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Evolution of the concept of cloud-climate feedbacks

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ABSTRACT

The early concept of cloud-climate feedback was formulated as involving solely cloud cover effects on planetary radiation, separate from precipitation, and consistent with simple climate models. However, more than 50 years later, this concept continues to dominate analyses, especially of climate model performance, even though multiple global data products now exist that quantify weather-to-decadal scale joint variations of cloud properties, radiative fluxes, precipitation, surface energy and water fluxes, atmospheric and surface properties, and the circulations of the atmosphere and ocean. A more complete, observation-based analysis of cloud feedbacks on weather, seasonal and interannual scales is now possible. Results to date indicate that the cloud-radiative feedback amplifies the positive cloud-precipitation feedback on the atmospheric circulation from weather-to-annual time scales. Further analysis extensions are suggested.

1. Introduction

In the 1970s growing attention was paid to the subject of climate variability, both natural and caused by human activities (GARP 16, 1975). Early satellite observations (e.g., Vonder Haar and Suomi (1971), Raschke et al. (1973)) were just starting to provide the first direct determinations of the components of the planetary radiation budget that were improvements over the previous pre-satellite estimates based solely on radiative model calculations and mostly northern hemisphere surface measurements (Hunt et al., 1986). Notable features of the global radiative fluxes at the top of the atmosphere (TOA) measured by early satellites were Vonder Haar and Suomi (1971), Raschke et al. (1973): (1) global, annual mean albedo is smaller than pre-satellite estimates and thermal radiation larger consistent with global mean balance, (2) clouds are a net negative effect, (3) the annual, hemispheric mean fluxes are nearly the same despite the land–ocean contrasts, but the seasonal variation is larger in the northern than southern hemisphere, (4) the main cloudy zones are identified by the spatial variations of the fluxes, even though cloud effects are smaller than previous estimates, especially in the tropics, (5) longitudinal variations in fluxes are more significant at lower than higher latitudes, and (6) systematic seasonal variations in the meridional flux gradients are apparent. Although clouds could account qualitatively for the observed large-scale spatial–temporal variations in fluxes (diurnal variations were not sampled), the quantitative connection of fluxes to cloud properties was still very uncertain and identified then as a major objective for research.

Consistent with the early, very simple models of the climate, cloud-climate feedback was formulated in terms of a linear relation between the changes of the global mean top-of-atmosphere (TOA) net radiative flux and changes of the global mean surface temperature. Only the effects of cloud cover changes were considered even though the flux changes related to several different cloud properties were noted (GARP 16, 1975). Precipitation was not explicitly included in this formulation. Use of this simple relationship to diagnose cloud feedback continues in most discussions today, especially in evaluation and comparison of results from climate models (e.g., Bony et al. (2006), Sherwood et al. (2020)), despite its many limitations and flaws (Aires and Rossow, 2003; Stephens, 2005). The flaws most relevant here are the focus solely on cloud-radiative effects, separately from cloud-precipitation effects, and the complete neglect of the cloud feedbacks on the atmospheric and oceanic circulations that also affect the surface temperature.

Some different approaches to evaluating cloud-radiative feedback in climate models, rather than simple "all-cloud" representations, have been reviewed by Bony et al. (2006) and Zelinka et al. (2012a,b). Because of the variety of cloud properties that can affect the TOA fluxes in different ways, Zelinka et al. (2012a,b) proposed an analysis that accounts for the effects of different cloud properties instead of a bulk aggregate "cloud" effect. This approach was extended to also account for cloud radiative effects on surface and in-atmosphere fluxes (Zhang et al., 2021). However, these model-evaluation methods still define feedback by a linear relation of **equilibrium** changes in the global mean cloud effects on the radiative fluxes and the global mean surface temperature. Hence, although providing a way to compare climate models in more detail, this analysis approach cannot be applied to observations.

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Over the past more than 50 years, there have been many more satellite and surface measurements of cloud properties, radiative fluxes and precipitation, atmospheric temperature and composition, oceanic temperature and salinity, as well as more accurate depictions of the large scale atmospheric and oceanic circulations. Moreover, climate models now have more complete physics. Diagnostic studies using these observational data products have been performed that provide a much more complete elucidation of the role of clouds in weather and climate. Over this time the warming of Earth has become readily apparent and the satellite observation records are now long enough to show that the clouds are changing (e.g. Tselioudis et al. (2024)). The rich collection of observations and analyses now available suggests that a more comprehensive perspective on cloud feedbacks is possible and needed to explain what is happening.

