Diagnosing Global Cloud Processes and Their Feedbacks on Weather and Climate in Observations and Models

William B. Rossow
May 2022

The ultimate goal of scientific research is to "understand" the processes and their interactions (feedbacks) within the physical system being studied. We say we understand a physical process and that our model of it is correct when we can write prognostic equations for the quantities involved in the process and that the functional form of the equations and any numerical parameters in it have been verified by observations. Numerical solutions to the equations then become the model of the process. A prognostic equation is an equation for the time-rate-of-change (partial time derivative) of a system variable; hence the time resolution of the observations and the time scales for significant variations of the process represented in the model become concerns in the development and evaluation. Often the rate of change depends on transfers or exchanges of something (mass, energy) that introduce dependence on spatial derivatives of quantities: atmospheric processes depend on the motions of the atmosphere in this way. This feature means that the spatial resolution of the observations and the spatial scales for significant variations represented in the model become additional concerns in the development and evaluation. Fine space-time resolution is needed to accurately represent the derivatives of the system variables (especially if the magnitudes are small), but a large range of scales also has to be encompassed to ensure that all relationships have been revealed and that any weak dependencies have been accurately measured and represented. Thus, the research goal is to determine the exact mathematical form of the time dependence of the physical variables and their relationships to other variables for each process such that the accuracy of the numerical solution of the equations (the model) is limited only by the space-time scales that are explicitly resolved. These goals are particularly important for the fidelity of model-based forecasts of a changing climate, where forecast verification is not an option (unlike weather forecasts) and observed (statistical) relationships in the current climate may not hold for a changing climate.

The definition of a partial derivative is that it represents the rate of change of only one variable with respect to one other variable at a particular point in a multi-variate (multi-dimensional) function-space with all other variables held constant at that point: this is the essence of conditional dependence in that the value of the partial derivative will vary as other quantities vary with location in the function-space. Therefore, exploring process relationships – measuring the partial derivatives and their dependence on other variables – in observations and models has to be conducted to account for conditional dependence to determine how the partial derivatives change with situation, ultimately determining what the functional form of this dependence is. Averaging the quantities over time and/or space distorts the conditional dependence; averaged quantities (especially if averaged separately) do not define a partial derivative. However conditional sampling can preserve statistical relationships. An obvious example of how averaging over time confuses cloud process relationships is the fact that a monthly average combines fair and stormy weather: cloud processes in the former situation have a very different relationship to atmospheric motions than in the latter situation since in fair weather there is no precipitation (or even clouds) and in stormy weather there can be (locally) very heavy precipitation and latent heating of the atmosphere that feeds back on the atmospheric motions. In fact in fair weather the atmosphere is cooling radiatively (even with some cloudiness) whereas in stormy weather the atmosphere is heating radiatively as well as by precipitation. Comparison of time-space averaged observations with time-space averaged model output is of very little use except to invalidate the model.

An alternative to representing a process by a prognostic equation, which is often used when complete understanding is lacking, is a diagnostic equation that predicts the "instantaneous and local" value of one variable as a function of the "instantaneous and local" values of other variables describing the state of the system (the conditions). Such a representation can work if the time step is "short" relative to the evolution of the system but "long" relative to the process to be represented. However, this approach still requires prognostic equations for state of the system.

The effect of material transports by atmospheric motions (water vapor and energy in cloud processes) on process time derivatives introduces space-time scale coupling, producing a joint space-time-scale spectrum of process variations. Since the atmospheric variation scales and cloud process scales may not match, the scale dependence of the coupling produces an additional conditional (scale) dependence of cloud processes and feedbacks.

The mathematical form of feedbacks, at least to first order, involves products of partial derivatives of the state and process variables with respect to each other (Aires and Rossow 2003); these products also represent implicit time derivatives. In the particular case of cloud-atmosphere feedbacks, the cloud microphysical process scales are smaller than the scales of the atmospheric motions that produce the clouds. Moreover, the diabatic heating by clouds, which feeds back on the atmospheric motions, occurs over two different, broad ranges of space-time scales: cloud radiative heating spans a much larger range of scales than precipitation (latent) heating because non-precipitating clouds are more extensive spatially and temporally than precipitating clouds and because radiative heating usually is weaker (slower) than precipitation heating. Additionally cloud processes affect the ocean and land, which have different response scales than the atmosphere but also feedback on the atmospheric motions through sensible and radiative heat exchanges (and indirectly through water vapor fluxes). All of these considerations mean that cloud feedbacks must be evaluated simultaneously over a very wide range of space-time scales encompassing the scales of cloud microphysics and turbulence, the scales of atmospheric motions (weather scales) and their coupling to the land and ocean (climate scales). Since cloud radiative and latent heating modify the atmospheric and oceanic circulations, cloud feedbacks must consider both effects together.

