On a Strategy for Satellite-based Cloud Research in the Next Decade

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1. What are the Cloud questions and how have they been addressed?

Cloud research began with a range of questions concerning processes explaining their microphysical and morphological properties and their weather-related variations, particularly focused on the production of precipitation and the occurrence of severe weather. These questions have been and continue to be investigated by numerous “field” experiments using a variety of surface- and aircraft-based measurements of cloud properties and their atmospheric environment. Although a few very ambitious experiments have been conducted that encompass whole storm systems over their whole lifecyle, these detailed field observations are still limited in the time-space scales that they cover and the number of different cases that have been studied, especially over oceans. Such studies have now been extended to include situations in (almost) all weather/climate regimes on earth and into the upper troposphere, lower stratosphere. Increasing emphasis on climate change shifted more attention to the properties of clouds that determine their effects on the planetary radiation budget. Advances in this area were driven more by satellite observations that had the advantage of global coverage and much more comprehensive sampling of cloud types covering the whole range of time-space scales of weather variability. Also the basic cloud properties that could be retrieved from satellite measurements have been shown to provide fairly accurate reconstructions of the cloud radiative effects. Specific experimental satellites added more detail about the properties of clouds, most notably AQUA/TERRA and CloudSat/Calipso. The ultimate cloud-climate question is: what feedbacks on climate change are produced by cloud processes, both radiation effects and water exchanges (precipitation), i.e., how do the weather-scale variations integrate into effects on the global energy and water cycles?

The link between cloud microphysical processes and the whole range of weather-scale cloud property variations and between weather- and climate-scale variations and feedbacks can be called “cloud dynamics.” Clouds exhibit variations over the whole range of time-space scales of atmospheric motions, from turbulence to the global circulation; clouds also express the larger scales of the response of the whole general circulation to changes in climate. Since most field and satellite measurements are incomplete in that they do not encompass all factors at work (i.e., they are situation limited) and are limited in the scales covered, an alternative research approach is to obtain many more samples of cloud behavior, enough to cover “all” situations and combinations of factors. This can be done with consistent, global, long satellite records. Although all of cloud research has significantly advanced the understanding of cloud processes and weather systems and some of their roles in climate variation, we still do not have an integrated (all-scale) understanding of cloud dynamics that explains the variety and reaction of the global distribution of cloud properties to local and global changes. To complete comprehensive answers to the whole range of cloud questions now requires investigating and understanding how cloud processes operate and feedback on and across all of these atmospheric variation scales – diagnosing cloud dynamics. Only satellite observations can provide the simultaneous coverage of all these variation scales.

2. What is the current situation?

The characteristics of satellite orbits necessitate a constellation of satellites to provide both high frequency sampling (intervals of order hours) and global coverage at small enough spatial scales (of order kilometers). Such observations could be obtained solely from sun-synchronous polar orbiters if there were enough of them (> 4 are required to achieve < 3 hourly sampling for instance), however, such coverage has actually been provided since the early 1980s by a combination of the geostationary and polar orbiting weather satellites operated by several nations. The imaging instruments on these satellites provide both frequent samples (at least 3 hr intervals in 1982) at very high spatial resolution (about 5 km scale). The International Satellite Cloud Climatology Project (ISCCP) exploited this satellite constellation to produce a continuous record of cloud properties that samples the whole globe at 10 km intervals every 3 hrs and that will soon span 35 years (1982-2017 and continuing). The NASA CERES project has also produced similar cloud products for the past 17 years. While there are many important and specialized cloud products that have been produced – there were 12 global cloud products compared in the GEWEX Cloud Assessment – based on satellite infrared (and microwave) sounders, polarimeters and (especially) lidars and radars, but only the ISCCP record covers multiple decades with sub-daily sampling. Despite the availability for the past 30-40 years of geostationary imagery with time intervals smaller than 3 hr, no systematic analysis of these data has been performed.

3. Why continue the current version of ISCCP?

The newest version of the ISCCP processing is now operational in the sense that routine data collection, quality checking, calibrating and processing are all conducted by an international group of operational (weather) satellite agencies. There are two major reasons to continue this version of cloud products. The obvious one is to extend the length of the record (beyond 35 years) of detailed cloud behavior to encompass even longer time scale variations that characterize the response of the atmospheric general circulation to slower (deeper) modes of ocean variability beyond the seasonal and ENSO time scales. For example, almost the whole of the ISCCP record has been characterized by one phase of the Pacific Decadal Oscillation. Other slow modes of variation, like the Arctic and Antarctic Annual Modes, have similar decadal time scales. The less obvious, but no less important, reason is that the ISCCP record represents a constant (uniform) background of information that can be used to tie together all of the older field and experimental satellite measurements (which represent more limited case studies) by providing the context of each case allowing comparisons that take account of their situation dependence.

