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Cloud macroscopic organization: order emerging from randomness

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Abstract

Clouds play a central role in many aspects of the climate system and their forms and shapes are remarkably diverse. Appropriate representation of clouds in climate models is a major challenge because cloud processes span at least eight orders of magnitude in spatial scales. Here we show that there exists order in cloud size distribution of low-level clouds and it follows a power-law distribution with exponent γ close to 2. γ is insensitive to yearly variations in environmental conditions, but has regional variations and land-ocean contrasts. More importantly, we demonstrate this self-organizing behavior of clouds emerges naturally from a complex network model with simple, physical organizing principles: random clumping and merging. We also show clear-cloudy sky symmetry in terms of macroscopic organization because of similar fundamental underlying organizing principles. The order in the apparently complex cloud-clear field thus has its root in random simple interactions. Studying cloud organization with complex network models is an attractive new approach that has wide applications in climate science. This approach is fully complementary to deterministic models and the two approaches provide a powerful framework to meet the challenge of representing clouds in our climate models when working in tandem.

1 Introduction

Low-level warm clouds exert strong negative radiative effect on the climate system by reflecting large fraction of incoming solar radiation back to space while emitting similar amount of longwave radiation as the Earth's surface (Ramanathan et al., 1989; Hartmann and Doelling, 1991). These warm clouds appear in widely different and seemingly chaotic forms and sizes. For instance, while stratocumulus cloud sheets over oceans can have relatively homogeneous appearance at spatial scales ~100 km, the inhomogeneity of trade cumulus and fair weather cumulus clouds can be easily appreciated at scales as small as 10 m (Wielicki and Welch, 1986; Cahalan and Joseph,

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1989; Zhao and Di Girolamo, 2007). The appearance, or macroscopic organization, of these clouds is regulated by a set of complex and interacting micro- and macro- scale processes (Klein and Hartmann, 1993; Stevens and Feingold, 2009) operating at spatial scales ranging from Kolmogorov scale ~1 mm to typical meteorological mesoscale ~100 km, a span of eight orders of magnitudes. The large spatial scale range is an insurmountable challenge for deterministic physical cloud models (Siebesma and Jonker, 2000; Stevens, 2005) and will be in the foreseeable future. Yet, these clouds are at the heart of uncertainties related to future climate simulations (Bony et al., 2006). We have to rely on observational and modeling techniques to derive the most essential part of cloud variability and its relationship with the environment in order to appropriately account for them in climate models.

2 Data and method

Despite the highly inhomogeneous appearance of trade cumulus and fair-weather cumulus clouds there exists order in a statistical sense (Cahalan and Joseph, 1989; Benner and Curry, 1998). An example is given in Fig. 1 where normalized number frequency ($P_k = N_k/(N\,S_k)$, where N_k is the number of clouds within the k-th size bin, N is the total number of clouds in a sample) is plotted against cloud size bin (K) on a log-log scale. A cloud is defined as a patch of cloudy pixels connected through four-neighbor connectivity (diagonal neighbors are ignored). The cloud size is simply taken as the number of pixels a cloud contains. We used MODIS 1-km resolution cloud mask and quality assurance data to construct the P_k-K diagrams. For every level-2 cloud product file cloud mask for the region [5 N~30 N, 170 W~155 W] is retrieved so that only confidently cloudy pixels are retained (Platnick et al., 2003). This is a trade cumulus dominated region during July. We then remove clouds whose diameters are less than 3 km. This is recognizing first that data at MODIS resolution (1 km) would introduce large uncertainties when used to study clouds at smaller scales (Wielicki and Welch, 1986; Zhao and Di Girolamo, 2007). It is also because we are interested in

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cloud organizations at scales larger than the typical break scale (∼1 km) observed for trade cumuli (Cahalan and Joseph, 1989)even though small-scale statistics are also rich and important (Neggers et al., 2003; Koren et al., 2008; Jiang et al., 2009). We use a computer program to automatically find clouds with different sizes based on the cloud mask [SOM]. Finally, any cloud that contains non-liquid cloudy pixels is removed according to quality assurance flags, for details see Platnick et al. (2003). July data from 2003–2010 are analyzed with each year yielding on the order of 100 000 liquid clouds.

