

¹ **How Often is the Stratocumulus-Topped Boundary**
² **Layer Well-Mixed? An Observational Perspective**

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3 Aircraft data from the VOCALS field campaign indicates that presence
4 of underlying cumulus is a reasonable proxy for thermodynamic decoupling
5 of the stratocumulus-topped boundary layer. Frequency of stratocumulus (Sc)
6 with and without underlying cumulus from 40 years of daytime surface ob-
7 server data is used to provide a global, phenomenological perspective on when
8 and where a mixed-layer model is appropriate for studying Sc. In general,
9 Sc is more likely to be well mixed where it occurs most often, though decou-
10 pling is frequently observed even in core Sc areas. If stratus is distinguished
11 from Sc, high latitude Sc is almost always well mixed. Deeper boundary lay-
12 ers are more likely to be decoupled. Overall, MLM arguments are sufficient
13 for understanding Sc behavior about 50% of the time.

1. Introduction

14 Clouds cool the planet by reflecting shortwave radiation back to space and warm the
15 planet by trapping longwave radiation near the surface. Because the longwave effect
16 increases with cloud altitude while compensation from shortwave reflection is height-
17 independent, Earth’s radiation budget is most sensitive to clouds in the planetary bound-
18 ary layer (PBL). Because of their large areal coverage and simple structure, stratocumulus
19 (Sc) clouds have been a focal point for PBL cloud research. The mixed-layer model (MLM)
20 of Lilly [1968] serves as the basis for much of this work and acts as guiding intuition for
21 most of the rest. This framework depends on total water mixing ratio (q_t) and liquid water
22 static energy (θ_l) being horizontally and vertically uniform (well-mixed) throughout the
23 PBL and liquid water content being adiabatic. These conditions are often found to the
24 west of subtropical continents, where turbulence generated by cloud-top radiative cooling
25 overpowers the stratifying effects of solar radiation, drizzle, and cloud-top entrainment.
26 But Sc is also observed in cases where the PBL has decoupled into separate surface-
27 and cloudtop-driven mixed layers connected by intermittent convection. These decoupled
28 cases can only be simulated with much more expensive and complex tools. This leads us
29 to ask whether MLM behavior is a sufficient proxy for real-world Sc feedback. To answer
30 this question, we calculate how frequently Sc are actually observed to be well mixed.

31 Previous studies provide partial answers to this question. Bretherton and Wyant [1997]
32 conclude that most of the Northeast Pacific Sc region is decoupled based on buoyancy
33 integral ratio values from Lagrangian MLM simulations forced by climatological July data.
34 Wood and Bretherton [2004] use a combination of satellite and reanalysis data from Sept-

35 Oct 2000 to characterize decoupling frequency over the Northeast and Southeast Pacific,
36 concluding that regions closer to the coast tend to be better mixed and that PBLs deeper
37 than 1 km were predominantly decoupled. Jones et al. [2011] investigate decoupling in
38 the Southeast Pacific using aircraft data. They find the PBL well-mixed 28% of the time
39 using an empirical decoupling threshold for cross-PBL differences in q_t and 45% of the
40 time using a threshold for difference between lifting condensation level and observed cloud
41 base. The fact that estimates from Jones et al. [2011] differ substantially depending on
42 what measure of decoupling is chosen suggests that decoupling metrics should be chosen
43 carefully.

44 In this paper we use a new approach to define decoupling - we take a PBL to be
45 decoupled if it bears visible signs of decoupling in the form of underlying cumulus (Cu).
46 Justification for our approach is given in Sect 2. With this metric, we are able to calculate
47 decoupling frequency from near-global long-term surface observer data in Sect 3. Using
48 surface observer data avoids problems of inadequate spatial and temporal coverage found
49 in previous work. Our phenomenological approach also frees us from the need to use
50 uncertain and approximate measurements.