Deducing causal relationships from observations, given the above discussion of conditional (and scale) dependence, is problematic because all processes are operating at once. The analysis approach of Aires and Rossow (2003) embodies the conditional dependencies by evaluating all of the possible partial derivatives at small time steps where they are all approximately first order. While a neural network as a statistical analysis tool can be trained to capture these dependencies given a sufficiently long record (large enough sample), this approximation does not quantify causal relationships but only identifies the leading relationships (correlations). Gengaga *et al.* (2015) attempted to diagnose causal relationships by incorporating dependence on time-lagged relationships in a formulation of the evolution of system entropy, but found that available methods for determining the entropy of measured quantities were so imprecise that a definitive analysis was precluded. Moreover, the available observations for such analyses may be too limited in size for describing multi-variate, multi-scale relationships, at least for climate scales.

Clouds are transient, but meta-stable phenomena, meaning that the evolution of some properties (microphysics) is faster than the gross dynamical time scale controlling their bulk properties (areal and vertical extent, duration, water content). In other words, the time derivatives of bulk properties over a cloud lifecycle are significant but very small over the scale of the time derivatives of cloud microphysical properties. So while the “internal properties” of a cloud can vary rapidly, they can be considered to be approximately in equilibrium (Khvorostyanov and Curry 2014) with the slower bulk variation over the cloud evolution lifecycle (formation-to-decay) of radiation, precipitation and their feedbacks on weather and climate that occur at the larger scales of the controlling atmospheric motions and their coupling to the land and ocean. In any case the time derivative of the bulk properties cannot be neglected in a diagnostic analysis. Averaging over time (or space) confuses the physical relationships.

Cloud (bulk) variability is driven by atmospheric motions, mostly the time derivative of relative humidity caused by vertical air motions (relative humidity increase by radiative cooling is a slower process that may be more important in the upper troposphere and polar regions). Thus, the time derivative of condensing cloud water mass is proportional to the atmospheric parcel cooling rate, mostly governed by its vertical velocity (Khvorostyanov and Curry 2014). The precipitation rate, which depends on cloud particle collisions, is proportional to the cloud water mass to some power greater than one (Khvorostyanov and Curry 2014). Hence the space-time spectrum of bulk cloud property variations is a distorted mapping of the spectrum of atmospheric motions, even though the variations of the internal properties of clouds are “microphysical”. Although cloud microphysical processes are universal, clouds look very different in different atmospheric situations and regions of Earth – conditional dependence – because of the different styles of dynamical motions. The variation power spectrum is related directly to the strength of the variation autocorrelation: stronger/weaker autocorrelation produces steeper/shallower “red” power spectra – meaning that there is larger variability at larger scales (Gilman *et al.* 1963). The observed space-time spectrum of clouds (Zhangvil 1975, Rossow and Cairns 1995) is similar to that of the atmospheric dynamics. The autocorrelations of relative humidity, temperature and pressure at the surface (indicative of large-scale motions) are all similar, > 0.1 for time lags < 10 days (Weber and Talkner 2001). Precipitation still shows an autocorrelation though much weaker than that of relative humidity, over time lags of 2-4 days (Weber and Talkner 2001). In summary, the bulk cloud properties and relevant process-quantities (relative humidity and precipitation) vary more on the larger space-time scales of atmospheric motions.

Clouds perturb atmospheric radiative heating/cooling on a spectrum of scales: given that space and time variations of the atmosphere are coupled (fluid dynamics), the smaller spatial scale disturbances are shorter-lived. Hence, the more significant perturbations occur at larger scales – storm systems up to general circulation scale (again a "red" spectrum). Some clouds (about 10%) are a source of atmospheric latent heating by precipitation at smaller space-time scales than radiative heating: the larger and longer-lived storms are much rarer but produce most of the latent heating effect (Rossow *et al.* 2011, Feng *et al.* 2012, Tan *et al.* 2015, Polly and Rossow 2016). These two heating effects feed back on the atmospheric motions that produced the clouds but at very different scales: precipitation heating is more intense but for shorter durations and at smaller spatial scales than radiative heating. Moreover, the weather systems that relatively rapidly heat the atmosphere by precipitation and radiation are much rarer than those that slowly cool it by radiation (Rossow *et al.* 2016).

Clouds also modulate ocean temperature and salinity, which couples atmospheric and oceanic circulations, but the scales of cloud variability are different than the scales of ocean responses. Thus, clouds couple the components of the climate's energy-water cycle with atmosphere-ocean circulation dynamics across a wide range of space-time scales. The coupling of cloud effects to the ocean introduces much longer time scales, longer even than the available data records. This is another motivation for extending the length of detailed data records of the relevant atmospheric and surface properties. In the meantime, as the records grow longer, analyses of exchanges of energy and water can characterize cloud feedbacks over progressively longer-scale climate variation modes.