3 Results

The scale-free power law relationship between number frequency and cloud size holds for all the years (2003–2010) analyzed. The multi-year mean of the exponent γ for the power law relationship $P_k \sim K^{-\gamma}$ is 1.95 +/– 0.036 with 0.036 being the standard deviation. Correlation coefficient between Log(P_k) and Log(K) is all greater than 0.99 (same for other plots). Interestingly, the observed γ is nearly identical to estimates for warm oceanic convective clouds that are smaller than ∼1 km (Kuo et al., 1993; Benner and Curry, 1998; Zhao and Di Girolamo, 2007). We postulate that the scale-free behavior has no break between scales of $\varnothing$ (10 m) and of $\varnothing$ (100 km), four orders of magnitude difference. The break reported in previous studies is probably due to insufficient sampling of larger clouds (recall that $P_k \sim K^{-\gamma}$) because they used only a few cloudy scenes with each covering an area ∼10 000 km^2 or less (Zhao and Di Girolamo, 2007). In comparison, we used about 200 cloudy scenes every year with each covering ∼1 000 000 km^2, roughly 4 orders of magnitudes increase in total sampling for larger clouds.

The power law exponent γ is rather constant during the eight-year period. This is unexpected because despite the generally homogeneous trade wind circulation within a particular month there exists strong yearly variation. For example, the mean cloud fraction reported by MODIS fluctuates by more than 30% over these years. The invariant

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behavior indicates the warm clouds organization is much less sensitive to environmental conditions than the bulk cloud fraction. Observing the scale-free behavior and the insensitivity of exponent to large-scale conditions, we hypothesize that these warm trade cumulus clouds have robust intrinsic statistical organizations, or self-organized. This is supported by analyses from other regions such as trade cumuli over the Caribbean Ocean and Subtropical South Pacific and fair-weather cumuli over the west Amazon Basin (Fig. 1d). Cloud organizations at these locations have similar characteristics: cloud size distribution follows a power law ($P'_k \sim K^{-\gamma_{\text{eff}}}$, $P'_k = N_k/N$) and the exponent γ_{eff} (γ_{eff} is equivalent to $\gamma - 1$, where γ is the slope for the distribution if P_k is used instead of P'_k) is insensitive to yearly variations in large-scale condition. However, γ_{eff} does have regional differences, for instance, it is 1.1 for trade wind cumulus over the Caribbean ocean and 0.83 (Terra) ~0.91 (Aqua) for fair-weather cumulus over the Amazon. Finally, the diurnal variation in γ_{eff} has a land-ocean contrast: the variation is larger over land than over ocean (Fig. 1) and while values in the early afternoon (Aqua) are consistently smaller than those in the mid-morning (Terra) over ocean, suggesting an increase in overall cloud size, it is the opposite over land (it is in transition season of September over Amazon).

4 Model

Using a large eddy simulation model, it was demonstrated that simulated cloud sizes follow similar power-law distribution (Neggers et al., 2003). However, the quantitative explanation for this cloud behavior is still a scientific challenge (Neggers et al., 2003). Here we introduce a new stochastic model approach to explain the observed cloud self-organization. With the model we want to address the question: what stochastic mechanisms are driving the clouds to organize in the observed fashion? In this model a cloud, a collection of connected cloudy pixels, is abstracted as a vertex in a graph with the edges connected to the vertex as the cloudy pixels. The degree of a vertex then represents cloud size and the cloud P_k-K relationship is characterized by the degree

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distribution of a graph (Barabasi and Albert, 1999). To construct the graph we first note two key physical cloud-organizing processes and represent them with corresponding organizing principles in our stochastic model. First we observe that in nature cloud merging is common (Tao and Simpson, 1984; Nicholls and LeMone, 1980), which can be readily appreciated with naked eyes in the afternoon of a summertime fair-weather day. One of the organizing principles for our network model is thus two vertices can be randomly selected and merged at N vertices per time interval while vertices are created at C per interval. If the merged vertices are already connected the edge between them will be removed after merging. Redundant edges with common neighbors of the merged vertices are also removed. Second, we recognize the observation that clouds often appear in patches over the ocean (Malkus, 1954). It is hypothesized that clouds tend to "clump" together because existing clouds can provide a favorable environment for new cloud formations (Randall and Huffman, 1980). To reflect cloud clumping our second organizing principle is preferential attachment: when a new vertex is added to the graph, edges will be created at M per time interval to randomly selected vertices. The probability of selecting a vertex is proportional to $k_j / \sum_{i=1}^{n} k_i$, where k_i, k_j are degrees of vertices i and j. We start the graph with a few vertices and edges and grow it based on these two organizing principles. The free parameters are M, N and C. A degree distribution is shown in Fig. 2 as an example. The degree distribution follows a power law and the exponent γ_g is around 1.14, comparable to cloud fields over the Caribbean. Our model can effectively reproduce the range of observed γ with different combinations of cloud (vertex) creation and cloud merging rates. Conceptually, we have the following picture: individual cloud patches and cloudy pixels randomly pop up constantly, the cloud fields organize by randomly merging and clumping and through these random interactions macroscopic order (a power law distribution in cloud size) emerges. We show that this conceptual view of cloud organization can be effectively understood with our stochastic model on a graph, often called complex network models (Albert and Barabasi, 2002; Newman, 2003; Dorogovtsev et al., 2008).

