Observed Large-scale Controls on Marine Cloud-topped Boundary Layers and How Wayne Schubert Influenced the Science

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Wayne Schubert's Seminal Papers (1979)

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Marine Stratocumulus Convection. Part I: Governing Equations and Horizontally Homogeneous Solutions

Marine Stratocumulus Convection. Part II: Horizontally Inhomogeneous Solutions

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These papers very clearly present the theoretical framework of the well-mixed stratocumulus-topped boundary layer. They were (and are) an inspiration for the student!

But they were also an inspiration for the observationalist as well as the theorist (or modeler).

In this poster I present 3 examples of how Wayne Schubert's work influenced observational analyses of the marine cloud-topped boundary layer.

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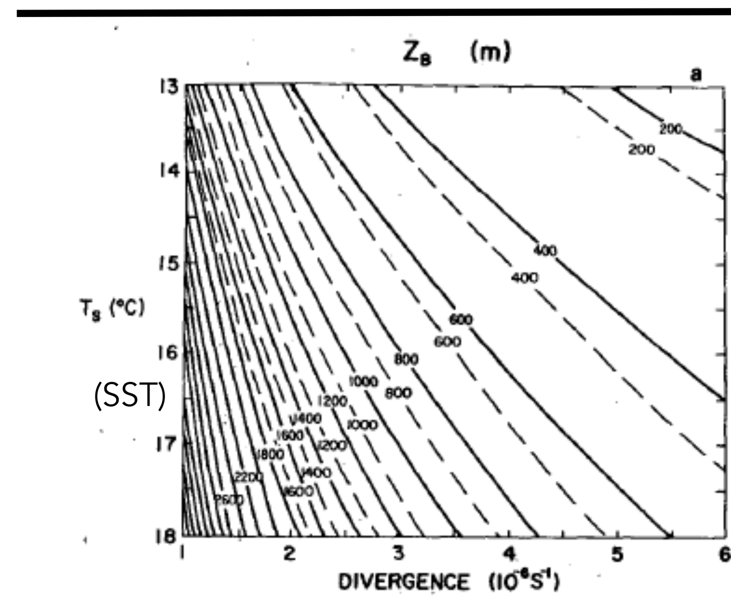
What *external factors* control marine cloud-topped boundary layers?

Based upon his theoretical model, Wayne Schubert specified the external factors that control the solution of the marine-cloud-topped boundary layer. Modern observational studies use similar sets of variables.

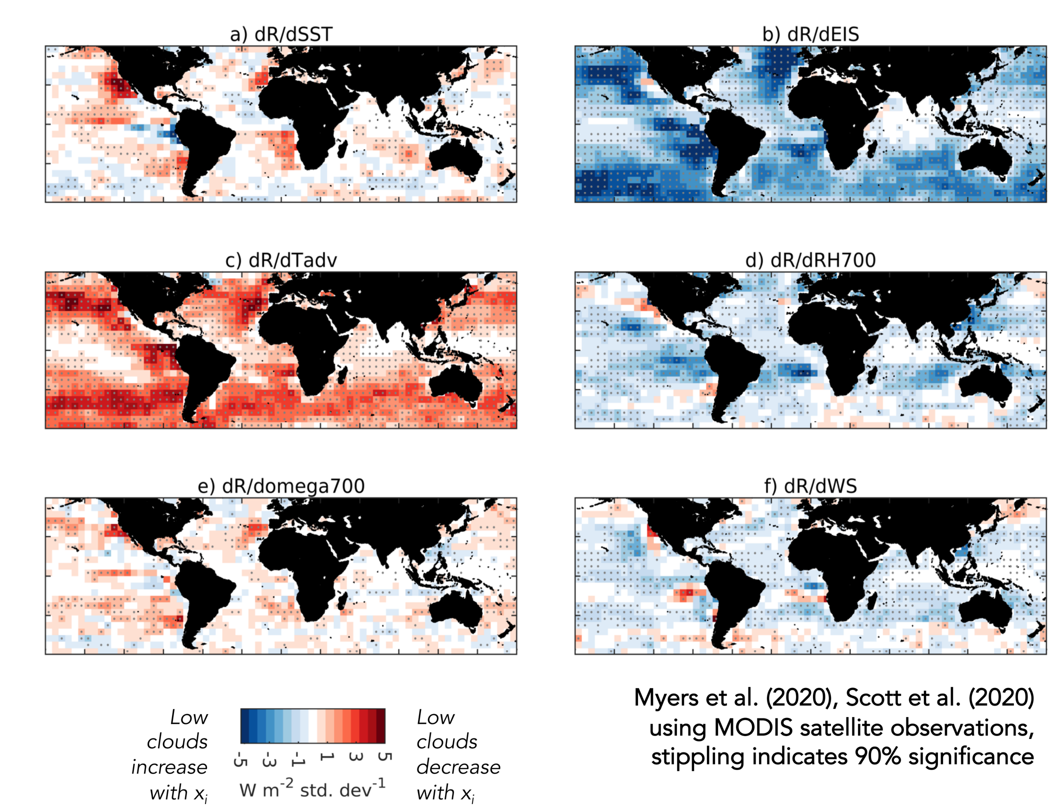
Wayne Schubert's External Factors: Externally specified parameters		External Factors in Current Studies
large-scale divergence	D	subsidence velocity (omega700)
wind speed	V	wind speed (WS)
saturation moist static energy at sea surface temperature and pressure	h_S^*	SST → sea-surface temperature (SST); estimated inversion strength (EIS)
saturation mixing ratio at sea surface temperature and pressure	q_S^*	SST → sea-surface temperature (SST); estimated inversion strength (EIS)
moist static energy just above cloud top	h_+	estimated inversion strength (EIS)
water vapor mixing ratio just above cloud top	q_+	relative humidity at 700 hPa (RH700)
downward longwave flux just above cloud top	$LW_+^\downarrow$	
total shortwave absorption	SW	??
whether SST is increasing or decreasing following the wind (Part II)		temperature advection (Tadv) $-V * \nabla SST$