Measuring scale- and situation-dependent cloud process time derivatives requires certain kinds of observations: synoptic (simultaneous) coverage of at least the dominant (larger spectral amplitude) space and time scales of variability and comprehensive coverage of the variables that define the conditional dependence (process relationships). Most conventional cloud observations generally do not measure the time evolution of an air parcel, even for microphysical scales. Surface observations at a point do not cover the dominant range of spatial scales (only up to a few tens of kilometers) and the time variability is mostly advected spatial variability confounded with a little time variability. Volume-scanning measurements from the surface can monitor time variations in the accessible volume up to of order 100 km, which is very useful for smaller-scale convective storms (*cf*. Pope *et al*. 2009a,b). Aircraft measurements cover a somewhat larger range of spatial scales (still only of order 1000 km), but only provide non-synoptic sampling of spatial variability with no time variability (except at time scales greater than daily if repeated flights into the same volume are made). Satellite observations are of two types. Low-earth-orbiting (LEO) satellites are employed to carry large (and expensive) instruments to obtain global coverage with high spatial resolution; however their low frequency time sampling (up to two times daily for each satellite) precludes observations of cloud evolution except on the very largest scales. Geostationary earth orbiting (GEO) satellites provide synoptic sampling covering spatial scales from a few kilometers up to 10,000 km with incomplete global coverage; however they do provide very high frequency time sampling (intervals as small as 5-15 minutes today). By combining observations from a multi-LEO and multi-GEO constellation of satellites, it is possible to obtain cloud measurements that cover at once (synoptically) the whole range of atmospheric-oceanic circulation and cloud process space and time scales over the whole globe.

To cover the range of conditional dependencies of the cloud processes (time derivatives) also requires a long time record to obtain many samples of each type of situation and to encompass the longer time scales introduced by the ocean, which is now possible with satellite constellation observations covering several decades. Ancillary data about the state and motion of the atmosphere (and ocean) with similar coverage and space-time-scale resolution are also needed to define the conditions associated with the cloud property variations. Particularly important is the advent of microwave humidity sounders on multiple LEO satellites that begins to provide time-resolved below-cloud humidity measurements. These remarks apply not only to measurements of clouds and the atmospheric conditions but also to model representations – time-space-averaged outputs are not very informative.

Two specific ideas for diagnostic evaluation of climate models have been proposed that have an aspect of measuring process time derivatives. The first, called CAPT (CCPP ARM Parameterization Testbed, where CCPP is Climate Change Prediction Program and ARM is Atmospheric Radiation Measurement program), proposes using short-term (weather forecast) analysis to evaluate process errors in climate GCMs (Phillips *et al.* 2004). This approach is practical only for the atmospheric component of climate models both because data for initializing the ocean circulation and land moisture are incomplete and because the time scales for a forecast run may not be long enough to encompass ocean and land variations and their related feedbacks (indeed the proposal often indicates that the ocean SST is fixed). The procedure is to initialize the climate model with the observed "true" (atmospheric) state, run it forward in time like a weather forecast run, and compare the final state to observations. This is a form of time derivative evaluation – a low-resolution finite difference estimate – but the comparison of the final model state to observations, while giving a detailed quantification of "errors" of the individual properties of the model climate, cannot separately ascribe errors to specific processes without very many more experimental runs (lots of sensitivity experiments) and very much more analysis to disentangle all the coupled processes.

The second idea follows a suggestion by Leith (1975) to relate the statistical variation relationships of quantities found at shorter time-scales (*e.g.*, monthly to interannual scales) in the current climate to the longer-time-scale variations of a changed climate. This is also a (very) low-resolution kind of time derivative analysis that can provide a better focus on more "process-like" relationships (Klein and Hall 2015). The concept is based on the fluctuation-dissipation theorem (Nyquist 1928) that fast processes are in quasi-equilibrium during slow, weakly forced changes and that the linear response of the system projects onto the internal (natural) modes of variability (this idea might be applied to the microphysical evolution of clouds on short-time atmospheric variations in the free atmosphere). Thus, observed relationships in "natural" variations are proposed to approximate the relationships in a (slow, weak) climate change. However, the limited length of observation records means that the observed variations still include only a limited amount of the ocean variations. That is the transient responses may not be the same, even in sign, as the longer-term or equilibrium responses (*cf.* Wang and Rossow 1998). Moreover, the relationships in this type of analysis are usually described as correlations that may not define actual physical (causal) connections. For instance, the correlation of two quantities may occur because they are correlated to or separately caused by a third quantity. As cloud processes couple atmospheric and oceanic circulations and their energy and water exchanges, the correlations that are exhibited on short time scales may not hold in a changed climate. Still, if the variations of energy and water exchanges are examined in this way, they may provide some insight to cloud-climate feedback processes.

