Southeast Pacific Stratocumulus Cloud Top Heights

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1. Introduction

Marine boundary layer height observations, or its proxy, cloud top height, serve as a critical test of cloud simulations, and to deductions of mean cloudtop entrainment. Stratocumulus cloud top heights in the southeast Pacific (SEP) are known to exceed those of Californian stratus, which has consequences for how drizzle affects the sub-cloud thermodynamic profile in the different regions. SEP stratocumulus cloud top height diurnal variations are also more pronounced than those of the Californian stratus because of diurnal variations in the free-tropospheric subsidence. This has consequences for the mean cloud deck radiative impact, although the connection between boundary layer depth variability and the associated cloud properties is not yet well-characterized.

Despite the utility of well-characterized cloud top heights for southeast Pacific stratocumulus, its spatial structure has not yet been observationally assessed. Satellite data provides an efficient observational approach. For our study we selected MODIS data because of its high radiometric accuracy, 4x/times daily overpasses, and wide (~ 2300 km) swath. In addition, MODIS overlaps with six month-long cruises that included (high-quality Vaisala RS-90 series) radiosonde launches. These allow an empirical deduction of a depth-varying lapse rate, to account for the decoupling that may be present within the deeper SEP boundary layer. The cruises (tracks are shown in Fig. 1) were spread over 6 years and sampled a range of conditions, adding robustness to their parameterization. All combined, the cruises launched about 180 radiosondes at times close to the 4x/daily MODIS overpasses.

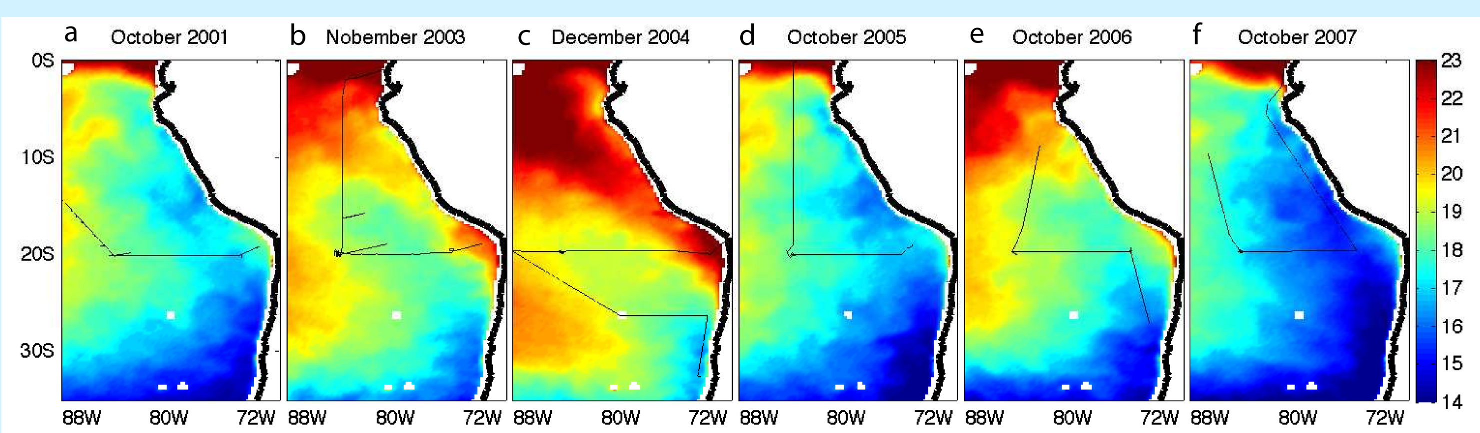
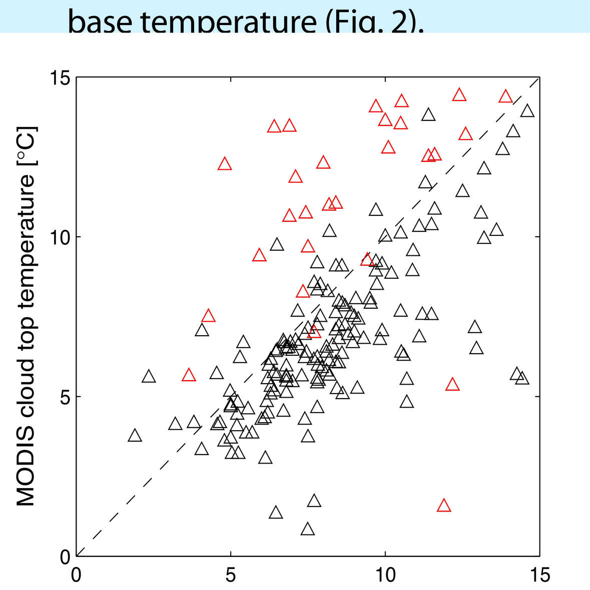