This paper discusses several lines of evidence that have been published in the past few decades that, together, provide a more complete concept of cloud feedbacks but also identify the analytical obstacles to a complete analysis. Rather than trying to cite the literature comprehensively, only some overview or key papers or the latest papers in a series are cited here as they provide the more complete citations to previous work. Possible approaches for further progress are suggested.

2. Background summary

The first satellite measurements of TOA radiative fluxes by Explorer VII in 1959 (and following TIROS flights) (Vonder Haar and Suomi, 1971) and in more detail by NIMBUS-3 in 1969–70 (Raschke et al., 1973) were followed by a series of satellite missions providing ever more detail and accuracy: NIMBUS-6/7 in 1970–80s (Kyle et al., 1993), the Earth Radiation Budget Experiment in 1980–90s (Wielicki et al., 2002), and the Clouds and Earth's Radiant Energy System in 2000–2020s (Loeb et al., 2018). The Geostationary Earth Radiation Budget mission provided direct (but not global) measurements of the diurnal flux variations (Harries et al., 2005). These missions, along with others providing more accurate determinations of the incident solar flux, also determined the average cloud effects on the reflected solar and emitted thermal fluxes at TOA: in the global, annual average, clouds decrease the absorbed solar (SW) radiation by about twice as much as they decrease the thermal (LW) emission. The incident solar flux is 340 ± 0.5 Wm^{-2} and the absorbed and emitted fluxes are about 238 ± 4 Wm^{-2} (L'Ecuyer et al., 2015), where the uncertainty range indicates the variety of available estimates (see also Kyle et al. (1990), Raschke et al. (2016)). Estimates of the average cloud radiative effect (CRE, difference of all-sky and clear-sky fluxes) are about −(46–49) Wm^{-2} for TOA SW CRE and about +(27–28) Wm^{-2} for TOA LW CRE (e.g., Loeb et al. (2018), Zhang and Rossow (2023)).

From the 1980s until now, several concerted national and international efforts were organized to obtain better information about cloud properties, precipitation, and surface radiative, sensible and latent heat fluxes, in addition to improved measurements of atmospheric temperature, humidity and composition. Diagnoses of atmospheric and ocean circulations have also been significantly improved. Basic cloud properties, beyond those available from surface observations (latest results in Eastman et al. (2011), Eastman and Warren (2013)), were documented from globally complete satellite observations by the International Satellite Cloud Climatology Project (ISCCP, latest results in Rossow et al. (2022)): cloud cover, top temperature/pressure and optical thickness, now available with global coverage at 10 km and 3 hr intervals. Many more global satellite cloud data products have been released and compared (Hughes (1984) reviews earlier results, Stubenrauch et al. (2024)) and the results extended to other cloud properties, particularly particle sizes (e.g., Guignard et al. (2012), Platnick et al. (2017)) and phase (e.g., Coopman et al. (2020)) and, especially, cloud vertical structure by CloudSat and CALIPSO (Mace and Zhang, 2014). Likewise during this period, satellite-based precipitation determinations have provided complete global coverage and at least daily time sampling, first by the Global Precipitation Climatology Project (Huffman et al., 2009), augmented and enhanced by Tropical Rainfall Measurement Mission, and now by Global Precipitation measurement Mission (Huffman et al., 2020).

The availability of the detailed and global satellite observations of basic cloud radiative properties from ISCCP, together with data for the key radiative properties of the surface and atmosphere, also made possible the direct calculation of radiative fluxes, which allows for a direct connection of cloud properties to their radiative effects. Both ISCCP (latest results in Rossow et al. (2022)) and the Surface Radiation Budget project (Stackhouse et al., 2011) determined TOA and surface fluxes that were evaluated against the direct measurements by satellites at TOA and collected at the surface by the Baseline Surface Radiation Network (Ohmura et al., 1998). Global estimates of atmospheric radiative flux profiles (Zhang and Rossow, 2023) were checked by calculations based on direct cloud vertical structure by CloudSat and CALIPSO (L'Ecuyer et al., 2008). These diagnostic studies have now quantified cloud effects, not only on SW and LW fluxes at TOA, but also on these fluxes at the surface and their vertical profiles in the atmosphere.