Some Possible Diagnostic Analyses

(1) Instantaneous associations of cloud-defined Weather States (WS) and other atmospheric properties and processes (motions, fluxes): We borrow two concepts from quantum mechanics. The first concept is to represent the continuum of atmospheric states and the associated cloud properties by a small set of (approximately) “discrete” states and represent the time variations as transitions among these states. These “weather states” collapse multi-variate relationships into a simpler representation of the time derivatives of cloud processes focusing on their bulk attributes, where the smaller scale variations are embodied in histograms of the cloud properties that form characteristic patterns. (These cloud property patterns are called Weather States because early weather forecasts were formulated based on varying cloud attributes.) The time transitions of one WS into another, especially associated with changing atmospheric properties and motions, can provide useful diagnostic relationships. The second concept is to search for statistical (probabilistic) relationships between these states and the properties of the larger scale atmospheric circulation. As we define the WS, they are substitutes for vertical motions but also represent the clouds produced by them. Thus, a diagnostic equation can be defined that relates the time variations of the cloud properties as represented by the WS to the time variations of the atmospheric properties (conditions).

(2) Time derivatives (lead, lag) of WS and atmospheric properties and processes: Measuring the time derivatives of the WS against the lead and lag time variations of atmospheric properties and motions (also their time derivatives) on larger scales could suggest feedbacks on the atmospheric circulation if composite diabatic heating (radiation, precipitation, surface sensible heat flux) magnitudes are determined for each WS (*e.g.*, Rossow *et al.* 2016).

(3) Similar studies can be performed where other properties of the atmospheric circulation are used to define the “states” and then composites of the cloud properties can be made including some microphysical quantities (*cf*. Pope *et al.* 2009a,b). The vigor of the divergent component of the general circulation that produces clouds might be denoted by the magnitude of the eddy kinetic energy. With respect to tropical deep convection, such properties as relative humidity, CAPE and vertical wind shear might be used to define states (*e.g.,* Jakob *et* al. 2005, Futyan and Del Genio 2007, Masunaga 2014, Masunaga and Luo 2016). In the extratropics, the surface pressure anomalies (especially the depth of a low pressure anomaly, Polly and Rossow 2016) plus relative humidity and horizontal wind shear could define dynamical states.

(4) Pattern analysis of the time variations of the global distribution of surface pressure anomalies showed that the dominant patterns for time scales longer than one year are the lowest order spherical harmonics, including one mode with east-west variation. These patterns looked like the basic AO, AAO (both symmetric and antisymmetric) and ENSO variation modes. A time spectral analysis of these variations and the associated changes of multiple atmospheric properties, including clouds, could be done. A similar analysis could also be done on other quantities, such as surface temperature and total cloud

amount, but the combined (joint) patterns could also be analyzed to relate variations of the atmospheric circulation and cloud properties.

(5) Such pattern analyses might also allow design of indices of general circulation strength and the rate of cycling of the energy and water cycle. Time variations of these indices could then be related to time variations of cloud property patterns (or weather states).

(6) Some examples of such analyses applied to observations are: Rossow and Cairns (1995), Jacob and Tselioudis (2003), Rossow *et al.* (2005), Jacob *et al.* (2005), Rossow and Pearl (2007), Jacob and Schumacher (2008), Chen and Del Genio (2008), Tromeur and Rossow (2010), Tselioudis *et al.* (2010), Haynes *et al.* (2011), Oreopoulos and Rossow (2011), Mekonnen and Rossow (2011), Tselioudis and Rossow (2011), Lee *et al.* (2013), Rossow *et al.* (2013), Tselioudis *et al.* (2013), Masunaga (2014), Tan *et al.* (2015), Rossow *et al.* (2016), Polly and Rossow (2016), Masunaga and Luo (2016), Luo *et al.* (2017), Mekonnen and Rossow (2018), Worku *et al.* (2019, 2020).

Possible Prognostic Analyses

(1) Track a cloud (*e.g.*, "cold" or "warm" cloud area) or circulation object (*e.g.*, surface pressure anomaly) to determine the joint lifecycle evolution of cloud properties (including WS) and atmospheric characteristics in air parcels: This analysis approach allows for rearranging time-space sampled measurements into composites that can define the lifecycle of different atmospheric-cloud events, thereby providing direct estimates of the joint time derivatives. A useful version of this approach is to consider cloud processes in the context of storm systems (but also fair weather conditions). This works well for larger-scale convective systems, where a distinctive cloud object is tracked (Machado *et al.* 1998, Fiolleau and Roca 2013), and for extratropical cyclones where the surface low pressure anomalies are tracked (Hodges 1994, Bauer *et al.* 2013, Polly and Rossow 2016).

(2) Track air parcels to determine the joint evolution of its properties and clouds (or WS): Another form of tracking analysis uses reanalysis (or analysis) winds to track air parcels placing cloud and atmospheric properties into a Lagrangian framework (Luo 2004, Wernli and Davies 1997).

(3) Both of these tracking approaches can then be used to estimate the partial (conditional) time derivatives directly in the Lagrangian frame. Some examples of such analyses applied to observations are: Wernli and Davies (1997), Machado *et al.* (1998), Simonds (2000), Luo and Rossow (2004), Machado and Laurent (2004), Wernli and Schwierz (2006), Futyan and Del Genio (2007), Naud *et al.* (2010), Feng *et al.* (2012), Fiolleau and Roca (2013), Bouniol *et al*. (2016), Polly and Rossow (2016), Vant-Hull *et al.* (2016).

