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History of the International Satellite Cloud Climatology Project

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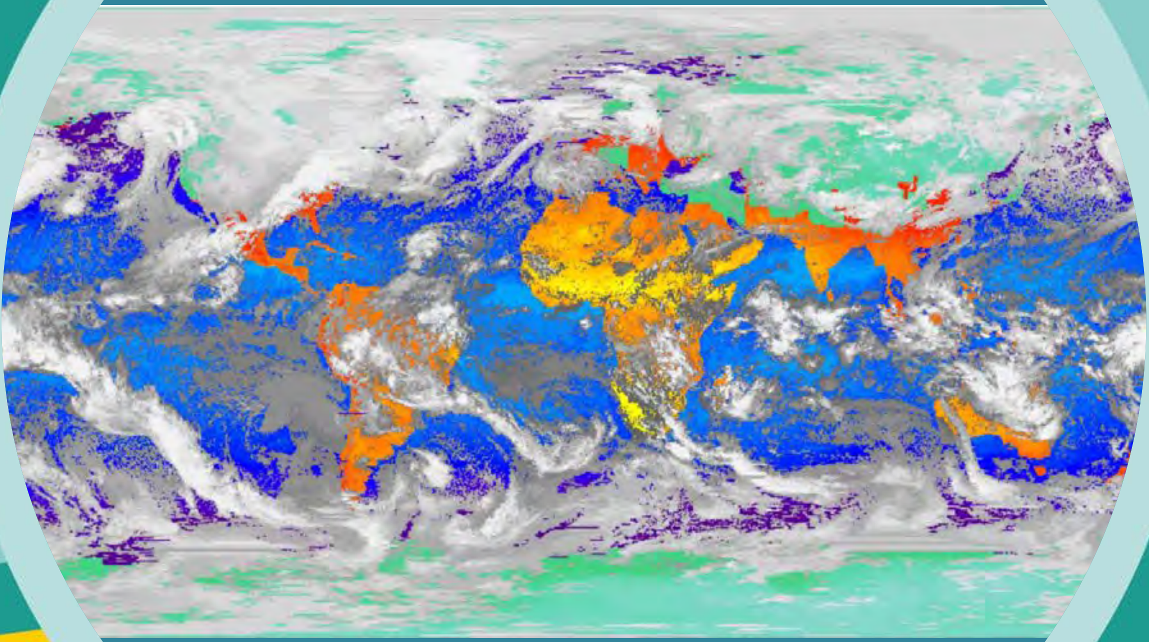

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This report was authored by William B. Rossow, Emeritus Distinguished Professor, City College of New York, formerly Senior Scientist at NASA Goddard Institute for Space Studies.

The International Satellite Cloud Climatology Project (ISCCP) was established in 1982 as part of WCRP to collect weather satellite radiance measurements and to analyze them to infer the global distribution of clouds, their properties, and their diurnal, synoptic, seasonal and interannual variations. The resulting datasets and analysis products are used to study the role of clouds in weather and climate, both their effects on radiative energy exchanges and their role in the global water cycle.

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Executive Summary

The International Satellite Cloud Climatology Project (ISCCP) was formally established as the first project of the World Climate Research Programme (WCRP) in August 1982 to collect and analyze global satellite observations of Earth's clouds for climate research. This 40-year history emphasizes the evolution of ideas about the purposes of the project and how that evolution shaped the characteristics of the data products. The history first covers a period before ISCCP, the planning workshops, the project initiation and the development in the first project phase, followed by a discussion of the evolution of the project concept to articulate more specifically the tasks required to quantify cloud effects on radiation exchanges in climate. The history continues with the production of the first version of the cloud data products in the late 1980s and early 1990s. Significant achievements at this stage were: (1) establishment and release of the first absolute radiance calibrations for the global constellation of weather satellite imaging instruments, (2) development and testing of a cloud detection procedure from quantitative evaluations of available ideas, (3) production of usefully accurate determinations of cloud radiative effects by employing radiative transfer models both for retrieval and flux calculations with consistent cloud microphysics and (4) provision of globally uniform depictions of diurnal, synoptic, and seasonal cloud variations. The interruption of satellite radiance calibration monitoring by the aerosols injected into the stratosphere by the Mt. Pinatubo volcano led to a period of evaluation based on an international set of supporting field experiments. Also, the reorganization of ISCCP within the Global Energy and Water Cycle Experiment (GEWEX) under WCRP shifted the project focus to include clouds and precipitation along with clouds and radiation. These events led to a second version of the data products produced from the 1990s into the early 2010s. This new version included improved polar cloud and cirrus detection, identification and treatment of ice clouds and release of higher resolution products for cloud process studies. The subsequent use of the new products led to better understanding of cloud types and their vertical structures, which allowed determination of radiation flux profiles. Analysis of patterns in mesoscale cloud property distributions helped advance understanding of cloud processes, including precipitation, in different meteorological situations. The advent of more advanced satellite cloud measurements in the late 1990s and 2000s supported a second revision that enhanced the usefulness of the ISCCP products for cloud process studies. In the 2010s, a growing emphasis on extending the length of record for climate studies led to the decision to transition the project to a fully operational organization to provide long-term context for field and other satellite measurements. The evolution of the project concept finally encompassed elucidating the complete role of clouds in weather and climate variations. On-going studies using ISCCP products include diagnosis of exchanges of radiative and latent energy by clouds, evolution of cloud properties over the lifecycle of tropical and extratropical storms, and estimates of cloud feedbacks on weather systems. The final sections summarize the accomplishments of ISCCP, discuss the status of knowledge about clouds and cloud processes as of 2022, and briefly outline of the next measurements and analyses.

Contents

1. Foreword

Dear reader,

It is with great pleasure and pride that WCRP published this report by W.B. Rossow in its report series. The report summarizes the interesting journey of the International Satellite Cloud Climatology Project (ISCCP), the first project of the World Climate Research Programme (WCRP). ISCCP was formally initiated in 1982, became part of WCRP's core project GEWEX, and continues today, now as a fully operational activity and sustained international collaboration between weather satellite agencies. As a result, the ISCCP data record is the longest, globally complete, highest time resolution cloud product covering 1983–2018 and with further extensions soon. The ISCCP products or analysis results have been cited in more than 12,000 peer-reviewed papers.

Prof. William B. Rossow is a distinguished atmospheric scientist who also headed the ISCCP. It is a pleasure to read this report in which W. Rossow covers the history of the mission preparation during which the need for such a cloud project was identified, and the implementation of the project. The report also emphasizes the scientific concepts that motivated the analysis, their evolution and thereby their impact on design and use of data products. W. Rossow also addresses the remaining gaps, the continued relevant and potential new future direction of such projects. Lessons from ISCCP will better prepare us for future international data and science initiatives. Reading the report might also stimulate the next generation to follow in its footsteps.

I am very grateful to W. Rossow for providing this historic perspective of the ISCCP mission and I am quite confident that the readers will enjoy reading this report as much as I enjoyed it myself. As ISCCP started as the first project of WCRP, it is only apt that this report authored by Prof. William B. Rossow appears as a WCRP report.

Prof. Dr. Detlef Stammer,
Chair of the Joint Scientific Committee, World Climate Research Programme

2. Introduction

The International Satellite Cloud Climatology Project (ISCCP) was formally established as the first project of the World Climate Research Programme (WCRP) in August 1982 to collect and analyze global satellite observations of Earth's clouds to support climate research. This history emphasizes the evolution of the ideas about the purposes for which the data products would be and have been used and how that evolution shaped the characteristics of the data products.

The first sections describe some events prior to ISCCP (Section 2), the planning workshops (Section 3), the project initiation (Section 4) and the development in the first project phase (Section 5). The evolution of the project concept during this early period articulated more specifically the tasks needed to quantify cloud effects on radiation exchanges in climate (Section 6). The production of the first version of the cloud data products is recounted and the reorganization of ISCCP within the Global Energy and Water Cycle Experiment (GEWEX) under WCRP is discussed in Section 7. The interruption of satellite radiance calibration monitoring by the aerosols injected into the stratosphere by the Mt. Pinatubo volcano led to a period of evaluation based on an international set of supporting field experiments and to a revision of the processing to account for ice phase clouds in a second version of the data products (Section 8). The evolution of the project concept during this period to be more useful for studying cloud processes is summarized in Section 9. The advent of more advanced satellite cloud measurements in the late 1990s and 2000s supported another revision of the analysis (Section 10), but a growing emphasis on extending the length of record for climate studies also led to the decision to transition the project to a fully operational organization (Section 11) and processing (Section 12). The evolution of the project concept finally encompassed the study of cloud processes to elucidate the complete role of clouds in weather and climate variations (Section 13). The accomplishments of ISCCP are summarized in Section 14 and the status of knowledge about clouds and cloud processes as of 2022 is discussed in Section 15. Section 16 presents a brief discussion of what measurements and analysis should occur in the future.

3. Planning Prior to ISCCP (1958–1978)

Following the International Geophysical Year in 1958 and the advent of Earth-observing satellites in 1959 (notably Verner E. Suomi’s Earth radiation budget instrument on Explorer-VII that provided the first direct look at top-of-atmosphere planetary radiation, the large-scale patterns of which are dominated by cloud systems, *cf*. Weinstein and Suomi, 1961), the 1960s and 1970s saw atmospheric research becoming more coordinated through international organizations. Such global coordination was motivated in part by the scientific realization that longer-range weather forecasts needed global observations as input to global atmospheric models, that the World War II atmospheric observing infrastructure could be exploited and built upon for this purpose, and that the advent of operational weather satellites made routine global observations a reality. The first experimental weather satellite, the Television–Infrared Operational Satellite (TIROS-1), was launched by the National Atmospheric and Space Administration (NASA) in early 1960, followed by further testing in the TIROS, Applications Technology Satellite (ATS), Environmental Science Services Administration (ESSA) and Synchronous Meteorological Satellite (SMS) series over the 1960s and 1970s. Follow-on versions of these satellites became operational at the National Oceanic and Atmospheric Administration (NOAA) in the 1970s: the first polar orbiting weather satellite, NOAA-1, was launched in 1970 and the first geostationary weather satellite, the Geostationary Operational Environmental Satellite (GOES-1), was launched in 1975. The primary international coordinating entities were the World Weather Watch to collect observations and the Global Atmospheric Research Program (GARP) to improve weather forecasting models, both established in 1967 under the joint auspices of the United Nations' World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) (Battan, 1967; White, 1967; Roberts, 1967; Smagorinsky, 1967; Tepper, 1967).

As planning moved ahead under GARP for a global, year-long observing and model-based forecasting experiment, eventually conducted in 1979 (the First Global GARP Experiment, FGGE), a series of international conferences discussed concerns about climate change, both understanding its natural variations and forecasting changes that might be induced by human activities. The series culminated in the 1974 International Study Conference in Wijk, Sweden, organized by WMO, ICSU and the United Nations Environmental Program (chaired by Bert Bolin, U. Innsbruck), the results of which were reported in 1975 (GARP-16, 1975). The conference reviewed the current understanding of climate and the causes of its variations and recommended research activities needed to advance the modeling of climate and climate change. At this time, results were already available from enough years of CO_2 atmospheric abundance measurements to show a steady increase since 1958. The year 1975 also saw the publication of two papers that presented numerical atmospheric general circulation model forecasts of climate change produced by a doubled atmospheric CO_2 abundance and a 2% increase in solar insolation (Manabe and Wetherald, 1975; Wetherald and Manabe, 1975). One result of these discussions was the reorganization of the international coordination of research activities into WCRP in 1979, initiated by the First World Climate Conference held in Geneva in that year.

4. Planning a Cloud Project (1978–1982)

While preparations for FGGE and the transformation of GARP into WCRP were underway in the late 1970s, a smaller follow-up workshop was held to plan a project to address one of the primary deficiencies of climate understanding identified by the Wijk conference [also highlighted by a US National Academy of Sciences report (Charney, 1979) as the major source of model climate forecast uncertainty], namely understanding the role of clouds in climate, especially their radiative feedback on climate change. The Oxford, UK, workshop, organized by the GARP Joint Organizing Committee in October 1978 (see Annex 2 for the chronology of ISCCP planning, data management and scientific oversight meetings), formulated the first plan to exploit the developing operational weather satellite system to produce a global cloud climatology to supplement available climatologies from surface weather observations (Annex 3A), which were generally limited to the Northern Hemisphere. The first workshop report was drafted by Garth Paltridge (Commonwealth Scientific and Industrial Research Organization, CSIRO) and Thomas H. Vonder Haar (Colorado State University, CSU). Three subsequent workshops to refine the project plan were held in Balatonalmádi, Hungary (June 1980), in Ft. Collins, Colorado, USA (August 1980, WCP-6 1981), and in Hamburg, Germany (August 1981), now under the auspices of the WCRP Joint Scientific Committee (JSC). The Climate Working Group of the International Radiation Commission (IRC under ICSU) was identified as an *ad hoc* Working Group on Radiative Fluxes (WGRF), chaired by Thomas H. Vonder Haar, to provide scientific oversight of a cloud project (it was formally established as a WCRP Working Group in 1987).

There were also two scientific conferences held in 1980: one at NASA Goddard Institute for Space Studies (GISS) in New York City (NYC) in October, organized by William B. Rossow and James E. Hansen at the request of Robert A. Schiffer (NASA HQ) (Rossow, 1981) and a Workshop on Cloud Climatology for General Users in December in Washington, DC, organized by NOAA National Environmental Satellite System (NESS). NOAA's interest was in developing the satellite cloud observations to enhance weather forecasting. NASA's interest was to complement a planned and continuing series of satellite missions to measure the Earth's radiation budget. Following Explorer-VII in 1959, several satellites in the Nimbus series continued to enhance the measurement details: Nimbus-3 in 1969, which carried multi-wavelength radiometers (Raschke and Bandeen, 1970), and then broadband radiometers on Nimbus-6 starting in 1975 (Jacobowitz *et al.,* 1979) and Nimbus-7 starting in 1978 (Jacobowitz *et al.,* 1984). Plans were already being made for a follow-up experiment with broadband instruments to be called the Earth Radiation Budget Experiment (ERBE, Barkstrom and Smith, 1986), which began in 1984.

These planning workshops produced a more detailed project plan and the conferences continued to shape the project's scientific goals for cloud-climate research. Based on the

Hamburg meeting, Robert A. Schiffer (who was seconded from NASA to WCRP as Director of Radiation Projects in January 1981) and William B. Rossow drafted a Preliminary Implementation Plan for ISCCP that was distributed for comments in January 1982 (WCP-20, 1982). ISCCP was then formally established at an international planning meeting in Geneva, Switzerland in August 1982 (WCP-28, 1982) and the Preliminary Implementation Plan revised in November 1982 (WCP-35, 1982b). After a full data systems test in May 1983, data collection began on 1 July 1983 and continues today.

In the report of the Wijk conference (GARP-16, 1975), the main issue related to understanding the role of clouds in climate and climate models was identified as "cloud-radiative feedback" defined in terms of cloud effects on the radiation budget at the top-of-atmosphere (TOA). There was little mention (other than some comments about coupling of the climate components by cloud processes) of any other aspect of cloud effects on radiation exchanges, *e.g.*, radiative heating/cooling at the surface (cloud feedback on the ocean circulation) or radiative heating/cooling of the atmosphere (cloud feedback on the atmospheric circulation). Precipitation was discussed separately with no connection to clouds *per se* (an approach still followed observationally today) and was discussed only in terms of water at the surface (not as feedbacks on atmospheric and oceanic circulations). The 1980 NASA GISS conference discussed a broader view of the role of clouds in climate that included both radiation and precipitation processes, but judged attacking the cloud-radiation problem to be more feasible at that time based on available satellite-based cloud analyses (see Annex 3B).

The Wijk, NASA GISS and NOAA NESS conferences (also Charney, 1979) recommended producing a global cloud climatology from satellite measurements to advance understanding of cloud-radiative feedback. This cloud climatology – defined at that time as monthly averaged, global maps of "clouds" – was to be produced from a combination of ground-based and satellite-based observations, but the specific cloud properties needed to determine the cloud effects on the planetary radiation budget were not articulated. Implicitly, the cloud properties of interest in these meetings seemed to be total cover fraction, the total amounts of high, middle and low-level clouds; and the amounts of some “cloud types” – some conventional (morphological) types were named. This information would not actually have sufficed to determine the cloud radiative effects on radiative fluxes. In the GARP-16 recommendations, it appeared that (like precipitation) the role of satellite observations would mostly be to provide information over oceans to be added to that already available over land from ground-based observations (Annex 3A). The uses of this climatology were described mainly as input to climate models that specify the clouds or as verification of climate models that calculate clouds. There was a curious lack of ideas for using the global satellite observations to improve the understanding of cloud processes (both radiation and precipitation); all that was recommended for this purpose was two field campaigns, one to focus on subtropical marine stratus and trade cumulus and one to focus on extra-tropical frontal cloud systems and cirrus. Tropical deep convection was mentioned only in the discussion of precipitation, but not in terms of the cloud radiative effects.

5. Initiating the Project (1982–1983)

The first version of the project plan based on the Oxford workshop envisioned collecting satellite imager radiances at the two wavelengths then common on all weather satellites, namely visible (about 0.6 μm wavelength, VIS) and thermal infrared (about 10 μm wavelength, IR), from a constellation of five geostationary and one or two polar orbiting satellites, all of which were to be operational in the 1980s. This combination of satellites could provide global coverage at 500 km and 3 hr intervals (at least), the latter required to properly sample diurnal variations, and could provide data for a 5 yr period. The resulting products were described as containing cross-calibrated radiances from the separate satellites and global cloud information, where the specific properties of clouds to be obtained were not described at first.

Three main obstacles to implementing such a project were identified: managing the very large data volume, overcoming the non-uniformity of the data, and developing a cloud analysis procedure. The first obstacle was to be solved by some kind of volume reduction procedure, such as sampling or spatial averaging, applied directly to the radiance data that would likely have to be done in real-time by the satellite operators to be feasible. The second problem did not look difficult since the spectral responses of all the satellite measurements at the two common wavelengths were very similar. This similarity occurred because the operational satellite imagers were all designed to provide all-day imaging of cloud features to support weather forecasting; thus, they all made measurements in the portions of the spectrum where atmospheric effects were smallest and contrast between cloudy and clear conditions generally largest (IR for all-day coverage and VIS for daytime detail at higher spatial resolution–the difference in image pixel sizes between VIS and IR was a technology limit). Based on early research at CSU for the GARP Atlantic Tropical Experiment (GATE) presented at the Oxford workshop, it seemed feasible to cross-calibrate all of the geostationary satellite radiometers to an under-flying sun-synchronous polar orbiter, which was also needed for polar coverage. However, the specific contents and formats of the various satellite image datasets then available were not uniform; in particular, the methods of encoding and calibrating the radiances were different.

The third task, development of a cloud analysis procedure, was to be investigated before and during data collection based on early cloud studies using satellite observations (Annex 3B). The archival of the reduced-volume radiance datasets was planned to ensure that the cloud analysis could be repeated as better approaches became available and also to make it easier for the rest of the research community to analyze the data as well. Archival of the radiance data made possible the later revisions of the ISCCP products. At the time this idea – saving and making available the inputs to the analysis ("raw" data) – was an unusual one.

Based on the comments received about the first draft project plan from the Oxford workshop, it was revised to add more details, including organizing the collection of data into twelve geographic sectors to reduce the volume reduction task (but special full resolution radiance data subsets were to be collected to support field experiments). The reduced volume radiances were to be globally merged at a central location. The project plan also called for a specific research program to develop and test cloud analysis procedures, but left open the question of the need for ancillary data for such an analysis.

At the next meeting at Lake Balaton in June 1980 (with the report refined at a follow-up meeting at Ft. Collins in August 1980 and published as WCP-6 in January 1981), much more detail was developed, including defining both the space-time scales of radiance sampling and product averaging based on a survey of satellite sampling characteristics by Roy Jenne (National Center for Atmospheric Research, NCAR), as well as listing some specific cloud properties to be obtained. The radiance volume was to be reduced to a manageable volume by sampling at 32 km and 3 hr intervals (retaining all orbits of the polar orbiters) – the radiance data to be globally merged – and the cloud results averaged to 250 km and 15 day intervals. The cloud information to be obtained was listed as total cloud cover fraction, as well as the amounts of cirrus, middle-level, low-level and deep convective clouds, and the top-heights and IR brightness temperatures (radiances) for these cloud types. Also mentioned as possible cloud properties that might be obtained were cloud size distribution, optical depth, base heights and phase.

The Hamburg workshop in August 1981 reviewed current cloud research activities and datasets (*cf.* Platt, 1981) and evaluated the proposed project plans from the Oxford, Lake Balaton and Ft. Collins workshops. These discussions resulted in a preliminary Implementation Plan for ISCCP distributed to potential participants for comment in January 1982 (published as WCP-20 in April 1982). The reduced volume radiances were now to be collected at both 8 km (the smallest common spatial interval available) and 32 km sampling intervals (still every 3 hr, which was the smallest common time interval available). The higher resolution dataset was seen as insurance against the effects that the volume reduction might have on the results; the lower resolution dataset was to be globally merged. The cloud product was to represent monthly averages (mapped at 250 km intervals) with some statistics of shorter-term variations, particularly the mean diurnal cycle. The specific contents of the cloud product remained the same as defined at the Lake Balaton workshop.

There were two key presentations at Hamburg that advanced the project concept over the earlier ideas. Nicolas Beriot (Centre de Meteorologie Spatiale, CMS) presented results from a detailed cross-calibration procedure employing matched images from the polar orbiter and geostationary satellites that demonstrated its feasibility and accuracy. William B. Rossow illustrated the results of an end-to-end analysis of satellite VIS/IR radiances that carried through from a retrieval of cloud radiative properties (cover fraction, top temperature, optical thickness) to their use to calculate top-of-atmosphere and surface radiative fluxes, which suggested the feasibility of producing a more specific and physical cloud property product (this work was published in Rossow *et al.*, 1989, and Rossow and Lacis, 1990). At this time, most satellite cloud analysis procedures (Annex 3B) determined only cloud cover fraction, but a few identified some cloud types from the radiances. Based on the discussions of possible analysis approaches, a study plan for comparing existing cloud detection – cloud fraction algorithms was formulated, led by Frederick Mosher (Space Science and Engineering Center, SSEC): the first two international algorithm comparison workshops were held in Ottawa, Canada (May–June 1982), and in NYC, USA (December 1982). The final version of the project structure was defined in terms of the needed data centers, data exchange procedures and their processing tasks.

ISCCP was officially inaugurated in Geneva in August 1982 (WCP-28, 1982) where the Preliminary Implementation Plan was reviewed and commitments for participation were obtained: at this time there were commitments for Sector Processing Centers (SPC, for reducing the radiance data volume) for the NOAA polar orbiters, Meteosat, GOES-East and GOES-West, for the Global Processing Center (GPC) and an International Archival Center (ICA). Table 1 shows the chronology of data center commitments through the whole project time period. No changes were made to the data product contents listed in the January version of the Preliminary Implementation Plan except to indicate, at the request of the WCRP JSC, the highest priority quantities: total, cirrus and low-level cloud amounts and cirrus top-height and physical temperature. In addition, ancillary data required for a physical cloud retrieval were identified: snow/sea ice cover and atmospheric temperature-humidity profiles. An algorithm change policy was also adopted; a change would be instituted only if a better algorithm could be demonstrated, in which case the whole dataset would be reprocessed (archival of a reduced-volume version of the data made this feasible). Based on the Geneva meeting discussion and comments received, the final version of the Preliminary Implementation Plan was released in November 1982.

Table 1: Chronology of ISCCP data collection and processing centers

Processing Center	*Past Committed Agencies*	*Currently Committed Agencies*
SPC for Europe/Africa Sector	ESA (1983–1995)	EUMETSAT (1995–current)
SPC for Indian Ocean Sector	IMD (1986)	EUMETSAT (1998–current)
SPC for Asia Sector	CMA (2005–2009)	
SPC for West Pacific Sector		JMA (1983–current)
SPC for East Pacific Sector	CSU (1983–2008)	NOAA (2008–current)
SPC for Americas Sector	UWS (1983–1985) AES/MSC (1986–2008) CSU (2008–2011)	NOAA (2011–current)
SPC for Afternoon Polar Orbiter		NOAA (1983–current)
SPC for Morning Polar Orbiter	NOAA (1983–2010)	EUMETSAT (2010–current)
SCC	MeteoFrance (1983–2009)	NOAA (2016–current)
GPC	NASA GISS (1983–2016)	NOAA (2016–current)
ICA		NOAA (1983–current)

The first session of the ISCCP Working Group for Data Management (WGDM) was held in December 1982 in NYC to refine the details of the Hamburg-based plans and to organize a Data Systems Test of the data exchange procedures (WCP-42, 1982). The membership of this group was composed of the representatives from the participating data centers, two representatives from the IRC (Thomas H. Vonder Haar and Ehrhard Rashcke, U. Koln) to provide scientific advice, a representative from the WCRP Joint Planning Staff (JPS, Thomas Kaneshige), and the Project Manager (Robert A. Schiffer). At this meeting more detailed specifications were made of radiance data formats. The early results and preliminary conclusions from the first two cloud algorithm comparison workshops were also reviewed, which supported two key modifications of the data products: (1) the higher spatial resolution (smaller pixel size) VIS data were now to be averaged to match the IR pixel size before sampling to 8 km (called B1 data) and 32 km (called B2 data) intervals every 3 hr and (2) the cloud properties to be retrieved were now to be amount (or cover fraction), top-temperature/height and optical depth for total cloudiness and for cloud types to be identified from the retrieved cloud properties instead of the radiances. The project description was published in July 1983 in the *Bulletin of the American Meteorological Society* (BAMS) (Schiffer and Rossow, 1983).

