turbulent fluxes, and thermodynamic covariances)
- Diagnoses all third-order moments following Cheng, Canuto, and Howard (2005)
  - ➡ all physical parameterizations from standard third-order closure are kept (including the fourth-order moments), but the tendency terms are assumed to be zero:
  - ➡ length scale calculated using "free path" method using a parcel's initial TKE

$$\cancel{\frac{\partial \overline{u_i'u_l'\theta_l'}}{\partial t}} = -\overline{u_j'u_i'u_l'}\frac{\partial \overline{\theta_l}}{\partial x_j} - \overline{u_j'u_l'\theta_l'}\frac{\partial \overline{u_i}}{\partial x_j} - \overline{u_j'u_i'\theta_l'}\frac{\partial \overline{u_l}}{\partial x_j} - \frac{\partial \overline{u_j'u_i'u_l'\theta_l'}}{\partial x_j}$$
$$+\frac{g_i}{\theta_{v_0}}\overline{u_l'\theta_l'\theta_v'} + \frac{g_l}{\theta_{v_0}}\overline{u_i'\theta_l'\theta_v'} - \frac{1}{\rho_0}\left(\overline{u_l'\theta_l'\frac{\partial p'}{\partial x_i}} + \overline{u_i'\theta_l'\frac{\partial p'}{\partial x_l}}\right)$$
$$+\overline{u_i'u_l'}\frac{\partial \overline{u_j'\theta_l'}}{\partial x_j} + \overline{u_l'\theta_l'}\frac{\partial \overline{u_i'u_j'}}{\partial x_j} + \overline{u_i'\theta_l'}\frac{\partial \overline{u_j'u_l'}}{\partial x_j}$$
$$+\nu_{\theta_l}\overline{u_i'u_l'\frac{\partial^2\theta_l'}{\partial x_j^2}} + \nu\overline{u_l'\theta_l'\frac{\partial^2 u_i'}{\partial x_j^2}} + \nu\overline{u_i'\theta_l'\frac{\partial^2 u_l'}{\partial x_j^2}}$$

Subgrid-scale Condensation

- Makes use of CLUBB scheme (assumed double Gaussian PDF) from Larson et al. (2002)