A few of the diagnostic studies described above have specifically examined how cloud properties interact with larger scale dynamical motions by looking at changes of cloud property patterns with the circulation variations, *e.g.*, the Madden-Julian Oscillation (Tromeur and Rossow 2010, Worku *et al.* 2019, 2020), seasonal and El Nino Southern Oscillations (Tselioudis and Rossow 2011), and the African Easterly Wave (Mekonnen and Rossow 2011, Mekonnen and Rossow 2018). Some prognostic studies have estimated time derivatives for tropical deep convection (Machado and Laurent 2004, Luo *et al.* 2010, Takahashi and Luo 2012, Fiolleau and Roca 2013) and for extratropical cyclones (Polly 2016).

More such studies are needed to cover a wider range of these phenomena and, especially, to extend them to other climate regimes. With the advent of active cloud and precipitation satellite sensors, special attention needs to be paid to polar cloud processes using similar diagnostic and prognostic analysis approaches. To complete the feedback loop, the time derivatives of cloud properties and atmospheric motions need to be connected by determining the time derivatives of the atmospheric heating/cooling rates by radiation and precipitation as well as their variation over the lifecycle of weather events. An analysis like that of Tselioudis and Rossow (2011) that looks at the global distribution of the cloud property variations and consequent diabatic heating of the atmosphere with overall changes of the general circulation would begin to elucidate global cloud feedbacks.

Only a few model studies have applied some of these types of analysis approaches to general circulation models (*e.g.,* Bauer and Del Genio 2006, Williams and Tselioudis 2007, Chen and Del Genio 2008, Williams and Webb 2009, Naud *et al.* 2010, Booth *et al.* 2013). Another approach to evaluating cloud-radiative effects in general circulation models uses “radiative kernals”, which decompose the total effect using mesoscale histograms of cloud top pressure and optical thickness (Zelinka *et al.* 2012a,b, Zhang *et al.* 2021). A low resolution version of this is to determine radiative flux perturbations associated with cloud types (Hartmann *et al.* 1992, Chen *et al.* 2000). Many more model analyses are needed to better evaluate cloud process representations in weather and climate models. In fact, with the large amount of satellite-based data products that are global in coverage and resolving sub-daily time variations, it is now possible to directly evaluate model time derivatives of many of the model variables against observations.

Some other types of analyses that encompass the whole range of atmospheric dynamical scales are needed to investigate scale coupling among cloud processes and land-ocean-atmosphere interactions: (1) joint space-time spectra of cloud water path (possibly mean particle size and phase) and water vapor (particularly relative humidity), cloud height and vertical velocity, precipitation (accumulated and intensity) and low-level convergence, (2) cross-spectra of these cloud properties with atmospheric variables (vertical motions, static stability, wind shear). With the availability of observation-based diagnostics of the global energy and water exchanges within the atmosphere and between the atmosphere and land-ocean surface that resolve the weather-scale variations (Kummerow *et al.* 2019), it is now possible to directly evaluate climate (weather) model cloud processes in the senses described above – deriving the prognostic equations.

References

Aires, F., and W.B. Rossow, 2003: Inferring instantaneous, multi-variate and non-linear sensitivities for the analysis of feedback processes in a dynamical