6. First Project Phase (1983–1988)

The first phase of the project encompassed three parallel activities: (1) testing radiance data exchange procedures leading to routine data collection and designing the format and contents of the versions of the radiance datasets to be archived, (2) implementing the radiance cross-calibration procedures leading to the first deliveries of the calibrated, navigated radiance data (called B3 data, a unified form of B2 data), and (3) developing and testing a cloud analysis procedure, including identifying and obtaining needed ancillary data, and refining the contents of the cloud products leading to the first deliveries of the cloud products (called C data).

A Data Systems Test, planned at the First Session of WGDM, was conducted in May 1983 using the preliminary design for data formats, contents and exchange procedures outlined in the Preliminary Implementation Plan. (This WG was originally established for ISCCP, was later expanded to support other WCRP radiation projects, and then under GEWEX to support additional data projects.) Data were collected from Meteosat-2, the second Geostationary Meteorological Satellite (GMS-2), GOES-4, GOES-5 and NOAA-7 (see Annex 4 for chronology of satellites with cloud relevant instruments). The data collection and reduction for each satellite were performed by the operating agencies, rather than sub-dividing the tasks into the smaller sectors as originally envisioned. The results of this test (along with early results from the first two algorithm comparison workshops) were reviewed at the Second Session of WGDM held at NASA GISS in NYC later that month (WCP-52, 1983). At this session the exchange data tape formats and contents were refined and finalized. Also, commitments for the SPC for GMS and the Satellite Calibration Center (SCC) were received (Table 1). The cloud algorithm comparisons suggested the feasibility of a physical analysis approach (based on a radiative transfer model) that required ancillary data to specify atmospheric temperature-humidity and ozone as well as snow and sea ice cover. Possible sources for these ancillary data were identified: operational data products to support weather forecast analyses were being routinely produced and would cover the planned ISCCP time period of 1983–1988 (weather forecast analyses changed frequently, producing inhomogeneous records; "reanalyses", where the analysis procedure remained constant over the time period, only became available in the 1990s). It was decided that the product map grid should be coordinated with that to be used by NASA ERBE; however, in the end, ISCCP adopted an equal-area grid to provide globally-uniform sampling statistics, rather than the equal-angle grid of ERBE (see discussion of the rationale in Rossow and Garder, 1984). It was also decided that radiance histogram information should be retained in each map grid cell to characterize smaller scale cloud variations. The grid cell size was equivalent to 2.5° at the equator, which produced an average number of samples in the histograms of about 70.

After the successful Data Systems Test and with sufficient commitments for all the planned data processing centers in hand, systematic collection and volume reduction of the radiance data began on 1 July 1983. The B2 (32 km) version of the radiance data was to be delivered to the GPC; the B1 (8 km) version was sent to the ICA. Some details of the format and contents of the B3 radiance datasets to be archived, as well as the implementation of the cross-calibration procedure, remained to be worked out. Progress on these topics was reviewed at the Third Session of WGDM held in Tokyo, Japan, in March 1984 (WCP-82, 1984). A preliminary version of the B3 calibrated radiance data was disseminated for comment in November 1984. The comments received were reviewed at the Fourth Session of WGDM in Darmstadt, Germany, in February 1985 (WCP-102, 1985; also as WMO/TD-62 in July 1985). At this meeting the B3 data format and contents were set, a draft of the ISCCP Description of Reduced Resolution Radiance Data circulated for comment, and the cross-calibration procedure (see below) approved. The final version of the documentation was published as WMO/TD-58 in July 1985 and routine deliveries of B3 data to the archives began in October 1985.

The final form of B3 data had matched-size VIS-IR radiance pixels with appended calibrations (radiances encoded uniformly in 8-bit count values, count-conversion tables for each image/orbit with two different physical representations for each wavelength) and appended navigation information (earth location, satellite-view and solar illumination angles) in a uniform format (the READ software, released with the data, worked for all data even though there are actually some small differences in format). A change from previous planning was that the B3 data were not merged globally, but remained separate by satellite to facilitate processing and regional studies. Instead, the cloud products were to be merged globally (see Data Management Plan, WMO/TD-4, 1986). The ISCCP B3 data product was described in BAMS in December 1985 (Schiffer and Rossow, 1985).

The second parallel effort was development and testing of the procedure for cross-calibrating the geostationary satellite radiometers to the reference polar orbiter, the basic idea of which was presented at Hamburg in August 1981 and with more details at Geneva in August 1982 (see WCP-28, 1982) by Nicholas Beriot. Once the SCC commitment was obtained in May 1983 (Table 1), further work to implement this procedure began. The testing included defining the form and contents of the results of the procedure that would be documented and delivered to the GPC to produce the B3 data. In March 1984 (Third WGDM), the need for monitoring the calibration of the reference radiometer (the Advanced Very High Resolution Radiometer, AVHRR, on afternoon polar orbiters) was identified. The GPC undertook this task. In February 1985 (Fourth WGDM), the reference calibration for AVHRR was accepted as accurate enough in an absolute sense, based on some early evaluations of retrieved quantities, so that the results of the cross-calibration could be accepted for delivery of B3 data. The cross-calibration procedure was implemented in 1985 and routine production and delivery of B3 data commenced in October 1985 (full documentation published in WMO/TD-58, December 1985). The archived B1 data were not re-calibrated or navigated but remained in their original formats.

The procedure for monitoring the calibration of AVHRR had to be adapted to also provide for the transfer of the reference standard from NOAA-7, which failed in January 1985, to the follow-on satellite, NOAA-9. The first results were reviewed at the Fifth Session of WGDM in Paris in June 1986 (WCP-123, also as WMO/TD-161 in January 1987). The testing of the monitoring and transfer procedures was completed and reviewed at the Sixth Session of WGDM at Ft. Collins in June 1987 (WCRP-3, also as WMO/TD-210 in January 1988). The first results of the polar calibration monitoring procedure (Brest and Rossow, 1992) and the cross-calibration procedure (Desormeaux *et al*., 1993) were not published until 1992–1993 after more evaluations (WCRP-77, also as WMO/TD-520, in December 1992). To allow for easier revision of the calibration when more information became available without replacing the whole B3 dataset, as had already happened, the calibration tables in the B3 data were put into a separate, much smaller data product, called BT data (radiance count-conversion tables for each image or orbit), which would be updated as needed.

Even before ISCCP was formally established and data collection began, work recommended at the early workshops (especially Hamburg) was started to develop and test the cloud processing algorithm (the third parallel effort) by first comparing the performance of existing methods (Annex 3B) for identifying clouds in satellite radiance images at a workshop in Ottawa, Canada, in May–June 1982. This activity continued at workshops at NASA GISS in NYC in December 1982 and April 1983, followed by a review of preliminary results and conclusions by the IRC Working Group on Clouds and Radiation in April 1983 at NASA Langley Research Center (LaRC). The available analysis methods were tested by applying them all to the same radiance images to detect the presence of clouds and to determine cloud cover fraction in a common map grid (map cells 2.5° in size). Some methods used only one radiance, VIS or IR, and some used both. Key conclusions were (WCP-73, 1984): (1) all methods produced quantitatively similar cloud fractions in general with a larger spread of values in the middle range; (2) the cloud cover fraction estimates in the small domains were not much degraded even by averaging radiances to about 32 km, but sampling produced even smaller changes and was preferred; (3) larger differences were associated with “hard to detect” cloud types that only produce small variations in the radiances (cirrus in VIS, low-level broken clouds in IR); and (4) larger differences also occurred in some specific situations, such as snow-covered land or mountainous terrain, where some methods performed better than others.

The latter two conclusions suggested that the final ISCCP cloud detection algorithm might better be composed of multiple tests on both VIS and IR radiances (IR only at night), combining all of the methods but used differently depending on situation, defined mainly by surface characteristics. These results also suggested that the various tests would work better if they were used to identify the less variable clear sky conditions to estimate clear radiance values at all locations and times rather than identifying the much more variable radiances associated with cloudiness. Then a simple threshold test could label each pixel as cloudy if its radiance values differed from the estimated clear sky values by more than its (situation-dependent) uncertainty. It was also noted that, given the finite size of image pixels (about 5 km), estimates of cloud cover fraction by counting the number of cloudy pixels (cover fraction either 0 or 1) in a small domain is somewhat more accurate if the detection threshold is not too small, which made the cover fraction errors more nearly random. Differences in effective detection thresholds explained the larger spread of results at intermediate cloud cover fractions.

These results were summarized in a report (WCP-73 in March 1984), and, after one further workshop at NASA Goddard Space Flight Center (GSFC) in April 1984, submitted to a scientific journal (Rossow *et al.,* 1985). Some further small refinements were developed at the fifth workshop held in Honolulu in August 1985, particularly increasing the situation dependence of the various detection tests, where the situations are defined by the ancillary data. As testing of the proposed cloud detection method continued, a polar cloud algorithm workshop was held in Tokyo in August 1986 (WCP-131, also as WMO/TD-170 in March 1987) where the results of several algorithms specifically designed for polar conditions were compared to the version of the ISCCP algorithm existing at that time. The resulting conclusions that affected the design of the final ISCCP-C cloud algorithm were to emphasize the use of snow/ice ancillary data to adjust the tests and the situation-dependent threshold parameters and to reduce the algorithm emphasis on extreme radiance values in such cases. More investigation of the angle dependence of VIS radiances was recommended as well as exploiting the extra wavelength channels available on the AVHRR. The latter was not implemented until the second algorithm version.

Based on the cloud algorithm comparison studies (but also see Platt, 1983; Arking and Childs, 1985; Seze and Desbois, 1987 for other relevant tests), the ISCCP cloud detection procedure finally employed multiple tests (representing a combination of the various existing methods) on the space and time variations of the separate VIS and IR radiances to estimate clear radiances for each pixel at each time and then applied situation-dependent radiance thresholds to partition the radiances into clear and cloudy categories. The multiple tests with situation-dependent parameters are used to determine clear sky radiances because these values are generally less variable in space and/or time than cloudy sky radiances, making for more robust statistics. Cloud detection was determined by thresholds in either VIS or IR. By detecting cloud presence in each image pixel, cloud cover fraction (cloud amount, CA) is estimated over a map grid cell (a small domain about 280 km in size) by counting the cloudy pixels and a detection uncertainty is defined by the number of pixels “close” to the cloud-clear dividing radiance values (“close” defined to be within the estimated uncertainty of the determined clear sky radiance values, also situation-dependent).

The detection of cloud presence in each image pixel allowed for retrieval of one quantity from each radiance, cloud top temperature (TC) from IR and cloud optical depth (TAU) from VIS for each cloudy pixel or surface temperature (TS) from IR and surface reflectivity (RS) from VIS for each clear pixel (these two surface properties are also retrieved from the estimated clear radiances at each location). The retrievals employed ancillary data to specify atmospheric temperature-humidity profiles and ozone abundance as well as snow and sea ice cover (as well as separating land-water locations and identifying rough/high topography). Cloud top pressure (PC) is also determined from the level in the atmospheric temperature profile corresponding to TC. (PC instead of height is determined to position clouds relative to atmospheric mass over the globe.) During daytime, the retrieval of TC/PC is corrected for radiation transmitted from below through small TAU clouds; at night, no correction is possible–all clouds are blackbodies. However, the IR-only analysis results are reported at all times of day to allow for consistent studies of diurnal variability and to document the effects of the TAU-based correction of TC/PC.

The most comprehensive proposal for the contents of the ISCCP-C cloud products was reviewed at the Fifth WGDM meeting in June 1986 (WCP-123, also as WMO/TD-161), where the global merger procedure was also defined in terms of the satellite with the "best" view (closest to nadir) at each location and time. Based on this definition of the products, a preliminary version of the C1 (global gridded, 3 hr) data was disseminated for comment later that year. After further review of more comments at the Sixth WGDM in Ft. Collins in June 1987 (WCRP-3, also as WMO/TD-210), a more complete version of the contents of the C1 data was defined. However, processing could not begin at this time because the polar orbiter calibration transfer from NOAA-7 to NOAA-9 was still being evaluated and very little of the needed ancillary data had yet been obtained by the GPC. In the same year, the WCRP JSC approved the extension of ISCCP through June 1990.

In December 1987, the First Session of WGRF was held at Greenbelt (WCRP-10, 1988): this working group (chaired by Thomas H. Vonder Haar) was formally established under WCRP to provide scientific oversight to radiation projects in addition to ISCCP, namely the Surface Radiation Budget project (SRB) and the Baseline Surface Radiation Network (BSRN). The latter two were initiated in 1987 and 1989, respectively. Just prior to the meeting, a revised version of the C1 data was distributed for comment. Review of comments and suggestions (including from the WGRF meeting) was conducted at the Seventh Session of WGDM in Banff in July 1988 (WCRP-13, also as WMO/TD-252 in December 1988) at which the absolute calibration procedure for the polar orbiters was accepted, including the transfer from NOAA-7 to NOAA-9. Also, the cloud detection procedure was modified to account for more situations using radiance distribution-shape tests. Identification of nominal cloud types in terms of combinations of PC and TAU values, rather than radiances, was decided upon; average properties (PC/TC, TAU) of these cloud types were to be reported in addition to the more detailed histograms of these quantities. The definition of the ISCCP-C data contents (both C1 and C2) was finalized. A final review of the project data management procedures, analysis plans and data contents was conducted at the Second Session of WGRF in Geneva in October 1988 (WCRP-20, 1989; also as WMO/TD-291). Deliveries of ISCCP-C data began at this time (full documentation published in WMO/TD-266, December 1988).

7. Summary of Concept Evolution (1978–1988)

By the end of 1988, discussions, research and workshops had transformed the ISCCP concept from its initial form in 1978 – concerned solely with top-of-atmosphere cloud-radiative effects (as emphasized by the Charney, 1979 report) but considering only cloud amount and types – to what was finally implemented. During this period, a broader view of cloud processes in weather and climate was discussed at three science conferences: (1) the Workshop on Clouds in Climate: Modeling and Satellite Observational Studies held at NASA GISS in October 1980 (Rossow, 1981); (2) the NOAA NESS Workshop on Cloud Climatology for General Users held in Washington, DC, in December 1980; and (3) Clouds in Climate II: A WCRP Workshop on Modeling and Observations held in Columbia, Maryland, in October 1987, organized by Robert A. Schiffer and Albert Arking (NASA GSFC). This broader view described clouds as a dynamic atmospheric process important in both weather and climate because of their effects on radiation exchanges, their production of precipitation, and the feedbacks of these processes on the atmospheric and oceanic circulations (there was a very brief summary of this viewpoint in Appendix 4 of GARP-16, 1975). Although the WCRP Science and Implementation Plans (WMO/TD-6, 1984 and WMO/TD-80, 1985, respectively) included these topics, they were discussed in separate sections reflecting the separately-organized activities. However, by 1988, when ISCCP-C data processing and deliveries began, the concept had evolved to a more specific idea of what the cloud data would be and how they could be used to study cloud effects on radiation as well as the beginnings of ideas about how to study clouds and precipitation. This concept informed the design of ISCCP-C to emphasize the cloud physical properties, rather than radiances; to provide cloud, surface and ancillary quantities together to facilitate physical analysis; and to provide much more detail on the smaller scale cloud variations.

Reducing the radiance images operationally produced by the weather satellite agencies to a more manageable volume and putting them into a more scientifically useful format were identified as key tasks, not only to make ISCCP feasible, but to facilitate the data use by the research community. Initially planned and finally implemented after testing alternative ideas, the volume reduction was accomplished by simple sampling in space and time. Instead of a global merger of the resulting radiance images, they were kept separate for each satellite, which was more convenient for managing the processing and for supporting regional and field-study analyses. The scientific utility was enhanced by four key modifications of the B2 (original 32 km) data to produce the archived B3 data: the image formats were slightly modified (same radiance encoding) so that a single program could read the data from any satellite, the pixel sizes for both radiance channels were matched, the individual image pixels were Earth-located with solar-illumination and satellite-viewing geometry appended, and an absolute calibration of the radiances provided in two alternate forms (in fact, the BT calibration data separately provided the original, normalized and absolute calibrations to document the calibration processing stages). Although the B1 data were also archived, their formats remained in their original forms with little navigation or geometry information and only the nominal IR calibration included. The B3 radiance calibration information was ultimately provided as a separate, updatable dataset (BT data) so that calibration could be revised as more information became available: the key to this capability is that all information is appended rather than modifying the original image radiances. This approach also means that any use of radiance data from the same satellites can use the ISCCP calibration results. Thus, the archival of the ISCCP-B3/BT dataset provided a reduced volume, navigated and calibrated, multi-satellite dataset providing global coverage every three hours in an effectively uniform format that was much more convenient for research (Schiffer and Rossow, 1985). This product eventually covered the period from July 1983 through December 2009. This alone was a significant contribution of ISCCP to Earth studies.

The next task was to develop a cloud analysis approach, the first part of which is to decide whether clouds are present at each location (image pixel) and time, usually combined with a determination of total cloud cover fraction in some small domain. Of the cloud algorithms available at the beginning of ISCCP (*cf.* Annex 3B) and tested in the series of comparison workshops, some determined area coverage as proportional to the radiances in small domains and some used various radiance space and/or time variation statistics in small domains (including histogram clustering) to partition the radiance distributions into cloudy and clear portions (*cf.* Rossow *et al.*, 1985). The advantage of the latter types of approaches is that the partitioned radiance distribution can then be analyzed to retrieve one physical cloud property for each radiance value (and a surface property in clear locations), whereas the former type limits subsequent analysis by using the radiance information for the cloud cover determination.

Based on the comparison results and further testing, the final ISCCP procedure was a combination of the proposed tests on the radiance variations on several nested space-time scales with situation-dependent parameter settings. The key change from earlier methods was to use the tests to identify clear scenes and then estimate the less-variable clear radiances for all locations and times, rather than determining cloud cover directly. The relative weight given to each test varies with situation. Time variation tests were found to be more effective because the clear radiances are usually much less variable than cloudy radiances and much less variable in time than in space (*cf.* Rossow and Garder, 1993a, 1993b). The situation-dependence also considered more categories, defined by surface conditions, than in the earlier methods. This analysis approach had the advantage of providing clear sky radiances at each location, which are used to retrieve the surface properties (TS, RS) that are then used to represent the surface under clouds in the cloud retrieval. This is a more radiatively consistent approach. The differences between the estimated clear radiances and the observed values at each pixel are then compared to situation-dependent threshold values to indicate whether each pixel is cloudy or clear: differences larger than the threshold value are labeled cloudy. The thresholds are set by the situation-dependent uncertainties of the clear sky radiances.

The estimate of cloud cover fraction was then made only for the gridded versions of the products by counting the number of cloudy pixels divided by the total number of pixels present in each map grid cell. This meant that cloud cover in a single pixel was assumed to be either zero or one for retrieval of TC and TAU. This way of estimating an area is a form of the Monte Carlo area estimate if the error in each pixel is approximately random. Later investigations (Wielicki and Parker, 1992; Rossow and Garder, 1993b; Rossow *et al.*, 1993) showed this to be true because the finite detection thresholds produced over- or under-estimates of cloud area for some pixels. A similar effect occurs for the retrieved cloud properties assuming complete absence or coverage by clouds: over- and under-estimates occur in some pixels that begin to average out over the area of the map grid (*cf.* Rossow, 1989).

The detection thresholds were defined by the estimated situation-dependent uncertainty of the clear radiance values so that counting the number of cloudy pixels within one threshold interval of the cloud-clear dividing value (clear sky value plus threshold) for a detection provided a cloud cover fraction uncertainty estimate. This was another key development, as later results showed that the majority of the cloud fraction and cloud property retrieval errors are produced by missed or false detections (Rossow *et al.,* 1993, see also discussion in Rossow, 1989). The situation dependence was ultimately decided by locations defined by surface properties as combinations of land-water, snow-ice cover and topography (see Rossow and Garder, 1993a).

Although the stated goal of ISCCP from the earliest planning focused on cloud radiative effects on climate, the specific cloud properties needed to determine these effects were not articulated at first. The earlier workshops described the contents of the cloud products as cloud cover fraction, cloud type amounts and cloud type heights (following the recommendations in GARP-16, 1975), but these quantities would not have sufficed to determine cloud effects on radiation exchanges. Moreover, although the cloud types were listed in terms of the conventional morphological types, how they were to be identified in satellite radiance images was not known. One suggestion from earlier studies was that the cloud types could be associated with particular portions of or even clusters in the joint distributions of the visible-infrared radiances (Vonder Haar, 1970; Shenk *et al.,* 1976; Desbois *et al.,* 1982; Desbois and Seze, 1984; Arking and Childs, 1985; Inoue, 1987).

At the Hamburg workshop, William B. Rossow presented an analysis of VIS/IR radiances from the NOAA-5 polar orbiter in which cloud cover, top temperature and visible optical thickness were retrieved for each cloudy pixel, based on radiative transfer models of the narrowband radiances, and the results used in a broadband radiative transfer model to calculate global, daily, top-of-atmosphere (TOA) and surface (SRF) total solar and terrestrial radiative fluxes (both models using the same cloud microphysics and ancillary information about surface and atmospheric properties). Comparison of the results to other more direct measures of these fluxes demonstrated useful accuracy (Rossow and Lacis, 1990). Arking and Childs (1985) also demonstrated a 3-channel radiative-theory-based retrieval where the third channel was used to retrieve cloud particle sizes. Further testing and evaluation of these results led to adapting this analysis approach for ISCCP. In 1987, the SRB project was initiated (Whitlock *et al.,* 1995) to use the ISCCP cloud and ancillary data products in a similar fashion to determine global surface radiative fluxes. The SRB results were to be evaluated by measurements from the BSRN, established in 1989 to coordinate a set of high-quality surface stations (Ohmura *et al.,* 1998). Later, determinations of TOA fluxes were added to SRB products to be evaluated by the ongoing NASA ERBE mission.

Given what was known about clouds in the 1980s, there were important limitations on their representation in both the VIS/IR radiance and solar/terrestrial flux radiative models. In the cloud retrievals in the ISCCP-C data (and radiative fluxes calculated from them, *cf*. Zhang *et al.,* 1995, and Rossow and Zhang, 1995, as well as SRB), all clouds were represented as single, liquid water layers containing no gas (equivalent to a physically very thin layer) with fixed microphysical properties, namely spherical droplet size distribution with an effective radius of 10 µm. This limitation motivated the choice of retrieving TAU from VIS radiances as its value is less sensitive to the cloud microphysical model (as was later borne out). The estimate of TAU at the VIS wavelength could be converted to an optical thickness at the IR wavelength, based on the adopted cloud microphysical model, and used to correct the TC values for IR radiation from the surface and atmosphere below the cloud. Both the corrected and blackbody values of TC were reported during daytime. Although the effects on the radiances of ozone and water vapor were accounted for in the cloud retrieval model, there was no treatment of aerosols; however, most of the tropospheric aerosol effect was effectively included in the retrieved surface reflectivity (the radiative flux model of Zhang *et al*., 1995 included aerosol effects). The surface in the retrieval model was also treated in a simple manner with an IR emissivity of unity (the retrieved quantity, TS, was thus a brightness temperature, which is smaller than the physical temperature) and an isotropic visible reflectivity (aerosol scattering would make this a slightly better approximation) except for open water, for which an early anisotropic reflection model was used. Better representations of clouds and surfaces would have to wait for further observational and research results (Zhang *et al.,* 1995 explicitly test the radiative flux uncertainties caused by all these limitations). However, later it was shown that the retrieval of cloud and surface properties from radiation measurements with a narrowband radiative transfer model and calculation of their effects on radiative fluxes with a broadband radiative transfer model with consistent cloud, atmosphere and surface representations still produces usefully accurate results even with these limitations (Rossow and Zhang, 1995).

Early ideas about representing the smaller-scale variability of clouds within each map grid cell included simple statistics, such as the spatial (and temporal) variances of the radiances, and/or some form of the radiance distribution histograms within each cell. Reporting the amount of various cloud types was also discussed as a means to represent this variability, although a method for identifying the cloud types in the satellite images was not described. The use of the radiance histograms for identifying cloud (or scene) types had been suggested by Vonder Haar (1970) and Shenk *et al.* (1976). This idea was considerably developed by Desbois *et al.* (1982), who applied a quantitative method for partitioning 3-channel (3 dimensional) radiance histograms. Inoue (1987) also developed cloud type identifications based on the joint distributions of two IR wavelengths. Key aspects of the final ISCCP-C products were the decision to reduce volume by simple sampling and to map the results into an equal-area map grid: these features preserved the statistical distribution information in the images approximately uniformly over the globe as was later demonstrated (Rossow and Garder, 1984; Seze and Rossow, 1991).