2. Cu as a Decoupling Metric

51 To establish the validity of using observer reports of Cu under stratocumulus as an in-
52 dicator of decoupling, we examine aircraft data from the VOCALS Regional Experiment
53 [Wood et al., 2011] which occurred between October and November 2008 in the stratocu-
54 mulus region off the coast of Chile. Our data comes from sub-cloud level legs from 13
55 mostly pre-dawn to mid-afternoon flights of the National Science Foundation C-130 air-

56 craft which transited between 70-85°W and 17-30°S. This dataset and the computation
 57 of sub-cloud legs is described in detail in Jones et al. [2011]. Flight segments are classi-
 58 fied as well-mixed if the mean difference between lidar-derived cloud base z_b and lifting
 59 condensation level LCL is less than 150 m and decoupled if $z_b - \text{LCL} > 150$ m. Cases
 60 are Cu-coupled if they are decoupled and the minimum $z_b - \text{LCL}$ difference over the leg
 61 is < 30 m. We call the set of all cases without Cu “ordinary Sc” following WMO [1975].
 62 These cases should appear well mixed under visual inspection.

Using a traditional decoupling metric, the fractional occurrence of well-mixed conditions
 is

$$F_{\text{true}} = \frac{f(\text{well-mixed})}{f(\text{well-mixed}) + f(\text{decoupled})} \quad (1)$$

where $f(x)$ is the frequency of occurrence of cloud-type x . If we take decoupled conditions
 to only exist when Cu is detected, we get

$$F_{\text{approx}} = \frac{f(\text{ordinary})}{f(\text{ordinary}) + f(\text{Cu-coupled})}. \quad (2)$$

63 Values for F_{true} and F_{approx} are summarized in Table 1. F_{approx} overpredicts the occurrence
 64 of well-mixed conditions by about 20%. While this is a large amount, it is small enough
 65 that F_{approx} can give us a rough sense of whether decoupled Sc are important.

66 Since daytime observations are more available and more reliable, we also test the effect
 67 of day-time versus night-time sampling. Differences between metrics are larger during the
 68 day and F_{true} peaks at night, in agreement with previous work [Nicholls, 1984; Caldwell
 69 et al., 2005]. The amplitude of the diurnal cycle is weak, however, a feature also shown
 70 in the next section using global data.

3. Decoupling from Global Ship Observations

Our global analysis is based on an updated version of the Edited Cloud Report Archive [Hahn et al., 1988] as described by Norris [1998b]. This consists of many millions of records taken from the Comprehensive Ocean-Atmosphere Data Set (COADS) archive between 1954 and 1997 and subset to include only volunteer observations. COADS records specify the dominant observed cloud type from a list of 9 low cloud types (C_L). Based on results from Norris [1998a], we define C_{L4} (Sc from spreading Cu) and C_{L8} (Cu under Sc) as decoupled Sc and C_{L5} (ordinary Sc) as well-mixed. Stratus (C_{L6}) have visibly smooth bottom, resulting from either a lack of turbulence or to very strong turbulence which has homogenized air to the point that rolls aren't visible. The latter case (which Norris [1998b] shows occurs mostly in the tropics) should be included as well-mixed cloud. Non-turbulent C_{L6} (formed frequently by broad uplift in midlatitudes) is mechanistically very different than Sc. Stratus is omitted from our base analysis but included in Fig. 2c as a sensitivity study. Decoupled types are given preference whenever decoupled and well-mixed cloud types are simultaneously present. This results in a tendency to under-predict well-mixed clouds which will oppose the tendency to over-predict by including Cu-free decoupled cases as well-mixed. Because our goal is to get a qualitative rather than quantitative sense of decoupling frequency, these details should not affect our conclusions.

