Albedo Susceptibility of Marine Low Clouds: Where and When to Find Susceptible Clouds

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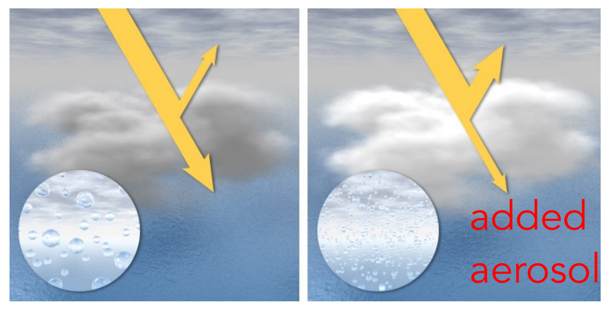
What is Albedo Susceptibility (S_0)

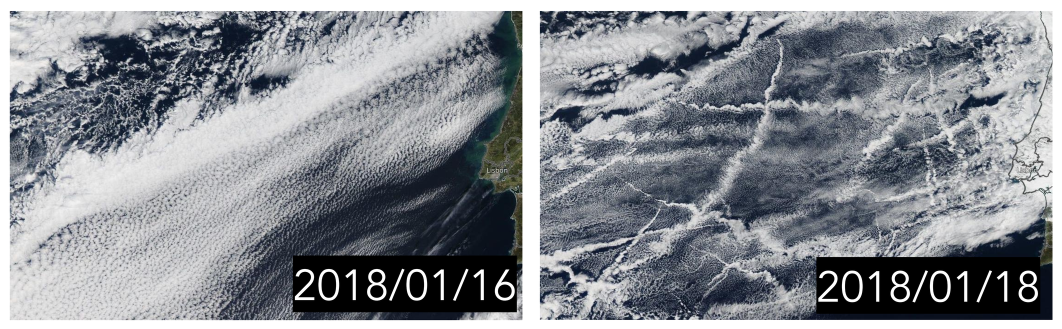


- S_0 **- Changes in cloud shortwave albedo (A_c) due to perturbations in cloud droplet number concentration (N_d).**
- ***Twomey effect*** (timescale ~5-10mins) - added aerosol serves as extra cloud condensation nuclei, leading to more smaller droplets (more nuclei competing for same amount of condensate), assuming constant liquid water path (LWP). This leads to **brighter clouds.**
- Subsequent changes in cloud condensate, e.g. LWP, can manifest ~20hrs after the perturbation. The **sign of S_0** depends on the LWP adjustment term.

$$S = \frac{dA_c}{dN} = \overbrace{\boxed{\frac{A_c(1-A_c)}{3N}}}^{\text{Twomey}}\left(1 + \overbrace{\boxed{\frac{5}{2}\frac{d\ln LWP}{d\ln N}}}^{\text{LWP adj}}\right)$$

Why Important to Understand and Quantify

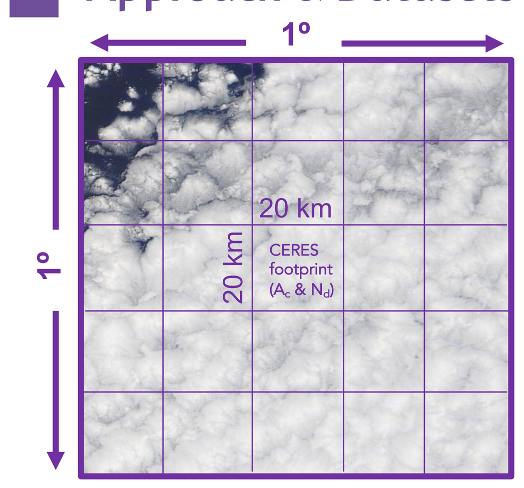
- Routine ship emissions do not always lead to detectable **shiptracks**.
- Both the Twomey effect and the LWP adjustment are dependent on the **cloud regimes** & the **large-scale meteorological conditions**.
- It is important to characterize the cloud/meteorology regimes associated with the susceptible (and less susceptible) conditions, as well as their **geographical preference** & **frequency of occurrence**.