1. Quasi-third-order closure predicts or diagnoses:

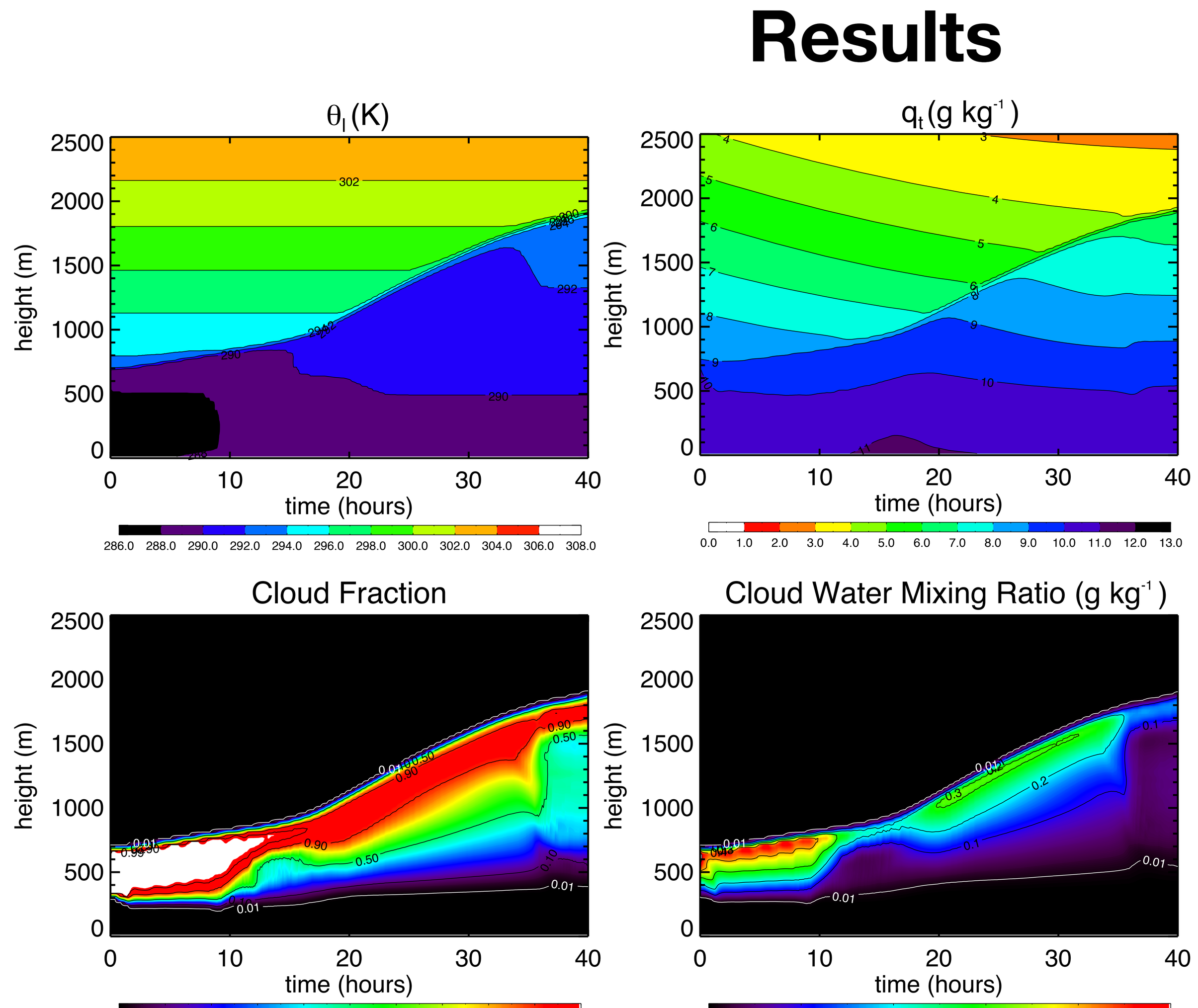


2. CLUBB scheme calculates a joint double-Gaussian PDF, then diagnoses cloud fraction, cloud water, and cloud water flux

Model Setup

- Standard ASTEX Lagrangian case setup (except 25m constant Δz)
- Interactive RRTMG radiation
- Khairoutdinov and Randall (2003) warm-rain microphysics
- Single-column model framework