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Using complex network models to study both fundamental physics (e.g. magnetism and condensed matter) and other natural (e.g. cell biology and disease transmission) and social systems (collaborative network for movie stars and scientists) is an active interdisciplinary research area (Albert and Barabasi, 2002; Newman, 2003; Dorogovtsev et al., 2008). Here we illustrate cloud self-organization behavior observed from satellite data emerges from the model once the graph organizing principles mimic the underlying physical mechanism: clumping and merging. Because of the striking analogy between statistical mechanics and cloud organization: macroscopic order emerges based on random, simple microscopic interactions, we propose to adopt a "cloud statistical mechanics" approach to study macroscopic behavior of clouds (Yuan and Li, 2010). The rich and growing arsenal for studying complex networks can provide powerful tools for studying cloud organization in depth with more sophisticated network models. Due to the abstract construct of the model the approach can be used to understand and study a host of phenomena in climate sciences. A few examples are provided in the following.

Stratocumulus clouds often appear as relatively homogeneous and inter-connected cloud decks. The cloud size distribution as defined here does not often obey power law for overcast stratocumulus region [SOM]. However, in light of recent fascinating developments on the organization of open cell convection as stratocumulus decks breaking up (Stevens et al., 2005; Xue et al., 2008; Wang and Feingold, 2009; Feingold et al., 2010), we note an intriguing analogy between the organization of trade cumuli and that of clear sky patches inside the broken stratocumulus decks (Fig. 3) as following: First, in the case of open cell cloud fields precipitation is mechanically organizing these open cell convections by generating mesoscale circulations (Stevens et al., 2005; Xue et al., 2008; Wang and Feingold, 2009; Feingold et al., 2010) and two "clear sky cells" can merge if some clouds at the cell edge randomly break; second, similar to cloud clumping, once a clear sky cell grows in size it is difficult for new clouds to generate inside them due to the spatial limit of precipitation outflow influence and possibly the limiting available aerosol particles due to drizzle (Wood et al., 2010). Given these two observations we postulate that fundamental organizing principles are nearly identical for organization of trade cumuli and organization of clear sky cells inside open cell regime. Our analysis of clear sky statistics over two regions with frequent appearance of open cell convections (Wood and Hartmann, 2006) confirms this postulation (Fig. 3). The sizes of clear sky cells follow a power law distribution. Again, this striking symmetry between apparently different organizations of cloudy and clear sky stems from similar fundamental organizing principles when viewed abstractly.

5 Discussions

Similarly, we can use the cloud statistical mechanics approach to investigate the organization of deep convective clouds. It was shown that the distribution has similar scaling behavior for deep convective clouds (Mapes and Houze, 1993; Machado and Rossow, 1993; Wilcox and Ramanathan, 2001). Noting that cloud merging and clumping are also common for deep convective clouds (Tao and Simpson, 1984; Mapes and Houze, 1993) we suggest that organizations of seemingly completely different forms of convection can be understood with the same organizing principles on a complex network model. Furthermore, precipitation organization shows similar power law behavior (Lovejoy, 1982) and can be considered a direct result of deep convective cloud organization. The moisture organization in atmosphere may also be understood with the complex network model approach (Kahn and Teixeira, 2009). Robust statistical relationships captured from this approach can also find applications in calculating cloud related radiation (Cahalan et al., 1994; Marshak et al., 1994; Barker et al., 1996).