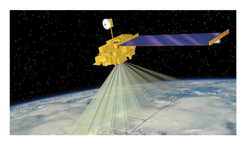


Goals

- Quantify albedo susceptibility of marine low clouds and produce a satellite-derived **climatological susceptibility map**.
- Distinguish **susceptibility regimes** (brightening & darkening) and quantify their **frequency of occurrence**.
- Associate susceptibility regimes with large-scale meteorological conditions: a focus on their **seasonal covariability**.

Approach & Datasets





Climate Change Service

ECMWF

- Collect satellite (Aqua & Terra) snapshots (1°x 1°) of **single-layer liquid clouds** (homogeneous meteorology across snapshot)
- Linear regression (ln-ln space) of A_c on N_d

$$S_0 = \frac{d\,ln(Ac)}{d\,ln(N_d)}$$

Acknowledgements & References

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Zhang, J. and Feingold, G. (2022). Distinctive regional meteorological influences on low cloud albedo susceptibility over global marine stratocumulus regions, *in prep*, GRL.

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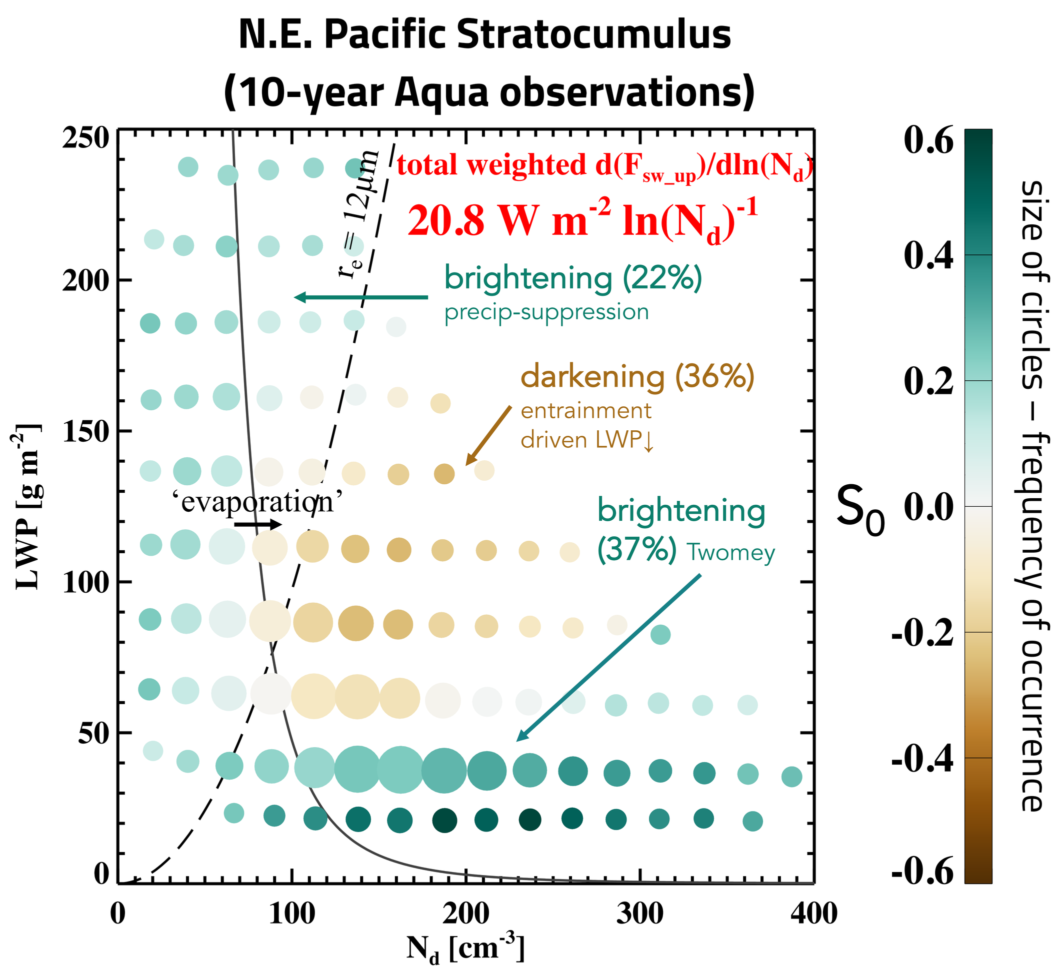
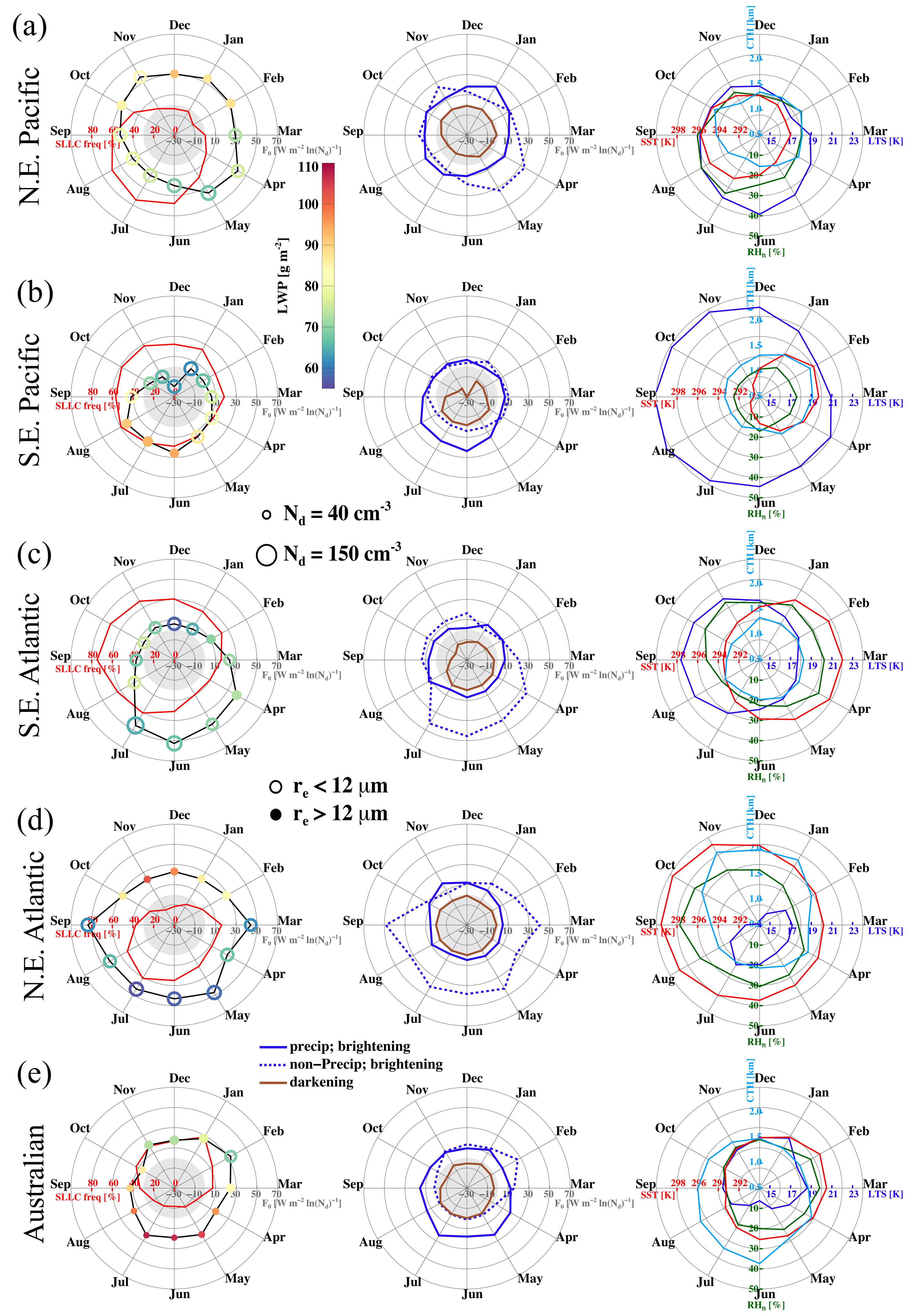
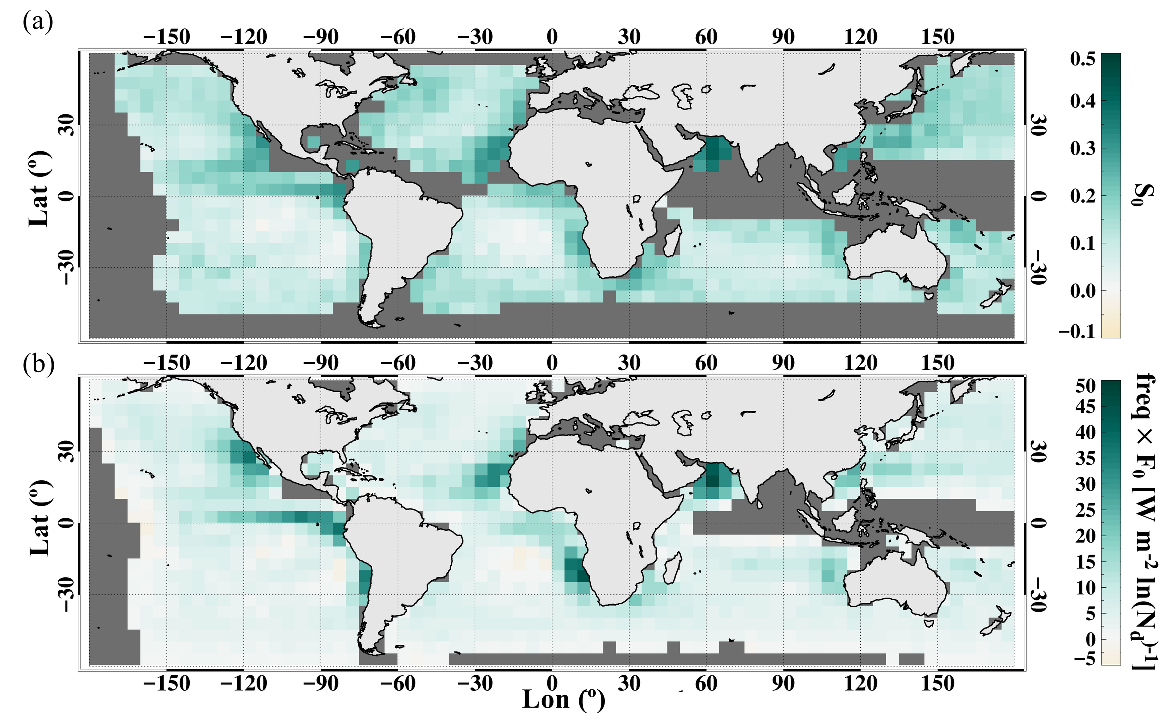
Albedo Susceptibility Regimes in LWP-N_d Space