Equilibrium Solution of Boundary Layer Depth as a function of SST and Divergence from Schubert's 1979 Model



Wayne emphasized SST and divergence (i.e. vertical velocity) in the solutions of the mixed-layer model but observationally inversion strength (EIS) and horizontal temperature advection (Tadv) are found to be most important

Sensitivity of Low-Cloud Radiative Effects to External Factors in Satellite Observations $\frac{\partial R}{\partial x_i}$



Myers et al. (2020), Scott et al. (2020) using MODIS satellite observations, stippling indicates 90% significance

Methods for Satellite Data Analysis

The influence of external factors on inter-annual variability in marine boundary layer clouds is observationally estimated using multi-linear regression of R on x_i:

$$dR = \sum \frac{\partial R}{\partial x_i} dx_i$$

R is the SW+LW radiative effect of low clouds
x_i is an external factor

The x_i include sea surface temperature (SST), estimated inversion strength (EIS), subsidence velocity and relative humidity at 700 hPa (omega700, RH700), wind speed (WS), and horizontal temperature advection (Tadv) using the NOAA OI SST v2 and reanalysis (ERA5) datasets.

Wayne was Right, but with Some Surprises!

- As Wayne emphasized, **sea surface temperature SST** is very important, but it is mainly the value of SST relative to the temperature above the boundary layer, as measured by the **Estimated Inversion Strength EIS**, that matters (stronger inversions → more cloud). The independent effect of SST is smaller.
- Wayne's non-equilibrium solutions (Part II) showed that whether SST is increasing or decreasing following the wind was quite important. Observations show that **temperature advection TAdv** is one of the 2 most important external factors (more cold advection → more cloud). This highlights the importance of non-equilibrium solutions.
- The direct effect of **subsidence velocity omega700** is relatively small, and counter-intuitive (more subsidence → less cloud), but it must be kept in mind that this is the influence independent of inversion strength (Myers and Norris 2013).

Where are marine stratocumulus?

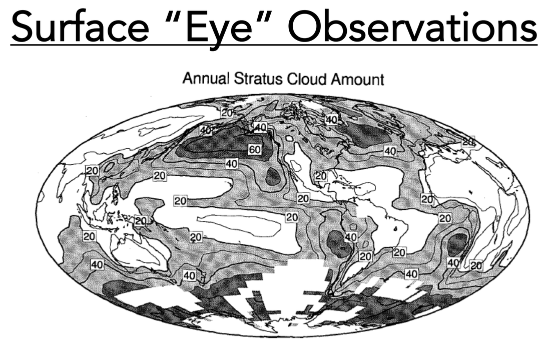
In the era before systematic global cloud climatologies, Wayne Schubert used scattered observational data to predict where subtropical marine stratocumulus preferentially occur.