Although the ISCCP data products provide the highest frequency sampling over the longest global record, they are limited in two important ways. The products are based on radiance measurements at only two wavelengths – the only two that were common across the whole satellite constellation in 1982. This condition remained true until 2004. This fact limits the cloud properties that can be retrieved to two: total column optical thickness and cloud top temperature of the uppermost cloud layer, along with cloud amount. These retrievals use empirically-based microphysical properties (particle size distribution and shape) that are dependent on an empirically-based phase determination from cloud top temperature. Moreover, these properties are assigned to single cloud layers (with empirically—based physical thicknesses). These features have proved to be adequate for determining cloud radiative effects with good accuracy and detail, but they limit the usefulness of the ISCCP products for relating cloud behavior to precipitation formation and storm evolution. The 3 hr sampling interval of ISCCP allows for study of the evolution of larger-scale, longer-lived cloud and storm systems but is too coarse, together with the lack of detailed microphysical information, to examine the formation of precipitation and the evolution of boundary layer cloudiness.

4. What are the remaining cloud questions and how can they be addressed?

The key questions about clouds concern how the cloud processes at smaller scales link across weather scale variations to the general circulation of the whole atmosphere – how the relatively well-observed and understood cloud-scale physics interacts with the whole scale-range of atmospheric motions to produce the variety of cloud types and behavior that have been observed and how the global distribution of cloud properties feeds-back on the general circulations of the atmosphere and ocean. To address the full range cloud dynamics time-space scales requires an extended global record (to give adequate situation sampling) at even higher frequency than ISCCP (at least 30 min intervals) with enough additional spectral radiance measurements to provide more detailed information about cloud microphysics and layer structure.

Achieving global coverage at higher sampling frequency than ISCCP's 3 hourly sampling requires that the necessary constellation (at least two polar orbiters and 5 geostationary satellites) all make measurements at enough common wavelengths that usefully describe more properties of clouds. At the beginning of ISCCP in 1982, there were only two common channels, visible (about 0.6 microns) and "window" infrared (about 11 microns). This remained true until 2004 when a channel at about 3.9 microns became available on all weather satellites. The situation is now evolving more rapidly such that by 2020 (the launch of the second advanced GOES), there will be 10 channels in common on all weather satellites. This constellation could provide global measurements at intervals as small as 30 min (limited by the polar region coverage), possibly even 15 min. These 10 channels would add information about cloud phase and particle size and some additional (though incomplete) information about cloud layering.

5. The 2017-2027 Decadal Survey context

Much of the sentiment expressed above was specifically called out in the ESAS2017 DS report. The report recognized that real advances in modeling and prediction require observations that actually resolve cloud processes (measure time derivatives of cloud properties) and connect these processes from storm-scales to general circulation scales. Weather prediction advances in the coming decade will come from scientific and technological innovation in computing, the representation of physical processes in parameterizations, coupling of Earth-system components, the use of observations with advanced data assimilation algorithms, and the consistent description of uncertainties through ensemble methods and how they interact across scales. Localized cloud processes and their connection to and influence on larger scale cloud systems is a central theme both to the discussion of progress in weather forecasting (Figure 1) and to the Clouds, Convection and Precipitation designated measurements (CCP) recommended by the DS ESAS2017. A critical piece of this recommendation is the call to better utilize the available satellite information on clouds, particularly from the suite of advanced instruments on operational and experimental polar orbiting satellites, that would then be explicitly tied to the newer observations of cloud microphysics and dynamics proposed fro CCP. A central foundational piece of the CCP recommendation is to develop further time resolved cloud properties from spectral radiance data available from the present generation of geostationary satellites which, together with polar orbiter coverage of the polar regions, can globally measure the time derivative of cloud dynamics across all space-time scales and provide the context tying together the lower-time-resolution, but more advanced measurements. Equally important as time resolution is analysis of the observations in the frame of weather system lifecycles (Lagrangian) to observe how the cloud processes evolve dynamically.