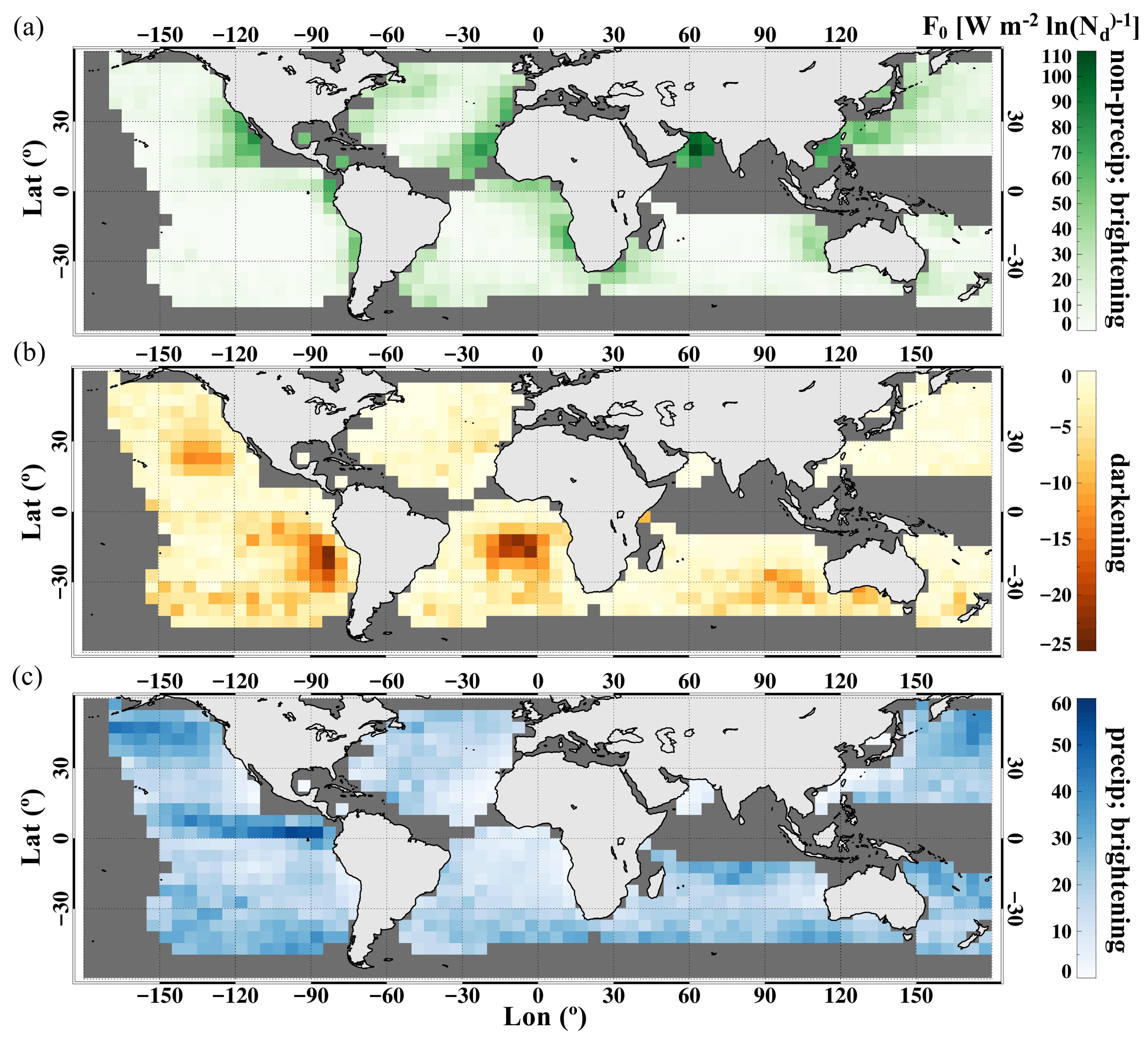
- **+ve S_0** left of the r_e = 12 μm isoline consistent with the **precipitation-suppression induced brightening** potential.
- **-ve S_0** right of **evaporation-entrainment feedback (EEF)** curve presents clouds with **darkening** potential.
- **+ve S_0** for non-precip thin clouds (LWP<60 gm^{-2}; weak entrainment velocity) presents the most frequently occurring **Twomey brightening** potential. [Twomey effect ~ $(1-A_c)/3$]