Wayne Schubert's Predictions (1979)

TABLE 1. The five principle cool coastal dry climates, their accompanying desert names and their bordering cool ocean currents.

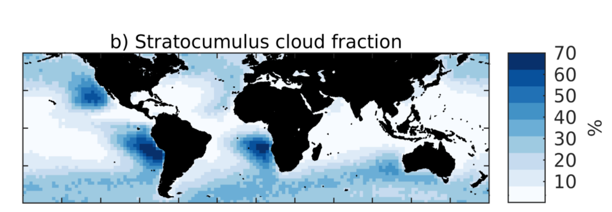
Region	Desert	Ocean current	Actual Regimes
Coastal California and Mexico	Sonoran	California	✓
Coastal Ecuador, Peru and Chile	Peru and Atacama	Peru or Humboldt	✓
Coastal northwestern Africa	Sahara	Canaries	✓
Coastal southwestern Africa	Namib	Benguela	✓
Coastal northeastern Africa	Somali	Somali	✗

Surface "Eye" Observations



Warren et al. (1988)

Satellite Observations



Cesana et al. (2019) using CloudSat and Calipso observations

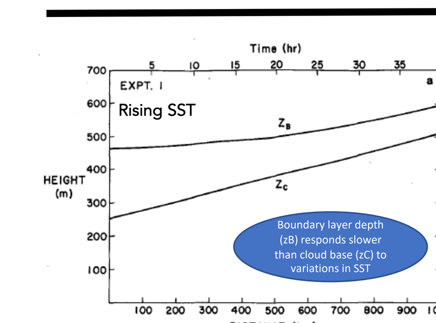
Wayne was Mostly Right, but with Some Surprises!

- The **Somali** region lacks stratocumulus probably because the environment is relatively unstable.
- The **Australia** region also has stratocumulus. Wayne Schubert's papers mentioned that there are clouds there, but he didn't explicitly identify this regime probably due to the lack of station data

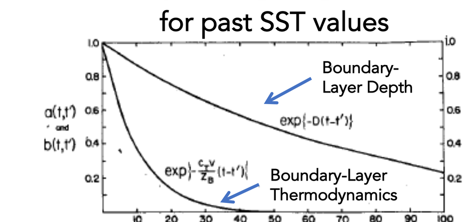
Over what *time-scales* does the environment control the clouds?

Wayne Schubert's explained why thermodynamics respond faster than boundary layer depth to variations in environmental factors. This inspired observationalists to perform Lagrangian analyses (i.e., track clouds following backward trajectories of boundary layer air).

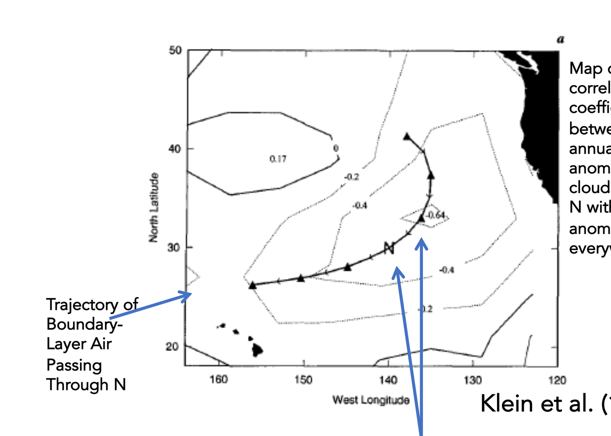
Response to SST Increase from Schubert's 1979 Model



Analytic weighting functions for past SST values



Observational Evidence for Time-scales of Cloud Response



Klein et al. (1995)

Clouds at Station N are best correlated with SSTs approximately 24-36 upwind of N

Wayne was Right

- Observations show that clouds vary with SST approximately 24-36 hours upwind
- Numerous Lagrangian studies have been performed *(Bretherton and Pincus 1995, Mauger and Norris 2010, Sandu et al. 2010, Eastman and Wood 2018)*

Lawrence Livermore National Laboratory

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