Figure 1: Monthly-mean TMI sea surface temperatures for each of the 6 cruises with black lines indicating the ship track. Cooler near-coastal SSTs caused by oceanic upwelling is apparent, with warming occurring as the Southern Hemisphere moves into its summer (panels a, b, and c). The October cruises (panels a, d, e, and f) sample the month of the climatologically maximum cloud extent. Of these, the 2006 and 2007 cruises (panels e and f) occurred during a warm and cool ENSO phase respectively.

2. Cloud top height parameterization

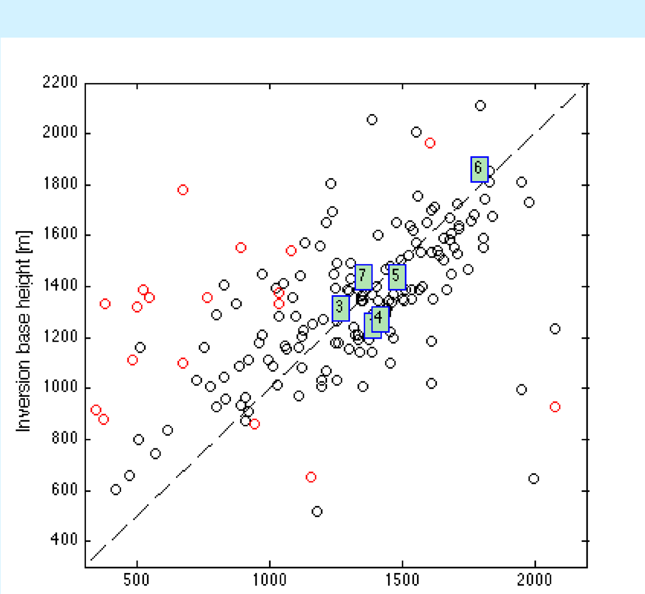
We use daily MODIS Collection-5 cloud top temperatures from both the *Terra* and *Aqua* platforms, derived from the 11 µm equivalent brightness temperatures. The Level-2 data first determines the cloudy pixels, then subsamples these from the original 1 km spatial resolution at nadir to a 5 km spatial resolution. First we compare the MODIS-retrieved cloud top temperatures to the cloud-capping inversion base temperature (Fig. 2).



For the completely overcast (5-km-scale areas), the MODIS-derived cloud top temperatures are less than the sonde-derived inversion base temperatures by a mean value of 1.3 K (a height difference of about 150 m).

We lack an explanation. The sondes (RS-90 series except for 2001) possess improved temperature sensor responses capable of delineating sharp thermal changes to < 100 m. For the dry subtropical subsiding atmosphere, uncertainty in the correction for the overlying water vapor path by the MODIS algorithm is thought to be < 0.5 K (Dong et al., 2008). Although cloud tops do extend above the inversion base at times, as shown by wind profilers that indicate maximum humidity and temperature gradients occur ~ 100 m above inversion base (de Szoeke et al., 2008), in the mean, radar-derived cloud top heights are most closely associated with the inversion base minimum temperature. We welcome suggestions.

Fig 2: MODIS cloud top temperature versus sonde-derived inversion base temperature. 1-km pixels classified as cloudy but subsampled from 5-km areas with cloud fractions < 0.9, indicated in red, suggest some surface contamination of the satelite-retrieved cloud top temperature.



