Constraints on Low Cloud Feedbacks from Observed Climate Variability

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Low Clouds: Primary Contributor to net CRE over Global Oceans

CERES Flux-by-Cloud-Type Dataset

Myers et al., upcoming AGU Monograph
In CMIP6, spread of low cloud feedback and ECS has increased relative to CMIP5.
In CMIP6, spread of low cloud feedback and ECS has increased relative to CMIP5.
Parameterization of unresolved boundary layer process likely explains model uncertainty

[Diagram showing the processes occurring in the stratocumulus-topped boundary layer, including subsidence, evaporation, longwave cooling, solar heating, and entrainment.]
Parameterization of unresolved boundary layer process likely explains model uncertainty
upon how low clouds may change in response to increases in greenhouse gases (e.g., Bony and Dufresne 2005) and changes in the anthropogenic contribution to aerosol loading (see Lohmann and Feichter 2005, for a recent review). This increasingly necessitates observational programs that can couple the small-scale processes critical to cloud formation with the atmospheric general circulation (Brenguier and Wood 2009; Wood et al. 2011b).

This review seeks to summarize our current state of knowledge about stratocumulus clouds with a focus upon what we have learned from observations and process models about their climatological distribution, key elements of their structure and dynamics, and their microphysical properties. Particular emphasis is placed upon the interactions among key processes, in particular the importance of internal feedbacks within the stratocumulus system, and the interactions between microphysics, radiation, turbulence, and entrainment. It may also be useful here to mention what this review does not include. We do not include a detailed discussion of the hierarchy of numerical modeling approaches for understanding stratocumulus clouds, nor do we discuss the way in which these clouds are parameterized in large-scale numerical models. Chemistry–cloud interactions are important and interesting but are not treated here.

This review is organized as follows. Section 2 provides an overview of the climatology of stratocumulus, including

![Figure 1](image1.png)

**Figure 1.** Satellite imagery demonstrating the tremendous wealth of form for stratocumulus clouds on the mesoscale. (left) A 250-m resolution visible reflectance image (λ = 0.65 μm) taken at 1235 UTC 7 Apr 2001 using the MODIS over the northeast Atlantic Ocean (note the Azores and Canary Islands). (top-right inset) A higher resolution (15 m) visible image (λ = 0.8 μm) taken at approximately the same time using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). (bottom-right inset) Detail from the main image.

![Figure 2](image2.png)

**Figure 2.** Schematic showing the key processes occurring in the stratocumulus-topped boundary layer.

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**External Cloud-Controlling Factors**

- Free troposphere (dry)
- Inversion
- Boundary layer
- Subsidence
- Wind
- Evaporative cooling
- Latent heating
- Turbulent mixing
- Longwave cooling
- Solar heating
- Drizzle
- Surface fluxes energy & moisture
- Entrainment

adapted from Wood 2012
Framework to Observationally Constrain Low Cloud Feedbacks

Given

i. spatially-resolved sensitivity of low cloud radiative fluxes to meteorological cloud-controlling factors from observed climate variability
   *(meteorological cloud radiative kernels developed by Scott et al. (2020))*

ii. how these factors will change in response to climate warming
   *(resolved by GCMs)*

we can predict the marine low cloud feedback.
Not first to apply this framework*.

Our study is unique in its near-global scale and its constraints on the pattern of the low feedback.

*Qu et al. 2015; Zhai et al. 2015; Myers and Norris 2016; Brient and Schneider 2016; McCoy et al. 2017; Cesana and Del Genio 2021
Framework to Observationally Constrain Low Cloud Feedbacks

We decompose the low cloud feedback at each 5° x 5° ocean grid box between 60°S and 60°N as

$$\lambda_{\text{cloud}} = \frac{dR}{dT} = \sum \frac{\partial R}{\partial x_i} dx_i dT$$

- $R$ low cloud radiative flux
- $x_i$ one of six cloud-controlling factors
- $T$ global mean surface temperature
Framework to Observationally Constrain Low Cloud Feedbacks

We decompose the low cloud feedback at each 5° x 5° ocean grid box between 60°S and 60°N as

\[
\lambda_{\text{cloud}} = \frac{dR}{dT} = \sum \frac{\partial R}{\partial x_i} \frac{dx_i}{dT}
\]

- \( R \): low cloud radiative flux
- \( x_i \): one of six cloud-controlling factors
- \( T \): global mean surface temperature