system: The Lorenz model case study. *Q. J. Roy. Meteor. Soc.*, **129**, 239-275, doi:10.1256/qj.01.174.
Bauer, M., and A. DelGenio, 2006: Composite analysis of winter cyclones in a GCM: Influence on climatological humidity. *J. Climate*, **19**, 1652-1672. doi:10.1175/jcli3690.1.
Bauer, M., G. Tselioudis and W.B. Rossow, 2016: A new climatology for investigating storm influences in and on the extratropics. *J. Appl. Meteorol.*, **55**, 1287-1303, doi:10.1175/jamc-d-15-0245.1.
Booth, J.F., C.M. Naud, and A.D. Del Genio, 2013: Diagnosing warm frontal cloud formation in a GCM: A novel approach using conditional subsetting. *J. Climate*, **26**, 5827-5845, doi:10.1175/jcli-d-12-00637.1.
Bouniol, D., R. Roca, T. Fiolleau and D.E. Poan, 2016: Macrophysical, microphysical, and radiative properties of tropical mesoscale convective systems over their life cycle. *J. Climate*, **29**, 3353-3371, doi:10.1175/jcli-d-15-0551.1.
Chen, Y., A.D. Del Genio, 2008: Evaluation of tropical cloud regimes in observations and a general circulation model. *Climate Dynamics*, **32**, 355-369, doi:10.1007/s00382-008-0386-6.
Feng, Z., X. Dong, B. Xi, S.A. McFarlane, A. Kennedy, B. Lin and P. Minnis, 2012: Life cycle of midlatitude deep convective systems in a Lagrangian framework. *J. Geophys. Res.*, **117**, (1-14), doi:10.1029/2012jd018362.
Fiolleau, T., and R. Roca, 2013: Composite life cycle of mesoscale convective systems from geostationary and low Earth orbit satellite observations: method and sampling considerations. *Quart. J. Roy. Met. Soc.*, **139**, 941-953, doi:10.1002/qj.2174.
Futyan, J.M., and A.D. Del Genio, 2007: Deep convective system evolution over Africa and the tropical Atlantic. *J. Climate*, **20**, 5041-5060, doi:10.1175/jcli4297.1.
Gencaga, D., K.H. Knuth and W.B. Rossow, 2015: A recipe for the estimation of information flow in a dynamical system. *Entropy*, **17,** doi:10.3390/e17010438, 438-470.
Gilman, D.L., F.J. Fuglister and J.M. Mitchell, 1963: On the power spectrum of "red noise". *J. Atmos. Sci.*, **20**, 182-184, doi:10.1175/1520-0469(1963)020<0182:otpson>2.0.co;2.
Hartmann, D.L., M.E. Ockert-Bell and M.L. Michelsen, 1992: The effect of cloud type on Earth's energy balance: Global analysis. *J. Climate,* **5**, 1281-1304, doi:10.1175/1520-0442(1992)005<1281:teocto>2.0.co;2.
Haynes, J.M., C. Jakob, W.B. Rossow, G. Tselioudis and J. Brown, 2011: Major characteristics of southern ocean cloud regimes and their effects on the energy budget. *J. Climate*, **24**, 5061-5080, doi:10.1175/2011jcli4052.1.
Hodges, K.I., 1994: A general-method for tracking analysis and its application to meteorological data. *Mon. Wea. Rev.*, **122**, 2573-2586, doi:10.1175/1520-0493(1994)122<2573:agmfta>2.0.co;2.
Jacob, C., and G. Tselioudis, 2003: Objective identification of cloud regimes in the tropical western Pacific. *Geophys. Res. Lett.*, **30**, 2082, doi:10.1029/2003gl018367.

Jacob, C., G. Tselioudis and T. Hume, 2005: The radiative, cloud and thermodynamic properties of the major tropical western Pacific cloud regimes. *J. Climate*, **18**, 1203-1215, doi:10.1175/jcli3326.1.

Jacob, C., and C. Schumacher, 2008: Precipitation and latent heating characteristics of the major tropical western Pacific cloud regimes. *J. Climate*, **21**, 4348-4364. doi:10.1175/2008jcli2122.1.

Khvorostyanov, V.I., and J.A. Curry, 2014: *Thermodynamics, Kinetics, and Microphysics of Clouds*, Cambridge, pp. 782, doi:10.1017/cbo9781139060004.

Klein, S., and A. Hall, 2015: Emergent constraints for cloud feedbacks. *Curr. Clim. Change Rep.*, **1**, 276-287, doi:10.1007/s40641-015-0027-1.

Kummerow, C., P. Brown, R. Adler, S. Kinne, W Rossow, P. Stackhouse, C.A. Clayson, M. McCabe, D. Mirales and C. Jimenez, 2019: The GDAP Integrated Product. *GEWEX NEWS*, **29**, 3-6.

Lee, D., L. Oreopoulos, G.J. Huffman and W.B. Rossow, 2013: The precipitation characteristics of ISCCP tropical weather states. *J. Climate*, **26**, 772-788, doi: 10.1175/jcli-d-11-00718.1.

Leith, C.E., 1975: Climate response and fluctuation dissipation. *J. Atmos. Sci*., **32**, 2022-2026, doi:10.1175/1520-0469(1975)032<2022:crafd>2.0.co;2.

Luo, Z., and W.B. Rossow, 2004: Characterizing tropical cirrus life cycle, evolution and interaction with upper tropospheric water vapor using Lagrangian trajectory analysis of satellite observations. *J. Climate*, **17**, 4541-4563, doi:10.1175/3222.1.

Luo, Z.J., G.Y. Liu and G.L. Stephens, 2010: Use of A-train data to estimate convective buoyancy and entrainment rate. *Geophys. Res. Lett.*, **37**, (1-5), doi:10.1029/2010gl042904.

Luo, Z., R.C. Anderson, W.B. Rossow and H. Takahashi, 2017: Tropical cloud and precipitation regimes as seen from near-simultaneous TRMM, CloudSat and CALIPSO observations and comparison with ISCCP. *J. Geophys. Res. Atmos*, **122**, 5988-60003, doi:10.1002/2017jd026569.

Machado, L.A.T., and W.B. Rossow, 1993: Structural characteristics and radiative properties of tropical cloud clusters. *Mon. Wea. Rev*, **121**, 3234-3260, doi:10.1175/1520-0493(1993)121<3234:scarpo>2.0.co;2.