A best-fit line relates the inversion base height z_inv to T_inv and the 3-day-mean TMI SST according to $SST - T\_inv = 0.0069*z\_inv + 1.05$. This is incorporated into a MODIS cloud top height estimate z_top, as well as the 1.3 K offset between T_top and T_inv. We find

$$z\_top = (SST\_tmi - T\_top - 2.35)/0.0069 \qquad (1)$$

with SST_tmi and T_top in K, z_top in m, applicable to cloud tops between 800 and 2000 m (Fig. 3). The comparison between z_top and z_inv has a correlation coefficient of 0.73, rmse of 275 m and a bias of -14 m for overcast pixels (N=156). Values from each cruise follow the same tendency. Cloud top heights are slightly underestimated for inversion bases < 900 m. Note the buoy-mean cloud top height for 2006, a warm ENSO phase year, is ~ 300 m higher than for other years.

Fig 3: Sonde-derived inversion base height versus the MODIS cloud top height estimated using Eqn. 1. Red circles correspond to cloud fractions < 0.9. Boxes indicate 6-day buoy-mean values at 20S, 85W, with the number indicating the last digit of the cruise year.

3. Implications, inc. lapse rate

If a sea-air temperature difference of 0.5 K is assumed (Klein and Hartmann, 1993), and the 1.3 K offset ignored, an "effective" lapse rate Γ_eff (K/km) can be constructed: $\Gamma\_eff = 6.4 + 1.05/z\_top$, with z_top in km. This effective lapse rate is steepest (7.7 K/km) for the most shallow boundary layer of 800 m (for which it is slightly overestimated, see fig. 3), and decreases to 6.9 K/km for the deepest boundary layer of 2 km. The inverse dependence on the cloud top height accounts empirically for an increased decoupling for the deeper boundary layers (Wood and Bretherton, 2004; Betts et al., 1992). They are slightly higher than the ~6.5 K/km deduced over the North Pacific during FIRE, and over the North Atlantic during ASTEX. Ultimately ship cruise data on the sea-air temperature difference will be incorporated into the lapse rate derivation, which will also allow us to examine if the temperature difference scales with boundary layer depth (cloud top height).

Eqn. 1 places cloud top (and inferred boundary layer height) somewhere intermediate between the lower cloud top heights (by 100-200 m) corresponding to the Wood and Bretherton (2004) parameterization, and the higher cloud top heights corresponding to the Garreaud et al. (2001) fixed lapse-rate values. Ahlgrimm and Randall (2006), who used Geoscience Laser Altimeter System data, place cloud top heights higher yet.

Monthly-mean cloud top heights constructed for each of the 6 cruises (Fig. 4) show an apparent raising of the cloud top heights with the seasonal progression (and by inference boundary layer depth). Cloud tops are also higher during the warm ENSO phase of Oct. 2006 than the cool ENSO phase of Oct. 2007.

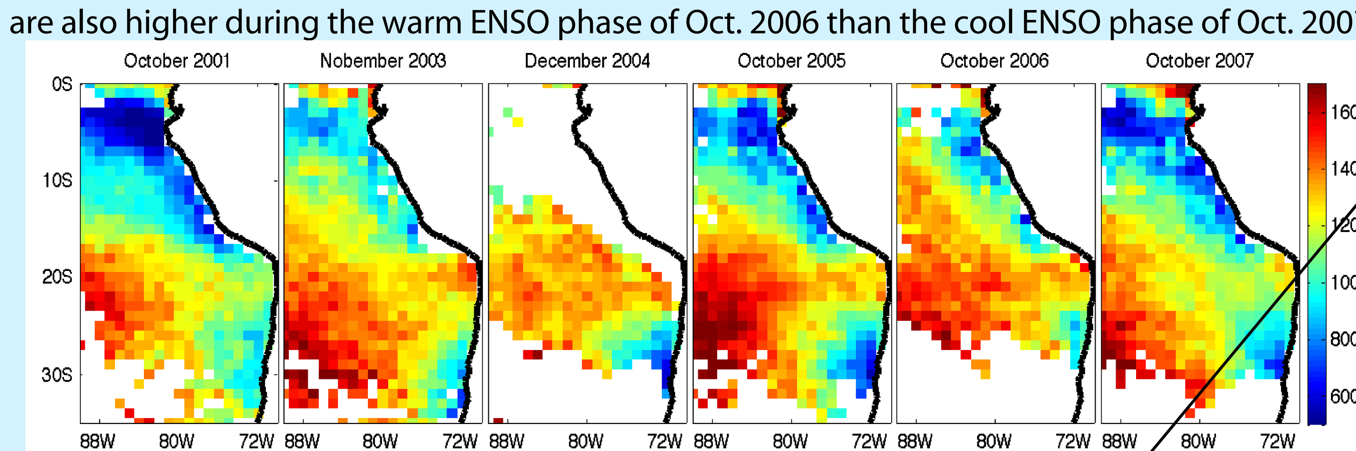


Figure 4: MODIS -derived mean cloud top heights for each of the cruises. Values are only shown when comprised of 10 daily-mean (Terra only) samples or more (cloud fraction > 0.9).