More importantly, the cloud statistical mechanics approach and deterministic cloud models are fully complementary to each other. On one hand, observations on the behavior of cloud macroscopic properties can provide directions and challenges for deterministic models to determine microscopic processes that are responsible. For example, while our stochastic model can effectively produce the regional variation of

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γ, the actual clumping and merging rates (or other factors that contribute to different cloud organization) should come from observations or deterministic model simulations with detailed microphysical processes (Siebesma and Jonker, 2000; Neggers et al., 2003). On the other hand, insights on microscopic processes can in turn improve the construct of stochastic models. An example is the issue of aerosol-cloud interactions. Recent simulations suggest increased aerosol concentration leads to stronger evaporation at cloud sides, which results in more small, cloud cells (Jiang et al., 2009). This microscopic influence of aerosols would be expected to change cloud macroscopic organization since it can modify cloud merging and clumping rates. The interplay between these two approaches has a great potential to pinpoint processes that are most critical for cloud macroscopic properties and to faithfully model these properties using computationally cheap stochastic models.

In summary, we show a self-organization of warm cumulus clouds at spatial scales ranging four orders of magnitude under relatively homogeneous environment. A novel stochastic model constructed on a graph can effectively capture the essential cloud organization behavior and its regional variations. We demonstrate that clear sky organization in a broken stratocumulus field has the same behavior because of similar underlying organizing principles. Studying cloud statistical mechanics on complex networks in tandem with deterministic cloud models could provide a powerful framework for advancing our understanding on clouds and this study barely scratches the surface.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/11/1105/2011/ acpd-11-1105-2011-supplement.pdf.

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References

Albert, R. and Barabasi, A. L.: Statistical mechanics of complex networks, Rev. Mod. Phys., 74(1), 47–97, 2002.

Barabasi, A. L. and Albert, R.: Emergence of scaling in random networks, Science, 286, 5439, 509–512, 1999.

Barker, H. W., Wielicki, B. A., and Parker, L.: A parameterization for computing grid-averaged solar fluxes for inhomogeneous marine boundary layer clouds.2. Validation using satellite data, J. Atmos. Sci., 53(16), 2304–2316, 1996.

Benner, T. C. and Curry, J. A.: Characteristics of small tropical cumulus clouds and their impact on the environment, J. Geophys. Res-Atmos., 103(D22), 28753–28767, 1998.

Bony, S., Colman, R., Kattsov, V. M., Allan, R. P., Bretherton, C. S., Dufresne, J., Hall, A., Hallegatte, S., Holland, M. M., Ingram, W., Randall, D. A., Soden, B. J., Tselioudis, G., and Webb, M. J.: How well do we understand and evaluate climate change feedback processes?, J. Climate, 19(15), 3445–3482, 2006.

Cahalan, R. F. and Joseph, J. H.: Fractal statistics of cloud fields, Mon. Weather Rev., 117(2), 261–272, 1989.

Cahalan, R. F., Ridgway, W., Wiscombe, W. J., Bell, T. L., and Snider, J. B.: The albedo of fractal stratocumulus clouds, J. Atmos. Sci., 51(16), 2434–2455, 1994.

Dorogovtsev, S. N., Goltsev, A. V., and Mendes, J. F. F.: Critical phenomena in complex networks, Rev. Mod. Phys., 80(4), 1275–1335, doi:10.1103/RevModPhys.80.1275, 2008.

Feingold, G., Koren, I., Wang, H., Xue, H., and Brewer, W. A.: Precipitation-generated oscillations in open cellular cloud fields, Nature, 466(7308), 849–852, doi:10.1038/nature09314, 2010.

Hartmann, D. L. and Doelling, D.: On the net radiative effectiveness of cloudss, J. Geophys. Res-Atmos., 96(D1), 869–891, 1991.

Jiang, H., Feingold, G., and Koren, I.: Effect of aerosol on trade cumulus cloud morphology, J. Geophys. Res-Atmos., 114, D11209, doi:10.1029/2009JD011750, 2009.

Kahn, B. H. and Teixeira, J.: A Global Climatology of Temperature and Water Vapor Variance Scaling from the Atmospheric Infrared Sounder, J. Climate, 22(20), 5558–5576, doi:10.1175/2009JCLI2934.1, 2009.

Klein, S. A. and Hartmann, D. L.: The seasonal cycle of low stratiform clouds, J. Climate, 6(8), 1587–1606, 1993.