**observation-based** sensitivity of low cloud radiative flux to a perturbation in some cloud-controlling factor (*meteorological cloud radiative kernels from Scott et al. (2020))*

- \( \frac{\partial R}{\partial x_i} \): change in cloud-controlling factor per degree global mean warming, predicted by 18 CMIP5 and CMIP6 models in abrupt4xCO2 simulations
Framework to Observationally Constrain Low Cloud Feedbacks

Complete set of cloud-controlling factors $x_i$ includes (from reanalysis):

- sea-surface temperature (SST)
- estimated inversion strength (EIS)
- horizontal surface temp. advection
- free-tropospheric relative humidity
- free-tropospheric subsidence
- near-surface wind speed
How do we estimate low cloud radiative anomalies $R'$ globally?

We apply Zelinka cloud radiative kernels $k = k(\tau, p)$ to satellite-retrieved low-level (>680 hPa) cloud fraction $L = L(\tau, p)$ normalized by the fraction $F$ of the grid box unobscured by higher-level clouds:

$$R' = \bar{F} \sum_{p=1}^{2} \sum_{\tau=1}^{T} k(L/F)'$$

Cloud fraction histograms from MODIS (TERRA+AQUA), ISCCP, PATMOS-x

- These fluxes are exclusively due to changes in unobscured low-level clouds
- We apply a similar equation to the CERES Flux-by-Cloud-Type dataset
Observational Meteorological Cloud Radiative Kernels

Scott et al. (2020) derived from July 2002 – December 2018 CERES-FBCT data

- a) $\partial R / \partial SST$
- b) $\partial R / \partial EIS$
- c) $\partial R / \partial T_{\text{adv}}$
- d) $\partial R / \partial RH_{700}$
- e) $\partial R / \partial \omega_{700}$
- f) $\partial R / \partial WS$

$W \text{ m}^{-2} \text{ s}^{-1}$

related from July 2002 – December 2018 CERES-FBCT data

Scott et al. (2020)
Validation of the multi-linear approach

How well does the method predict out-of-sample extremes in the observational record?

Test Case: Northeast Pacific Marine Heatwave
Marine Heatwave Test Case

2015 observations

Out-of-sample prediction based on 1983-2002-derived meteorological kernels
The linear method is valid for SST perturbations spanning ~2.4 K.

Increasing SST was the primary driver of the low cloud reduction.
Results: Feedback Constrained by Satellite Cloud Observations

\[ \lambda_{\text{cloud}} = \frac{dR}{dT} = \sum \frac{\partial R}{\partial x_i} \frac{dx_i}{dT} \]

- Positive feedback in eastern ocean basins and middle latitude North Pacific
- Weaker feedback in trade cumulus regions
Which cloud-controlling factors drive this feedback?
Dominant Feedback Components: SST and Est. Inv. Strength

\[ \frac{dSST}{dT} \]

Due to 4xCO2

\[ \frac{\partial R}{\partial SST} \quad \frac{dSST}{dT} \]

Feedback component

\[ \frac{\partial R}{\partial EIS} \quad \frac{dEIS}{dT} \]

Strong positive SST-driven feedback in eastern ocean basins

Positive EIS-driven feedback in midlatitudes

Negative EIS-driven feedback in tropics
What physical mechanisms produce these feedback components?
Meteorological conditions inducing a positive low cloud feedback

- Tropical Ascent
  - Warmer SST

- Trade Cumulus
  - Warmer SST
  - Stronger upward surface latent heat flux
  - More cloud-top entrainment drying

- Eastern Ocean Stratocumulus

- Midlatitudes
  - Warmer SST
  - Weaker inversion
  - More cloud-top entrainment drying

$\theta(z)$
Meteorological conditions inducing a positive low cloud feedback

- Tropical Ascent
- Trade Cumulus
- Eastern Ocean Stratocumulus
- Midlatitudes

- Warmer SST
- stronger upward surface latent heat flux
- more cloud-top entrainment drying

Meteorological conditions inducing a *small* negative low cloud feedback

- Tropical Ascent
- Trade Cumulus
- Eastern Ocean Stratocumulus

- Stronger inversion
- less cloud-top entrainment drying
Regime-partitioned cloud feedbacks
(defined using climatological EIS, $\omega_{700}$)
Stratocumulus (strong subsidence, sharp inversion)
Trade cumulus (weak subsidence, weak inversion)
Tropical ascent
Midlatitudes (variable $\omega_{700}$, sharp inversion)