4. Regional features & diurnal sampling

The mean cloud top height field for October 2005, 2006, 2007 combined (Fig. 5) is shown for each of the 4 MODIS overpass times (irregularly sampled at 2230, 0130, 1030, 1330 LT).

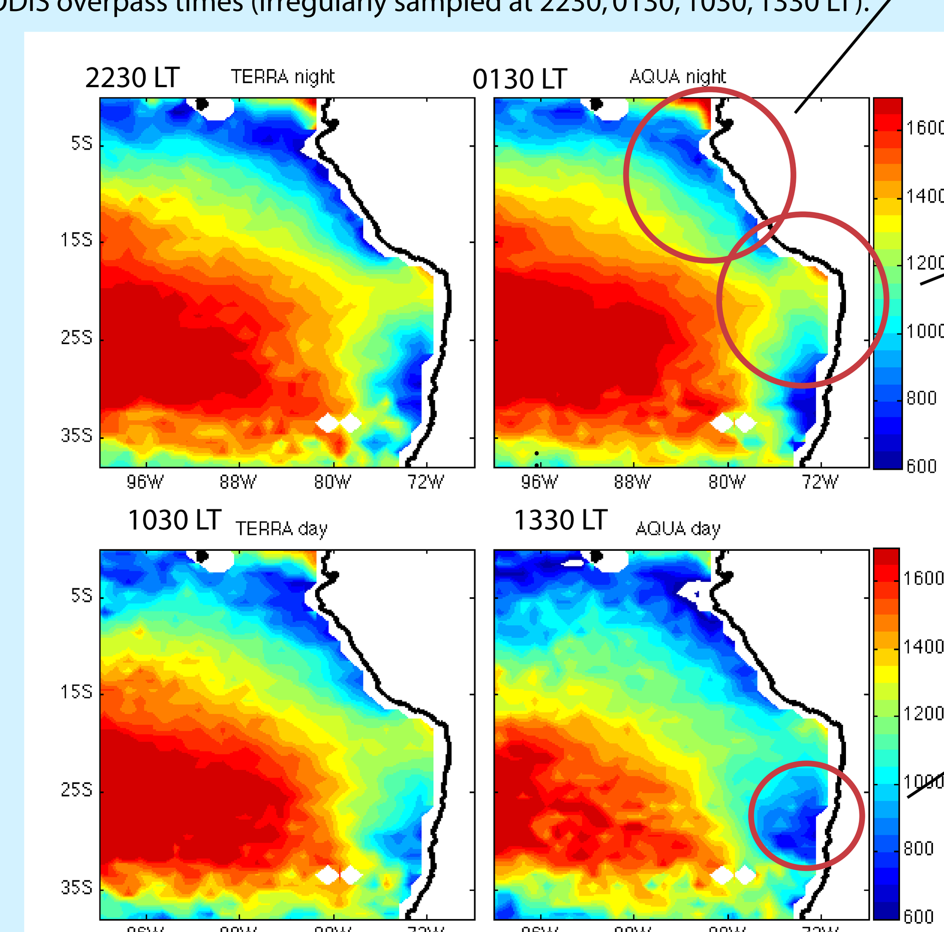


Figure 5: Mean MODIS cloud top height field for October 2005-2006-2007, at each of the 4 overpass times.

Which platform/time is closest to the 4xdaily mean? Terra-day.

This helps explain why cloud top heights derived from the Terra-based daylight-only 780-km swath Multi-Angle Imaging SpectroRadiometer data (Garay et al., 2008), are basically consistent with MODIS Terra-day/MODIS-diurnal mean values. Swath-limited CALIPSO, on the Aqua platform, has noisy cloud top heights, and misses the diurnal-mean elevated Arica Bight (~70W, 20S) CTHs, partly because the CTHs are somewhat suppressed at 1330 LT.