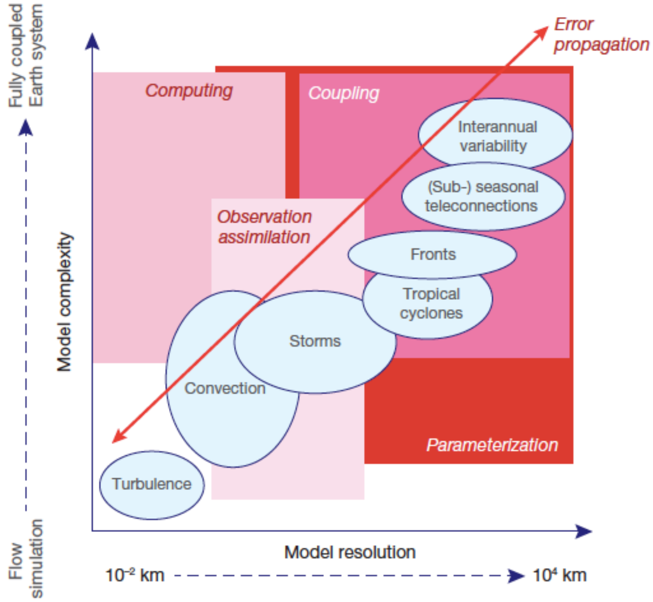

FIGURE 1 The notional process for advancing weather forecast skill (from Bauer et al., 2015), chapter 3 ESAS2017. This shows how scales of interactions, many involving processes of the moist atmosphere connect with uncertainties at the basic process level propagating up in space and time to forecasts on the larger scale

Figure 1 shows a schematic of physical processes as a function of spatial scale: as the range of scales encompassed by Earth System models (weather forecasting through to climate variation) increases, the more complex the model physics has to be. Figure 2 is a similar schematic of processes that shows the relationship between their space and time scales and the different satellite approaches that cover these scales: the key to progress now is to resolve the processes (e.g. measure time derivatives) but also at the same time encompass the coupling of these processes across the whole range of variation scales and geostationary observations provide the important capability of addressing fast processes projected onto longer time and larger spatial scales. Continuing the original ISCCP and initiating a more advanced version with much better time resolution provides the basis for interpreting the more detailed satellite measurements employing multi-instrument analysis but with sparser time sampling. All these components would fulfill much of the DS recommended CCP program.

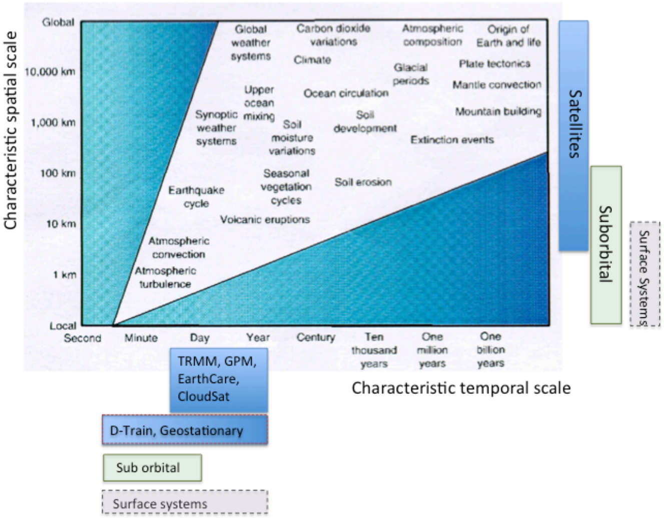

Figure 2 The unique position that geostationary observations occupy in Earth-observing strategies. The figure presents different observing methods overlain on characteristic space and time scale of Earth system processes.

6. Organizational Issues and recommendations

Looking at the whole set of cloud products that are now available shows that the experience of using different combinations of the available channels exists in the research community, although a single analysis using them all does not presently exist. Experience with the development and structuring of large-volume, complex analysis systems has already been obtained by the ISCCP, CERES, MODIS/AIRS teams. Hence we recommend that:

> *NASA sponsor a series of international workshops covering cloud detection and identification methods and physical retrievals of cloud properties to build a team with expertise covering all parts of a 10-channel retrieval using already developed, efficient methods for such multi-variate analyses. This team would then develop a unified analysis approach built around the current geostationary radiance data record augmented by MODIS/VIIRS and sounder cloud information, leading to the full implementation of ISCCP-2 with data collection starting about 2020-21.*

The other practical issue is handling the very large data volume. The newer ISCCP products begin with the two-wavelength radiance images sampled to 10 km intervals every 3 hr (including all polar orbits). To obtain sampling at 3 km every 30 min at 10 wavelengths would produce a radiance dataset that is about 180 times larger (per month) than ISCCP, about 3 Tb/month. We believe that the most feasible and least costly approach to processing would follow the recommendation that:

> *Data collection and analysis be to organized as a multi-institutional (multi-national) processing chain similar to ISCCP. The satellite operators, including those already providing data for ISCCP, would be responsible for collecting, quality checking and sub-sampling their 10-channel radiance images with initial calibration to about 2 km and 30 min intervals and providing these data to an analysis center that would conduct a refined calibration and the quantitative cloud analysis. Other institutions could provide needed ancillary data products, most particularly other atmospheric and surface properties that affect the same radiances. The resulting data products could be archived and distributed by existing data centers. This structure can support both the on-going version of ISCCP and the new advanced version, ISCCP-2.*

7. Needed Developments of Analysis Steps

(1) Pixel Navigation: One of the most effective tests for detecting clouds (actually detecting clear conditions, then cloudiness) is to examine the statistics of the time variations of radiances at each location (usually for small regions larger than one pixel), but for these tests to work the image navigation has to be accurate over time. If the navigation causes pixel-level locations to vary over time on any time scale from image-to-image up to at least one month, then the time-variation tests will be misleading, especially near coastlines or snow-ice margins. Current experience is that the routine accuracy of the navigation of operational satellite images is not better than about 10-20 km. This situation has to be accounted for in the processing.