Cumulus And Stratocumulus CloudSat-CAlipso Dataset (CASCCAD; Cesana et al. 2019)
Regime-averaged Marine Low Cloud Feedbacks

90% CI due to uncertainty in $\partial R / \partial x_i$ and $dx_i/dT$
Regime-averaged Marine Low Cloud Feedbacks

**Obs:** Positive stratocumulus & midlatitude cloud feedbacks (from amount *and* optical depth)

**Obs:** Near-zero trade cumulus feedback, consistent with large-eddy simulations*

**CMIP6:** more realistic midlatitude feedback

*e.g. Radtke et al. (2021)
Obs: Positive 60S-60N feedback
**Obs:** Positive 60S-60N feedback

0.19±0.12 W m⁻² K⁻¹
**Obs:** Positive 60S-60N feedback 0.19±0.12 W m\(^{-2}\) K\(^{-1}\)

**Several CMIP6 models:** beyond upper limit of best estimate due to:
- i) more realistic midlatitude feedback yet
- ii) persistently positive trade cumulus feedback

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**Feedbacks Scaled by Fractional Planetary Area**

**SW+LW**

<table>
<thead>
<tr>
<th>Stratoscumulus</th>
<th>Trade cumulus</th>
<th>Tropical ascent</th>
<th>Midlatitudes</th>
<th>60S-60N</th>
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<tbody>
<tr>
<td>(7.7%)</td>
<td>(18.2%)</td>
<td>(14.5%)</td>
<td>(19.7%)</td>
<td>(64.4%)</td>
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</table>

**MODIS 02-18 low**

**CERES 02-18 low**

**ISCCP-H 83-02 up to 560hPa**

**PATMOS-x 82-02 up to 560hPa**

**CMIP5**

**CMIP6**

- (7.7%) (18.2%) (14.5%) (19.7%) (64.4%)

**Satellite Observations**

**GCMs**

- amount
- total
- optical depth

**Best estimate**
**Obs:** Positive 60S-60N feedback

\[0.19 \pm 0.12 \text{ W m}^{-2} \text{ K}^{-1}\]

**Several CMIP6 models:**

- beyond upper limit of best estimate due to:
  - i) more realistic midlatitude feedback yet
  - ii) persistently positive trade cumulus feedback
Weak sensitivity of trade cumulus to SST perturbations relative to stratocumulus explains different feedbacks.
Independent observational evidence from active satellites

Cesana et al. (2019) and Cesana and Del Genio (2021) also conclude that the trade cumulus feedback is near-zero.
Implications for ECS
Two methods
Implications for ECS Method 1: Emergent-Constraint Approach
Implications for ECS Method 1: Emergent-Constraint Approach
3% chance that ECS > 5 K
8% chance that ECS < 2.5 K

*Models with very low or very high climate sensitivities are likely unrealistic.*
Implications for ECS Method 2: Update to Climate Sensitivity (S) Inferred from Multiple Lines of Evidence

Sherwood et al. (2020) derive near-global marine low cloud feedback of $0.37 \pm 0.37 \text{ W m}^{-2} \text{ K}^{-1}$ (sum of tropical and midlatitude marine low cloud amount and high-latitude low cloud optical depth feedbacks)
Implications for ECS Method 2: Update to Climate Sensitivity (S) Inferred from Multiple Lines of Evidence

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Our estimate: $0.19 \pm 0.12 \text{ W m}^{-2} \text{ K}^{-1}$. More realistic because:

i) Explicit evidence that trade cumulus feedback weaker than stratocumulus feedback, in agreement with LES and independent observational evidence

ii) Most comprehensive set of cloud-controlling factors of all studies

→ Replace Sherwood et al. (2020) low cloud feedback value with ours, leaving all other terms unchanged.
Implications for ECS Method 2: Update to Climate Sensitivity ($S$) Inferred from Multiple Lines of Evidence

Our estimate points to a more moderate climate sensitivity ($\sim 3$ K)

The chance that $S > 5$ K has been reduced by more than half, from 3.1% to 1.2%
Implications for ECS Method 2: Update to Climate Sensitivity ($S$) Inferred from Multiple Lines of Evidence