The diurnal cycle of F_{approx} is presented in Fig. 1. This figure is based on data collected at 0, 6, 12, and 18 UTC with nighttime values limited to those with good illumination [as defined by Hahn et al., 2005]. Data is annually averaged (because seasonal differences were insignificant) and averaged to $10^\circ \times 10^\circ$ boxes to increase sample sizes. As found above

92 for VOCALS data, diurnal variations in F_{approx} are weak ($< 10\%$). As expected, well-
93 mixed conditions generally occur during night-time hours, though there is an interesting
94 tendency for peak F_{approx} near western coastlines to occur later in the morning. There is
95 also a clear hemispheric asymmetry in the amplitude of diurnal variations in F_{approx} , with
96 almost no variability in the northern hemisphere. This is perhaps explained by the fact
97 (shown later) that mean F_{approx} values tend to be smaller in the northern hemisphere and
98 that variations tend to scale with mean magnitude.

99 Fig. 2a shows the global map of annually-averaged daytime-only Sc frequency (=
100 $f(C_L4) + f(C_L5) + f(C_L8)$). This plot is similar to the low cloud plots shown in Klein and
101 Hartmann [1993] (hereafter KH93), but shows only Sc clouds. As in previous studies, Sc
102 is found to be prevalent off the west coasts of subtropical continents and at high latitudes.
103 Panel b shows the global annual-average distribution of F_{approx} with C_L6 omitted and
104 panel c shows F_{approx} with C_L6 taken to be decoupled Sc. In general, regions where Sc is
105 most frequent are also the regions where Sc is most likely to be well-mixed (a fact also
106 shown by Fig. 3a). In the subtropics, Sc is usually well-mixed near the west coast of
107 continents and becomes more decoupled further offshore [as noted by Wood and Brether-
108 ton, 2004]. Sc is not generally seen in convective regions to the east of continents (blue
109 areas in panel a, masked white in panel b). Well-mixed conditions are frequently found
110 at higher latitudes, particularly if distinction is made between stratocumulus and stratus.
111 This suggests that MLMs could be especially useful for polar work (though latent heat
112 of freezing [Ovchinnikov et al., 2011] and disconnection from the surface complicate pa-

113 rameterization). As alluded to previously, higher F_{approx} values are found in the southern
114 hemisphere.

115 Fig. 3b shows that F_{approx} is also strongly correlated with PBL depth. Our PBL depth
116 measurements come from spaceborne GPS Radio Occultation (GPS-RO) data from the
117 six satellites of the Constellation Observing System for Meteorology, Ionosphere, and
118 Climate (COSMIC)/Formosa Satellite 3 (FORMOSAT-3) [Rocken et al., 2000] converted
119 into PBL depth using the method of Guo et al. [2011]. Data from 2006-2009 is used with
120 measurements poleward of 60S/N omitted because of data quality concerns. Fig. 3b has 2
121 distinct maxima, suggesting that Sc cluster into shallow/well-mixed and deep/decoupled
122 modes.

123 Table 2 explores the seasonal and geographic variability of decoupling frequency. F_{approx}
124 is averaged (using cell-area weighting) over the 8 oceanic Sc regions identified in KH93 as
125 well as across the tropics (between 30N and 30S) and globe. The KH93 regions (included as
126 boxes in Fig. 2a) were chosen because MLM assumptions are most likely to be employed
127 in these areas. Reassuringly, F_{approx} in the Peru region is very similar to the values
128 computed from VOCALS data in Table 1. Sc in the 5 subtropical areas are more likely
129 to be well-mixed than the subtropical average, but frequency of decoupling varies widely
130 between regions. The Canary region is generally not well mixed [a result also found for
131 CMIP3 GCMs by Caldwell et al., 2012]. Interestingly, California - the best studied
132 region - is less frequently well mixed than regions off the coast of Peru, Namibia, and
133 Australia. Even in the most frequently well-mixed subtropical regions, a substantial
134 fraction of Sc is decoupled. This implies that understanding the response of well-mixed

135 Sc to global warming is insufficient for understanding subtropical Sc cloud feedback. Sc
136 in the circumpolar ocean is well mixed 65% of the time and 90% of Arctic Sc is well mixed
137 (neglecting stratus). North Atlantic Sc is also often well mixed, though the North Pacific
138 region is not. In the global average, ocean regions are covered by well-mixed Sc about
139 16% of the time and by decoupled Sc 14% of the time (including stratus as decoupled
140 raises this to 21%).