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Koren, I., Oreopoulos, L., Feingold, G., Remer, L. A., and Altaratz, O.: How small is a small cloud?, Atmos. Chem. Phys., 8, 3855–3864, doi:10.5194/acp-8-3855-2008, 2008.
Kuo, K. S., Welch, R. M., Weger, R. C., Engelstad, M. A., and Sengupta, S. K.: The 3-dimensional structure of cumulus clouds over the ocean. 1. structural-analysis, J. Geophys. Res-Atmos., 98(D11), 20685–20711, 1993.
Lovejoy, S.: Area-perimeter relation for rain and cloud areas, Science, 216(4542), 185–187, 1982.
Machado, L. A. T. and Rossow, W. B.: Structural characteristics and radiative properties of tropical cloud clusters, Mon. Weather Rev., 121(12), 3234–3260, 1993.
Malkus, J. S.: Some results of a trade-cumulus cloud investigation, J. Meteorol., 11(3), 220–237, 1954.
Mapes, B. E. and Houze, R. A.: Cloud clusters and superclusters over the oceanic warm pool, Mon. Weather Rev., 121(5), 1398–1415, 1993.
Marshak, A., Davis, A., Cahalan, R., and Wiscombe, W.: Bounded cascade models as nonstationary multifractals, Phys. Rev. E., 49(1), 55–69, 1994.
Neggers, R. A. J., Jonker, H. J. J., and Siebesma, A. P.: Size statistics of cumulus cloud populations in large-eddy simulations, J. Atmos. Sci., 60(8), 1060–1074, 2003.
Newman, M. E. J.: The structure and function of complex networks, Siam. Rev., 45(2), 167–256, 2003.
Nicholls, S. and Lemone, M. A.: The fair weather boundary layer in GATE – the relationship of sub-cloud fluxes and structure to the distribution and enhancement of cumulus clouds, J. Atmos. Sci., 37(9), 2051–2067, 1980.
Platnick, S., King, M. D., Ackerman, S. A., Menzel, W. P., Baum, B. A., Riedi, J. C., and Frey, R. A.: The MODIS cloud products: Algorithms and examples from Terra, IEEE Trans. Geosci. Remote Sensing, 41(2), 459–473, doi:10.1109/TGRS.2002.808301, 2003.
Ramanathan, V., Cess, R. D., Harrison, E. F., Minnis, P., Barkstrom, B. R., Ahmad, E., and Hartmann, D.: Cloud-Radiative forcing and climate- results from the Earth Radiation Budget Experiment, Science, 243(4887), 57–63, 1989.
Randall, D. A. and Huffman, G. J.: A stochastic-model of cumulus clumping, J. Atmos. Sci., 37(9), 2068–2078, 1980.
Siebesma, A. P. and Jonker, H. J. J.: Anomalous scaling of cumulus cloud boundaries, Phys. Rev. Lett., 85(1), 214–217, 2000.
Stevens, B.: Atmospheric moist convection, Annu. Rev. Earth Pl. Sc., 33, 605–643,