By the time the contents of the ISCCP-C products were defined, these concepts had evolved. By reporting the retrieved quantities with the same precision and proportional to the measured radiances and ensuring that every radiance value had a corresponding retrieval output, the radiance variation statistics were directly translated into the variation statistics of the cloud and surface properties retrieved from the radiances. Thus, smaller-scale variations were finally represented in ISCCP-C data in three ways: as spatial (and temporal) variances of each retrieved cloud and surface property, as histograms (1D and 2D) of the retrieved cloud properties (PC, TAU) instead of radiances, and as the properties of cloud types defined by a few characteristic combinations of PC and TAU (as suggested by the results of Desbois *et al.,* 1982; Arking and Childs, 1985; and Inoue, 1987). For IR-only results (reported all day), a 1D histogram of PC was defined with seven intervals. For VIS/IR results in daytime, a 2D histogram of PC in seven intervals and TAU in six intervals was defined. The seven cloud top pressure intervals in the IR-only results were also reduced to three IR-cloud types: low, middle and high, in pressure ranges approximating the classical definitions of these categories based on cloud base height (cloud tops were estimated to be approximately 1 km higher than cloud base). For VIS/IR, the seven PC by six TAU intervals were reduced to nine cloud types: low, middle, and high by thin, medium and thick. The relation of the “radiometric” cloud types to the classical morphological cloud types was later evaluated by direct comparisons with surface observations (Lau and Crane, 1995, 1997; Hahn *et al.,* 2001). These details of the ISCCP-C products were described in Rossow and Schiffer (1991).

8. First Analysis and Reorganization (1988–1996)

With better understanding of the radiance calibrations in hand, sufficient ancillary data obtained, and the cloud detection algorithm finalized, processing of ISCCP-C data commenced with the first data delivered to the archives in October 1988. The complete product documentation was published in December 1988 as WMO/TD-266. The features and contents of ISCCP-C data were defined as follows:

a) 32 km sampling of ≈ 5 km pixels mapped to 2.5°-equivalent equal-area map grid,
b) time interval 3 hr for C1 and calendar-monthly for C2 (including mean diurnal variation important to both weather and climate processes),
c) Cloud Amounts (CA), Top Pressures (PC), Top Temperatures (TC) and Optical Thicknesses (TAU) for Total cloud and nine VIS/IR cloud types and CA, PC and TC for three IR cloud types,
d) seven-interval PC Histogram (all day),
e) seven-interval PC by six-interval TAU joint Histogram (daytime),
f) spatial variances at each time (C1) and temporal variances of spatial means each month (C2),
g) surface temperature (TS) and visible reflectance (RS),
h) snow/sea ice cover, total ozone abundance, temperature-humidity profiles included.

Key publications to document this version of the ISCCP products were: (1) an article in BAMS that described the ISCCP-C cloud products and some highlights of the first results (Rossow and Schiffer, 1991), (2) a description and evaluation of the polar orbiter absolute radiance calibration methodology (Brest and Rossow, 1992), (3) the methodology, results and evaluation of the cross-calibration of the geostationary radiometers (Desormeaux *et al.,* 1993), and (4) the description, testing and evaluation of the ISCCP-C cloud detection and cloud amount algorithm (Rossow and Garder, 1993a, 1993b; Rossow *et al.,* 1993).

During this phase of ISCCP, the organization of WCRP changed with the establishment of GEWEX in 1989–1990 (chaired by Moustafa Chahine, Jet Propulsion Laboratory, JPL) in which ISCCP was included. This change was associated with the articulation of a broader view of the climate system, including the role of clouds. The GEWEX Science Plan (WCRP-40, also as WMO/TD-376 in August 1990) described a more complete concept of energy and water exchanges in the climate system. The specific role of cloud radiative effects on climate was also summarized in a December 1990 report for the IRC (Arking, 1991). The ISCCP WGDM was renamed the WGDM for Radiation Projects in 1990 to oversee data collection and processing for the SRB and the BSRN in addition to ISCCP (WCRP-51, First Session held in NYC in May 1990).

In the first issue of *GEWEX News* (Spring 1991), the director of the WCRP JPS, Pierre Morel, outlined this broader view of the climate, emphasizing the importance of the coupling of the components of the climate system by the exchanges of energy and water. These exchanges are all modified by cloud processes. The scientific advisory group (WGRF) that oversaw these projects was moved into GEWEX, still under the chairmanship of Thomas H. Vonder Haar (WCRP-35: Third Session held in Ft. Lauderdale in December 1989; WCRP-69: Fourth Session held in Palm Springs in September 1991), and was given, in addition, oversight of the Global Precipitation Climatology Project (GPCP) and the Global Precipitation Climatology Center (GPCC), thus combining clouds, radiation and precipitation projects into one organization (the WGDM membership was also expanded).

Although the radiance data collection continued, cloud product processing was interrupted by the injection of aerosols into the stratosphere by the Mt. Pinatubo volcano in June 1991, which interfered with the radiance calibration procedure that used the usually stable statistics of Earth observations as the reference. An *ad hoc* planning group met in NYC in May 1994 (reported in *GEWEX News*, 1994 August) to consider the next phase of ISCCP. They decided to terminate production of ISCCP-C (which finally covered the 8-yr period from July 1983 through June 1991) and to take advantage of the pause in processing (while waiting for the volcanic aerosol to clear away) to make improvements in the products based on the accumulation of research results from a set of international field experiments over the previous years. Also, the earlier proposal to exploit the additional wavelength measurements on polar orbiters to improve polar cloud detection (ISCCP Polar Cloud Algorithm Workshop in 1986, WCP-131) had been tested and could be implemented.

The international series of field campaigns, carried out in support of ISCCP, employed a wide range of ground-based instruments, new aircraft instrumentation and newer multi-spectral satellite measurements to provide significant new and more comprehensive information about cloud properties, especially about ice clouds (see Annex 1 for field experiment acronyms). A set of US-led field campaigns (Randall *et al.,* 1996) under the acronym FIRE (First ISCCP Regional Experiment) were conducted, two focusing on cirrus clouds (Cirrus-I in 1986 and Cirrus-II in 1991) and two focusing on marine boundary layer clouds (Marine Stratus in 1987 and the Atlantic Stratus Experiment, ASTEX, in 1992). Three European experiments (Raschke *et al.,* 1990, 1998) focused on cirrus clouds [the International Cirrus Experiment 1989 (ICE89), the European Cirrus Experiments from 1993 and 1994 (EUCREX93 and EUCREX94)], although some observations were also made of marine boundary layer clouds. Another sequence of campaigns, called the Western Pacific Experiment (WENPEX) and led by Japan, examined both cirrus (*e.g.*, Uchiyama *et al.,* 1999; Uchiyama and Fukabori, 1999) and low clouds (*e.g.*, Kuji *et al.,* 2000) over ocean (I in 1989, II in 1990 and III in 1991). Note that the focus of all these experiments on cirrus and marine stratus clouds followed the recommendations in GARP-16 (1975).

The results from these experiments evaluated satellite retrievals of cloud optical thickness in terms of water path (Lin and Rossow, 1994) and of droplet sizes in liquid clouds (Nakajima *et al.,* 1991; Han *et al.*, 1995; Raschke *et al.,* 1998; Kuji *et al.,* 2000) that led to extensive satellite-based global surveys (Han *et al.,* 1994; Nakajima and Nakajima, 1995). The EUCREX observations also provided a test of the retrievals from the polarized radiance measurements by a prototype of the Polarization and Directionality of Reflectance (POLDER) instrument before its first flight on the Advanced Earth Observing Satellite (ADEOS) in 1996 (*e.g.,* Parol *et al*., 1995). Cloud top temperature retrievals for low-level clouds over ocean were also evaluated against field measurements by lidar and aircraft (Wang *et al.,* 1999, and references therein). The FIRE Cirrus, EUCREX and WENPEX campaigns all contributed more information about the characteristics of ice clouds: in particular, that these clouds contained much smaller particles near cloud tops than previously thought based on earlier aircraft penetrations (Wielicki *et al.,* 1990; Heymsfield *et al.,* 1990 – see also CEPEX results in McFarquhar and Heymsfield, 1996) and exhibited a variety of crystal shapes dependent on temperature and humidity conditions (*e.g.,* Heymsfield *et al.,* 1990; McFarquhar and Heymsfield, 1996; Chepfer *et al.,* 1999) that produce significant variations of radiative effects (Stackhouse and Stephens, 1991; Raschke *et al.,* 1998). All this information formed the basis for a separate treatment of liquid and ice clouds in the revised products, called ISCCP-D.

An interesting footnote to reconstructing this history of ISCCP is that, with the advent of the internet and more common electronic document production, the detailed reporting of the meetings of relevant working groups ceased in the early 1990s in favor of more informal reporting in the *GEWEX News* (see references for further meeting reports). No longer were meeting agendas and participants lists reported; in some cases, even the dates and locations of the meetings were not reported. Thus, the subsequent history of ISCCP from this time forward is based more on the author's personal recollections.

9. Revision and Second Analysis (1996–2011)

Re-establishing the radiance calibration baseline was complicated by several events in addition to the temporary large increase in stratospheric aerosol produced by Mt. Pinatubo (Brest *et al*., 1997). Prior experience with establishing a calibration standard and its evolution for a new reference polar orbiter had indicated that at least two years of data were required for sufficient statistical robustness and to accurately measure any calibration trend. The Pinatubo volcanic eruption occurred about 2.5 yr after the start of NOAA-11 operations, but the early behavior of this radiometer appeared to show a rapid evolution that created uncertainty (Brest and Rossow, 1992). NOAA-11 failed suddenly in August 1994 and was not replaced by NOAA-14 until February 1995 (after the unsuccessful launch of NOAA-13). So, the radiance statistics by the mid-1990s included a 2.5 yr period where the NOAA-11 radiometer appeared to be degrading rapidly (August 1988–June 1991), a 2.5 yr period of increasing and then decreasing stratospheric aerosol (July 1991–December 1993), 8 months of NOAA-11 measurements after that during which the radiometer had nearly constant (or slightly improving!) sensitivity (January 1994–

August 1994), a 5 month gap in any reference measurements for VIS calibration (September 1994–January 1995), and collection of 2 years of data for NOAA-14 (February 1995–January 1997). The infrared calibration was successfully monitored and transitioned with reference to morning orbiter NOAA-12 across this gap. Only after looking at all this data together could the VIS calibration standard be re-established (WMO/TD-736; Brest *et al.,* 1997).

Evaluations of the ISCCP-C results focused on the accuracy of six quantities: total cloud amount, cloud fraction for broken cloudiness, detection and placement of optically thin cirrus, placement of thin clouds overlapping lower-level clouds, droplet sizes for liquid water clouds, and the identification and amount of ice clouds. Comparisons of ISCCP-C with cloud amounts (CA) estimated from surface observations showed that the largest errors in ISCCP-C were associated with missed or false detections (Rossow *et al*., 1993). Adjustments to the detection thresholds for ISCCP-D reduced the asymmetry of the distribution of these differences (Rossow and Schiffer, 1999); that is, the differences were now more nearly random (reducing the bias of averages). In particular, the ISCCP-C thresholds over land were too large, under-estimating total cloud cover, particularly cirrus, over land (Doutriaux-Boucher and Seze, 1998). Investigations of ISCCP-C results for broken cloudiness showed that the use of finite detection thresholds compensated for the effects of finite pixel size causing under- or over-estimates for some pixels that produced more nearly random errors; hence, domain values of cloud cover fraction were more accurate (Wielicki and Parker, 1992; Rossow *et al*., 1993).

Comparisons to results from other satellite instruments more sensitive to thinner, upper-level clouds showed, as expected, that ISCCP-C under-detected very thin cirrus and placed detected but isolated thin cirrus at a height representing its effective radiating temperature (Liao *et al.* 1995a, 1995b; Jin *et al.,* 1996). The former study also showed that the tops of clouds, particularly in the tropics, are "fuzzy" such that the radiative temperature indicates a lower height than the literal top height. This effect is exacerbated by clouds underlying an upper-level, thin cloud causing the top height to be under-estimated because the optical thickness of the upper layer is overestimated (assumed to be the total); the largest error occurs for thin cirrus overlying low-level clouds. As a result, about 25% (an amount of about 0.05) of upper-level clouds are mis-identified as mid-level clouds in ISCCP-C (Jin and Rossow, 1997).

Since all clouds in ISCCP-C were treated as liquid clouds with an assumed droplet size distribution, two studies evaluated the properties of liquid clouds, showing that the assumed droplet size (10 µm) was an overestimate over land and an underestimate over ocean, which introduced an uncertainty of TAU of only about ± 15% (Lin and Rossow, 1994; Han *et al.,* 1994, 1995). An estimate of the fraction of clouds that were actually ice at the top, about half, was made and a cloud top temperature at which about half of the clouds were ice or liquid was determined to be 260 K (Lin and Rossow, 1996).

Based on all the research results from field experiments, measurements by other satellite instruments and theoretical studies available by the mid-1990s, the following changes in the ISCCP cloud retrieval were made to produce the new ISCCP-D products (*cf*. Rossow and Schiffer, 1999): (1) the IR detection threshold over land was reduced from 6 K to 4 K, increasing cirrus detection; (2) the VIS radiance threshold was changed to a reflectance threshold reducing an under-detection bias at higher latitudes; (3) the VIS/IR thresholds were reduced and tests added on the additional 3.7 µm channel available on the polar orbiters over snow and sea ice covered locations, both day and night (based on the 1986 polar algorithm workshop conclusions, WCP-131), increasing cloud detections in polar regions; (4) for the daytime retrieval of cloud properties over snow and ice, another test on the 3.7 µm radiances was added to identify clouds in the visible with reflectances darker than the background in some geometries; and (5) coincident visible, infrared and microwave imager measurements suggested that ice clouds should be identified by cloud top temperatures < 260 K (Lin and Rossow, 1996), so ice clouds were now represented as a single layer composed of fractal-shaped ice crystals with an average effective radius of 30 µm and an aspect ratio of one (Mishchenko *et al*., 1996; see also Han *et al.,* 1999, 2005). In ISCCP-D, the assumed microphysics is also used to estimate cloud water path (WP) from the retrieved values of TAU, which is better related to precipitation formation than average TAU (which relates to radiation). Rossow and Schiffer (1999) compare in their Table 4 some cloud properties from ISCCP-C and ISCCP-D (see also Table 2 below). Overall, the most dramatic change was the increase of cloud amount (mostly cirrus) over land (by 0.10–0.15) and in the polar regions (by about 0.15); the introduction of ice phase clouds did not change the average cloud top pressures/temperatures much, but it did lower average optical thicknesses (from > 5 to < 4).

In this new version of the products, the pixel-level (Level 2) results were released for the first time as DX data, separately for each satellite. This more detailed product is directly useful for study of individual cloud systems, such as tropical convective storms or extratropical cyclones (*e.g.*, Machado and Rossow, 1993; Lau and Crane 1995), and better for matching with other observations. The 3 hr and monthly globally merged products, ISCCP Second Version Cloud Product (D1) and D2, respectively, corresponded to C1 and C2. In ISCCP-D, the map grid, ancillary datasets and retrieved surface properties remained the same as in ISCCP-C. The cloud type definitions in the PC-TAU histogram were simplified and ice-liquid alternatives introduced for middle and low-level clouds (all upper level clouds were assumed to be ice). In the D2 data, the nighttime monthly total cloud amount was increased at each location based on the monthly averaged daytime difference between the total VIS-IR cloud amount and the IR-only cloud amount (there was also a small adjustment made for locations over the Indian Ocean sector that had incomplete diurnal sampling because of a lack of geostationary coverage of this sector).

The first delivery of ISCCP-D products occurred in May 1996 (WMO/TD-737); the new version was first produced to replace the ISCCP-C for 1983–1991 (as planned) and then extended, finally covering 1983–2009. In addition, a new product was developed that estimated liquid and ice cloud particle sizes from the VIS and 3.7 µm radiance channels on the polar orbiting satellites (based on Han *et al.,* 1994, 1999). Although never released, its results were later included in the *GEWEX Cloud Assessment* (Stubenrauch *et al.,* 2012; Stubenrauch *et al.,* 2013), which contributed to the next revision of the ISCCP analysis. Routine processing of ISCCP-D continued until 2011.

Key publications documenting the ISCCP-D version were: (1) the TC threshold that separates liquid and ice clouds was estimated (Lin and Rossow, 1996), (2) the radiative model for ice clouds was based on field experiment results and theoretical investigations (Mishchenko *et al*., 1996; *cf.* Han *et al.,* 1999), (3) the revised and extended calibration of the polar orbiter radiances were described (Brest *et al*., 1997), and (4) the basis for the revision and description of the changes in the new products were summarized in BAMS (Rossow and Schiffer, 1999).

Several developments at the end of this period led to a new phase of the project: (1) retirement of personnel ended the MeteoFrance (SCC) commitment for normalizing the geostationary calibrations to the reference polar orbiter in 2009, which necessitated a replacement procedure be developed at the GPC, but later replaced by a procedure developed at NOAA National Centers for Environmental Information (NCEI; Inamdar and Knapp, 2015), (2) increases in computer capability made it feasible to switch the processing to the larger B1 radiance dataset (about an order of magnitude more data), sampled at 8 km (*cf.* Knapp *et al.,* 2007), and (3) evolution of data processing projects under GEWEX and of the research goals (discussed next), as well as the advent of numerous advanced satellite instruments, led to the idea of making ISCCP fully operational to support a more complete diagnosis of cloud-related processes by combining the advanced satellite observations with the ISCCP products providing a long-term context.

10. Summary of Concept Evolution (1996–2011)

To provide a more useful breakdown of the results, histograms of the cloud properties (PC-TAU during daytime, PC all day) were included in ISCCP-C and ISCCP-D for each map grid cell at each time; but also, the average properties of cloud types were defined by these histograms (in effect representing lower resolution histograms): high, middle, low and thin, medium, thick. In ISCCP-C, only nine types were defined (Rossow and Schiffer, 1991), but in ISCCP-D, fifteen types were defined (Rossow and Schiffer, 1999) because middle and low clouds could be either liquid or ice (high clouds were all ice). The cloud types were given classical morphological cloud type names, but this association only became clearer in studies by Lau and Crane (1995, 1997), who showed that the location of types in ISCCP-C and surface observations appeared in similar locations within tropical and midlatitude storm systems, and by Hahn *et al.* (2001), who showed some agreement between ISCCP-C and individually matched surface-observed cloud type identifications. The latter study, however, suggested that there was a better correspondence between characteristic areal mixtures of satellite cloud types and the surface cloud type identifications. This inspired an examination of the patterns in the PC-TAU histograms as suggested by Rossow and Schiffer (1991) and Rossow and Cairns (1995).

These ideas go back to the earliest satellite cloud studies that suggested a relationship between joint IR-VIS radiances and specific cloud types (Vonder Haar, 1970; Shenk *et al.*, 1976; Desbois *et al.,* 1982; Desbois and Seze, 1984; Arking and Childs, 1985; Inoue, 1987), which motivated the inclusion of the histograms in the ISCCP products. The first systematic analyses of the PC-TAU histogram patterns focused on the tropics, showing good correspondence with atmospheric conditions and identifying two distinct types of tropical deep convection producing very different amounts of precipitation (Jakob and Tselioudis, 2003; Jakob *et al.*, 2005; Rossow *et al.,* 2005b; Jakob and Schumacher, 2008; Rossow *et al.,* 2013). Switching between these convective types was identified as characteristic of MJO, AEW and Asian monsoon events (Tromeur and Rossow, 2010; Mekonnen and Rossow 2011, 2018; Wu and Chen, 2021, respectively). These so-called "Weather States" (or cloud regimes, see a discussion of the regime concept in dynamic meteorology in Michelangeli *et al.,* 1995) were later extended to global coverage, demonstrating a close association with atmospheric conditions and large-scale motions (Tselioudis *et al.,* 2013 for ISCCP-D; Tselioudis *et al.*, 2021 for the revised version, ISCCP-H).

During the 1990s and early 2000s, research activities expanded to specifically encompass more components of the global energy and water cycle (*cf*. Rossow, 1996), particularly with the organization of GEWEX (later the “EX” was changed to Exchanges, see WCRP-40). A number of heretofore separate WCRP data analysis activities (see Annex 5) were brought together under the GEWEX Radiation Panel (GRP, established from the WGRF in 1995, with Graeme L. Stephens, CSU, as first chairman): clouds and radiation (ISCCP and SRB/BSRN), precipitation (GPCP/GPCC), as well as new initiatives considering water vapor (the GEWEX Water Vapor Project, GVAP), aerosols (GEWEX Aerosol Climatology Project, GACP) and later ocean and land surface turbulent fluxes of energy and water, respectively, SEAFLUX in 1999 and

LandFlux in 2005. The second GRP chairman from 2001–2007 was William B. Rossow. New satellite instruments/missions (see WCRP-119 and Annex 4) produced new and improved information about clouds and aerosols [from the Moderate-resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging Spectro-Radiometer (MISR), POLDER, Advanced Infra-Red Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), CloudSat], radiative fluxes [from the Scanner for Radiation Budget (ScaRaB), Clouds and Earth's Radiant Energy System (CERES), and the Geostationary Earth Radiation Budget (GERB)], water vapor [from the Upper Atmosphere Research Satellite Microwave Limb Sounder (UARS MLS), Advanced Microwave Sounding Unit B (AMSU-B), AIRS, IASI], and precipitation (from the Tropical Rainfall Measuring Mission, TRMM). Another component of WCRP (called Stratosphere-troposphere Processes and their Role in Climate) coordinated improved stratospheric ozone, water vapor and aerosol data products from the Stratospheric Aerosol and Gas Experiment (SAGE) and UARS (Aura). Not only did the availability of all this new information allow for improving the ISCCP retrievals (see next section), but it also made possible much more complete and detailed diagnoses of the energy and water cycle and the cloud processes affecting it.

In particular, the radiative flux products (SRB using DX and ISCCP-FD using D1 cloud types) were revised to take advantage of the more detailed ISCCP-D products. Notably the new ISCCP-FD product (Zhang *et al.,* 2004) used a statistical model of cloud vertical structure to estimate global, radiative flux profiles every 3 hr for the first time. This model associated cloud vertical structure with each of the ISCCP cloud types based on an analysis of radiosonde humidity profiles (Rossow *et al.,* 2005a), which was later evaluated against Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)-CloudSat cloud profiles (Rossow and Zhang, 2010). In the 2010s, these revised radiative flux products were compared with others, mainly SRB/BSRN, ERBE/CERES, in a GEWEX Radiation Flux Assessment organized by GRP and led by Ehrhard Raschke (Raschke *et al.,* 2016). The GRP also conducted evaluations of data products for precipitation, water vapor and aerosols. The third GRP chairman from 2008–2013 was Christian Kummerow, CSU, when it was re-named the GEWEX Data and Assessment Panel, GDAP, and from 2014–2016 the chairman was Joerg Shultz, European Organization for Exploitation of Meteorological Satellites (EUMETSAT). All of these events (Annex 5), together with the initiation of SEAFLUX and LandFlux and the availability of advanced (weather) reanalyses, now made possible the study of weather-scale variations of all the exchanges comprising the global energy and water cycle (*cf.* Rossow *et al*., 2016), especially how the components are coupled by cloud processes that constitute a complete set of cloud feedbacks. An example of using such combinations of observations was the diagnosis of mean meridional energy and water transports by the atmosphere and ocean using the boundary fluxes (Zhang and Rossow, 1997); Romanski and Rossow (2013) used such combinations of data products to diagnose the generation rate of available potential energy. Eventually, an Integrated Product by GRP/GDAP that combined all these project data products with reanalyses [GDAP co-chairmen were Remy Roca, Laboratoire d'Etudes en Geophysique et Oceanographie Spatiales (LEGOS), and Tristan S. L'Ecuyer, U. Wisconsin, from 2017] was created that allows comprehensive study of the weather-scale energy and water cycle processes and exchanges (Kummerow *et al.,* 2019). See *GEWEX News* references for GRP/GDAP meeting reports (also Annexes 2 and 5).

11. Second Revision (2011–2014)

During the production period of the ISCCP-D products, one major field campaign and a number of advanced satellite measurements added even more detail to cloud knowledge, particularly about polar and ice clouds. In 1997–1998, the Surface Heat Budget of the Arctic (SHEBA) field campaign (Uttal *et al.,* 2002) deployed a large number of sea-ice-surface-based instruments, including cloud lidar and radar (Intrierie *et al.,* 2002) and temperature profiling from below the sea ice into the lower atmosphere (see Stramler *et al.,* 2011 for references to various datasets). ISCCP-DX results (with the additional 3.7 µm tests) colocated with the SHEBA ship were compared to this year-long dataset every three hours. In addition, other AVHRR-based cloud detection algorithms were evaluated as well. The results showed that the ISCCP-D algorithm in sunlit conditions over sea ice was too conservative – the VIS threshold was too large – so the ISCCP-D cloud amount was biased low. In wintertime (no visible data), the ISCCP-D algorithm tended to interchange cloudy and clear radiances in situations where near-surface temperature inversions were present such that the retrieved values of TC and TS were on average actually better estimates, respectively, of the surface and cloud top temperatures because the algorithm prefers warmer temperatures to represent clear sky conditions. The evaluations of other published algorithms (using more channels on the AVHRR, *e.g.,* Key and Barry, 1989) suggested better performance, so a new cloud detection algorithm employing all five channels on the AVHRR was developed and its parameters tuned against the SHEBA observations.