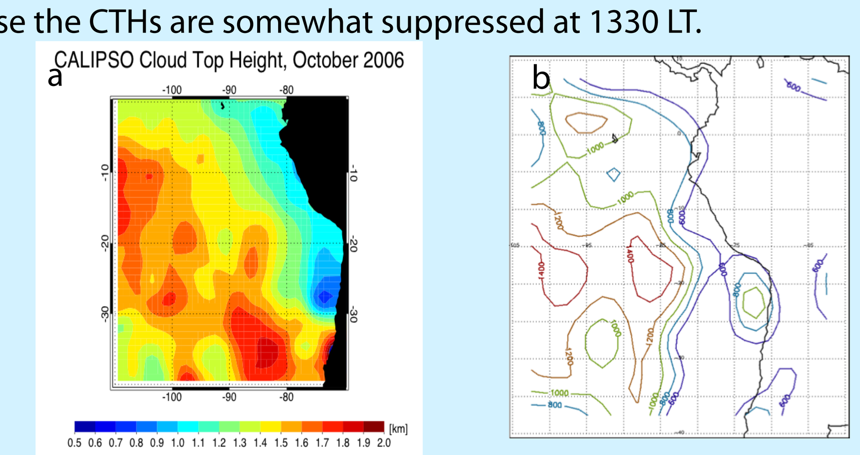
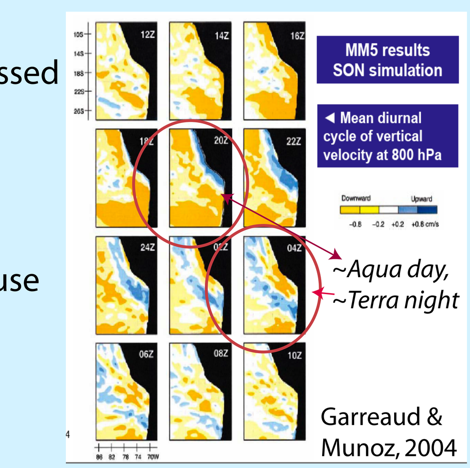


Figure 6: a) CALIPSO Oct. 2006 cloud top heights, courtesy of Rob Wood and Dong Wu. b) MISR Oct. 2006 cloud top heights, courtesy of Michael Garay.

Peruvian coastal subsidence diurnal cycle

Coastal area boundary layer depth is thought to undulate diurnally, parallel to the coast, from free-tropospheric subsidence changes induced by the daily cycle in sensible heating of the dry Andes mountains (Garreaud and Munoz, 2004; GM04). Is their model result consistent with our 4x daily snapshots?

The 4xtimes-daily values are plotted as anomalies from their mean in Fig. 7. The Aqua day plot shows a slight coastal anomalously elevated CTHs, and depressed CTHs further offshore. Terra-night CTH anomalies are out-of-phase with those from Aqua day. This is consistent with simulated diurnally-resolved vertical velocities (***w***). The diurnal range in CTH exceeds that found for modeled cloud tops in GM04, maybe because the diurnal responsiveness is sensitive to poorly-modeled cloud depth?



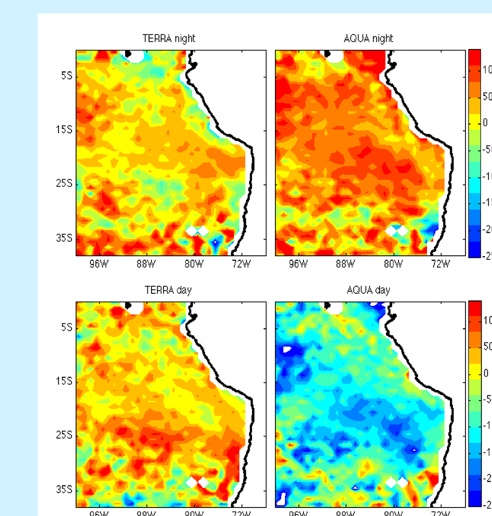


Figure 7: Figure 5, replotted as cloud top height anomalies from the diurnal-mean