Machado, L.A.T., W.B. Rossow, R.L. Guedes, and A.W. Walker, 1998: Life cycle variations of mesoscale convective systems over the Americas. *Mon. Wea. Rev*., **126**, 1630-1654, doi:10.1175/1520-0493(1998)126<1630:lcvomc>2.0.co;2.

Machado, L.A.T., and H. Laurent, 2004: The convective system area expansion over Amazonia and its relationships with convective system life duration and high-level wind divergence. *Mon. Wea. Rev.*, **132**, 714-725, doi:10.1175/1520-0493(2004)132<0714:tcsaeo>2.0.co;2.

Masunaga, H., 2014: Free-tropospheric moisture convergence and tropical convective regimes. *Geophys. Res. Lett.*, **41**, 8611-8618, doi:10.1002/2014gl062301.

Masunaga, H., and Z.J. Luo, 2016: Convective and large-scale mass flux profiles over tropical oceans determined from synergistic analysis of a suite of satellite observations. *J. Geophys. Res. Atmos.*, **121**, 7958-7974, doi:10.1002/2016jd024753.

Mekonnen, A., and W.B. Rossow, 2011: The interaction between deep convection and easterly waves tropical North Africa: A weather state perspective. *J. Climate*, **24**, 4276-4294, doi:10.1175/2011jcli3900.1.

Mekonnen, A., and W.B. Rossow, 2018: The interaction between cloud regimes and easterly wave activity over Africa: Convective transitions and mechanisms. *Mon. Wea. Rev.*, **146**. 1945-1961, doi:10.1175/mwr-d-17-0217.1.

Naud, C.M., A.D. Del Genio, M. Bauer and W. Kovari, 2010: Cloud vertical distributions across warm and cold fronts in Cloudsat-CALIPSO data and a general circulation model. *J. Climate*, **23**, 3397-3415, doi:10.1175/2010jcli3282.1.

Nyquist, H., 1928: Thermal agitation of electric charge in conductors. *Phys. Rev.*, **32**, 110-113, doi:10.1103/physrev.32.110.

Oreopoulos, L., and W.B. Rossow, 2011: The cloud radiative effect of ISCCP weather states. *J. Geophys. Res.*, **116**, (1-22), doi:10/1029/2010jd015472.

Phillips, T.J., G.L. Potter, D.L. Williamson, R.T. Cederwall, J.S. Boyle, M. Fiorino, J.J. Hnilo, J.G. Olson, S. Xie and J.J. Yio, 2004: Evaluating parameterizations in general circulation models. *Bull. Amer. Meteor. Soc.*, **85?**, 1903-1915, doi:10.1175/bams-85-12-1903.

Polly, J., and W.B. Rossow, 2016: Distribution of midlatitude cyclone attributes based on the MCMS database. *J. Climate*, 6483-6507, doi:10.1175/jcli-d-15-0857.1.

Polly, J.B., 2016: *Diabatic Heating by Cloud Processes Associated with Extratropical Cyclones*. PhD Thesis, The City College of New York, pp. 139.

Pope, M., C. Jakob and M.J. Reeder, 2009a: Objective classification of tropical mesoscale convective systems. *J. Climate*, **22**, 5797-5808, doi:10.1175/2009jcli2777.1.

Pope, M., C. Jakob and M.J. Reeder, 2009b: Regimes of the north Australian wet season. *J. Climate*, **22**, 6699-6715, doi:10.1175/2009jcli3057.1.

Rossow, W.B., and R.A. Schiffer, 1991: ISCCP cloud data products. *Bull. Amer. Meteor. Soc.*, **72**, 2-20, doi:10.1175/1520-0477(1991)072<0002:icdp>2.0.co;2.

Rossow, W.B., and B. Cairns, 1995: Monitoring changes of clouds. *Climatic Change*, **31**, 305-347, doi:10.1007/978-94-011-0323-7_11.

Rossow, W.B., and R.A. Schiffer, 1999: Advances in understanding clouds from ISCCP. *Bull. Amer. Meteor. Soc.*, **80**, 2261-2287, doi:10.1175/1520-0477(1999)080<2261:aiucfi>2.0.co;2.

Rossow, W.B., G. Tselioudis, A. Polak and C. Jakob, 2005: Tropical climate described as a distribution of weather states indicated by distinct mesoscale cloud property mixtures. *Geophys. Res. Lett.*, **32**, (1-4), doi 10.1029/2005gl024584.

Rossow, W.B., and C. Pearl, 2007: 22-year survey of tropical convection penetrating into the lower stratosphere. *Geophys. Res. Lett.*, **34**, L04803, (1-4), doi: 10.1029/2006gl028635.

Rossow, W.B., A. Mekonnen, C. Pearl and W. Goncalves, 2013: Tropical precipitation extremes. *J. Climate*, **26**, 1457-1466, doi: 10.1175/jcli-d-11-00725.1.