(2) Radiance Calibration (0.45, 0.68, 0.86, 1.6, 3.9, 6.2, 7.3, 8.6, 10.4, 12.4, 13.3 microns): Since all of these channels are common to all satellites (with some small differences in spectral response), it should be possible to extend to all wavelengths the current ISCCP procedures for normalizing all geostationary radiances to the reference polar orbiter (afternoon). Some investigation is needed to determine whether the simple contrast between cloudy and clear scenes over oceans will suffice to provide maximum dynamic range for all channels. The 3.9 micron channel will have to be normalized as both a solar and thermal channel to cover its dynamic range. All channels, even the infrared ones, should use view-angle-dependent procedures as the angle-dependence is likely to useful for retrievals. The main problem is obtaining absolute calibration for all channels for the reference polar orbiter.

(3) Ancillary Product Development: The needed ancillary datasets are surface types (land-ocean, topography, land-type or vegetation-type), snow-ice cover, atmospheric temperature and composition, and aerosols. All of these can probably benefit from some updates and more testing of accuracy. Key problems to investigate are near-surface temperature and humidity, especially

diurnal variations over land, and what additional gas abundances, besides ozone, are needed. Aerosols might be retrieved in clear scenes and assumed to be present under “nearby in time” clouds, like surface properties.

(4) Cloud Detection: Detection of the presence of cloud, rather than identifying types of cloud, is best done at the two wavelengths where the atmosphere is most transparent, 0.68 and 10.4 microns. Hence the current ISCCP detection algorithm already achieves most of the desired result. The main exception to this cloud detection in the polar regions, especially during wintertime, so investigation is needed to explore whether the any additional channels can improve performance in these regions. For instance the 1.6 and 3.9 micron channels are likely beneficial with solar illumination. The value of the other thermal infrared channels (6.2, 7.3, 8.6, 10.4, 12.4, 13.3) to provide better discrimination in the dark, especially when low-level temperature inversions are present, should be investigated using Calipso for verification.

(5) Situation Recognition: Where the additional wavelengths may provide an improvement over ISCCP is in identifying specific situations that can refine the retrieval. The most important cases are resolving the ambiguity of the location of optically thin clouds, especially at night, but also possibly providing some indication of multi-layer cloud structure. This possibility should be investigated using MODIS/VIIRS and AIRS/IASI with Calipso and CloudSat as verification. Also separating dust clouds or large pollution events from water clouds might be possible; this can be checked using MODIS-POLDER and Calipso.

(6) Multi-wavelength Radiative Transfer Model: A rigorous radiative transfer model (or solar and thermal infrared models) with consistent physical representations of the gaseous atmosphere, aerosols, surface and clouds must underpin the development of the retrieval process (see item 9): solar wavelengths are 0.45, 0.68, 0.86, 1.6, and 3.9 microns and thermal infrared wavelengths are 3.9, 6.2, 7.3, 8.6, 10.4, 12.4, 13.3 microns.

(7) Surface Property Retrieval: The albedo can be measured at 0.45, 0.68, 0.86, 1.6, 3.9 microns. The surface temperature and emissivity might be obtained from 3.9, 6.2, 7.3, 8.6, 10.4, 12.4, 13.3 microns. In both cases accurate representation of the atmospheric aborption/emission at the longer and shorter wavelengths will depend on the quality of the ancillary data.

(8) Cloud Property Retrieval: Employing all the channels during daytime should allow for the ISCCP retrieval of cloud top temperature and optical thickness to be extended to better phase discrimination and effective particle size retrievals. Additional effort should be focused on how much of the added information can be obtained during nighttime. This is the main investigation needed for ISCCP-2.

(9) Efficient but Rigorous Method: The best approach that is both efficient and “rigorous” is to use a Neural Network trained by a Radiative Transfer Model. The design of such a system has been demonstrated and has several advantages over other theoretically similar ideas (e.g., optimum interpolation). A key feature of such a retrieval method is that a quality check procedure can be run that puts a sampling of the results back into the RT model and compares the calculated radiances to the input values.

(10) Statistics: Beyond mere “random” statistical measures, joint distributions and situation-dependent sorting of results are most likely to be informative of processes. The most obvious item of this type for ISCCP-2 is a joint optical thickness – particle size histogram sorted by phase. Some re-investigation of the spatial scale that provides enough samples (number of pixels) and meaningful structure is warranted.