Our estimate points to a more moderate climate sensitivity (~3 K)

The chance that $S > 5$ K has been reduced by more than half, from 3.1 % to 1.2 %

**Emergent-Constraint Approach:** major limitations for inferring real-world climate sensitivity
Summary

Observational meteorological cloud radiative kernels \times GCM simulations of meteorological changes = low cloud feedbacks with warming

✓ Valid for observed out-of-sample extreme event
✓ Predicts positive stratocumulus and midlatitude low cloud feedbacks
✓ Predicts near-zero trade cumulus feedback
✓ Predicts 60S-60N feedback of $0.19 \pm 0.12$ W m$^{-2}$ K$^{-1}$
✓ Implies ECS near 3 K, reduces likelihood of very low or very high ECS

References


**Meteorological Cloud Radiative Kernels**

*Meteorological cloud radiative kernels* quantify the response of top-of-atmosphere marine low cloud radiative effect to local large-scale meteorological perturbations. They were developed by Scott et al. (2020) and applied in Myers et al. (2021). These kernels are derived using cloud-controlling factor (CCF) analysis, which is based upon theoretical and high-resolution model evidence that marine boundary layer properties, including cloudiness, are predominantly determined by large-scale meteorological environmental factors. In our analysis, these CCFs include sea-surface temperature (SST), estimated inversion strength (EIS), horizontal surface temperature advection (Tadv), relative humidity at 700 hPa (RH700), vertical velocity at 700 hPa (ω700), and near-surface wind speed (WS).

The *meteorological cloud radiative kernels* are calculated by applying multi-linear regression of detrended interannual monthly anomalies of satellite-derived low cloud radiative flux onto anomalies in CCFs from a reanalysis.
Can be used to investigate:

- Cloud feedbacks associated with internal climate variability (e.g. ENSO, AMO)
- Cloud feedbacks associated with paleoclimates
- Multi-decadal cloud trends
- The performance of global climate models and large-eddy simulations
Thank you!
Extras slides
Marine Low Cloud Feedback

a) MODIS

b) CERES-FBCT

c) ISCCP

d) PATMOS-x

e) CMIP5

f) CMIP6
a) Regime-averaged marine low cloud feedbacks

- CanESM2
- CCSM4
- HadGEM2-ES
- MIROC5
- MIROC-ESM
- MPI-ESM-LR
- MRI-CGCM3
- CanESM5
- CNRM-CM6-1
- CNRM-ESM2-1
- E3SM-1-0
- GFDL-CM4
- HadGEM3-GC31-LL
- IPSL-CM6A-LR
- MIROC-ES2L
- MIROC6
- MRI-ESM2-0
- UKESM1-0-LL

b) Scaled marine low cloud feedbacks

- MODIS & CERES
- ISCCP & PATMOS
- Best estimates (ERA5) (MERRA-2)
- total
- optical depth

Satellite Observations

- MODIS
- CERES
- ISCCP
- PATMOS
- ERA5
- MERRA-2
- CMIP5
- CMIP6

Optical depth

(7.7%) (18.2%) (14.5%) (19.7%) (64.4%)

Satellite Observations
a) Regime-averaged SW marine low cloud feedbacks

- MODIS
- CERES-FBCT
- ISCCP
- PATMOS-x
- LES
- CMIP5
- CMIP6

Satellite Observations

GCMs

b) Scaled SW marine low cloud feedbacks

- MODIS
- CERES
- ISCCP
- PATMOS-x
- LES
- CMIP5
- CMIP6

Satellite Observations

GCMs

(7.7%) (18.2%) (14.5%) (19.7%) (64.4%)

Stratocumulus
Trade cumulus
Tropical ascent
Midlatitudes

60S-60N
a) Regime-averaged marine low cloud feedbacks

- MODIS 02-17 low
- ISCCP-H 02-17 low+mid
- ISCCP-H 83-02 low+mid
- ISCCP-H 02-17 minus 83-02

b) Scaled marine low cloud feedbacks

<table>
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<tr>
<th>Region</th>
<th>Satellite Observations</th>
<th>CMIP5</th>
<th>CMIP6</th>
<th>MODIS 02-17</th>
<th>ISCCP 02-17</th>
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<th>ISCCP difference</th>
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**a) CMIP5 mean minus ISCCP low cloud fraction**

**b) CMIP6 mean minus ISCCP low cloud fraction**