Evaluation of the best resulting algorithm against the CALIPSO lidar detections (Winker *et al.,* 2010) for both poles and all seasons showed that, while the results were improved (by design) in the vicinity of the SHEBA campaign (Beaufort and Chukchi Seas) and over Arctic sea ice, they were actually worse elsewhere in the polar regions, especially over land areas but even over Antarctic sea ice. Moreover, since subsequent AVHRRs no longer consistently provided the 3.7 μm measurements during daytime as used in ISCCP-D, all tests on this wavelength were dropped in the next version (called ISCCP-H) to enhance the homogeneity of the ISCCP record. Thus, the only change made to the ISCCP-H cloud detection algorithm in the polar regions, other than some small reductions in the VIS/IR threshold magnitudes, was in winter (no VIS) over snow/ice surfaces: the algorithm now re-labels "clouds" with TC values just a little colder than the IR clear-cloudy dividing value as "clear", and "clear" TS values warmer than the IR clear-sky estimate as "cloudy" to (partially) account for the reversed results found in the comparison to SHEBA measurements.

Key new satellite instruments (see Annexes 3B and 4) that became available in this period and that led to refinements of the ISCCP cloud retrieval radiative model were:

a) (1996) POLDER launched on ADEOS [and again on the Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL) mini-satellite in 2004 with the Aqua satellite];
b) (2000–2002) MODIS launched on Terra and Aqua;
c) (2002) AIRS launched on Aqua;
d) (2006) IASI launched on the Meteorological Operational satellite-A (Metop-A), also Metop-B in 2012 and Metop-C in 2018;
e) (2006) CALIPSO (Winker *et al.,* 2010); and
f) (2006) CloudSat (Stephens *et al.,* 2002) – the latter two co-orbiting with Aqua.

Studies using coincident POLDER and MODIS measurements produced better estimates of the cloud top temperature that (statistically) separates liquid and ice clouds (Riedi *et al.,* 2010, also Coopman *et al.,* 2020) and of the average sizes of liquid cloud droplets over ocean and land (also Platnick *et al.,* 2003). Analyses of the AIRS and IASI measurements provided better and more extensive estimates of ice cloud particle sizes (Stubenrauch *et al.,* 2004, 2006, 2005, 2008, 2010). In addition, these infrared sounders and multi-spectral imagers were used to evaluate the ISCCP surface temperature retrievals (Jimenez *et al.,* 2012), which is an indirect evaluation of the cloud detection algorithm (missed cloud causing an underestimate of surface temperatures, overestimates of surface temperature causing false detections), as well as the IR calibration of AVHRR (which had not been rigorously evaluated before, but see Cao and Heidinger, 2002; Knapp, 2008). The combined CALIPSO and CloudSat results also provided the first direct climatology of cloud vertical structure (Mace *et al.,* 2009; Li *et al.,* 2015), which confirmed cruder estimates in 1999–2000 based on radiosonde humidity profiles (Wang *et al.,* 2000; Rossow *et al.,* 2005a; Rossow and Zhang, 2010).

All of these results came together in 2004–2010 as part of the *GEWEX Cloud Assessment* led by Claudia Stubenrauch [Laboratoire d'Meteorologie Dynamique (LMD), Stubenrauch *et al*., 2012, 2013). By the early 2000s, there were at least a dozen global cloud products available, besides ISCCP-D, produced by various research projects from analysis of a variety of satellite measurements; however, the differences and similarities of these products were not known.

Notable conclusions from these studies that influenced the subsequent revision of the ISCCP products were as follows (Stubenrauch *et al*., 2012, 2013): (1) total cloud amount depends more on differing instrument sensitivity to thin cirrus than the analysis approach for the same type of instrument: global cloud amount systematically decreases from lidar to IR sounder to VIS/IR imager – ISCCP-D was missing about 0.05 very thin clouds (*cf.* Liao *et al.,* 1995a, 1995b), suggesting some small reduction of detection thresholds was still possible in certain situations; (2) partitioning of liquid/ice cloud amounts suggested a shift of the threshold temperature used by some methods, including ISCCP, to colder values to better separate the two phases; (3) overall particle size estimates were similar to the unreleased ISCCP analysis (which was part of the comparisons), including a systematic land-ocean difference for liquid clouds (*cf.* Han *et al.,* 1994), but also indicating a bi-modal size distribution for ice clouds that suggests the existence of two types of ice clouds where the relative amounts of each indicated smaller particles for optically thinner ice clouds; (4) cloud vertical distribution differences were as expected, where imager-based results tended to overestimate middle-level clouds and underestimate high-level clouds because of the effects of multiple layers (the comparison also confirmed that the thinnest clouds in ISCCP-D were placed at too high an altitude due to a code error).

A persistent feature of the ISCCP-C and ISCCP-D cloud amounts was a systematic dependence on satellite view angle, increasing cloud amount with angle increasing from nadir to slant view. The explanation proposed was the presence of a small amount of very thin, high-level cloudiness that could be detected better at slant than nadir angle (Rossow *et al*., 1993). Evidence in the 1990s for persistent, optically very thin clouds near the tropopause (summarized in Rossow and Schiffer, 1999) was confirmed by CALIPSO in the 2000s. ISCCP-D represented such clouds, some of which are detected in the IR (especially at slant view) but not the VIS channel, by placing them at the tropopause and solving for a TAU value consistent with the temperature there (the code error in ISCCP-D was corrected in ISCCP-H).

The first piece of evidence was the detection of such clouds by SAGE II, where the early analyses were focused on Polar Stratospheric Clouds (McCormick *et al.,* 1982), but later results were summarized globally in Wang *et al*. (1996). In a study comparing SAGE II cloud detections with ISCCP-C, not only were such clouds seen – particularly clouds with optical thicknesses below the detection threshold for ISCCP – but also tropical cloud tops were generally found to be “fuzzy” with a slow downwards increase of optical thickness over significant vertical distances, up to 2.5 km (Liao *et al.,* 1995a, 1995b). This characteristic means that the apparent cloud top location based on observed temperature, IR radiance) will be lower in altitude than the literal top (detected by lidar for instance). Further comparison of ISCCP-C cloud detections and top locations with analysis of High-resolution Infrared Sounder

(HIRS) data (*cf.* Wylie and Menzel, 1999), which determines cloud top pressure directly, showed not only some clouds missed by ISCCP (Jin *et al.,* 1996; see also Stubenrauch *et al.*, 1999), but also quantified the frequency of occurrence of optically thin cloud overlying lower-level clouds, in which case the ISCCP cloud top will be biased low (Jin and Rossow, 1997). These results were clarified when the HIRS and SAGE II datasets were directly compared (Wylie and Wang, 1997, 1999). SAGE II, being a limb-viewing instrument, was the most sensitive cloud detector (spectral dependence discriminated between ice clouds and aerosols), finding more cloud than HIRS. The additional clouds found by SAGE II, but missed by HIRS, were located at or just below the tropopause (Wylie and Wang, 1997, 1999; *cf.* Stubenrauch *et al.,* 2005, 2012). The CALIPSO results confirmed these details (Mace *et al.,* 2009; Mace and Zhang, 2014; Li *et al.,* 2015; Liu *et al.,* 2019). Although the presence of these very thin clouds produces an angle dependence in the ISCCP results, the products were not "corrected" as this would constitute removal of actual clouds (see Knapp *et al.,* 2021).

Detecting and retrieving the properties of polar clouds are especially difficult both because the radiance magnitudes are small (in some cases at the limit of instrument sensitivity) and because the relative contrast between cloudy and clear conditions is even smaller. In fact, under some conditions, the sign of the radiance difference is reversed: clouds can be darker than the ice-snow surface in VIS in some viewing geometries (spring and autumn especially) or warmer than the surface in winter when surface temperature inversions occur. However, the availability of more reliable observations in the polar regions, especially over the high ice sheets in Greenland and Antarctica, was lacking until the advent of active sensors, radar on CloudSat (Stephens *et al.*, 2002) and especially the lidar on CALIPSO (Winker *et al.,* 2010), provided the needed information. Evaluations of ISCCP-C results, despite the uncertainties of surface observations and some other satellite results, clearly showed a significant under-estimate of CA at both poles, especially over land areas (*e.g.*, Schweiger and Key, 1992). Threshold changes, plus the addition of tests on 3.7 µm radiances, as suggested by Key and Barry (1989), Yamanouchi and Kawaguchi (1992) and Raschke *et al.* (1992) at the ISCCP workshop (WCP-131), reduced the overall bias in ISCCP-D values of CA (see Fig. 16 in Rossow and Garder, 1993b for a test of this change). However, the disagreement in the seasonal phase of ISCCP CA with surface observations in the north persisted from ISCCP-C to ISCCP-D, even though some early studies suggested that the winter cloud amounts from surface observations were likely biased low (Curry and Ebert, 1992, but see also Hahn *et al.,* 1995). Rossow and Schiffer (1999, Fig. 4) showed that the diurnal variations of polar cloud TAU in ISCCP-D were much better behaved than in ISCCP-C. Further refinements of the detection thresholds in ISCCP-H, despite the removal of the 3.7 µm tests and better treatment of ice clouds, improved agreement with the combined CloudSat–CALIPSO results (Liu *et al.,* 2012 for the Arctic, Bromwich *et al.,* 2012 for the Antarctic), most notably good agreement on the phase of the seasonal variations of the ISCCP-H values of CA and PC (Rossow *et al.,* 2022). Still, in ISCCP-H, the values of CA are slightly under-estimated and the values of PC are over-estimated.

In addition, these studies also provided for a better representation of the cloud properties assumed in the ISCCP-H retrieval models: (1) POLDER measurements provided a better scattering model for ice clouds (Baran and Labonnote, 2007), (2) coincident POLDER-MODIS phase determinations indicated that ice and liquid clouds would be better separated (half liquid, half ice) by a top temperature of 253 K instead of 260 K (Riedi *et al.,* 2010, later Coopman *et al.*, 2020), (3) retrievals from various instruments provided better information about liquid and ice cloud particle sizes (see Stubenrauch *et al.,* 2012), and (4) CloudSat–CALIPSO cloud profiles (together with results based on radiosonde humidity profiles) provided statistics of the finite thicknesses of cloud layers at various heights (Mace *et al.,* 2009; see also Li *et al.,* 2015).

An international group of more than 80 scientists reviewed many of these research results at a symposium held at the City College of New York in April 2013, sponsored by GEWEX and the participating satellite agencies, to mark the 30th anniversary of the establishment of ISCCP (Rossow, 2014). The presentations and discussions highlighted the capability to quantify the cloud effects on TOA, SRF and in-atmosphere radiative fluxes, the beginning of systematic analyses of water vapor-clouds-precipitation dynamics and aerosol effects in different meteorological situations, and the start of comprehensive diagnoses of cloud-influenced energy and water exchanges in weather and climate. Topics identified as needing more work by exploiting existing and planned satellite observations emphasized deep convection dynamics (including extratropical) and ice cloud properties and behavior.

Figure 1. Founders and facilitators of ISCCP at 30th anniversary symposium. Clockwise from lower left: Robert A. Schiffer (founder, International Project Manager, NASA/USA), Thomas Vonder Haar (founder, Chairman of WGRF oversight, representative of IRC, CSU/USA), William B. Rossow [Head of GPC, 2nd Chairman GRP oversight, later Project Manager, NASA/City College of New York (CCNY)/USA], Christian Kummerow (3rd Chairman GRP oversight, CSU/USA), Ehrhard Raschke [founder, representative of IRC, member of WGRF, U. Koln/U. Hamburg/ Max Planck Institute (MPI)/Germany]; Not pictured: Garth Paltridge (founder, CSIRO/Australia), Pierre Morel (founder, Director WCRP JPS, France), Roy Jenne (founder, NCAR/USA), Graeme Stephens (1st Chairman GRP oversight, CSU/JPL/USA).

Based on all these results, the following changes in the ISCCP cloud retrieval were made to produce the ISCCP-H (Rossow *et al.,* 2022): (1) small changes in detection thresholds were made in specific situations (*e.g.*, mountainous terrain, near sea ice edge) and in the polar regions in particular to partially offset removal of 3.7 µm radiance tests (the largest change occurred over Antarctica in summer), which further improved polar cloud amounts (Rossow *et al.,* 2022); (2) the cloud-clear distinction near the dividing clear sky threshold was reversed over snow and ice at night (winter); (3) liquid water clouds were identified by top temperatures ≥ 253 K and assumed to be composed of a distribution of droplets with 13 µm average effective radius over land and 15 µm average effective radius over ocean (these results differ from Han *et al.,* 1994 because a lower TC threshold was found to better identify liquid clouds); (4) ice clouds were identified by top temperatures < 253 K and assumed to be composed of crystals with 27 µm average effective radius for optical thicknesses < 3.6 and 34 µm average effective radius for clouds for optical thicknesses ≥ 3.6 (this division by optical thickness produces about the right proportion of each type seen in the results and makes microphysical sense, *cf.* Khvorostyanov and Curry, 2014); (5) although these ice crystal sizes are used to calculate cloud water paths, the variation of ice cloud visible reflectivity with viewing-illumination geometry, which is relatively insensitive to particle sizes in this range (*cf.* Han *et al.,* 2005), is assumed to follow an empirical model derived from POLDER results (Baran and Labonnote, 2007); (6) cloud layers were given an explicit physical thicknesses, including gas (and saturated water vapor amount), of 100 hPa near the surface (but a low cloud layer can be thinner to preserve a minimum clear boundary layer of 20 hPa thickness), increasing linearly to 200 hPa at the tropopause; and (7) the availability of a global product quantifying the monthly average optical properties of stratospheric and tropospheric aerosols over time (Kinne *et al.,* 2013) was exploited to account for aerosol scattering-absorption in the cloud and surface property retrievals.

Several corrections to the ISCCP-D retrievals were made for ISCCP-H: (1) there were two flaws in the ice optical thickness look-up tables, one that produced a gap in values near 2 and one that limited values to < 50 in extreme solar geometries; (2) the incorrect placement of optically thin clouds detected only by IR tests above the tropopause was changed to place them at the tropopause; and (3) the overestimate of large surface temperatures was reduced by using surface air instead of surface skin temperature to determine water vapor absorption in the retrieval. Again, these changes and corrections demonstrated the value of archival of the "raw" inputs to allow for re-processing.

Other changes made in ISCCP-H are: (1) switching the radiance dataset from B3 (32 km sampling) to B1 (8 km sampling) and mapping results in a 1°-equivalent equal-area grid; (2) refining the VIS radiance calibration, with an aircraft-based anchor in the 1980s and a MODIS-based anchor in the 2000s (Rossow and Ferrier, 2015) and also slightly adjusting the IR calibration for AVHRRs on NOAA-14 to NOAA-19 (based on Cao and Heidinger, 2002; Knapp, 2008; Jimenez *et al.,* 2012); (3) specifying ozone absorption coefficients specific to each imaging instrument's spectral response; (4) accounting for variations of land surface infrared emissivity to retrieve physical surface temperatures instead of brightness temperatures; and (5) replacing all of the ancillary products (topography and land-water mask, ozone, sea ice and snow cover, atmospheric temperature-humidity profiles) with more up-to-date, more homogeneous operational products.

One particular improvement for ISCCP-H is that the new version of the atmospheric temperature-humidity profile product explicitly represents the diurnal variations of temperature in the lower atmosphere over land areas and the occurrence of near-surface temperature inversions over the polar and some nighttime desert regions in winter.

The Level 2 (pixel-level) results were released in two forms, as HXS data (separate by satellite like DX data) and a new HXG data (globally merged on an equal-angle 0.1° map grid). The latter product is better for tracking the motions of cloud systems. A gridded version of the results for each satellite every 3 hours, separately, was also released as HGS data (like unreleased DS data), including the ancillary data, which provides regional versions of the main cloud products. The globally merged product every 3 hours is called HGG (like D1 data), the monthly averaged results at each of eight times daily are called HGH, and the total monthly averaged results are called HGM (like D2 data). In ISCCP-H, an interpolation over the time steps and locations where data are missing is performed directly in the HGG maps, including adjustments of nighttime CA and TC/PC values based on the daytime differences between VIS/IR and IR-only results and interpolation of the VIS retrievals of TAU/WP and cloud type amounts over the nighttime. The ISCCP-H products currently cover the period from July 1983 through December 2018 but will soon be extended. Production of this version of ISCCP is now operational (see next two sections) with full documentation online (Rossow, 2017; also Young *et al.,* 2018; Rossow *et al.,* 2022).

Key papers at this stage were: (1) evaluation of ISCCP-D against other products (Stubenrauch *et al.,* 2012, 2013), (2) evaluation and revision of radiance calibrations (Rossow and Ferrier, 2015), (3) comparison of long-term records of ISCCP-H against other products (Karlsson and Devasthale, 2018), and (4) documentation of ISCCP-H (Young *et al.,* 2018; Rossow *et al.,* 2022).

12. Transition (2014–2016)

As scientific goals evolved in the 1990s–2000s, especially relating to diagnosing energy and water exchanges as feedbacks on climate, the need for maintaining and extending the ISCCP data record to provide a long-term context for the combined analysis of other data products (generally with lower time resolution and shorter records) led to discussions in the early 2000s by the GRP, led by John J. Bates (NCEI), about transitioning the ISCCP processing from a research environment to fully operational processing (research-to-operations, R2O) to continue the record. These discussions also articulated the need for extending other data processing efforts to build up a weather and climate observing system for which transitioning ISCCP could serve as a pathfinder. Since the collection and pre-processing of the radiance images for ISCCP were already done routinely by the operational satellite agencies, only the radiance cross-calibration (by SCC and GPC) and cloud analysis (by GPC) parts of the project needed to be transformed. Some planning began in 2008 but specific actions did not occur until 2012. In addition to revising the ISCCP analysis procedures and products to create ISCCP-H, as described above, and acquiring improved ancillary data products, this transition entailed expanding and automating the data quality checking procedures and re-engineering (modernizing) the research-style processing code for a more flexible computer system implementation in an operational environment. By 2014, these changes were completed. After a period of testing and refinements, as well as training of the new processing team at NCEI, operational processing of the new ISCCP-H products began in 2016 (full documentation published online as the *Climate-Algorithm Theoretical Basis Document*, Rossow, 2017).

The transition of ISCCP processing to an operational form identified a number of lessons about the structure of the analysis code and the processing system important for a research-quality operational system (Rossow and Bates, 2019). One key lesson is that the processing code should be very modular in structure. In the case of the ISCCP code, each satellite is processed separately for each month in steps that produce the Level 2 (pixel-level) version (HXS). Then a gridded version (HGS) is produced from HXS combined with the ancillary data. The HGS products are merged to produce the global, 3 hr, gridded product, HGG. The monthly averages are produced (HGH from HGG and HGM from HGH). There is also a globally merged Level 2 product produced from HXS (HXG). In addition, the needed ancillary input datasets each have their own processing stream to set them up (sometimes to merge or modify them) and to check their quality. These products are also separately archived. The conclusion is to delay mergers of information to later stages of product production. At each stage there is a quality checking (QC) procedure run to produce statistics that monitor the uniformity of the results: these QC results are designed to make anomalous behavior appear as deviations from the norm. All of these components of the analysis system are separate program modules. This structure not only makes it easier to distribute the processing among multiple computers, none of which need be very large, but also makes it easier to identify where in the processing stream any anomalous results are being produced.

The other key lesson is that the R2O transition is best accomplished with simultaneous funding for both the original research team and the new operations team to work together on testing the code and writing the documentation. The training of the operations team is especially important for transferring the knowledge of how to operate the processing system, of the rationale underlying its design features, of understanding and interpreting the output of the quality checking procedures, of deciding what to investigate and how to fix any identified problems, and of the meaning and limitations of the scientific results. The last is crucial for recognizing features of the result that might be real (on Earth) or are caused by changes in satellite instrument behavior. All of this training needs to be documented to provide a basis for passing on this knowledge because the personnel of the operations team will change over time.

In this case, the R2O transition of ISCCP processing led to some other changes in the processing and the products. The availability of more computer capability made possible an improved radiance normalization approach that not only uses all of the radiance data (now a much larger dataset with 8 km sampling) to generate much more robust statistics, but also allows for cross-comparison of all pairs of satellites viewing the same locations to provide more consistent results across the whole satellite constellation. This approach had been considered at the beginning of ISCCP but was not feasible then. This new procedure has been implemented for processing ISCCP-H.

To reach a wider user community, as well as to better conform to data format standards now established in the operational environment, the data format adopted is a widely used standard data format (NetCDF) that has more extensive metadata included. This format replaced the unique formats of earlier products. The quality information contained in the ISCCP-H gridded data products was expanded to provide an explicit estimate of uncertainty in all of the retrieved cloud and surface properties at each location and time: this uncertainty is directly related to the decision that separates the radiances into clear and cloudy categories (missed or false cloud detections generally cause the largest errors).

In addition, a reduced-content BASIC version of the gridded data products is now available for general (non-research) users. This product is a simplified version of the HGG/HGH/HGM products, reduced to just the main cloud, atmosphere and surface variables without the more detailed quality and algorithm performance information. Product documentation was also expanded beyond the usual description and documentation of the scientific theory of the analysis and product contents (Rossow, 2017) to include an Operations Guide for the processing personnel and a Users Guide to more fully explain how to use the data products.

Figure 2 (created by Kenneth R. Knapp, NCEI) illustrates the number of satellites that have been processed to date to compose the ISCCP record (see also Annex 4): the left-hand panel shows the longitude coverage at the equator by geostationary satellites and the right-hand panels show the time-period coverage by “afternoon” and “morning” polar orbiters.

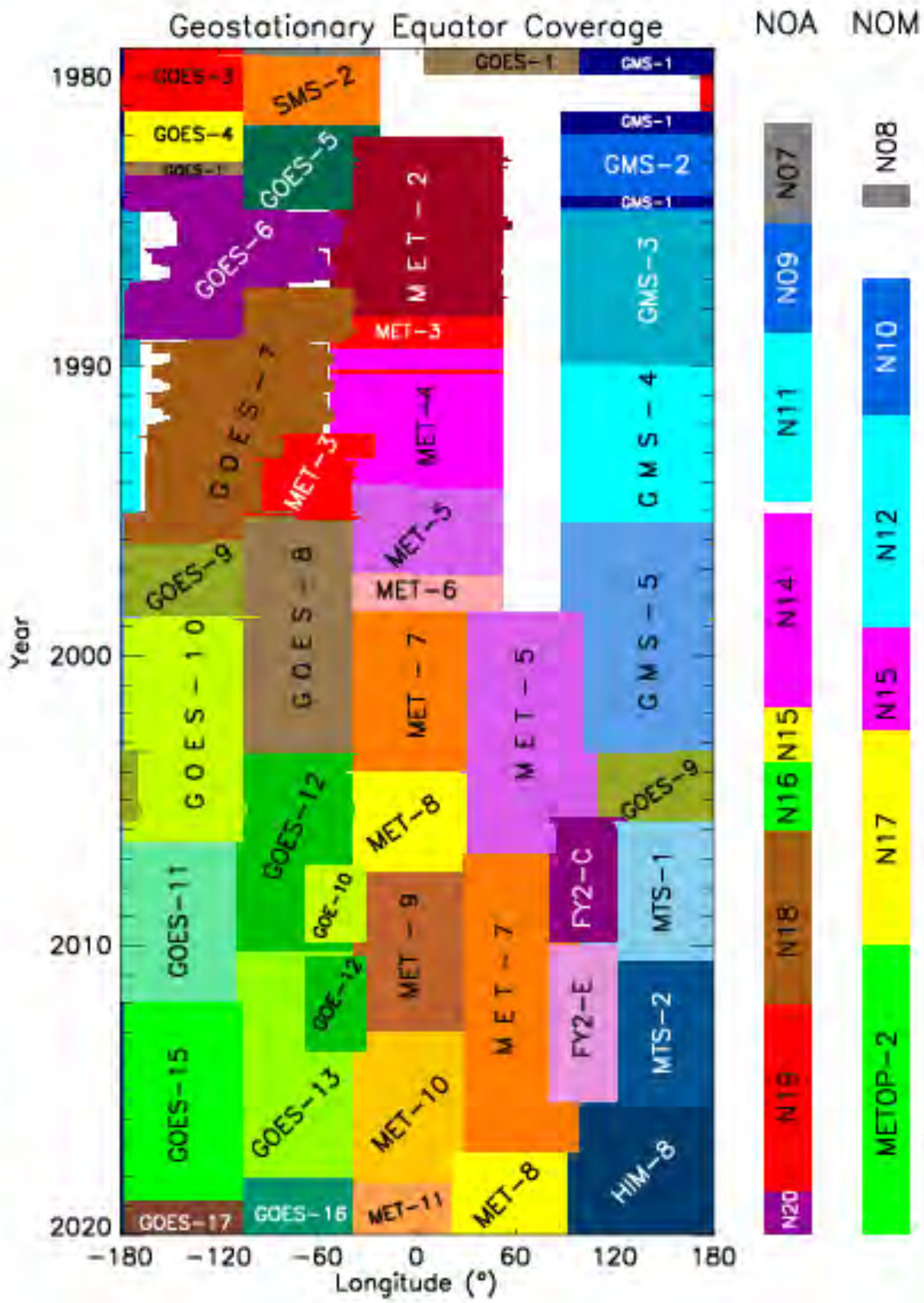

Figure 2. The left panel illustrates in color the variation with time of the longitude coverage at the equator by individual geostationary weather satellites from 1979 to 2020. The right bars show the corresponding variation in time of polar orbiter coverage in the "afternoon" (NOA) and "morning" (NOM) orbits. This figure also appeared in Rossow *et al.* (2022).