Rossow, W.B., Y-C. Zhang and G. Tselioudis, 2016: Atmospheric diabatic heating in different weather states and the general circulation. *J. Climate*, **29**, 1059-1065, doi:10.1175/jcli-d-15-0760.1.

Simnonds, I., 2000: Size changes over the life of sea level cyclones in the NCEP reanalysis. *Mon. Wea. Rev.*, **128**, 4118-4125.
Takahashi, H., and Z Luo, 2012: Where is the level of neutral buoyancy for deep convection? *Geophys. Res. Lett.*, **39**, (1-6), doi:10.1029/2012gl052638.
Tan, J., C. Jakob, W.B. Rossow and G. Tselioudis, 2015: The role of organized deep convection in explaining observed tropical rainfall changes. *Nature*, **519**, 451-454. doi:10.1038/nature14339.
Tromeur, E., and W.B. Rossow, 2010: Interaction of tropical deep convection with the large-scale circulation in the Madden-Julian oscillation. *J. Climate*, **23**, 1837-1853, doi:10.1175/202009jcli3240.1.
Tselioudis, G., E. Tromeur, W.B. Rossow and C.S. Zerefos, 2010: Decadal changes in tropical convection and possible effects on stratospheric water vapor. *Geophys. Res. Lett.*, **37**, L14806, (1-4), doi:10.1029/2010gl044092.
Tselioudis, G., and W.B. Rossow, 2011: Time scales of variability of the tropical atmosphere derived from cloud-defined weather states. *J. Climate*, **24**, 602-608, doi:10.1175/2010jcli3574.1.
Tselioudis, G., W.B. Rossow, Y-C. Zhang and D. Konsta, 2013: Global weather states and their properties from passive and active satellite cloud retrievals. *J. Climate*, **26**, 7734-7746, doi:10.1175/jcli-d-13-00024.1.
Vant-Hull, B., W.B Rossow and C. Pearl, 2016: Global comparison of lifecycle properties and motions of multi-day convective systems: tropics, mid-latitude; land and ocean. *J. Climate*, **29**, 5837-5858, doi:10.1175/jcli-d-15-0698.1.
Weber, R.O., and P. Talkner, 2001: Spectra and correlations of climate data from days to decades. *J. Geophys. Res.*, **106**, 20,131-20,144, doi:10.1029/2001jd000548.
Wernli, H., and H.C. Davies, 1997: A Lagrangian-based analysis of extratropical cyclones. I: The method and some applications. *Quart. J. Roy. Met. Soc.*, **123**, 467-489, doi:10.1002/qj.49712354211.
Wernli, H., and C. Schwierz, 2006: Surface cyclones in the ERA-40 dataset (1958-2001). part I: Novel identification method and global climatology. *J. Atmos. Sci.*, **63**, 2486-2507, doi:10.1175/jas3766.1.
Williams, K.D., and G. Tselioudis, 2007: GCM intercomparison of global cloud regimes: Present-day evaluation and climate change response. *Clim. Dyn.*, **29**, 231-250, doi:10.1007/s00382-007-0232-2.
Williams, K.D., and M.J. Webb, 2009: A quantitative performance assessment of cloud regimes in climate models. *Climate Dyn.*, **33** (1), 141-157, doi:10.1007/s00382-008-0443-1.
Worku, L.Y., A. Mekonnen and C.J. Schreck, 2019: Diurnal cycle of rainfall and convection over the Maritime Continent using TRMM and ISCCP. *Int. J. Climatol.*, 1-10, doi:10.1002/joc.6121.
Worku, L.Y., A. Mekonnen and C.J. Schreck, 2020: The impact of MJO, Kelvin, Equatorial Rossby waves on the diurnal cycle over the Maritime Continent. *Atmosphere*, **2020**, 11, 711, doi:10.3390/atmos11070711.
Zelinka, M.D., S.A. Klein and D.L. Hartmann, 2012a: Computing and partitioning cloud feedbacks using cloud property histograms. Part I: Cloud radiatve kernals. *J. Climate*, **25**, 3715-3735, doi:10.1175/jcli-d-11-00248.1.

Zelinka, M.D., S.A. Klein and D.L. Hartmann, 2012b: Computing and partitioning cloud feedbacks using cloud property histograms. Part II: Attribution to changes in cloud amount, altitude and optical depth. *J. Climate*, **25**, 3736-3754, doi:10.1175/jcli-d-11-00249.1.

Zhangvil, A., 1975: Temporal and spatial behavior of large-scale in tropical cloudiness deduced from satellite brightness data. *Mon. Wea. Rev.*, **103**, 904-920, doi:10.1175/1520-0493(1975)103<0904:tasbol>2.0.co;2.

Zhang, Y-C., Z. Jin and M. Sikand, 2021: The top-of-atmosphere, surface and atmospheric cloud radiative kernels based on ISCCP-H datasets: Method and evaluation. *J. Geophys. Res. Atmos.*, **126**, doi:10.1029/2021jd035053.