doi:10.1146/annurev.earth.33.092203.122658, 2005.
Stevens, B. and Feingold, G.: Untangling aerosol effects on clouds and precipitation in a buffered system, Nature, 461(7264), 607–613, doi:10.1038/nature08281, 2009.
Stevens, B., Vali, G., Comstock, K., Wood, R., Van Zanten, M. C., Austin, P. H., Bretherton, C. S., and Lenschow, D. H.: Pockets of open cells and drizzle in marine stratocumulus, B. Am. Meteorol. Soc., 86(1), 51–57, doi:10.1175/BAMS-86-1-51, 2005.
Tao, W. K. and Simpson, J. : Cloud interactions and merging- numerical simulations, J. Atmos. Sci., 41(19), 2901–2917, 1984.
Wang, H. and Feingold, G.: Modeling Mesoscale Cellular Structures and Drizzle in Marine Stratocumulus. Part I: Impact of Drizzle on the Formation and Evolution of Open Cells, J. Atmos. Sci., 66(11), 3237–3256, doi:10.1175/2009JAS3022.1, 2009.
Wielicki, B. A. and Welch, R. M.: Cumulus cloud properties derived using LandSat satellite data, J. Clim. Appl. Meteorol., 25(3), 261–276, 1986.
Wilcox, E. M. and Ramanathan, V.: Scale dependence of the thermodynamic forcing of tropical monsoon clouds: Results from TRMM observations, J. Climate, 14(7), 1511–1524, 2001.
Wood, R. and Hartmann, D. L.: Spatial variability of liquid water path in marine low cloud: The importance of mesoscale cellular convection, J. Climate, 19(9), 1748–1764, 2006.
Wood, R., Bretherton, C. S., Leon, D., Clarke, A. D., Zuidema, P., Allen, G., and Coe, H.: An aircraft case study of the spatial transition from closed to open mesoscale cellular convection over the Southeast Pacific, Atmos. Chem. Phys. Discuss., 10, 17911–17980, doi:10.5194/acpd-10-17911-2010, 2010.
Xue, H., Feingold, G., and Stevens, B.: Aerosol effects on clouds, precipitation, and the organization of shallow cumulus convection, J. Atmos. Sci., 65(2), 392–406, doi:10.1175/2007JAS2428.1, 2008.
Yuan, T. and Li, Z.: General Macro- and Microphysical Properties of Deep Convective Clouds as Observed by MODIS, J. Climate, 23(13), 3457–3473, doi:10.1175/2009JCLI3136.1, 2010.
Zhao, G. and Di Girolamo, L.: Statistics on the macrophysical properties of trade wind cumuli over the tropical western Atlantic, J. Geophys. Res-Atmos., 112(D10), D10204, doi:10.1029/2006JD007371, 2007.

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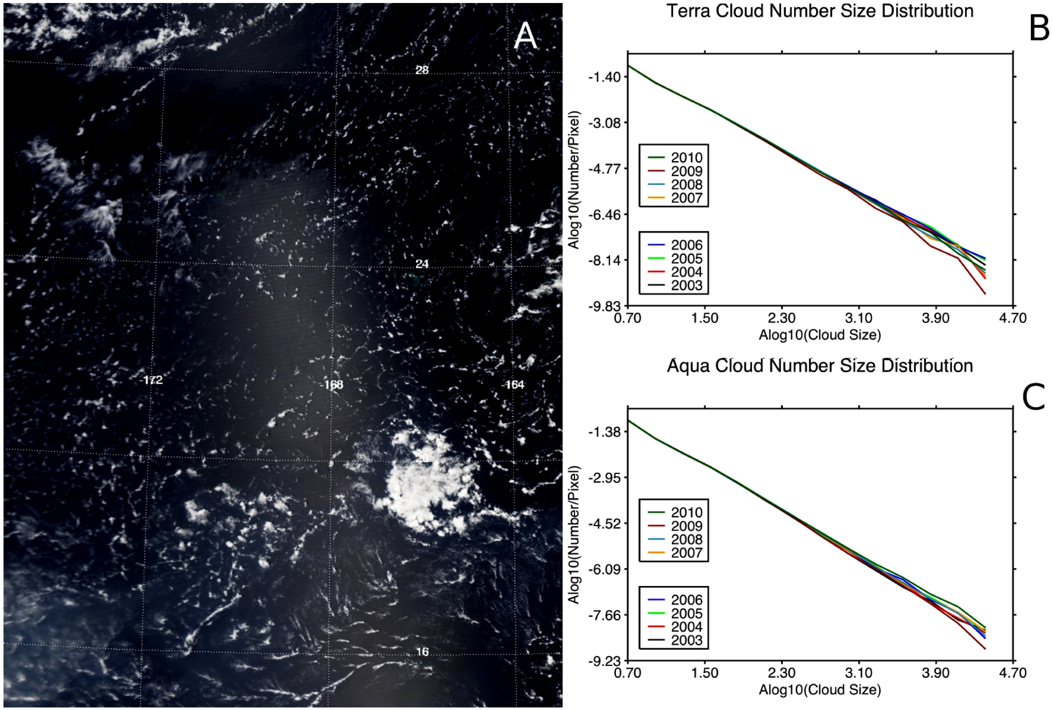

Fig. 1. **(A)** a MODIS visible image covering roughly the area between 15 N and 30 N and between 163 W and 176 W. The diversity and complexity of apparent cloud appearance can be appreciated. **(B)** Cloud size frequency distributions for eight years using Terra data. **(C)** same as in (B) but using Aqua data. The yearly variation in cloud organization is small as is for its diurnal variation (see text).