The China Meteorological Administration (CMA) contributed B1 and B2 imaging data from its FY-2 geostationary satellite series from 2005 through 2010 (FY-2C from August 2005 through November 2009 and FY-2E from January 2010 through November 2010), but funding limits at the GPC at this time precluded processing these data. Likewise, the Brazilian National Institute for Space Research (INPE) collected and delivered data from spare GOES satellites for more than 3 years (GOES-10 from July 2009 through November 2009 and GOES-12 from June 2010 through August 2013), but the same funding limitations prevented processing. However, the Chinese and Brazilian satellites covered geographic sectors that were already covered by other satellites during this period. This figure makes clear the need for the quality checking and cross-comparison capabilities in the operational processing system in order to monitor product alterations that might be introduced by satellite changes.

13. Operational Analysis (2016–2022)

Rossow *et al.* (2022) illustrated in their Table 1 the changes in cloud properties between ISCCP-D and ISCCP-H in comparison with the range of values from the *GEWEX Cloud Assessment*. Table 2 below illustrates for one year the evolution of the average cloud properties from ISCCP-C to ISCCP-H. Relative to the whole record (see Fig. 3), this year exhibited higher cloud amount (CA) by nearly 0.04, lower top pressure/temperature (PC/TC) by about 10 hPa/1 K and lower optical thickness (TAU) by about 0.04. Also shown are CA values for the north pole (NP) and south pole (SP) defined by averages over latitude poleward of 60°. Despite the many refinements in the retrieval model, the globally averaged results are little changed, except for the CA increases over land from ISCCP-C to ISCCP-D and over the polar regions from ISCCP-C to D to H. Overall (1983–2018) global average cloud properties (with seasonal variations included) are: CA = 0.660 ± 0.018, PC = 564.7 ± 14.6 hPa, TC = 261.7 ± 1.7 K and TAU = 4.17 ± 0.34. Note how small the variations of global monthly average values are despite much larger weather-related variability. However, more important differences among these product versions appear in the cloud type and/or regional information, particularly for ice and polar clouds. The evaluation of ISCCP-H discussed in Rossow *et al.* (2022), especially for the seasonal variations in the polar regions, shows good agreement with other advanced sensor results. The *GEWEX Cloud Assessment* is being updated.

Table 2: Comparison of the main average cloud properties from ISCCP-C to ISCCP-D to ISCCP-H for one year, 1986

Quantity	*C2*	*D2*	*HGM*
CA	0.634	0.686	0.695
land	0.461	0.589	0.597
water	0.712	0.730	0.736
NP	0.520	0.683	0.681
SP	0.526	0.686	0.682
TC	262.8	261.5	260.6
land	254.6	253.9	253.2
water	266.6	264.7	263.5
TAU	5.7	3.8	3.8
land	6.9	3.8	3.8
water	5.3	3.8	3.8

Figure 3 shows the whole ISCCP-H record through 2018 of the global, monthly anomalies (mean seasonal variation removed) of the basic cloud properties. Although some artifacts in the sampling and retrieval of cloud properties distort the early part of the record, the slow decline in cloud amount (CA) appears to be real and associated with a decrease in optically thin, low-to-mid-level cloudiness (Rossow *et al.,* 2022). The decrease in the amount of these cloud types also accounts for the small overall increases in average cloud top pressure/temperature (PC/TC) and optical thickness (TAU). Whether these variations are associated with recent warming of the climate or with a change of long-term oceanic anomalies (or both) is not yet known. Accounting for the radiative effects of aerosols in ISCCP-H removed an anomaly in TAU and slightly reduced the anomalies in PC/TC associated with the Pinatubo eruption in 1991–1993, but did not change the retrievals of CA because aerosol information does not enter into the cloud detection procedure. Other detailed results of ISCCP-H are discussed in Rossow *et al.* (2022).

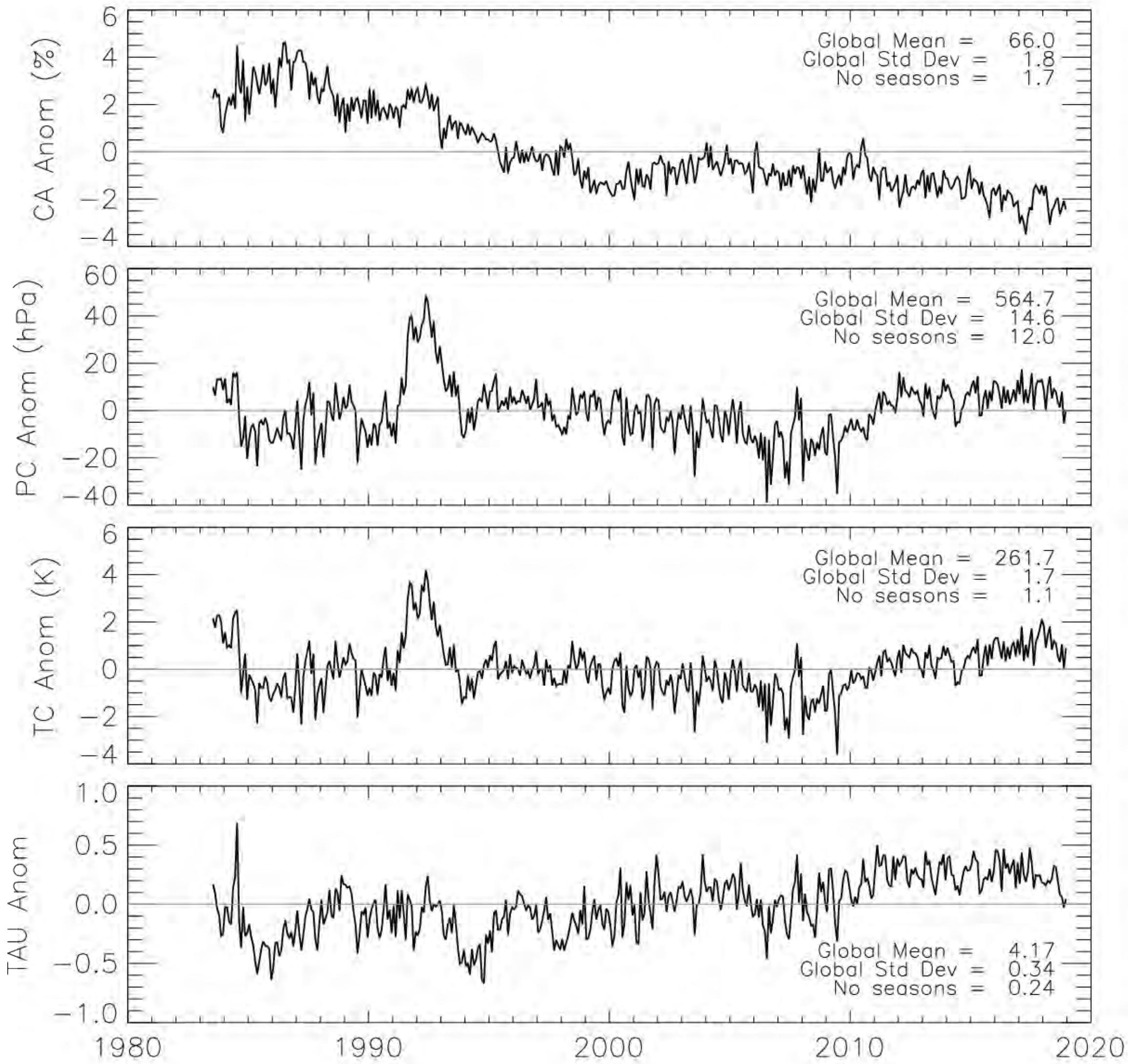

Figure 3. Anomalies of monthly global averages (mean seasonal variation removed) of cloud amount (%), cloud top pressure (hPa), cloud top temperature (K) and cloud optical thickness over the whole ISCCP record with the mean and standard deviation shown. This figure also appeared in Rossow *et al.* (2022).

In 2019, the reference polar orbiter imager must be changed to a completely new instrument (Visible Infrared Imaging Radiometer Suite, VIIRS) on NOAA-20. The characteristics of this instrument are so different from the previous AVHRRs that significant effort has been needed to produce a compatible (sampled) version of these data and relate its absolute radiance calibrations to the previous values (Kenneth R. Knapp has produced a reduced version of VIIRS data called VGAC data). Once this transition is completed, the new, more comprehensive cross-calibration procedure will be applied to the whole ISCCP record back to the beginning. As of this writing in 2022, efforts will next be made to find some missing imaging data in the earlier years, reduce some artifacts in the ancillary data records, and then the whole ISCCP record from 1983 onwards will be re-processed as ISCCP-H2 to increase the uniformity of the record and then continued.

14. Summary of Concept Evolution (2011–2022)

Although the WCRP Science and Implementation Plans in the 1980s had articulated a more comprehensive view of the climate system than discussed in GARP-16, specifically citing the need to diagnose the energy and water exchanges that couple the components of the climate system, little organized observational action on these objectives occurred in the 1980s and 1990s. Instead, several separate data projects were initiated (ISCCP, SRB/BSRN, GPCP/GPCC), along with ocean-focused projects (Tropical Ocean Global Atmosphere, World Ocean Circulation Experiment). With the formation of GEWEX in 1989–1990, a more integrated view of the global energy-water cycle was reiterated in the GEWEX Science Plan (WCRP-40, see also Pierre Morel's comments in the first issue of *GEWEX News,* 1991 Spring), outlining the needed analyses of observations and models, including the role of cloud processes, in the exchanges and transports. The pre-existing projects were brought together under the GEWEX Radiation Panel (GRP), though they continued to operate separately through the 1990s and 2000s. Also started in the 1990s were GVAP and GACP. Planning also began to complete the observational analysis of the remaining energy and water exchanges.

The 1999 ISCCP BAMS article indicated that the inclusion of water cycle studies and cloud-circulation dynamics feedback in the research goals influenced the design of the ISCCP-D data products, particularly the addition of the water path variable (related to cloud water mass) and the release of the more detailed Level 2 (pixel-level) results for the first time. The GRP set of energy and water exchange analyses were completed by organizing SEAFLUX in 1999 (Curry *et al.,* 2004), which used SRB surface radiative fluxes based on ISCCP as one input to determine the ocean surface turbulent fluxes of heat and water (sea ice not accounted for), and then organizing LandFlux in 2005 (Vinukollu *et al.,* 2011) to determine the same fluxes over land surfaces (snow not accounted for).

In the 2008, GRP (renamed GDAP in 2012) began work on an integrated data product that combined all of these project data products, together with atmospheric reanalysis winds, into a complete diagnosis of the exchanges of energy and water at the top-of-atmosphere, the surface and in the atmosphere in one dataset. The first version of the GEWEX Integrated Product was released in 2019 (Kummerow *et al.,* 2019) covering the period 1998–2015. Since these products are not yet entirely consistent in the values of some parameters used (especially surface and near-surface atmospheric temperatures) and snow- and ice-covered surfaces are not treated, more work is needed. The purpose behind these data analysis efforts was summarized by the chairman of the GEWEX Scientific Steering Group, Graeme L. Stephens (JPL, *GEWEX News* 2019 Quarter 4). Despite some limitations, all of these data products, supplemented by many experimental satellite and field experiment measurements, now make possible systematic and thorough evaluations of energy and water exchange processes explicitly during all types of weather.

In all this reformulation and revision of concepts, what was and still is oddly missing is the concept of using the satellite observations directly to diagnose cloud processes by measuring time derivatives and their parametric dependence, although a beginning has been made with the organization of GEWEX Process Evaluation Study in 2015. Instead, the ISCCP and the many later cloud data products have been used primarily for describing cloud property statistics with which to calculate their radiative effects and to compare with model representations, usually only in a time-averaged sense. Water vapor and precipitation are observed, studied and compared separately. This is, essentially, a "static" rather than a dynamic use of the observations; although the monthly to interannual variations of global distributions are examined, the time variability at weather (process) scales, especially systematic diurnal variations, is usually not evaluated. With the data products now available, quantitative evaluations of the correlated time variations of water vapor, cloud water, precipitation, radiative flux profiles and atmospheric circulation can be done.

Cloud process continues to be thought of as best addressed by field campaigns combined with high resolution modeling, but such measurements do not provide estimates of the time derivatives of the cloud properties and related quantities (water vapor, precipitation, radiative fluxes, temperature, winds) that represent cloud processes and are explicitly calculated in numerical models. Ground-based measurements represent (mostly) advected spatial variations over limited time-space domains and aircraft measurements document only spatial variability but not at the same time. Moreover, the spatial scales covered by typical field experiments with aircraft are only ~ 1000 km and the measurements do not always document the dependence of local conditions on larger-scale weather systems or global variations. Likewise, the location and duration of field experiments means that their results are specific to particular atmospheric situations, particularly specific seasons. All of these features mean that the results from field experiments are hard to generalize into a comprehensive understanding of cloud processes. One way to use the extensive, global satellite datasets, like ISCCP, is to establish the “context” of each field campaign relative to others and in terms of the larger-scale variations to allow comparisons among the results (*e.g.*, Remillard and Tselioudis, 2015). To date, little such use has been made of any of the global satellite products.

Looking at the whole planet (*cf.* Rossow and Cairns, 1995), it is clear that cloud variations express the whole range of space-time scales of the atmospheric circulation variations, from boundary layer turbulence (1 km, 10 min) through weather systems (100–1000 km, 30–2000 min) up to the global general circulation (10,000 km, 1–30 days and longer). Only a constellation of polar orbiters and geostationary satellites, like that used for ISCCP, can provide the needed, time-resolved information covering this whole range of scales simultaneously. In other words, satellite observations are the observing system that can provide a complete view of cloud dynamics encompassing simultaneously the whole range of scales of the atmospheric circulation and determining cloud and atmospheric property time derivatives, especially by tracking storms or air masses (see below). ISCCP can now provide direct estimates of the time derivatives of the bulk cloud properties with a long enough record for examining the dependence of these time derivatives on weather and seasonal conditions and the larger time scale variations induced by ocean variability. What is still needed is to expand the set of cloud properties beyond the three (horizontal cover fraction, top temperature/pressure, optical thickness) that ISCCP measures with even higher time resolution (this will be discussed in Sections 15 and 16). However, such a cloud-dynamics diagnosis is already possible with the ISCCP datasets and the GEWEX Integrated Product.

Early ideas about how to provide more detailed cloud information in the ISCCP products were described in terms of determining the amount and height of cloud types: the types were identified in early planning only in terms of the classical names for clouds of different morphology (an updated version of Luke Howard's classification, *cf*. Hamblyn, 2001; WMO, 1956, 1975, 1987). Pre-ISCCP studies, some presented at the earliest planning meetings, exploited 2D or 3D radiance histograms to determine cloud amounts and to assign portions of them to some cloud types (*cf*. Desbois *et al.,* 1982; Arking and Childs, 1985; Inoue, 1987). In the ISCCP products, this idea was implemented in two ways, one by defining cloud types by three intervals each of top pressure (PC) and optical thickness (TAU), instead of radiances, as an approximation of the conventional cloud types classified from surface weather observations (see Rossow and Schiffer, 1991, 1999; see also Lau and Crane, 1995, and Hahn *et al.,* 2001). In ISCCP-H, these nine types are reported separately for liquid and ice phase as well. In addition to the properties of the types defined by PC-TAU combinations (including averages of their other properties), more detailed histograms of PC-TAU, rather than radiances, were also included in the ISCCP products.

The 1991 ISCCP BAMS article (Rossow and Schiffer, 1991) suggested the idea of using the mesoscale patterns in the joint histograms of PC-TAU to identify cloud regimes (*cf*. Rossow and Cairns, 1995), but this was not taken up until the 2000s (first by Jakob and Tselioudis, 2003; see more discussion below).

The 1999 ISCCP BAMS article (Rossow and Schiffer, 1999) suggested the use of ISCCP Level 2 data to identify, track and composite over cloud system life cycles the properties of individual cloud systems (or storms). Early work (Machado and Rossow, 1993; Machado *et al.,* 1998) replaced tracking in radiance images, as in earlier studies, with tracking using the ISCCP Level 2 cloud properties (PC and TAU). Follow-up work quantified the properties of tropical deep convection including size distributions, lifecycle evolution of properties and cloud type components, and storm propagation speeds (Machado *et al.,* 1998; Machado and Laurent, 2004; Fiolleau and Roca, 2013; Vant-Hull *et al.,* 2016). Futyan and Del Genio (2007) developed the lifecycle idea further by defining the growth-mature-decay stages in terms of minimum cloud top temperature and maximum cloud system size (*cf.* Inoue *et al.,* 2009).

Another way to examine the evolution of individual clouds is to use horizontal wind data (from reanalyses) to track air parcels and then composite the evolution of cloud (and other atmospheric) properties along these trajectories (*cf.* Luo and Rossow, 2004). Surface pressure anomalies can be used to track extratropical cyclones (Bauer *et al.,* 2016) so that the cloud and atmospheric attributes of these storms can be compiled (*cf.* Haynes *et al.,* 2011; Polly, 2016; Polly and Rossow, 2016). All of these approaches provide a Lagrangian view of the cloud processes that allows for direct estimation of the process time derivatives. Such analysis approaches using satellite cloud and atmospheric products to study cloud dynamics are now increasing and being expanded to combine more observations (see, *e.g.,* Takahashi and Luo, 2012; Masunaga, 2014; Masunaga and Luo, 2016; Takahashi *et al.,* 2021).

The determination of cloud radiative effects advanced in the 1990s and early 2000s from calculation of top-of-atmosphere and surface fluxes using the ISCCP-C (Darnell *et al*., 1992; Zhang *et al.,* 1995; Rossow and Zhang, 1995; and SRB – Whitlock *et al.,* 1995) to the calculation of radiative flux profiles (and heating rates) (ISCCP-FD, Zhang *et al.,* 2004) by combining the ISCCP-D with a cloud vertical structure model based on radiosonde humidity profiles (Rossow *et al.,* 2005a). (See also Stackhouse *et al.,* 2011 about the updated SRB products.) The launch of CloudSat and CALIPSO in 2006 provided direct measurements of cloud vertical structure (which were compared to the vertical structure model in Rossow and Zhang, 2010, leading to an updated flux profile product called ISCCP-FH). Improved radiative flux profile calculations were based directly on these new results (*e.g*., L'Ecuyer *et al.,* 2008). It is notable that more direct determinations of the top-of-atmosphere radiative fluxes (Loeb *et al.,* 2021) appear to be consistent with the long-term decrease in CA from ISCCP-H shown in Fig. 2.

Subsequent research with the ISCCP-D PC-TAU histograms has shown that characteristic mixtures of cloud properties exhibit stronger connections with the large-scale atmospheric circulation and weather than individual cloud types (Jakob and Tselioudis, 2003; Rossow *et al.,* 2005b; Jakob *et al.,* 2005; Jakob and Schumacher, 2008; Tromeur and Rossow, 2010; Mekonnen and Rossow, 2011; Tan *et al.,* 2013; Tselioudis *et al.,* 2013; Mekonnen and Rossow, 2018; Worku *et al.,* 2019, 2020; Tselioudis *et al.,* 2021) – this result was suggested by Hahn *et al.* (2001) in comparing the conventional cloud types from surface observations with the ISCCP cloud types. Similar analyses have been done with MODIS cloud products (*e.g.*, Oreopoulos *et al*., 2014, 2017).

Parallel work, particularly using new satellite measurements, has advanced knowledge about cloud microphysical properties: ice crystal sizes (AIRS/IASI: Stubenrauch *et al.,* 2008, 2010) and cloud phase (POLDER/MODIS: Riedi *et al*., 2010; Coopman *et al.,* 2020), cloud vertical structure (CloudSat/CALIPSO: Mace *et al.,* 2009; Li *et al.,* 2015) and precipitation in all forms [TRMM: Huffman *et al.,* 2007 and the Global Precipitation Mission (GPM): Skofronick-Jackson *et al.,* 2017; Huffman *et al.,* 2020; Takahashi *et al.,* 2021]. These results represent a rich new set of cloud process information, but they have not yet been combined with the ISCCP-based results on global cloud variability, storm or cloud system evolution from tracking, and the Weather State analyses connected to atmospheric circulation.

Thus, the evolution of ideas for using the ISCCP products went from determining average cloud properties and radiative fluxes at the top-of-atmosphere, to investigating cloud effects on radiative flux profiles and cloud-precipitation relationships, to diagnosing the connection between the atmospheric circulation (weather) and cloud dynamical properties. This evolution has led to refinements of the ISCCP product contents supported by ongoing evaluations from other satellite instruments and field experiments. In addition to adding estimates of cloud phase and water path, the emphasis in later products has shifted to the Level 2 details, especially in the latest ISCCP-H with 8 km sampling (gridded at 0.1° in HXG). The uses of global, high-space-time-resolution satellite cloud measurements to study cloud processes, as summarized above, is a significant change from earlier concepts that envisioned only field experiments for this purpose. Much more can be done with the datasets already available.

Two important analysis concepts that have not evolved very much over the decades are the concepts of climate sensitivity and cloud-climate feedback and how to estimate them from observations. For instance, these concepts are defined by Bony *et al.* (2006) in exactly the same terms as used in the 1980s (*cf*. Arking, 1991). These formulations are both flawed, especially when applied to observations.

Climate sensitivity is usually defined as a simple ratio of any imposed change of the global mean top-of-atmosphere (TOA) **net** radiation and a change in global mean surface temperature (averaged separately and ignoring other aspects of the climate): quantitative disagreements in estimates of even this simple quantity are produced by its evaluation from a variety of sources over various time periods, with or without an adjustment to account for the more rapid equilibration of the stratosphere. The concept is fundamentally flawed in five ways: (1) a ratio of separately averaged, finite changes of two quantities over limited time spans is neither a partial nor total time derivative relating these two quantities (despite usually being represented as one of these) because it does not account for conditional dependence, especially non-linear space-time variations; (2) the infrared portion of the TOA net flux is part of the climate system response, so this approach confuses forcing and response; (3) the ratio assumes that small changes of surface temperature are produced only by direct TOA net radiation changes in linear proportion, which ignores not only the non-linear relationship between the space-time variations of radiative fluxes and temperatures, but also ignores the effects on surface temperature of changes of atmospheric and oceanic circulations that may also be induced by the radiation changes – induced circulation changes redistribute the temperature changes; (4) evaluation of the ratio from observations, even over decades-long records, does not in any case represent the equilibrium climate change, which depends on changes of the ocean and ice sheets on even longer time-scales; and (5) the ratio includes unforced and uncorrelated variations of surface temperature and net radiation (especially the longwave component), which may or may not partially offset the forced changes. Despite these flaws, the use of this concept persists today.

Climate feedbacks are defined by analogy to a simple electric circuit to formulate the analysis approach, which may be applicable to "toy-models" of climate, where there are only a few known (linear) relationships among a small number of variables. Experiments with more complicated models are, nevertheless, evaluated in the same way, even though the use of this analogy effectively assumes that the feedbacks are linearly separable and constant, which is not true of the actual climate feedbacks, especially those involving clouds and water, or even of the modeled feedbacks. Experiments with more complicated climate models can be done where one particular relationship at a time is isolated to evaluate “effective” partial derivatives (*e.g.,* Hansen *et al.,* 1984), but the results for many feedbacks cannot simply be added together because the processes interact as evidenced by the fact that their estimated magnitudes depend on the order in which they are evaluated in such experiments. In any case, such “relationship isolation” experiments cannot be done with observations of the real climate where all processes are operating simultaneously, so such model results cannot be verified. A review by Stephens (2005) highlights these and other fundamental conceptual difficulties with this definition of feedbacks and illustrates the wide variety of quantitative estimates that result from using different data sources in different ways. However, the research literature continues to report results using this approach with little quantitative consensus (*e.g.*, Bony *et al.,* 2006, who also comment on the sources of disagreement).

In fact, the mathematical formulation of feedbacks that comes from the electric circuit analogy can be rigorously shown to be inapplicable to the real climate, even approximately (Aires and Rossow, 2003). To derive the usual feedback expression from a general representation of a perturbed system (even in the case of a small perturbation) requires six assumptions about the climate, none of which are true. In particular, the assumptions that the feedbacks are constant in time and linearly separable are clearly false, as the feedbacks depend on energy-water exchange processes coupled by cloud processes. Further, they show that such an analysis does not even work for a simple (though non-linear) three-parameter model: Lorenz’s "toy" atmospheric model that illustrated chaos in a simple system (Lorenz, 1984). Even in this model, the feedbacks are "state-dependent", that is, time-dependent. Aires and Rossow also demonstrate that even multi-variate (linear) regression will not correctly diagnose the relationships in this model. They propose an alternative analysis that estimates the situation-dependent first-order relationships (partial derivatives) among variables that might be applicable to observations and for evaluations of models.