4. Conclusions

141 Our study provides a global perspective on how often Sc is decoupled. We find presence
142 of Cu to be a reasonable proxy for decoupling (based on VOCALS aircraft data). Sc
143 is more likely to be well-mixed at night, but diurnal variations are weak. Consistent
144 with previous work covering more limited areas and shorter time periods, we find that
145 Sc is frequently decoupled (even in core Sc regions), though regions with more Sc tend
146 to be well-mixed more frequently. As in Wood and Bretherton [2004], deeper Sc-topped
147 PBLs tend to be decoupled more often. On the whole, MLM assumptions are appropriate
148 roughly 50% of the time in major Sc regions. This suggests that MLM studies can be
149 used to understand a significant but not dominant component of Sc response to warming.
150 Arctic Sc appears well mixed most of the time, but stratus - which can't be modeled with
151 a mixed-layer model - is also frequent at high latitudes.

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152
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Table 1. Frequency of F_{approx} and F_{true} from VOCALS data (as described in the text) followed by the number of legs used for computing each frequency.

Subset	F_{approx}	F_{true}	Cu legs	Non-Cu Decoupled Legs	Ordinary Legs
All	0.64	0.49	30	12	83
Day	0.68	0.48	8	5	25
Night	0.62	0.50	22	7	58

Table 2. Fraction of Sc which is well-mixed for KH93 oceanic Sc regions. Where possible, the season of maximum Sc frequency is indicated in bold.

	DJF	MAM	JJA	SON
Peru	0.53	0.52	0.66	0.63
Namibia	0.66	0.67	0.76	0.77
California	0.48	0.48	0.57	0.48
Australia	0.60	0.59	0.61	0.61
Canary	0.37	0.40	0.45	0.36
N. Pacific	0.34	0.45	0.53	0.41
N. Atlantic	0.64	0.67	0.74	0.66
Circumpolar	0.62	0.68	0.63	0.66
Arctic	0.95	0.87	0.88	0.91
Subtropics	0.35	0.34	0.36	0.35
Global	0.46	0.45	0.45	0.45

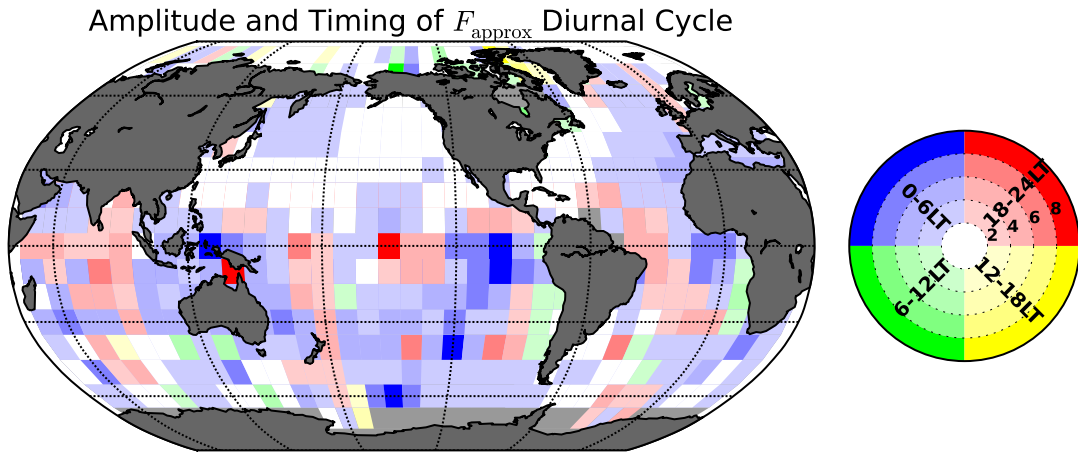


Figure 1. Local time of maximum F_{approx} (in colors) and diurnal-cycle amplitude (in color intensity). Areas with < 10 Sc observations are shaded light gray.