Climatological Maps of Marine Low Cloud Albedo Susceptibility



- Geographical distributions of marine low-cloud **(a)** albedo susceptibility (S_0) and **(b)** the product of **radiative susceptibility (F_0)** and annual frequency of occurrence of single layer liquid cloud (SLLC), derived from the Aqua dataset (2005-2007).
- **Radiative Susceptibility (F_0)** is the product of S_0, f_c and downwelling SW flux; **+ve value indicate cooling.**
- An **overall brightening potential** over global oceans, more pronounced over subtropical coastal stratocumulus, especially when the frequency of occurrence of SLLC is taken into account (**panel b**).



- Geographical distributions of the **radiative susceptibility (F_0) in 3 regimes**: **(a)** non-precipitating brightening, **(b)** darkening, and **(c)** precipitating brightening.
- The 3 regimes are separated based on the **sign of S_0 and a critical LWP value** (calculated using an effective radius of 12 μm) of all individual 1°× 1° snapshots within a 5°× 5° area. Only areas with SLLC frequency of occurrence greater than 0.1 are shown.
- **Non-precip brightening** dominates coastal regions, where annual-mean N_d is high and the MBL is shallow.
- Over the remote oceans where MBLs are deeper and clouds are thicker and mostly precipitating with lower f_c, **brightening potential associated with rain suppression** is the dominant regime.
- **Thicker marine stratocumulus** (high f_c and non-raining) that populate the remote parts of global subtropical stratocumulus decks show the strongest cloud darkening potential, especially over **S.E. Pacific/Atlantic where it overcomes the brightening in annual mean.**

Seasonal Covariability between Albedo Susceptibility and Large-scale Meteorology

- **Left column:** Monthly mean radiative susceptibility (**F_0; black**) and **frequency of occurrence of SLLC** (**red**). **Color** of the circle indicates monthly mean **LWP**. **Size** of the circle indicates monthly mean **N_d**. Open (closed) circles indicate likely **precipitating (non-precipitating)** condition, based on calculated critical LWP values with r_e = 12 μm.
- **Middle column:** Monthly mean **F_0 into 3 regimes**: non-precipitating brightening (**dotted blue**), darkening (**brown**), and precipitating brightening (**solid blue**).
- **Right column:** Monthly mean **meteorological** conditions: **LTS (blue), RH_{ft} (green), SST (red), and CTH (cyan).**

- Among 5 subtropical stratocumulus regions, **S.E. Pacific is the least susceptible**, owing to a predominant cloud darkening regime that is consistent with the dry free-tropospheric, cool ocean surface, and the stable atmosphere; **N.E. Atlantic is overall the most susceptible**, especially Mar.-Sept. when LWP is low and N_d is relatively high.
- What can we **learn from seasonal covariabilities** among meteorology, cloud frequency and albedo susceptibility
  - The most susceptible conditions/months can coincide with the least frequent warm cloud occurrence (e.g. NE Pacific, SE Pacific, SE Atlantic, Australian);
  - High susceptibilities can coincide with high N_d (e.g. SE Atlantic, NE Atlantic);
  - SST, LTS and RH_{ft} evolve **distinctively** even among major subsidence regions (i.e. SE Pacific, SE Atlantic and NE Pacific);
  - Distinctively covarying meteorological factors leads to **drastically different susceptibility evolutions** among global stratocumulus regions;

Take-home points

- Distinct **regimes** of albedo susceptibility appear in **LWP-N_d** variable space, consistent with **precip-suppression**, **entrainment feedback**, and **Twomey brightening** processes.
- Satellite observations (CERES-MODIS) indicate an **overall cloud brightening** potential (annual mean) for global (60°S – 60°N) marine low clouds, most pronounced over **subtropical coastal regions** where marine stratocumulus prevail.
- Entrainment driven **negative LWP adjustments** offset the Twomey & precip-suppression brightening over **remote oceans** where deeper, thicker, mostly non-precipitating clouds populate (darkening **overcomes** brightening in annual mean over **remote S.E. Pacific/Atlantic**).
- **Distinct regional covariabilities** between low-cloud albedo susceptibility and the large-scale meteorological conditions are observed over global marine stratocumulus regions.