Gencaga *et al*. (2015) use the same Lorenz model to illustrate another analysis approach that tries to overcome the limitations of correlating the variations of quantities, which does not indicate the “direction” of information flow; but they find that the problems associated with any feedback system that has simultaneous two-way interactions among multiple processes limit the usefulness of such an approach even when applied to Lorenz' simple model, much less observations of the much more complicated climate system. In particular, there are not enough samples for statistically stable results. For the climate, multi-process coupling is also scale-dependent; that is, the coupling or feedback strengths depend on time and space scales.

Cloud feedback analyses also suffer from the lack of identification of which property of clouds is being considered (implicitly this usually means that only cloud cover fraction is considered) and from an approach that assumes that there is only one cloud effect on the climate (usually only on surface temperature). Limiting the analysis to one cloud property or one effect is not useful for the reasons given above. Even cloud radiative feedback involves different effects in the shortwave and longwave parts of the radiative exchanges (including detailed spectral-height-latitude dependence), the magnitudes of which depend on the different characteristics of the situation (surface and atmosphere) in which the clouds are embedded. That is, the cloud-radiative effect is situation-dependent: the same change in cloud properties produces different radiative effects in different situations (the simplest example is the contrast of cloud radiative effect on solar radiation between day and night). The atmospheric heating by radiation and precipitation feeds back on the atmosphere-ocean circulations on different scales, the former affecting larger space-time scales than the latter. In addition, the cloud processes affect the atmospheric circulation on very different time scales from their effect on the ocean circulation, yet the atmosphere and ocean are also coupled by exchanges of energy and water (and momentum).

Moreover, the actual cloud feedback loop is not considered at all in these studies: cloud processes heat/cool the atmosphere (*cf.* Rossow *et al.,* 2016) and feed back directly on the motions that produced them. The usual formulation of cloud feedback tries to relate the global mean cloud-radiative effects to global mean surface temperature (again, usually separately averaged), but cloud properties do not depend on the global mean surface temperature. Rather the atmospheric circulation depends on the gradients of atmospheric temperature and changes in these gradients by cloud processes (*cf.* Stephens, 2005). Because of the connection of clouds and the atmospheric (and oceanic) circulation, cloud radiative effects necessarily involve changes in both these general circulations that also affect surface temperature and its space-time distribution. None of these connections with the circulations is accounted for in the usual analyses.

Developing an adequate feedback analysis approach, especially one applicable to observations, remains a major problem for quantifying the role of clouds in climate, but diagnosing cloud processes from observations (conditional partial time derivatives) can be done, *e.g.*, applying the method proposed by Aires and Rossow (2003), and can be used to improve model process fidelity. With the global, long-term data records now available for a complete range of energy and water exchanges, cloud feedbacks on weather (shorter-term) variations can be directly evaluated and a beginning made to estimate feedbacks on the ocean circulation. Evaluation of these time derivatives can lead to more realistic weather and climate models that then can be used to estimate climate sensitivity.

15. Accomplishments of ISCCP

At the time of writing of this history, the number of research literature citations to the main documents of ISCCP is greater than 8500.

a. Summary of the evolution of the goals of ISCCP:

(1) Obtain a global cloud “climatology” (defined as maps of monthly averages) to be used (mostly) for climate model evaluation or input, although the motivation was stated as

evaluating cloud-radiative feedback on Earth's radiation budget at the top-of-atmosphere. Precipitation was considered as a separate topic concerning the amount of surface water. Space-time scales of products needed: global coverage at 500 km intervals, at least a 5 year record at 15-day intervals (with proper diurnal sampling). Product contents: total cloud cover, (classical morphological) cloud type amounts and their heights.

(2) Determine cloud radiative effects on radiative fluxes at top-of-atmosphere and surface. Space-time scales of products needed: global coverage at 250 km intervals, at least a 10 year record at 3 hr intervals. Product contents: cloud radiative properties (area cover fraction, top and base temperatures/pressures, optical thickness, together with cloud type amounts, plus atmospheric temperature and composition (ozone, water vapor, aerosols) and surface temperature, albedo and snow/ice cover.

(3) Analyze the role of clouds in the global energy and water cycles, including both radiation and precipitation processes. Space-time scales of products needed: global coverage at 100 km intervals, multi-decadal record at 3 hr intervals. Product contents: add to (2)-contents the cloud water path, phase and particle sizes, coincident precipitation and diagnosed surface turbulent fluxes.

(4) Study dynamics of cloud feedbacks by quantifying atmospheric diabatic heating in synoptic weather events, particularly over storm lifecycles (Lagrangian frame). Space-time scales of products needed: global coverage at 10 km intervals, multi-decadal record at <1 hr intervals. Product contents: add to (3)-contents cloud and precipitation vertical structure and atmospheric motions.

(5) Diagnose cloud processes. Space-time scales of products needed: global coverage at 3–5 km intervals, multi-decadal record at 15–30 min intervals. Product contents: same as (4)-contents plus time-resolved aerosols and better treatment of surface properties. Cloud products combined with finer-resolution atmospheric properties and motions.

b. ISCCP accomplished, contributed to, or started on all of these goals with the following differences:

(1) Cloud types were identified by combinations of cloud top pressure and optical thickness, rather than radiances, which turned out to be useful, though not exactly the same as the traditional morphological cloud types (*cf*. Hahn *et al.,* 2001). However, the mesoscale histogram patterns, “weather states”, corresponded better with the dominant cloud type regimes and are well related to large-scale atmospheric motions (*cf.* Tselioudis *et al.,* 2013, 2021).

(2) Cloud base location cannot be estimated from passive satellite sensors, especially for multi-layered situations, but they can be estimated in a statistical way (Rossow *et al.,* 2005a). The first such results were based on cloud layer statistics from radiosonde humidity profiles (Wang *et al*., 2000). Later satellite radar-lidar results provided direct measures of cloud vertical structure that improved the climatological statistics associating cloud types with vertical profiles (Rossow and Zhang, 2010). Extension of the time period covered by simultaneous and direct measurements of cloud and precipitation vertical structures (along with below-cloud temperature and humidity profiles from microwave sounders) is needed but much more analysis can be done with already available datasets, particularly compositing three-dimensional structures of radiative heating in different types of weather events and at different stages of cloud system lifecycles.

(3) Cloud phase is only approximately identified by top temperature and particle size retrievals are not available from all satellites (Riedi *et al.,* 2010). The vertical variation of cloud phase and particle sizes (shapes) within cloud layers is not routinely determined. Nevertheless, the available results can be combined with other satellite products to estimate energy and water exchanges with useful accuracy (Kummerow *et al.,* 2019).

(4) Global aerosol information (separately for troposphere and stratosphere) and its time-space variations were not available for earlier ISCCP retrievals, but a monthly-averaged product was used for ISCCP-H. Aerosols were always included in the radiative flux calculations, but the detailed information has significantly improved.

(5) ISCCP spatial resolution is adequate for most of these goals, but the time resolution is limited to 3 hr intervals in current products and the active sensors needed to obtain vertical profiles of clouds and precipitation are usually on polar orbiters with 12 hr sampling intervals (actually much longer time intervals because of very small swath widths). However, these products can still be combined in statistical composites to study the life-cycle evolution of larger-scale storm systems.

c. Other key analysis concepts developed over the past several decades as part of or with contributions from ISCCP:

(1) A hierarchical data product structure, including archiving the input (with separate calibration), intermediate processing stages, ancillary data, and the output data in several space-time forms, facilitates different kinds of research uses (including regional studies). This structure also provides better quality control at many stages of the processing that helps locate any problems.

(2) Inclusion of the ancillary data used in the retrieval in the cloud data products facilitates diagnostic analyses that are physically consistent with the retrieval, such as determining radiative fluxes (*e.g.*, Zhang *et al.,* 2004) or analysis of the conditional dependence of cloud property variations.

(3) Estimation of cloud cover in small spatial domains by counting pixels with clouds present (pixel cover either 0 or 1) determined by finite (not minimum) detection thresholds, as ISCCP does, produces estimates in some pixels that are too high and in some too low (Rossow *et al.,* 1985; Rossow, 1989; Rossow *et al.,* 1993). This method is an approximate version of the Monte Carlo method for estimating areas – finite thresholds make area estimate errors more nearly random – providing more accurate cloud fraction estimates over small domains with sufficient sampling (Wielicki and Parker, 1992). This also helps reduce the retrieval errors on average.

(4) Preserving the smaller-scale distribution information contained in the radiances in the output physical quantities can be achieved by sampling, rather than averaging, to reduce data volume (Seze and Rossow, 1991), by ensuring that every measurement has an outcome, by making the precision and scaling of the retrieved physical quantities follow that of the radiances, by mapping the results in equal-area grids for globally uniform spatial statistics (Rossow and Garder, 1984), and by time averaging first over random variations at constant phases of regular variation periods (*e.g.*, diurnal, seasonal) and then over the regular periods. The ISCCP analysis and products have all of these features.

(5) Both radiatively-weighted and linear averaging of retrieved quantities, together, provide a useful parametric representation of the effects of small-scale cloud mass variability on area-averaged radiation that is useful for weather and climate model representations (Rossow *et al*., 2002).

(6) Cloud radiative effects at top-of-atmosphere and surface have been quantified with very useful accuracy (Zhang *et al.,* 2004), including the cloud type dependence of the fluxes (Chen *et al.,* 2000), and the association of atmospheric radiative heating rates with Weather States has been quantified (Oreopoulos and Rossow, 2011; Rossow *et al.,* 2016).

(7) Cloud dynamics (time derivatives) are revealed by tracking cloud systems and compositing results over their lifecycles (Machado and Rossow, 1993; Machado *et al.,* 1998; Futyan and Del Genio, 2007; Tan and Jakob, 2013; Fiolleau and Roca, 2013; Polly and Rossow, 2016), or by compositing the evolution of cloud properties by tracking air masses (Luo and Rossow, 2004; Masunaga and Luo, 2016), both of which require high space-time

resolution products (Level 2). Currently, the ISCCP products have the highest time resolution. Such diagnoses are needed to understand cloud processes in weather and climate beyond simply describing cloud property variation statistics. Such analyses with the more advanced satellite cloud, precipitation and atmospheric products now available are needed.

(8) Characteristic mesoscale mixtures of cloud properties, rather than individual cloud types, relate better to atmospheric conditions and motions (Hahn *et al.,* 2001; Tselioudis *et al.,* 2013; Tselioudis *et al.,* 2021); these mixtures are called cloud regimes or Weather States.

(9) Precipitation rates associated with Weather States have been quantified (Jakob and Schumacher, 2008; Rossow *et al.,* 2013; Lee *et al.,* 2013; Rossow *et al.,* 2016; Luo *et al*., 2017), including identifying those responsible for extreme precipitation events (Tromeur and Rossow, 2010; Tan *et al.,* 2013, 2015; Mekonnen and Rossow, 2011, 2018; Worku *et al.,* 2020).

16. Status of Cloud Knowledge and Understanding in 2022

Cloud Properties: Numerous globally and seasonally complete satellite surveys of cloud properties have been completed with reasonably good agreement among the available products (Stubenrauch *et al*., 2013; Karlsson and Devasthale, 2018), although more detailed comparisons are needed to explain the differences, particularly for specific cloud types or regions. Compared with pre-satellite knowledge of cloud properties mostly from land-based surface observations, which quantified total and morphological cloud type amounts and estimated cloud base heights for low-level clouds, the global statistical characterization of cloud properties and their diurnal to weather-scale to seasonal to interannual variations is nearly complete, encompassing horizontal coverage (both frequency of occurrence and amount when present), layer heights and thicknesses (especially detailed from lidar and radar), particle sizes at cloud top, and frequency of occurrence of liquid and ice phases (especially from combined multi-wavelength radiances and polarization measurements). A focus of both field experiments and satellite studies has been on low-level clouds over oceans and cirrus – the two types identified in GARP-16 for attention – as well as tropical deep convection with a focus on precipitation. The properties and environments of the first two types of clouds are now well characterized, even though the connections with boundary layer turbulence dynamics (Wood, 2012) and with upper atmospheric turbulence and radiative cooling effects still needs work. Significant progress has also been made in satellite-based determinations of the properties of Polar Stratospheric Clouds, first seen by the second Stratospheric Aerosol Mission (SAM-II, McCormick *et al.,* 1982), and understanding their role in stratospheric ozone depletion chemistry (Tritscher *et al.,* 2021).

The information that still needs improvement concerns the frequency of occurrence of mixed phase clouds, especially in the polar regions (*cf.* Cesana *et al.,* 2012). More detailed studies of the seasonal and weather-scale variations of cloud properties and structures, as well as precipitation, over mountainous terrain and in polar regions (where the various datasets do not agree well, *cf.* Eastman and Warren, 2010) are needed, especially over Antarctica. Ice clouds, in general, are still poorly quantified (*cf.* Waliser *et al.,* 2009), especially the vertical distributions of particle shapes and sizes and the possible diurnal and weather-related variations of their properties. Moreover, the formation of ice particles still has important uncertainties (Cantrell and Heymsfield, 2005). Several multi-decadal cloud products now suggest a small, long-term trend in global mean cloud amount (*cf.* Rossow *et al.,* 2022) that may be related to a warming trend or to slow ocean changes (see Fig. 2), but the cause needs to be investigated. However, there is currently a growing number (more than a dozen) of similar global cloud products being produced with no coordination; this multiplicity of products with little knowledge of how well they agree is creating confusion in research results that may inhibit progress.

<u>Clouds and Radiation:</u> The effects of clouds on radiative fluxes, especially at the top-of-atmosphere and the surface (the first goal of ISCCP), have been calculated from measured cloud, surface and atmospheric properties with very useful accuracy (Zhang *et al*., 2004; Raschke *et al.,* 2016) as evaluated by comparison with more direct measurements. These results are global in extent and resolve the diurnal cycle and longer-term variations. Flux profiles have also been estimated, globally using statistical models of cloud vertical structure (Zhang *et* al. 2004) and using lidar-radar-based cloud vertical structures with more limited space-time sampling (L'Ecuyer *et al*., 2008). The relationship of the fluxes to cloud properties has been examined in a number of different ways, from individual cloud types (Hartmann *et al.,* 1992; Chen *et al*., 2000) to mesoscale and global mixtures of cloud types (Oreopoulos and Rossow, 2011). Work has begun to relate these results to the circulation of the atmosphere (Tselioudis *et al.,* 2013; Li *et al*., 2013; Rossow *et al.,* 2016; Tselioudis *et al.,* 2021).

Two needed refinements of these calculated fluxes require more complete optical properties; cloud top particle sizes and phase have been measured, but their variation with weather conditions and within cloud layers is still to be examined. Likewise, extending and improving on the observations of cloud vertical structure is needed (a follow-up to CloudSat and CALIPSO will be a European mission called EarthCare), but the detailed dynamic evolution of cloud <u>and</u> precipitation (and water vapor) vertical structure needs to be related to synoptic weather variations to diagnose cloud processes. More detailed statistical composites of storm lifecycle variations could be formed with available data products (*cf*. Futyan and Del Genio, 2007; Fiolleau and Roca, 2013; Polly and Rossow, 2016). Radiative flux changes that might be associated with the long-term variations of clouds have now been observed (*e.g*., Wild *et al.,* 2008; Wild *et al*., 2013; Loeb *et al*., 2018a, 2018b; Loeb *et al.,* 2021).

<u>Clouds and Precipitation:</u> About 10% of clouds form precipitation between their formation and decay by particle collisions that remove water mass from the cloud. The collisional growth of liquid droplets is well-understood (*e.g.*, Khvorostyanov and Curry, 2014), but a general quantitative knowledge of precipitation rate (or intensity) evolution, particularly the frequency of occurrence of drizzle and very heavy precipitation, over the lifecycle of storms and the relation of accumulated precipitation amounts to cloud lifecycle and atmospheric motions on all scales are not yet complete. These features could be determined with available satellite data products. More complicated cloud particle collisions, namely of ice crystals (snow) or liquid with ice particles, and the formation of very large particles (graupel, hail), are not well-understood. The latter is key to severe precipitation events. Precipitation has generally only been quantified as accumulation over some time period at each location (Eulerian frame), but to understand the dynamics of precipitating cloud systems and the feedbacks on the atmospheric and oceanic circulations requires determination of the time evolution of precipitation intensity (instantaneous rate) over the life cycle of weather systems (Lagrangian frame). A start on such an analysis has been made by tracking precipitation features using a new high time resolution precipitation product (Takahashi *et al.,* 2021).

All of these characteristics of precipitation still need to be specifically related to the properties of the cloud systems and the atmospheric conditions/circulations that produce them (but see Masunaga, 2014; Masunaga and Luo, 2016). Progress in the remote sensing of clouds and precipitation (Stephens and Kummerow, 2007), especially obtaining higher time resolution precipitation measurements from the GPM mission (Skofronick-Jackson *et al*., 2017; Huffman *et al.,* 2020) to complement ISCCP products, together with more advanced cloud property retrievals (Stephens *et al.,* 2002; Platnick *et al.,* 2003; Winker *et al.,* 2010; Stubenrauch *et al.,* 2010), sets the stage for a global analysis of the dynamical relation of clouds and precipitation. Some first analyses based on the Weather States have identified characteristic transitions of tropical convective storm structure during Madden-Julian Oscillation (MJO) events, African Easterly Waves (AEW) and Asian Monsoons (respectively, Tromeur and Rossow, 2010; Mekonnen and Rossow, 2011, 2018; Wu and Chen, 2021). However, similar attention has not been paid to extratropical frontal convection.

Cloud Dynamics (Processes) and Cloud System Lifecycles: The formation and eventual decay of an individual cloud involves condensation and evaporation – vapor-particle exchanges – that depend on the relative humidity of the air. This process is well-understood (*e.g.*, Khvorostyanov and Curry, 2014), especially for liquid droplets. Even aerosol effects on this process for liquid clouds are well-understood at the microphysical level. What is not well documented is the nature and weather-scale variations of the aerosols and the scale dependence (from boundary layer turbulence through weather scales to climate scales) of the aerosol-cloud interactions (Fan *et al.,* 2016). Mixed-phase vapor exchanges can also be calculated, but knowledge about the nature of such clouds is limited. What still challenges our understanding is a more quantitative knowledge of ice crystal formation, shapes and rates of growth, as well as potential aerosol effects on them. Most clouds (about 90%) are non-precipitating clouds with a mass representing less than one percent of the *in situ* water vapor mass. They are formed out of water vapor and return to water vapor with no mass loss: they are a transient state of the air, but their lifetime is related to the atmospheric dynamics that produced them. Individual boundary layer clouds can have lifetimes of order 10s of minutes to hours, but midlatitude layer clouds in the free troposphere can last much longer, even though their microphysical properties evolve more rapidly than their lifetimes. Analyses of observations that account for the transient dynamics of clouds, instead of time-averaged properties, are needed.

The main limitation in understanding cloud processes is quantifying the relation of atmospheric motions on all scales at the same time to the evolution of cloud water mass and the statistics of their microphysical properties, particularly in the atmospheric boundary layer and polar regions. Current limitations on the time resolution of satellite cloud observations – ISCCP samples at 3 hr intervals but most of the advanced instruments sample at 12–24 hr intervals at best – constrain studies of cloud system lifecycles to larger-scale storms. The lifecycles of boundary layer clouds and isolated cirrus layers (*cf.* Luo and Rossow, 2004) – variations dominated by small-scale turbulence – are still not well characterized. To address the dynamics of smaller-scale turbulent cloudiness and to improve lifecycle analyses in general, the time sampling interval needs to be decreased to at least 30 min to allow for more accurate estimates of the cloud process time derivatives at smaller spatial scales. Such observations have to encompass the motion of cloud systems or air parcel motions to allow for a Lagrangian analysis. Although satellite imaging data are currently being obtained with even higher time resolutions, these data are not systematically analyzed to provide the needed cloud products. When high-time resolution cloud products are combined with other information (simultaneous and coincident) to characterize the properties of the atmosphere and its motions, a direct analysis of cloud variations across the whole range of space-time scales produced by atmospheric motions will provide better understanding of the coupling of clouds to other components of the weather and climate.

Clouds and Atmospheric Dynamics – Feedbacks on Weather: Clouds are produced (transiently) by atmospheric vertical motions that cause a decrease of temperature with a consequent increase in relative humidity leading to water vapor condensation. Radiative cooling can in some circumstances cause enough cooling to produce clouds, especially in the uppermost troposphere and polar regions. Hence, cloud mass variability appears across all the scales of atmospheric motions (*cf.* Rossow and Cairns, 1995), which are much larger than the microphysical process scales. The occurrence of clouds, in turn, causes heating of the atmosphere by radiation and precipitation – a positive feedback on the strongest motions but possibly a negative radiative cooling feedback on weaker, small-scale turbulent motions, especially in the upper and polar atmosphere (see contrasting diabatic heating of different Weather States discussed in Rossow *et al.,* 2016). Since the cloud radiative and latent heating occur on different space-time scales – radiative heating scales are generally larger than latent heating scales – the feedbacks on the atmospheric circulation couple to the cloud-inducing motions in a scale dependent manner, reinforcing some and damping others. How these cloud processes affect the evolution of meteorological events is not yet well quantified (*cf.* Tromeur and Rossow, 2010; Polly and Rossow, 2016).

The relationships between atmospheric motions and the variation of bulk cloud properties and consequent diabatic heating have not been characterized systematically from observations (*cf.* Romanski and Rossow, 2013), despite the availability of very large amounts of global satellite products and systematic weather reanalyses, nor has a quantitative theory of the relationships in meteorological events been developed for models. Analysis of the observation of these relations must be done in terms of the weather conditions – this sort of study has just begun using the cloud properties for classification (*e.g.*, Tselioudis *et al.,* 2013, Rossow *et al.,* 2016; Polly and Rossow, 2016; Tselioudis *et al.,* 2021). Other possibilities of this type of analysis would use other meteorological quantities (such as vertical motions or humidity) for classification (see McDonald and Parsons, 2018 for examples). Much more could be done with already available data products: it should now be possible to diagnose the complete cloud feedbacks on different weather systems.

Cloud Feedbacks on Climate Variations: The initial idea at the beginning of ISCCP – that measuring cloud properties to determine their effects on top-of-atmosphere radiative fluxes would tell something about cloud-radiative feedback on climate – was too simple and conceptually incomplete. First and foremost, to determine a feedback requires simultaneous and coincident observation of the variations of the whole feedback loop and diagnosis of the rates of exchange of energy among the components. The direct cloud-climate feedback loop is composed of atmospheric motions producing clouds, leading to cloud-induced diabatic heating of the atmosphere by radiation (primarily longwave) and precipitation, which alters the atmospheric motions. An indirect loop involves cloud cooling of the ocean by radiation (primarily shortwave) and evaporation, affecting its circulation, which couples back to the atmospheric circulation on longer time scales. These two loops need to be separated diagnostically. Secondly, such observations and diagnoses have to be conducted with sufficient time resolution to quantify the coordinated variations (time derivatives and their dependence on the history of conditions) and exchanges across all circulation-process time scales and to cover a long-enough time period to encompass actual variation of the climate. The ISCCP results – measuring cloud properties and calculating the effects of clouds on radiative fluxes – were a necessary first step.

These cloud results must now be combined with coincident precipitation measurements and other observations of the properties of the atmosphere (including its motions and the below-cloud humidity) and surface (especially temperature). However, the other exchanges of energy besides those directly related to clouds must also be accounted for. Hence, the GEWEX activity to produce a complete observation-based determination of the global energy and water exchanges, results now covering a 15 yr period, sets the stage for a true feedback analysis (Kummerow *et al.,* 2019). At least, these energy-water exchanges can be examined on seasonal scales and the time scales of some oceanic variations such as El Niño Southern Oscillation (ENSO) events. With the growing length of the ISCCP data record, it is possible to examine atmospheric variations (Arctic Oscillation, AO, and Antarctic Annular Oscillation, AAO) that might be associated with the slower ocean changes (such as the Atlantic Meridional Oscillation, AMO, and the Pacific Decadal Oscillation, PDO) and so diagnose at least the transient cloud feedbacks on these longer-than-seasonal time scales.

The ISCCP record and the energy-water exchanges determined from it could now be extended to more than 30 years (limited by microwave-based products) with sufficient time resolution to examine the mesoscale to global scale variations. Although model-to-model comparison diagnostics and protocols can make good use of the several proposed, simple feedback formulations (even though they are flawed) as well as other analysis ideas (Aires and Rossow, 2003; Klein and Hall, 2015), a proper feedback analysis formulation that can be applied to observations still needs to be developed. Meanwhile research could focus on diagnosing the physical equations for cloud processes to be employed in climate models (rather than "static" statistical comparisons of the outcome of the cloud parameterizations), which then can be evaluated against the variations in the long global data records.