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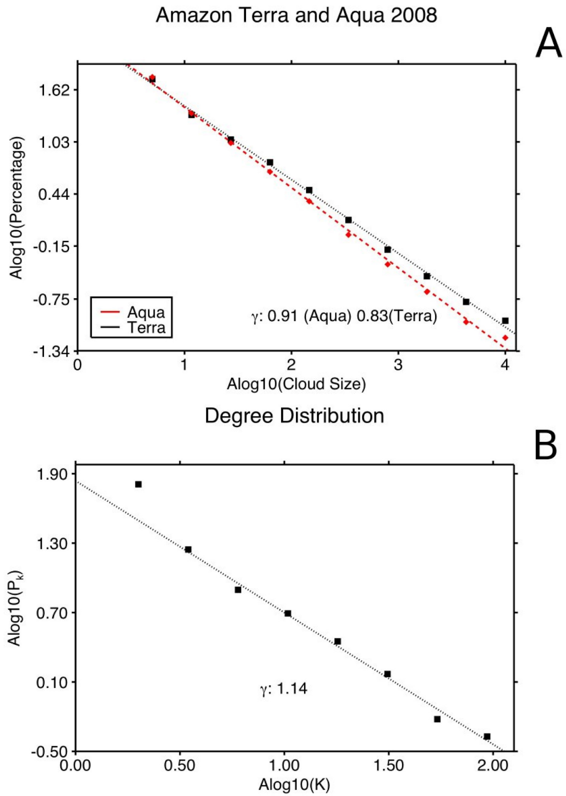

Fig. 2. (A) cloud size frequency distributions for September 2008 over the clean West Amazon. The two lines are for data from Aqua (in red) and Terra (in black). A more pronounced diurnal variation is noted compared to that over ocean. **(B)** degree distributions from the stochastic model run with $M = 2$, $C = 3$ and $N = 1$. We run the model until it has 4000 vertices. The exponent is close to that observed for trade cumuli over the Caribbean.

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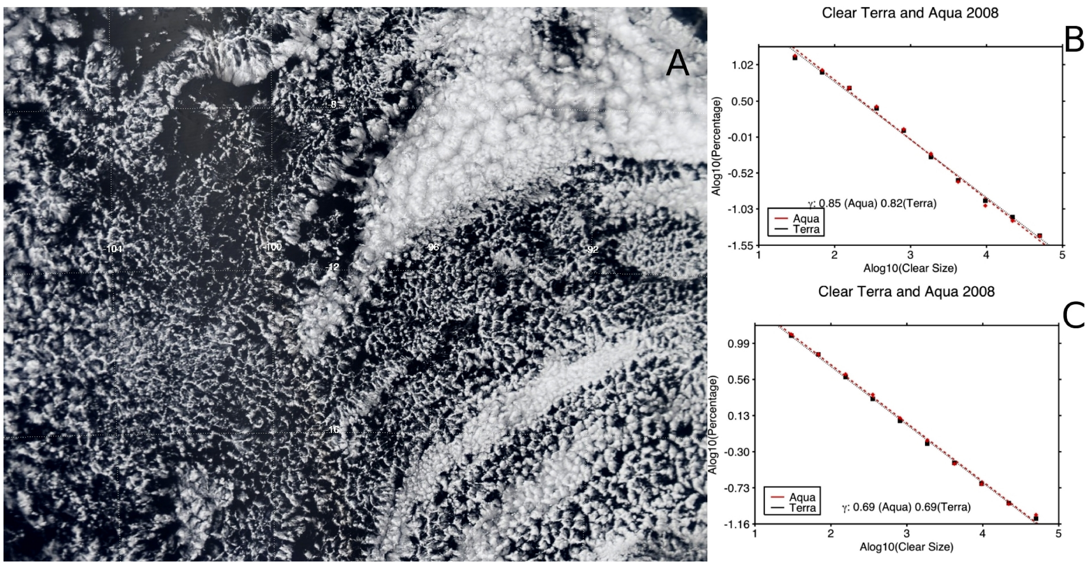

Fig. 3. **(A)** A visible MODIS image showing a stratocumulus deck breaking up. Open cell convections dominate the scene. It is over the Southern Pacific. **(B)** Clear sky size distributions for September, 2008 over the South Pacific open cell region (Wood and Hartmann, 2006). Both Aqua and Terra data are shown. **(C)** same as (B) but for open cell clouds over North Pacific (Wood and Hartmann, 2006).