Results



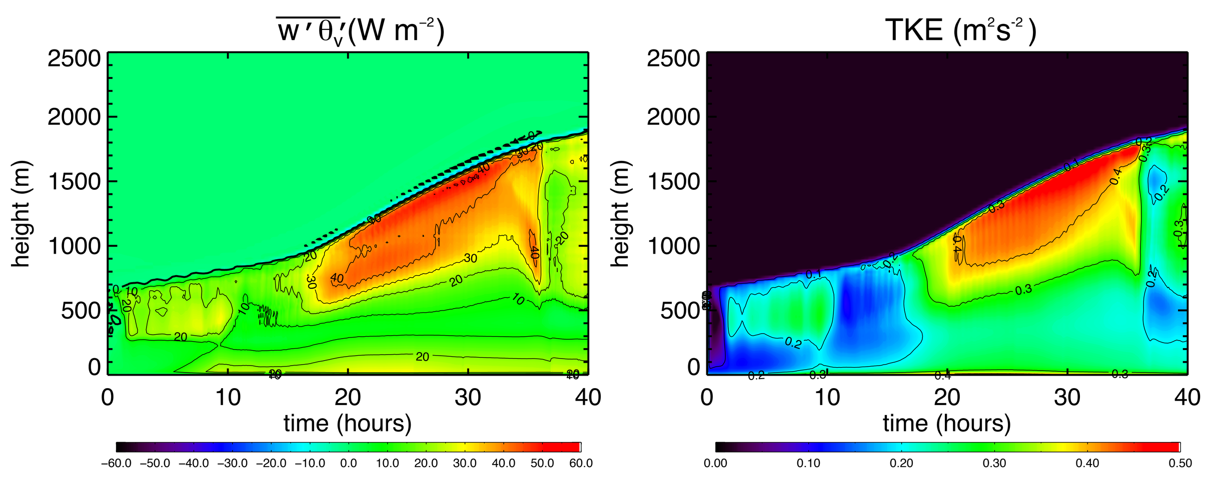
Mean Quantities and Clouds

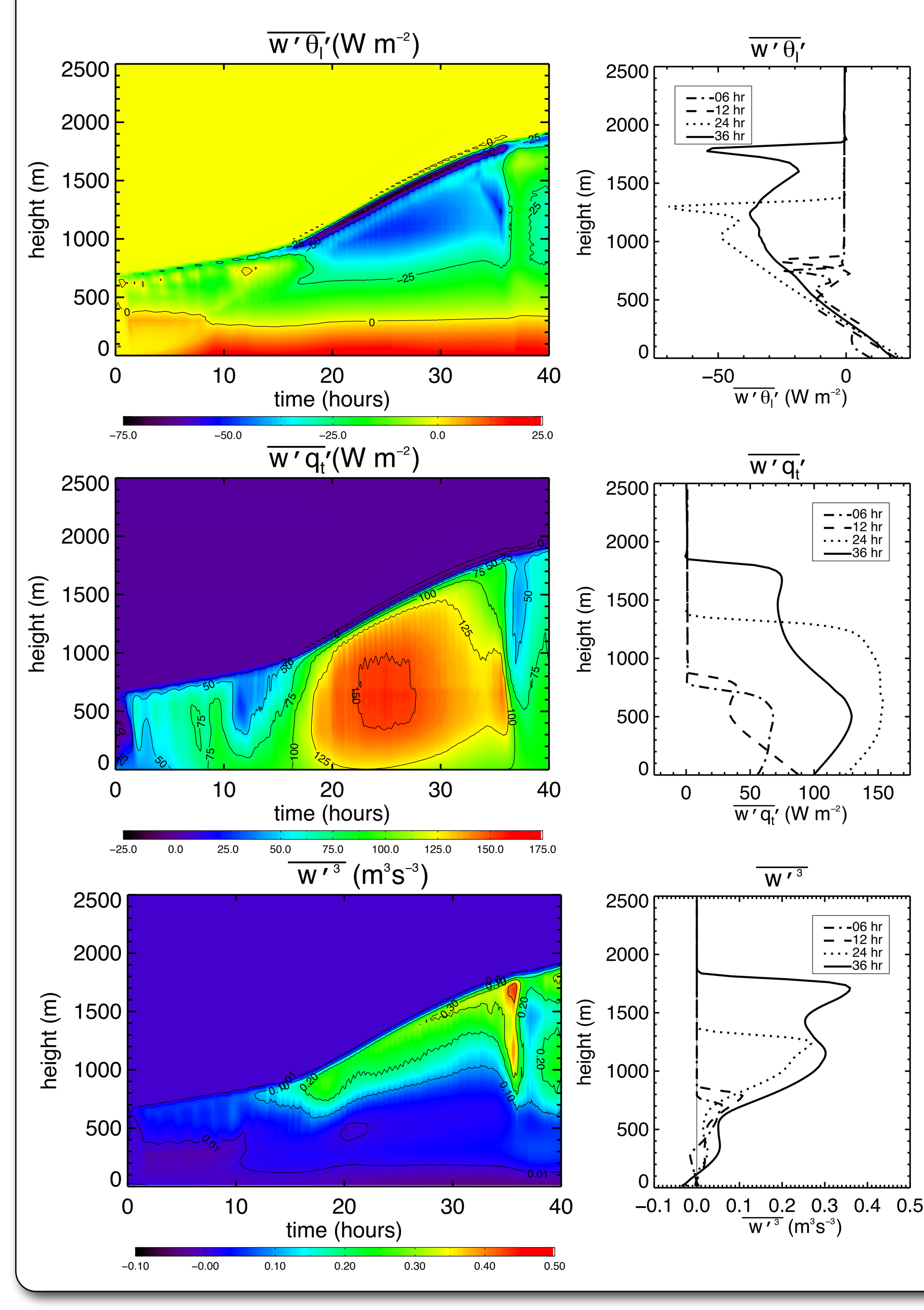
Time-height cross sections of the mean thermodynamic variables and cloud statistics show that the PBL deepens from ~700m to ~1900m over the 40 hour simulation. The initial stratocumulus cloud deck thins during daylight hours and reforms and deepens during the second night. Starting from daybreak on day 1, cumulus forms underneath the broken stratocumulus, and by hour 36 on the second day, cumulus extends from cloud base to ~1500m and is topped by only a thin layer of broken stratocumulus.