17. Future Satellite Cloud Measurements and Studies

The revisions of the analysis to produce the ISCCP-H products focused on maximizing time record homogeneity to begin characterizing climate-scale variations; hence only the VIS/IR radiances common to the whole operational satellite constellation are and will continue to be used to extend the record. Continuing evaluation of the accuracy of the results should examine four contributions to uncertainties (c*f.* Appendix 2 in Stubenrauch *et al.,* 2012): (1) the stability and uniformity over the record of the radiance calibrations, as well as their absolute accuracy (currently uncertainty is estimated to be about ±3% for VIS and IR); (2) the effect on the record of changes over time of satellite characteristics (*e.g.,* pixel size and spacing) and their orbital positions because of spatial irregularities in the results (*e.g.,* associated with the angle dependence of the retrievals); (3) any systematic changes in sampling (especially because of missing data) of time-of-day, day-night, land-water or geography; and (4) any systematic changes in the assumed properties of clouds used in the retrievals (such as average cloud particle size or the temperature statistically separating liquid and ice clouds). The new calibration procedure, which uses all of the data over the whole record, should maintain the uniformity of the radiance calibration. Pre-processing of new satellite imaging, as has become necessary for the new VIIRS instrument, should allow a near-approximation of the image characteristics over the whole record, because the same reasons for choosing the spectral responses continue (monitoring cloud motions) and because smaller pixel sizes can be averaged to larger sizes and sampled in space and time in a similar way. The routine data collection to support monitoring of the weather should prevent large changes in time and space coverage. The last item will have to be monitored by other more advanced measurements.

Although the relative accuracy of ISCCP-H may not be good enough to monitor a slow climate trend induced by increasing CO_2 abundance (the cause of the changes in Fig. 2 is not yet decided), the accuracy appears to be good enough to measure changes associated with the natural variation modes, weather events to MJO and seasonal changes, climate-scale events such as ENSO and now, possibly the PDO, AO and AAO as the record grows longer. Certainly, the ISCCP record is now long enough to provide many samples of all types of meteorological events and their seasonal and interannual variability, which allows for thorough statistical associations to be produced between cloud properties (types and mixtures), diabatic heating (radiation, precipitation) and atmospheric properties (temperature, humidity) and circulations. The ISCCP time resolution is good enough to estimate time derivatives of the bulk cloud properties. Cloud processes can be directly examined by combining the ISCCP samples with other more advanced measurements (covering more limited time periods at lower time resolution) to form statistical composite life cycles for process studies.

The many new and enhanced satellite instruments that have become available since ISCCP began (Table 3 lists mostly operational instruments, but see Annex 4) suggest several important cloud process studies that are already possible. Imaging instruments now have many more solar channels, some making multi-angle (MISR, Diner *et al.,* 2005) and/or polarimetric (POLDER) measurements, and more infrared channels approaching the capability of the earlier operational channel-sounders so that the time dependence of the near-cloud environment can be better determined (MODIS to VIIRS, https://www.jpss.noaa.gov). POLDER's polarimetric measurements are also useful for determining cloud top microphysical properties (*e.g.*, Riedi *et al.,* 2010; Coopman *et al.,* 2020); these observations have yet to be sorted by weather situation and directly associated with precipitation onset. Infrared sounders are now being replaced by infrared spectrometers that allow for more comprehensive, self-consistent retrievals of atmospheric, surface and cloud (especially ice cloud) properties (AIRS and IASI to the Cross-track Infrared Sounder, CrIS; https://www.jpss.noaa.gov). Microwave imagers are providing more frequency coverage, where higher frequencies are important for better characterization of ice clouds, and more frequent coverage reducing the time sampling intervals. Microwave sounders, especially for water vapor, provide (nearly) all-weather coverage – especially water vapor below clouds (AMSU to the Advanced Technology Microwave Sounder, ATMS; https://www.jpss.noaa.gov), which improves determination of the cloud-forming atmospheric variations. Active sensors, lidars (CALIPSO, Winker *et al.,* 2010) for aerosols and clouds and cloud layering (CloudSat, Stephens *et al.,* 2002) – next is a European mission called EarthCare – and precipitation (TRMM to GPM, Skofronick-Jackson *et al.,* 2017) radars provide the key vertical structure measurements. Most of these advanced sensors are still flying only on polar orbiters for global coverage with time sampling at ≥12 hr intervals (generally limited swath widths for the active sensors cause much longer sampling intervals), but these observations can be combined with higher frequency imaging data (clouds) to produce statistical composite lifecycle information. More analyses that combine multiple instrument measurements are needed to fully encompass the multi-variate relationships in cloud-atmosphere interactions.

Table 3: Key developments of (mostly) operational satellite instrumentation and analysis methods to study cloud processes

Decade	*Instrument*	*Analysis*
1970s	Imagers	Cloud cover
1980s	Imagers	Cloud cover, top-temperature, optical thickness (ISCCP)
	AVHRR	Split-window for SST but Inoue (1985, 1987) demonstrated identification and better vertical placement of transparent cirrus
	HIRS	Clear sky IR sounder for tropospheric temperature and water vapor plus microwave temperature sounder for all-sky conditions except precipitating clouds (Chedin *et al.*, 1985; Khalsa and Steiner, 1988; *cf.* Shi and Bates, 2011)
1990s	AVHRR	3.7 μm channel used to retrieve cloud droplet sizes (Nakajima *et al.*, 1991; Han *et al.,* 1994; Nakajima and Nakajima, 1995) and for polar cloud detection

	HIRS	provided direct cloud top pressure (Wylie and Menzel, 1999) and estimates of multi-layer clouds with thin upper layer (Jin *et al.*, 1996; Jin and Rossow, 1997)
	SMMR*, SSMI**	microwave imager, provided first estimate of multi-phase clouds (Lin and Rossow, 1994, 1996) and precipitation
	POLDER	cloud droplet sizes and cloud top phase (Riedi *et al.,* 2010), also improved ice cloud scattering angle dependence (Baran and Labonnote, 2007)
	AMSU-B	operational microwave sounder of water vapor under clouds (Ferraro *et al.,* 2005)
2000s	Geostationary imagers (MSG***, HIM****, GOES) and HIRS	6.7 µm channel provides better upper tropospheric water vapor (Bates *et al.,* 2001) and location of transparent cirrus (*cf.* Liou *et al.,* 1990), 6.7 µm channel combined with SSMT2 provides water vapor in cirrus (Luo and Rossow, 2004)
	HIRS	thin ice cloud particle sizes (Stubenrauch *et al.,* 2004, 2006)
	MODIS	more robust cloud droplet sizes and phase (Platnick *et al.*, 2003), vertical distribution of cloud droplet sizes (Chang and Li, 2002)
	POLDER-MODIS	temperature separating cloud phases (Coopman *et al.*, 2020)
	AIRS/IASI	ice cloud properties (Stubenrauch *et al.,* 2008, 2010), whole-spectrum profile analysis (*cf.* Aires *et al.*, 2002)
	AMSR	advanced microwave imager
2010s	VIIRS, ATMS, CrIS operational	more spectral information, joint analysis could characterize coincident cloud and atmospheric properties

*Scanning Multichannel Microwave Radiometer
**Special Sensor Microwave Imager
***Meteosat Second Generation
****Himawari (Japanese weather satellite)
*****Advanced Microwave Radiometer

An opportunity now exists because, as of 2022, all of the operational weather satellite imagers have (at least) 10 common spectral channels: 0.47, 0.64, 0.86, 1.6, 3.9, 6.2, 7.3, 8.6, 10.4, 12.4 µm (it was 2004 before a third channel became available in common across the whole constellation). These extra channels would allow retrieval of more cloud microphysical information (particle size and phase), key to connecting cloud variations with precipitation. The increased imaging frequency now common to these satellites allows reduction of the time sampling interval to at least 15–30 min, still with global coverage (multiple polar orbiters are available that allow such sampling in the polar regions). Reducing the time sampling interval allows for better study of the connection of smaller-scale turbulence and cloud properties and better identifying the conditions at precipitation onset. Moreover, the range and coverage of other operational satellite measurements of surface and atmosphere properties (particularly the microwave water vapor sounders) are now more extensive and frequent (6 hr sampling intervals).

While continuing the current ISCCP to extend the length of a homogenous time record, a new project in parallel could be established to collect and process these more extensive observations, based on the same operational agency arrangements for ISCCP (in fact, the data needed for ISCCP-H would be subsample of the newer radiance images). Based on the research and development work using these additional channels that has already been completed, the new products could extend the ISCCP cloud properties to include particle size and phase as well as improved information about cloud layering – at least identifying thin layers over lower layers. Such a product would refine the radiative calculations, especially better treatment of angle-dependence in the retrievals, and provide a closer connection between cloud properties and precipitation. The reduction of the time sampling interval to at least 30 min, which together with reanalysis winds and other satellite atmospheric properties, would directly tackle cloud dynamics by directly estimating cloud process time derivatives. Available computer power makes such a project feasible, especially with highly modular processing code, although the data volume might still have to be reduced by sampling to be only a couple of orders of magnitude larger than ISCCP B1 data. New analysis procedures, such as neural-network-based schemes (*e.g.,* Aires *et al.,* 2001, 2002), have been demonstrated that can perform the necessary multi-channel retrievals rapidly and with good accuracy. Such a project (called ISCCP-NG) has been proposed.

Despite the organization of satellite data analysis projects under WCRP and various national auspices and the routine exchange of data among the operational weather agencies (usually only radiances), there is still not a globally-coordinated data collection and analysis system that exploits the very rich set of measurements now available to routinely provide significantly-enhanced information for weather forecasting, cloud and weather process analysis, and climate-scale variation diagnoses of energy and water exchanges. There are many organizations that claim such coordination (by having meetings and issuing reports), but in practice, little of the data is actually analyzed into consistent physical information and stored for ready access, not only by the Earth research community, but also by other users in need of information about conditions on Earth. In many cases, such as with cloud products, there are now multiple products available, some produced from the same satellite source, that have not been thoroughly evaluated or even compared, so the fidelity of the information is not known. This confusing situation continues despite the call for a global observing and analysis system ever since the advent of satellites and the organization of GARP and WCRP in the 1960s and 1970s. Instead, many *ad hoc* arrangements are made for particular purposes without sustainable funding or long-term satellite agency commitments, especially for coordinating joint analysis efforts. ISCCP has survived as long as it has, beyond the originally planned 5 yr project, by piecing together a series of rationales to fund the continued collection and extension of processing of the weather satellite imaging data. Now the project is fully operational. Much more could be done for other datasets and products.

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Graeme Stephens chairman and 12 Years: The International Satellite Cloud Climatology Project (ISCCP) and its Regional Projects, Special Symposium held during the IUGG XXI General Assembly, Boulder, Colorado, USA, (3), Vol. 5, No. 4, GEWEX International Project Office, Washington DC, http://www.gewex.org.

1996 August: International Workshop on Research Uses of ISCCP Datasets, New York, New York, USA, April 1996, (13–14), Vol. 6, No. 3, GEWEX International Project Office, Washington DC, http://www.gewex.org.

1998 February: Report of 9th Session of the GEWEX Radiation Panel, Honolulu, Hawaii, USA, July 1997, (15–16), Vol. 8, No. 1, GEWEX International Project Office, Washington DC, http://www.gewex.org.

2002 November: Report of 13th Session of the GEWEX Radiation Panel, Zurich, Switzerland, August 2001, (8–9), Vol. 12, No. 4, GEWEX International Project Office, Washington DC, http://www.gewex.org.

2003 August: Report of 1st Session of GRP WGDMA, Asheville, North Carolina, USA, May 2003, (17–18), Vol. 13, No. 3, GEWEX International Project Office, Washington DC, http://www.gewex.org.

2004 February: Report of 14th Session of the GEWEX Radiation Panel, Victoria, Canada, November 2003, (11–13), Vol. 14, No. 1, GEWEX International Project Office, Washington DC, http://www.gewex.org.

2004 November: Report of 15th Session of the GEWEX Radiation Panel, Kyoto, Japan, October 2004, (17–19), Vol. 14, No. 4, GEWEX International Project Office, Washington DC, http://www.gewex.org.

2005 November: Report of 16th Session of the GEWEX Radiation Panel, Paris, France, October 2005, (17–18), Vol. 15, No. 4, GEWEX International Project Office, Washington DC, http://www.gewex.org.

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2009 February: Report of 19th Session of the GEWEX Radiation Panel, Cheju Island, South Korea, October 2008, (13–15), Vol. 19, No. 1, GEWEX International Project Office, Washington DC, http://www.gewex.org.

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2011 February: Report of 21st Session of the GEWEX Radiation Panel, Seattle, Washington, USA, August 2010, (12–15), Vol. 21, No. 1, GEWEX International Project Office, Washington DC, http://www.gewex.org.

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2014 August: Report of 3rd Session of the GEWEX Data and Assessments Panel, The Hague, Netherlands, July 2014, (10–11), Vol. 24, No. 3, GEWEX International Project Office, Washington DC, http://www.gewex.org.

2016 May: Report of 4th Session of the GEWEX Data and Assessments Panel, Xiamen, China, September 2015, (11–14), Vol. 26, No. 2, GEWEX International Project Office, Washington DC, http://www.gewex.org.

2017 November: Report of 5th Session of the GEWEX Data and Assessments Panel, Boulder, Colorado, USA, October 2017, (15–18), Vol. 28, No. 4, GEWEX International Project Office, Washington DC, http://www.gewex.org.

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Annex 1: Acronyms

AAO	Antarctic Annular Oscillation (of atmosphere, also Southern Annular Mode)
AATSR	Advanced Along-Track Scanning Radiometer (Envisat, ESA)
ADEOS	Advanced Earth Observing Satellite (JAXA, Japan)
AES	Atmospheric Environment Service (Canada)
AEW	African Easterly Wave
AGRI	Advanced Geostationary Radiation Imager (FY-4, China)
AIRS	Advanced Infra-Red Sounder (Aqua, NASA, USA)
AMO	Atlantic Meridional Oscillation
AMSR	Advanced Microwave Radiometer (Aqua, NASA, ADEOS-II, JAXA)
AMSU	Advanced Microwave Sounding Unit (NOAA, Metop, EUMETSAT)
AO	Arctic Oscillation (of atmosphere)
ARM	Atmospheric Research Mission (DOE, USA)
ASTEX	Atlantic Stratus Experiment (NASA, USA)
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (Terra, JAXA)
ATMS	Advanced Technology Microwave Sounder (JPSS, NOAA)
ATS	Applications Technology Satellite (USA)
ATSR	Along Track Scanning Radiometer (ERS-1/2, ESA)
AVHRR	Advanced Very High Resolution Radiometer (NOAA, Metop, EUMETSAT)
AVNIR	Advanced Visible and Near-Infrared Radiometer (ADEOS-I, NASDA)
B1	ISCCP Reduced resolution (8 km) imager radiance data
B3	ISCCP Reduced resolution (32 km) imager radiance data
BAMS	Bulletin of the American Meteorological Society
BSRN	Baseline Surface Radiation Network (WCRP/GEWEX)
BT	ISCCP Calibration data for B3 radiances
C1	ISCCP First Version Cloud Product (global, 2.5°, 3 hr)
C2	ISCCP First Version Cloud Product (global, 2.5°, monthly)
CA	ISCCP Cloud Amount (fraction 0 to 1)
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization (CALIPSO, USA/France)
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CNES, NASA)
CCNY	City College of New York (City University of New York, USA)
CEPEX	Central Pacific Experiment
CERES	Clouds and Earth's Radiant Energy System (Terra/Aqua, NASA, JPSS, NOAA)
CHAMP	Challenging Minisatellite Payload (Germany)
CMA	China Meteorological Administration
CMS	Centre de Meteorologie Spatiale (MeteoFrance)
CNES	Centre National d'Etudes Spatiales (France)
COARE	Coupled Ocean Atmosphere Regional Experiment (TOGA, WCRP)
COMS	Communication, Ocean and Meteorological Satellite (NMSC, Korea)
COSMIC	Constellation Observing System for Meteorology, Ionosphere, Climate (USA, Taiwan)
CrIS	Cross-track Infrared Sounder (Suomi NPP, NASA, JPSS, NOAA)

CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CSU	Colorado State University (USA)
D1	ISCCP Second Version Cloud Product (global, 2.5°, 3 hr)
D2	ISCCP Second Version Cloud Product (global, 2.5°, monthly)
DLR	Deutsches Zentrum fur Luft- und Raumfahrt
DMSP	Defense Meteorological Satellite Program (US Air Force)
DX	ISCCP Second Version Cloud Product (by satellite, 32 km, 3 hr)
EBAF	Energy Balanced and Filled dataset (CERES, NASA)
ENSO	El Nino Southern Oscillation (of ocean)
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment (NASA, USA)
ERBS	Earth Radiation Budget Satellite (NASA, USA)
ERS	Environmental Research Satellite (ESA)
ESA	European Space Agency
ESMR	Electrically Scanning Microwave Radiometer (Nimbus-6, NASA)
ESSA	Environmental Science Services Administration (NOAA, USA)
ETH	Swiss Federal Institute of Technology in Zurich (Switzerland)
EUCREX	European Cirrus Experiment
EUMETSAT	European Organization for Exploitation of Meteorological Satellites
FGGE	First Global GARP Experiment
FIRE	First ISCCP Regional Experiment
GACP	GEWEX Aerosol Climatology Project (WCRP/GEWEX)
GARP	Global Atmospheric Research Program (WMO, ICSU)
GATE	GARP Atlantic Tropical Experiment
GCOM	Global Change Observation Mission (JAXA, Japan)
GDAP	GEWEX Data and Assessment Panel (formerly GRP)
GEBA	Global Energy Budget Archive (ETH Zurich, Switzerland)
GEO-KOMPSAT-A	Geostationary Korea Multi-Purpose Satellite-A (COMS, Korea)
GERB	Geostationary Earth Radiation Budget (EUMETSAT)
GEWEX	Global Energy and Water Exchanges (formerly "Experiment")
GIIRS	Geostationary Interferometric Infrared Sounder (FY-4, China)
GISS	NASA Goddard Institute for Space Studies (USA)
GLI	Global Imager (ADEOS-II, JAXA)
GMS	Geostationary Meteorological Satellite (JMA, Japan)
GOES	Geostationary Operational Environmental Satellite (NOAA, USA)
GPC	ISCCP Global Processing Center (WCRP/GEWEX)
GPCC	Global Precipitation Climatology Center (WCRP/GEWEX)
GPCP	Global Precipitation Climatology Project (WCRP/GEWEX)
GPM	Global Precipitation Mission (NASA, USA)
GPS	Global Positioning System (USA)
GRACE	Gravity Recovery and Climate Experiment (NASA, USA, DLR, Germany)
GRP	GEWEX Radiation Panel
GSFC	NASA Goddard Space Flight Center (USA)
GVAP	GEWEX Water Vapor Project (WCRP/GEWEX)
HBT	ISCCP Third Version Radiance Calibration for B1 radiances
HGG	ISCCP Third Version Cloud Product (global, 1°, 3 hr)
HGH	ISCCP Third Version Cloud Product (global, 1°, monthly at 3 hr intervals)
HGM	ISCCP Third Version Cloud Product (global, 1°, monthly)
HGS	ISCCP Third Version Cloud Product (by satellite, 1°, 3 hr)
HIM	Himawari (Japanese weather satellite, JMA, Japan)

HIRS	High-resolution Infrared Sounder (NOAA, Metop, EUMETSAT)
HXG	ISCCP Third Version Cloud Product (global, 0.1°, 3 hr)
HXS	ISCCP Third Version Cloud Product (by satellite, 8 km, 3 hr)
IASI	Infrared Atmospheric Sounding Interferometer (Metop, ESA)
ICA	ISCCP Central Archive (NCEI, USA)
ICE89	International Cirrus Experiment, 1989
ICSU	International Council of Scientific Unions
IMD	India Meteorological Department
IMERG	Integrated Multi-satellite Retrievals for GPM dataset (NASA)
INPE	National Institute for Space Research (Brazil)
IR	Infrared Radiance at 10 µm wavelength in this document
IRAS	Infrared Atmospheric Sounder (FY-3, China)
IRC	International Radiation Commission (ICSU)
ISCCP	International Satellite Cloud Climatology Project (WCRP/GEWEX)
ISRO	India Space Research Organization
ISS	International Space Station
JMA	Japan Meteorological Agency
JPL	Jet Propulsion Laboratory (NASA, USA)
JPS	Joint Planning Staff (WCRP)
JPSS	Joint Polar Satellite System (NOAA, EUMETSAT)
JSC	Joint Science Committee (WCRP)
KMA	Korea Meteorological Adminstration
LaRC	NASA Langley Research Center
LEGOS	Laboratoire d'Etudes en Geophysique et Oceanographie Spatiales
LIS	Lightning Sensor (TRMM, NASA)
LMD	Laboratoire d'Meteorologie Dynamique (France)
LMI	Lightning Mapping Imager (FY-4, China)
MADRAS	Microwave Analysis and Detection of Rain and Atmosphere Systems (Megha-Tropiques, ISRO, India, CNES, France)
MERIS	Medium Resolution Imaging Spectrometer (ERS-1/2, ESA)
Metop	Meteorological Operational satellite
MHS	Microwave Humidity Sounder (NOAA, Metop, EUMETSAT)
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding (Envisat, ESA)
MISR	Multi-angle Imaging Spectro-Radiometer (Terra, NASA)
MJO	Madden-Julian Oscillation (of atmosphere)
MLS	Microwave Limb Sounder (UARS/Aura, NASA)
MODIS	Moderate-resolution Imaging Spectroradiometer (Terra/Aqua, NASA)
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
MPI	Max Planck Institute
MRIR	Medium-Resolution Infrared Radiometer (Nimbus-3, NASA)
MSG	Meteosat Second Generation (EUMETSAT)
MSU	Microwave Sounding Unit (NOAA)
MTG	Meteosat Third Generation (EUMETSAT)
MTSAT	Multifunctional Transport Satellite (JMA, Japan)
MWHS	Microwave Humidity Sounder (FY-3, China)
MWRI	Microwave Radiation Imager (FY-3, China)
MWTS	Microwave Temperature Sounder (FY-3, China)
NASA	National Atmospheric and Space Administration (USA)
NASDA	National Space Development Agency (Japan)
NCAR	National Center for Atmospheric Research (USA)

NCEI	National Centers for Environmental Information (NOAA, USA)
NESDIS	National Environmental Satellite, Data, and Information Service (NOAA, USA)
NESS	National Environmental Satellite System (NOAA, USA)
NEWS	NASA Energy and Water Study
NMSC	National Meteorological Satellite Center (KMA, Korea)
NOAA	National Oceanic and Atmospheric Administration (USA)
NPP	Suomi National Polar-orbiting Partnership (NASA, NOAA)
NSMC	National Satellite Meteorological Centre (China)
NYC	New York City
OMI	Ozone Monitoring Instrument (Aura, NASA)
OMPS	Ozone Mapping and Profiler Suite (JPSS, NOAA)
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (CNES, France)
PATMOS-x	Pathfinder Atmospheres -- Extended dataset (NOAA, USA)
PC	ISCCP Cloud Top Pressure (hPa)
PDO	Pacific Decadal Oscillation (of ocean)
POLDER	Polarization and Directionality of Reflectance (ADEOS/PARASOL, CNES)
PR	Precipitation Radar (TRMM, JAXA, NASA)
QC	Quality Check
R2O	Research-to-Operations
ROSA	Radio Occultation Sounder for Atmosphere (Megha-Tropiques, ISRO, India, CNES, France)
RS	ISCCP Surface visible Reflectance (%)
SAC	Scientific Applications Satellite (Brazil)
SAGE	Stratospheric Aerosol and Gas Experiment (NASA, USA)
SAM	Stratospheric Aerosol Mission (NASA, USA)
SAPHIR	Sounder for Atmospheric Profiling of Humidity in the Intertropics by Radiometry (Megha-Tropiques, ISRO, India, CNES, France)
SCAMS	Scanning Microwave Spectrometer (Nimbus-6, NASA)
ScaRaB	Scanner for Radiation Budget (Meteor-3/7, Resurs, Megha-Tropiques, CNES)
SCC	ISCCP Satellite Calibration Center (WCRP/GEWEX)
SEVIRI	Spinning Enhanced Visible Infrared Imager (MSG, EUMETSAT)
SHEBA	Surface Heat Budget of the Arctic (USA)
SMMR	Scanning Multichannel Microwave Radiometer (Nimbus-7, NASA)
SMS	Synchronous Meteorological Satellite (NASA, NOAA, USA)
SPC	ISCCP Satellite Processing Center (WCRP/GEWEX)
SRB	Surface Radiation Budget Project (WCRP/GEWEX)
SRF	Surface
SSEC	Space Science and Engineering Center (U. Wisconsin, NOAA, USA)
SSMI	Special Sensor Microwave Imager (DMSP, US Air Force)
SSMT2	Microwave Water Vapor instrument (DMSP, US Air Force)
SST	Sea Surface Temperature
S-VISSR	Stretched Visible Infrared Spin Scan Radiometer (FY-2, NSMC)
TAU	ISCCP Cloud Optical Thickness
TC	ISCCP Cloud Top Temperature (K)
TES	Thermal Emission Spectrometer (Aura, NASA)
TIROS	Television–Infrared Operational Satellite (NASA, NOAA, USA)
TMI	TRMM Microwave Imager (NASA)