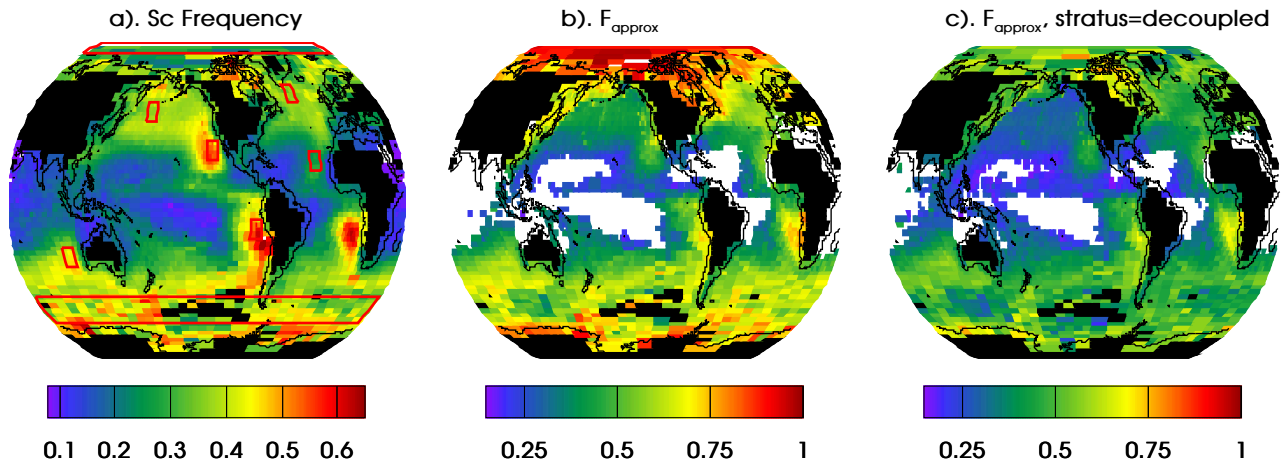


Figure 2. a). Frequency of occurrence of Sc ($f(C_{L4}) + f(C_{L5}) + f(C_{L8})$), b). fraction of the time Sc is well-mixed when present, and c). fraction of the time Sc is well-mixed when present under the assumption that C_{L6} is decoupled Sc. Cells over land are masked black and cells where Sc occurs < 20% of the time are masked white in panel b and c. Averaging regions for Table 2 are included as red boxes in panel a.

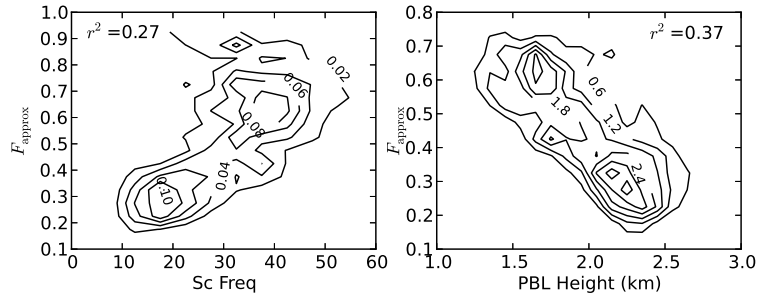


Figure 3. Joint PDFs of (a) Sc occurrence ($=f(C_L4) + f(C_L5) + f(C_L8)$) and (b) COSMIC PBL depth versus COADS F_{approx} . In panel b, data poleward of 60° latitude is masked to avoid PBL height retrieval issues.