Arica Bight

This region will be sampled well during the VOCALS Regional Experiment, and is the location of high cloud droplet number/accumulation mode aerosol concentrations of as-yet undetermined origin(s). The elevated cloud top heights relative to coastal areas to the south and north are thought to reflect dynamical blocking by the Andes of the coastal jet to its south, also evident as decreased surface winds (see poster by Painemal and Zuidema), with orographically-induced upward vertical velocities simulated for the Arica Bight by Munoz and Garreaud (2005; MG05). The Arica Bight diurnal variations shown in Fig. 5/7, are not consistent with the simulated 800 hPa ***w*** (note for example the early afternoon CTH minimum) suggesting other physical processes also influence local CTH variations. These locally-elevated cloud top heights may also help explain why CloudSat perceives stronger coastal shoaling of the Namibian stratus than for the SEP deck (see Riley et al. poster, and Fig. 8), as the Namibian coastline is more uniform, with less regional disruption expected of the stability capping the StCu deck.

Chilean Coastal Jet

The MODIS-derived cloud top heights show the spatial/diurnal characteristics of a shallow boundary layer associated with a coastal jet previously only seen in isolated soundings and select model simulations. The ~700 m CTHs are consistent with the MM5-simulated values of GM05 and MG 05, as is the lack of variation in the CT H (BLD), which MG05 explain is set by the (non-varying) altitude of the easterly zonal flow advecting warm air emanating off the continent. What these observations suggest does vary, however, is the spatial extent of the zonal flow: the early afternoon depressed coastal jet boundary layer extends further offshore than at other times. Coincidentally, a similar spatial structure to the diurnal amplitude in surface Quikscat winds is seen in GM05.

Applied more broadly....

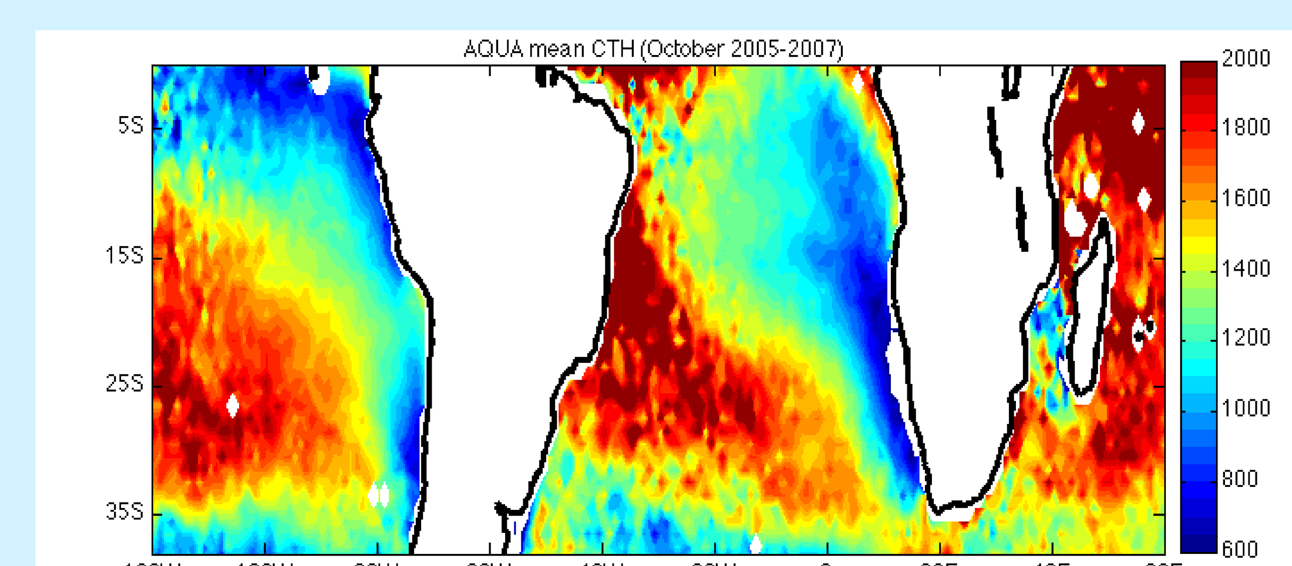


Figure 8: Mean MODIS cloud top height field for October 2005-2006-2007, Aqua only

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