TOA	Top of Atmosphere
TOGA	Tropical Ocean Global Atmosphere (WCRP)
TRMM	Tropical Rainfall Measuring Mission (NASA, JAXA)
TS	ISCCP Surface Temperature (K)
UARS	Upper Atmosphere Research Satellite (NASA, USA)
USA	United States of America
UWS	University of Wisconsin (USA)
VHRSR	Very High Resolution Scanning Radiometer (FY-1, NSMC)
VIIRS	Visible Infrared Imaging Radiometer Suite (JPSS, NOAA, USA)
VIRR	Visible and Infrared Radiometer (FY-3, China)
VIS	Visible Radiance at 0.6 µm wavelength in this document
WCRP	World Climate Research Programme
WENPEX	Western Pacific Experiment (Japan)
WGDM	Working Group for Data Management (WCRP/GEWEX)
WGRF	Working Group for Radiative Fluxes (WCRP)
WMO	World Meteorological Organization (UN)
WP	ISCCP Cloud Water Path (g/m^2)

Annex 2: Chronology of Planning and Oversight Meetings for ISCCP

1978 Oct	1st Planning Workshop, Oxford, UK
1980 Jun	2nd Planning Workshop, Balatonalmádi, Hungary
1980 Aug	3rd Planning Workshop, Ft. Collins, CO, USA
1980 Oct	Scientific Conference, New York, NY, USA
1980 Dec	Users Workshop, Washington, DC, USA
1981 Aug	4th Planning Workshop, Hamburg, Germany
1982 Aug	Establishment Workshop, Geneva, Switzerland

Algorithm Workshops

1982 Jun	1st Algorithm Workshop, Ottawa, Canada
1982 Dec	2nd Algorithm Workshop, New York, NY, USA
1983 Apr	3rd Algorithm Workshop, New York, NY, USA
1984 Mar	4th Algorithm Workshop, Greenbelt, MD, USA
1985 Aug	5th Algorithm Workshop, Honolulu, HI, USA
1986 Aug	Polar Algorithm Workshop, Tokyo, Japan

Working Group for Data Management

1982 Dec	1st WGDM for ISCCP, New York, NY, USA
1983 May	2nd WGDM for ISCCP, New York, NY, USA
1984 Mar	3rd WGDM for ISCCP, Tokyo, Japan
1985 Feb	4th WGDM for ISCCP, Darmstadt, Germany
1986 Jun	5th WGDM for ISCCP, Paris, France
1987 Jun	6th WGDM for ISCCP, Ft. Collins, CO, USA
1988 Jul	7th WGDM for ISCCP, Banff, Canada
1989 Apr	8th WGDM for ISCCP, New York, NY, USA
1990 May	1st WGDM for Radiation Projects, New York, NY, USA
1991 Sep	2nd WGDM for Radiation Projects, Palm Springs, CA, USA
1992 May	3rd WGDM for Radiation Projects, Lannion, France
1993 Oct	4th WGDM for Radiation Projects, Ottawa, Canada
1994 Jul	5th WGDM for Radiation Projects, Budapest, Hungary
1995-2002	WGDM for Radiation Projects Meets with WGRF
2003 May	1st WGDMA, Asheville, NC, USA
2004-2005	WGDMA for Radiation Projects Meets with GRP
2006 Nov	4th WGDMA for Radiation Projects, Greenbelt, MD, USA
2007 Sep	5th WGDMA for Radiation Projects, New York NY, USA
2008 Sep	6th WGDMA for Radiation Projects, Hong Kong
2009 Sep	7th WGDMA for Radiation Projects, College Park, MD, USA
2010-2011	Radiation Projects Representatives meet with GRP
2012-present	Radiation Projects Representatives meet with GDAP

Scientific Oversight by WGRF, GRP, GDAP

1987 Dec	1st WGRF, Greenbelt, MD, USA
1988 Oct	2nd WGRF, Geneva, Switzerland
1989 Dec	3rd WGRF, Ft. Lauderdale, FL, USA

1991 Sep	4th WGRF, Palm Springs, CA, USA
1992 May	5th WGRF, Lannion, France
1994 Jul	6th WGRF, Luneberg, Germany
1995 Jul	7th WGRF, Ft. Collins, CO, USA
1996 Jul	8th WGRF, Dublin, Ireland
1997 Jul	9th GRP, Honolulu, HI, USA
1998 Sep	10th GRP, St. Andrews, Scotland
1999 Sep	11th GRP, New York, NY, USA
2000 Apr	12th GRP, Ft. Collins, CO, USA
2001 Aug	13th GRP, Zurich, Switzerland
2003 Nov	14th GRP, Victoria, Canada
2004 Oct	15th GRP, Kyoto, Japan
2005 Oct	16th GRP, Paris, France
2006 Oct	17th GRP, Frascati, Italy
2007 Oct	18th GRP, Buzios, Brazil
2008 Oct	19th GRP, Jeju Island, South Korea
2009 Oct	20th GRP, Rostock, Germany
2010 Aug	21st GRP, Seattle, WA, USA
2011 Sep	22nd GRP, Tokyo, Japan
2012 Oct	1st GDAP, Paris, France
2013 Sep	2nd GDAP, Rio de Janeiro, Brazil
2014 Jul	3rd GDAP, The Hague, Netherlands
2015 Sep	4th GDAP, Xiamen, China
2016 Dec	5th GDAP, Washington, DC, USA
2017 Oct	6th GDAP, Boulder, CO, USA
2018 Nov	7th GDAP, Lisbon, Portugal
2020 Jan	8th GDAP, Tucson, AZ, USA
2020 Oct	9th GDAP, Online

Annex 3A: Cloud Datasets Based on Conventional Surface Weather Observations

All citations before 1984, except where noted by a date after the name, can be found in the review by Hughes (1984).

1896: First Cloud Atlas (Hildebrandsson and Teisserenc de Bort, 1896)
1917: Dines (1917)
1927: Brooks
1929: Simpson (1929)
1930: Brooks (1930)
1936: Shaw
1938: McDonald (1938) <atlas used by London>
1944: Haurwitz and Austin
1945: Landsberg
1954: Telegadas and London <total & type, NH only, used by London>, Seide
1956: WMO (1956) *International Cloud Atlas* (later two volumes in 1975 and 1987)
1957: London <widely used, NH zonal only, seasonal mean of total and type-height>
1977: Hastenrath and Lamb
1980: Berlyand and Strokina
1986: Warren *et al*. (1986) <most complete and detailed>, Henderson-Sellers (1986)
1988: Warren *et al*. (1988) <most complete and detailed>
2007: Warren *et al*. (2007) <update of Warren *et al*., 1986>
2009: Hahn and Warren (2009a, 2009b) <updates of Warren *et al*. 1986, 1988>
2011: Eastman *et al*. (2011) <update of Warren *et al*. 1988>
2013: Eastman and Warren (2013) <update of Warren *et al*. 1986>

Annex 3B: Cloud Datasets Based on Satellite Observations

All citations, except where noted otherwise by a date after the name, can be found in the reviews by Hughes (1984), Rossow *et al*. (1985), Rossow *et al.* (1989) or Stubenrauch *et al.* (2012).

1964: Arking, Rasool, Clapp <zonal, seasonal mean>
1968: Taylor and Winston
1969: Sadler <extensive, detailed, tropical only>, Kornfield and Hasler, Goodshall *et al.*
1970: Stamm and Vonder Haar
1971: Miller & Feddes <tropical only>, Goodshall
1972: van Loon <SH only>
1976: Sadler et al
1977: Reynolds and Vonder Haar
1981: Bean and Somerville
1982: Chahine, Coakley and Bretherton, Simmer et al.
1983: Rossow *et al.*
1984: Minnis and Harrison <diurnal, one geosat, one month>, Stowe, Coakley and Baldwin
1985: Arking and Childs <first radiatively complete>, Saunders
1987: Minnis *et al.*, Susskind *et al.*
1988: Hwang *et al.*, Stowe *et al*. (also in 1989) <global multi-year, Nimbus-7 IR only>
1990: Rossow and Lacis (1990) <global, 4 months, clouds & surface & radiation>
1991: Rossow and Schiffer (1991) <Release of ISCCP-C starting in 1988>
1996: SAGE-II: Wang *et al.* (1996)

1999: HIRS-NOAA: Wylie and Menzel (1999)
1999: Rossow and Schiffer (1999) <Release of ISCCP-D starting in 1996>
2003: HIRS-Path B: Radel *et al.* (also Stubenrauch *et al.* in 2006)
2003: MODIS: Platnick *et al.* (2003), (also Menzel *et al.* in 2008)
2004: POLDER: Parol *et al.*, (also Ferlay *et al.,* 2010)
2009: Merged CALIPSO-CloudSat data: Mace *et al.* (2009), Mace and Zhang (2014)
2010: CALIPSO: Winker *et al.* (2010), Liu *et al*. (2019)
2010: AIRS-CIRS, IASI-CIRS: Stubenrauch *et al.* (Guignard *et al.* in 2012; Stubenrauch *et al.,* 2017)
2010: CALIPSO-GOCCP: Chepfer *et al.*, MISR: Di Girolamo *et al.*
2011: MODIS-CERES: Minnis *et al.* (Minnis *et al*. in 2020), ASTR-GRAPE: Sayer *et al.*
2012: Heidinger *et al*., also Walther and Heidinger <Release of PATMOS-x in 2006>
2013: Karlsson *et al.* (2013) <CLARA-A1>
2017: Karlsson *et al.* (2017) <CLARA-A2>, Stengel *et al.* (2017 <Release of Cloud_cci-2 in 2014>
2018: Young *et al.* (2018) <Release of ISCCP-H starting in 2016>
2020: Stengel *et al.* (2020) <Release of Cloud_cci-3>

Annex 4: Chronology of Launch Dates for Operational and Experimental Satellites with Cloud-Relevant Instruments

1959: Explorer-VII (Suomi's Radiation Budget experiment)
1960: TIROS-1 (imager), TIROS-2 (imager), TIROS-3 (imager)
1966: ATS-1, ESSA-1 (imager), ESSA-2 (imager), ESSA-3 (imager)
1967: ATS-2 (imager), ATS-3 (imager)
1968: ATS-4 (imager)
1969: ATS-5 (imager), Meteor-1 (imager), Nimbus-3 (MRIR)
1970: NOAA-1 (imager) – first operational polar weather satellite
1972: NOAA-2 (imager)
1973: NOAA-3 (imager)
1974: SMS-1 (imager), NOAA-4 (imager)
1975: SMS-2 (imager), GOES-1 (imager) – first operational geostationary weather satellite, Nimbus-6 [Scanning Microwave Spectrometer (SCAMS), Electrically Scanning Microwave Radiometer (ESMR), Earth Radiation Budget (ERB)]
1976: NOAA-5 (imager, IR sounder)
1977: GOES-2 (imager), GMS-1 (imager)
1978: GOES-3 (imager), TIROS-N [AVHRR, HIRS, Microwave Sounding Unit (MSU)], Nimbus-7 (ERB, SMMR, SAM-II)
1979: NOAA-6 (AVHRR, HIRS, MSU), SAGE I
1980: Meteosat-1 (imager)
1981: NOAA-7 (AVHRR, HIRS, MSU), NOAA-8 (AVHRR, HIRS, MSU), Meteosat-2 (imager), GMS-2 (imager)
1982: GOES-4 (imager), GOES-5 (imager)
1983: GOES-6 (imager, experimental IR sounder)
1984: GMS-3 (imager), the Earth Radiation Budget Satellite (ERBS) (ERB), SAGE-II
1985: NOAA-9 (AVHRR, HIRS, MSU, ERBE)
1986: NOAA-10 (AVHRR, HIRS, MSU, ERBE)
1987: GOES-7 (imager, experimental IR sounder)
1988: NOAA-11 (AVHRR, HIRS, MSU), FY-1A (Very High Resolution Scanning Radiometer, VHRSR), Meteosat-3 (imager), Defense Meteorological Satellite Program F9 (DMSP-F9) (imager, SSMI)
1989: Meteosat-4 (imager), GMS-4 (imager)
1990: FY-1B (VHRSR), DMSP-F10 (imager, SSMI)
1991: NOAA-12 (AVHRR, HIRS, MSU), DMSP-F11 (imager, SSMI), UARS (Microwave Limb Sounder, MLS), Environmental Research Satellite (ERS-1) (Along Track Scanning Radiometer, ATSR)
1994: Meteosat-5 (imager), DMSP-F12 (imager, SSMI), Meteor-3/7 (ScaRaB)
1995: NOAA-14 (AVHRR, HIRS, MSU), DMSP-F13 (imager, SSMI), GOES-8 (imager), GOES-9 (imager), GMS-5 (imager), ERS-2 (ATSR)
1996: ADEOS-1 [Advanced Visible and Near-Infrared Radiometer (AVNIR), POLDER]
1997: DMSP-F14 (imager, SSMI), Meteosat-6 (imager), F-2A (Stretched Visible Infrared Spin Scan Radiometer, S-VISSR), TRMM [Precipitation Radar (PR), TRMM Microwave Imager (TMI), CERES, Lightning Sensor (LIS)]
1998: GOES-10 (imager), Meteosat-7 (imager), Resurs (ScaRaB)
1999: NOAA-15 (AVHRR, HIRS, AMSU-A&B), FY-1C (VHRSR), DMSP-F15 (imager, SSMI), Terra (MODIS, MISR, CERES)
2000: FY-2B (S-VISSR), Terra (MODIS, MISR)

2001: NOAA-16 (AVHRR, HIRS, AMSU-A&B), SAGE-III (Meteor-3M)
2002: NOAA-17 (AVHRR, HIRS, AMSU-A&B), FY-1D (VHRSR), MSG-1 [Spinning Enhanced Visible Infrared Imager (SEVIRI), GERB-2], Aqua [MODIS, AIRS, AMSU-A, Microwave Humidity Sounder (MHS), AMSR-E, CERES], Envisat-1 [Medium Resolution Imaging Spectrometer (MERIS), Advanced Along-Track Scanning Radiometer (AATSR), Michelson Interferometer for Passive Atmospheric Sounding (MIPAS)], ADEOS-2 [Global Imager (GLI), POLDER]
2003: DMSP-F16 (imager, SSMI), GOES-11 (imager), GOES-12 (imager)
2004: FY-2C (S-VISSR), Aura [MLS, Thermal Emission Spectrometer (TES), Ozone Monitoring Instrument (OMI)], PARASOL (POLDER)
2005: NOAA-18 (AVHRR, HIRS, AMSU-A, MHS), MSG-2 (SEVIRI, GERB-1), HIM-6 (imager) (Multifunctional Transport Satellite 1R, MTSAT-1R)
2006: Metop-A (AVHRR, HIRS, IASI, AMSU-A, MHS), DMSP-F17 (imager, SSMI), HIM-7 (MTSAT-2) (imager), CloudSat (CR, Stephens *et al.* 2002), CALIPSO (CALIOP, Winker *et al.,* 2010), Constellation Observing System for Meteorology, Ionosphere, Climate (COSMIC-1) (GPS)
2008: FY-3A [VIRR, Microwave Radiation Imager (MWRI), Infrared Atmospheric Sounder (IRAS), Microwave Temperature Sounder (MWTS), Microwave Humidity Sounder (MWHS)], FY-2E (S-VISSR)
2009: NOAA-19 (AVHRR, HIRS, AMSU-A, MHS), DMSP-F18 (imager, SSMI), Meteor-M (imager)
2010: FY-3B (VIRR, MWRI, IRAS, MWTS, MWHS), GOES-13 (imager), Communication, Ocean and Meteorological Satellite (COMS) (imager)
2011: GOES-15 (imager), Suomi National Polar-orbiting Partnership (Suomi NPP) [VIIRS, CrIS, ATM, Ozone Mapping and Profiler Suite (OMPS), CERES], Elektro-L-1 (imager), Megha-Tropiques [Microwave Analysis and Detection of Rain and Atmosphere Systems (MADRAS), Sounder for Atmospheric Profiling of Humidity in the Intertropics by Radiometry (SAPHIR), Radio Occultation Sounder for Atmosphere (ROSA), ScaRaB]
2012: Metop-B (AVHRR, HIRS, IASI, AMSU-A, MHS), MSG-3 (SEVIRI, GERB-3), FY-2D (imager), FY-2F (S-VISSR), Global Change Observation Mission-W1 (GCOM-W1) (AMSR2)
2013: FY-3C (VIRR, MWRI, IRAS, MWTS, MWHS), Elektro-L-2 (imager)
2014: DMSP-F19 (imager, SSMI), Meteor-2, HIM-8, FY-2G (S-VISSR)
2015: MSG-4 (SEVIRI, GERB-4)
2016: HIM-9 (imager), FY-4A [Advanced Geostationary Radiation Imager (AGRI), Geostationary Interferometric Infrared Sounder (GIIRS), Lightning Mapping Imager (LMI)]
2017: NOAA-20 (VIIRS, CrIS, ATMS, OMPS, CERES), FY-3D (VIRR, MWRI, IRAS, MWTS, MWHS), SAGE-III (ISS)
2018: Metop-C (AVHRR, HIRS, IASI, AMSU-A, MHS), GOES-16 (imager), FY-2H (S-VISSR), GOSAT-2 (imager), Aeolus (wind profiler)
2019: Geostationary Korea Multi-Purpose Satellite-A (GEO-KOMPSAT-A) (imager), Elektro-L-3 (imager), Meteor-M-2 (imager, sounder), COSMIC-2 (GPS)
2021: FY-4B (AGRI, GIIRS, LMI)

Annex 5: Notable Events that Advanced Knowledge of Components of the Global Energy and Water Cycle

See history of pre-satellite (Hunt *et al.,* 1986) and early satellite radiation budget analyses (House *et al.,* 1986).

GLOBAL RADIATION BUDGET

1917: Dines (1917) compilation
1929: Simpson (1929) compilation
1949: Brooks (1949) compilation
1957: London (1957) compilation
1959: Explorer-VII: Weinstein and Suomi (1961)
1963: Budyko (1963) compilation
1969: Nimbus-3 (MRIR): Raschke and Bandeen (1970)
1971: Vonder Haar and Suomi (1971) analysis
1973: Raschke *et al.* (1973) analysis of Nimbus-3
1974: Budyko (1974) compilation, Oort and Peixoto (1974), Peixoto and Oort (1974)
1975: Nimbus-6/7 ERB
1976: Oort and Peixoto (1976) analysis
1979: Jacobowitz *et al.* (1979) analysis of Nimbus-6
1983: Oort (1983) compilation
1984: Jacobowitz *et al.* (1984) analysis of Nimbus-7, ERBE: Barkstrom and Smith (1986)
1987: Initiation of SRB project to current date (*cf.* Stackhouse *et al.,* 2011)
1989: Establishment of BSRN project to current date (*cf.* Ohmura *et al.,* 1998)
1990: Kyle *et al.* (1990) Nimbus-7 and ERBE comparison, Rossow and Lacis (1990) NOAA-5 analysis
1991: GEBA: Ohmura and Gilgen (1991)
1992: Darnell *et al.* (1992) analysis of ISCCP C-Version, Hartmann *et al.* (1992) analysis of ISCCP and ERBE, Peixoto and Oort (1992) compilation
1993: Kyle *et al.* (1993) analysis of Nimbus-7
1994: First ScaRaB flight on Meteor-3/7: Kandel *et al.* (1998)
1995: First SRB SW product release (Whitlock *et al.,* 1995), Zhang *et al.* (1995) and Rossow and Zhang (1995) analysis of ISCCP C-Version
1998: Second ScaRaB flight on Resurs-01-4: Duvel *et al.* (2001)
1999: Gupta *et al.* (1999)
2000: CERES (Terra)
2002: CERES (Aqua), First GERB flight on MSG-1 (Harries *et al.,* 2005)
2003: Initiation of ARM program (Ackerman and Stokes, 2003)
2004: Zhang *et al.* (2004) analysis of ISCCP-D
2006: Wong *et al.* (2006) analysis of ERBS
2008: L'Ecuyer *et al.* (2008) analysis of CloudSat/MODIS
2009: Murphy *et al.* (2009) analysis of ocean heat
2011: Suomi NPP (CERES) mission, Kopp and Lean (2011) revised solar constant, SRB v3 (Stackhouse *et al.,* 2011)
2012: Loeb *et al.* (2012) analysis of CERES
2013: Kato *et al.* (2013) analysis of surface fluxes based on CERES
2015: L'Ecuyer *et al.* (2015) NASA Energy and Water Study (NEWS) compilation
2017: Joint Polar Satellite System (JPSS) (CERES)
2018: Loeb *et al.* (2018a) CERES EBAF product

GLOBAL WATER BUDGET

1905: Bruckner (1905) compilation
1969: Nace (1969) compilation
1974: Budyko (1974) compilation, GARP Atlantic Tropical Experiment
1975: First HIRS flight on Nimbus-6, Baumgartner and Reichel (1975) compilation
1978: SMMR flight on Nimbus-7
1979: First operational HIRS flight on TIROS-N (Shi and Bates, 2011)
1983: Peixoto and Oort (1983) compilation
1984: SAGE-II: (upper-troposphere–stratosphere, McCormick *et al.,* 1993)
1986: GPCP: Huffman *et al.* (1997) and GPCC: Schneider *et al.* (2008)
1987: Legates (1987), Berner and Berner (1987)
1988: First SSM/I flight on DMSP-F9 (F10 through F19): Hilburn and Wentz (2008), Anderson *et al.* (2010), snow: Shahroudi and Rossow (2014)
1991: Gaffen *et al.* (1991) analysis of troposphere radiosonde observations
1992: UARS (MLS) (upper-troposphere–stratosphere, Read *et al.* (1995), Sandor *et al.* (1998), Wu *et al.* 2005), Peixoto and Oort (1992) compilation
1994: GVAP: Randel *et al.* (1996), Tropical Ocean Global Atmosphere- Coupled Ocean Atmosphere Regional Experiment (TOGA-COARE)
1996: First GPS sounder: Ware *et al.* (1996)
1998: First operational AMSU-B flight on NOAA-15 (Ferraro *et al*., 2005), TRMM: Iguchi *et al.* (2000), Xie and Arkin (1998) analysis, SHEBA (Uttal *et al.,* 2002)
1999: Initiation of GEWEX SEAFLUX project: Curry *et al.* (2004), Land water storage (Rodell and Famiglietti (1999), First flight of AMSU-B
2001: SAGE-III (Meteor-3M), GPCP 1-degree: Huffman *et al.* (2001), Challenging Minisatellite Payload (CHAMP) GPS: Wickert *et al.* (2001)
2002: AIRS/AMSR-E flight on Aqua (Fetzer *et al.,* 2006)
2003: GPCP v2: Adler *et al.* (2003)
2004: Aura (MLS, TES): Livesey *et al.* (2007), Gravity Recovery and Climate Experiment (GRACE): Tapley *et al.* (2004), Landerer and Swinson (2012), Scientific Applications Satellite-C (SAC-C): Hajji *et al.* (2004)
2005: Initiation of GEWEX LandFlux project (Vinukollu *et al.,* 2011), Mehta *et al.* (2005)
2006: First IASI flight on Metop-A: Pougatchev *et al.* (2009), First COSMIC GPS
2007: TRMM multi-satellite analysis (Huffman *et al*., 2007), Schlosser and Houser (2007) compilation
2008: GPCC: Schneider *et al.* (2008), SSM/I products (Hilburn and Wentz, 2008)
2009: GPCP v2.1: Huffman *et al.* (2009)
2011: Suomi NPP (advanced sounders), Sahoo *et al.* (2011)
2012: GCOM-W1 (AMSR2)
2013: Trenberth and Fasullo (2013)
2014: GPM: Hou *et al.* (2014), Skofronick-Jackson *et al.* (2017), Adhikari *et al.* (2018)
2015: Rodell *et al.* (2015) NEWS compilation
2017: First JPSS (advanced sounders), SAGE-III (ISS)
2018: GRACE-Follow On
2019: COSMIC-2 (GPS): Anthes *et al.* (2008), Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC)
2020: GPM Integrated Multi-satellite Retrievals for GPM dataset (IMERG) (Huffman *et al.,* 2020; Takahashi *et al.,* 2021)
2022: GPCP v.3 release

GLOBAL GENERAL ENERGY BUDGET ANALYSES

1917: Dines (1917)

1929: Simpson (1929)
1949: Brooks (1949)
1955: Lorenz (1955)
1963: Budyko (1963)
1965: Krueger *et al.* (1965)
1967: Lorenz (1967), Wiin-Nielsen (1967)
1970: Newell *et al*. (1970), Saltzman (1970)
1974: Budyko (1974), Peixoto and Oort (1974), Oort and Peixoto (1974)
1976: Oort and Peixoto (1976)
1983: Oort (1983), Kung and Tanaka (1983) analysis of FGGE data
1988: Stuhlman and Smith (1988), Masada (1988) analysis of FGGE data, Savijarvi (1988, rawinsode data)
1990: Sheng and Hayashi (1990)
1992: Peixoto & Oort (1992), Sohn and Smith (1992) analysis of energy transport
1994: Siegmund (1994)
1997: Zhang and Rossow (1997) analysis of energy transport
2004: Hu *et al.* (2004)
2007: Li *et al*. (2007) reanalyses for 1979–2001
2008: Fasullo and Trenberth (2008a, 2008b)
2009: Levitus *et al.* (2009) global ocean heat content
2012: Bannon (2012)
2013: Romanski and Rossow (2013) analysis of satellite data products
2019: GEWEX Integrated Dataset (Kummerow *et al.,* 2019)