Results (continued)

4 Stages of Transition

1. hrs 0-10: nocturnal drizzling stratocumulus
2. hrs 10-18: daytime cumulus under thinning stratocumulus
3. hrs 18-36: cumulus under strengthened and recoupled precipitating stratocumulus
4. hrs 36+: mostly cumulus under thin, broken stratocumulus





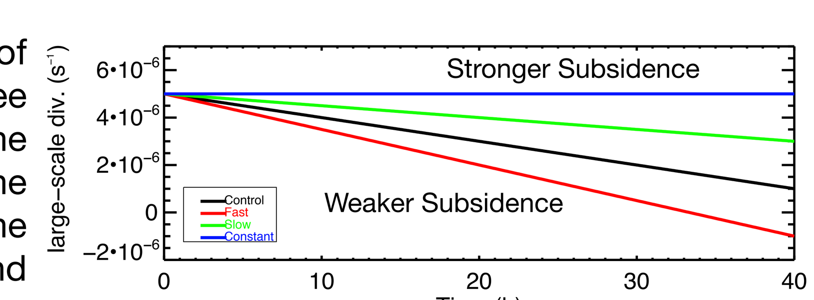
Turbulence Statistics

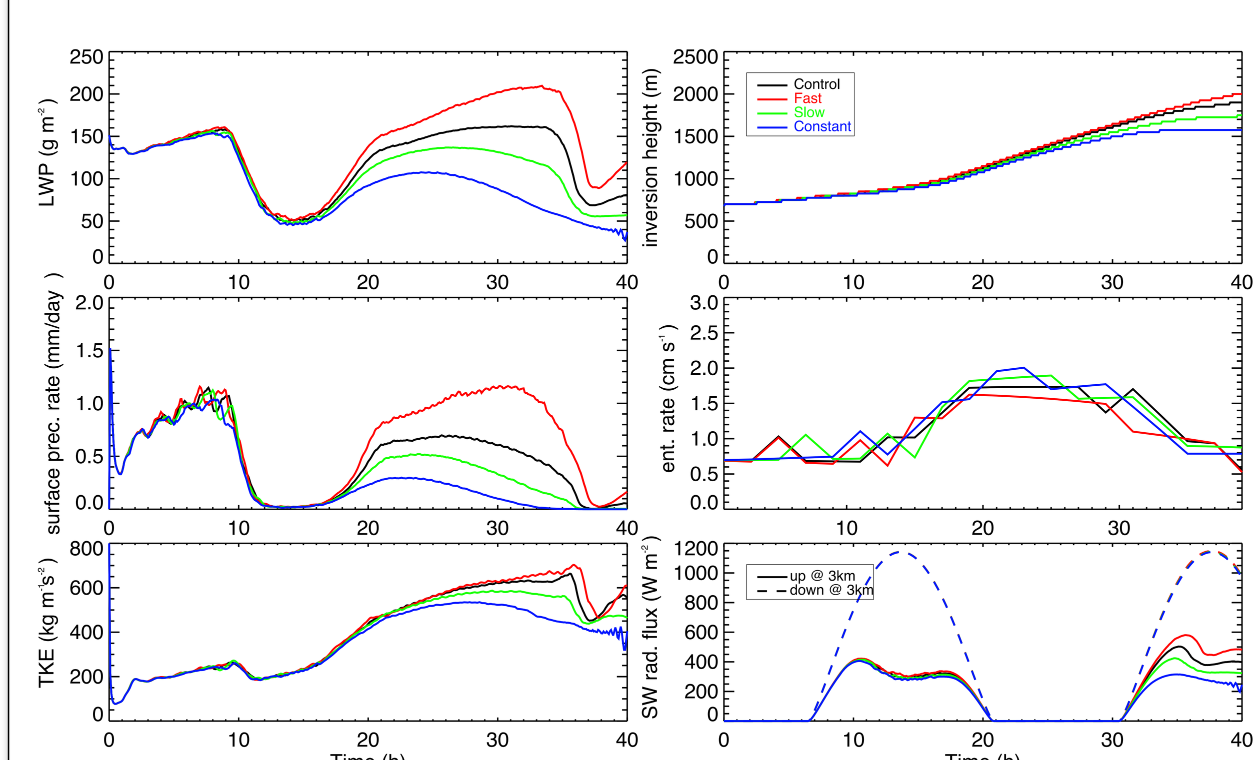
- **Stage 1**: Typical drizzling nocturnal stratocumulus with moderate in-cloud buoyancy production and TKE; low values of w-skewness indicate symmetrical updrafts/downdrafts
- **Stage 2**: Shortwave absorption weakens stratocumulus circulation, resulting in a thinning cloud deck, decoupling with the surface, and the cessation of precipitation; w-skewness increases, indicating a cumulus-under-stratocumulus regime
- **Stage 3**: The second nocturnal stage reestablishes strong cloud-top radiational cooling and strengthens the circulation; the buoyancy flux, heat flux, moisture flux, and TKE are all maximum during this stage; drizzle is reinitiated and the circulation appears mostly recoupled with the surface
- **Stage 4**: The second daytime period thins the stratocumulus deck significantly; the circulation becomes decoupled from the surface as the buoyancy flux and TKE reach minimum values at cloud base; values of the heat flux, moisture flux, and w-skewness all reach values typical of a cumulus regime from cloud base at ~500m to just below the remaining broken stratocumulus deck at 1700-1900m

Large-scale Divergence Sensitivity Test

Setup

The large-scale divergence determines the strength of subsidence above and within the boundary layer. Three additional simulations were run with differing evolutions of the large-scale divergence: one with constant divergence and the strongest subsidence, one with a slower decrease in the divergence with stronger subsidence than the control, and one with a faster decrease in the divergence implying weaker subsidence than the control.





- Larger divergence values (implying stronger subsidence) lead to drier and warmer air being entrained into the PBL.
- The constant divergence case (blue) with the strongest subsidence predicts the thinnest cloud and weakest circulation, creating the shallowest boundary layer.
- The fastest decreasing divergence case (red) has the weakest subsidence, and predicts the thickest cloud, highest inversion height, and most reflected shortwave radiation.

Conclusions

- The quasi-third-order closure turbulence parameterization with the assumed double-Gaussian PDF subgrid-scale condensation scheme displays skill simulating the transition from stratocumulus to cumulus.
- Four distinct stages of the transition are predicted, from a typical nocturnal drizzling stratocumulus regime to a daytime cumulus regime under a thin, broken stratocumulus deck.
- The transition is strongly affected by the large-scale divergence and subsidence rate, with stronger subsidence creating a thinner cloud, reduced precipitation, and a shallower boundary layer.

References

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