The availability of all of these global data products means that a much more comprehensive evaluation of the role of clouds in weather and climate is now possible, especially combining radiative flux and precipitation data products. Today there are data products (global, most sampled at least at 100 km intervals, covering more than a decade at sub-daily intervals) for radiative fluxes (including atmospheric profiles), energy and water fluxes at the surface, atmospheric winds and ocean currents, atmosphere and ocean temperatures, variable compositions (ozone, water vapor, salinity), clouds, aerosols, snow and sea ice cover, topography, land surface type and properties, and soil moisture (see for example Kummerow et al. (2019)).

3. Limitations of the simple feedback concept

Posing cloud-climate feedback as a change in the bulk (global, annual mean) TOA energy balance affecting the change of global average surface temperature has led to a focus on the effects of cloud cover changes on the TOA radiative fluxes (as summarized above). This is misleading because only part of the SW flux affects the surface temperature directly. Moreover, this focus neglects the heat transports by and the cloud feedbacks on the atmospheric and ocean circulations that also directly affect the surface temperature (Stephens (2005) provides a more extensive discussion). Both Aires and Rossow (2003) and Stephens (2005) emphasize that the several climate feedback processes are coupled, particularly clouds, radiation and precipitation, and cannot be linearly added together. Moreover, mixing the SW and LW components of the TOA fluxes together conflates the climate forcing (solar flux) with the primary climate response (LW emission) and neglects that they act on different parts of the climate system: the SW primarily heats the surface while the LW primarily cools the atmosphere. The connection of the surface heating to the atmosphere and ocean circulations occurs via several heating/cooling processes (sensible heat exchange, evaporation-precipitation, radiation) but the key point is that surface temperatures that result are an "indirect" consequence of the coupled atmospheric and oceanic circulations produced by the non-local distribution of heating, not solely by its global average.

The observed space and time variations of clouds clearly signify the atmospheric motions that produce them. The heating effects of cloud processes, radiation (mostly LW) and precipitation, directly feedback on the atmospheric motions rather than on the surface temperature. Thus, the diagnostic focus of cloud feedbacks should be on the weather/seasonal/annual-scale energy and water exchanges, that is, the atmosphere–ocean dynamics as modified by cloud processes. The existence of different cloud types and their different behaviors argues that the diagnosis of cloud effects needs to separate the properties of clouds and their feedbacks produced by different weather conditions as well as over their seasonal-to-interannual variations that affect the ocean. This follows the suggestion by Aires and Rossow (2003) to look at the multivariate relationships involved on shorter time scales. A closer examination of cloud processes at "weather" scales can also be directly used to improve the fidelity of climate model representations of these processes and to directly evaluate their feedbacks on these scales by using the measured time derivatives of cloud properties, radiative fluxes and precipitation. The multitude of global observations and diagnostic analyses now available make this kind of analysis possible.

4. Implications of some previous results

Earth's cloud cover is arranged in a near-equatorial band and two midlatitude bands of large cloud cover with tops in the upper troposphere separated by zones of broken or extensive but low-level cloud cover. Continents are generally less cloudy than oceans (the ocean-covered Arctic is very cloudy while the "continent-covered" Antarctic is relatively less cloudy). The cloud vertical distributions in these zone are distinctive with some vertically extensive (convective) clouds but mostly layered clouds only a few kilometers thick (Mace and Zhang, 2014; Wang et al., 2000) that occur more frequently in the lower or upper troposphere (see Stubenrauch et al. (2024)). This arrangement reflects the large-scale and deep (troposphere filling) atmospheric circulation. The lower latitude Hadley circulation is composed of an upwelling zone and convective clouds near the equator and downwelling zone with boundary layer clouds in the subtropics. The midlatitude baroclinic eddy zones contain both upwelling and downwelling motions with vertically extensive clouds near the fronts and mixtures of high-level and low-level clouds elsewhere. The upwelling regions and vertically extensive clouds are all closely associated with significant precipitation. That the general cloud characteristics at smaller scales are dramatically different in the upwelling and downwelling regions has long been known from surface observations (latest version in Eastman et al. (2011), Eastman and Warren (2013)). Satellite observations also showed the same dynamic associations of the basic cloud properties (Lau and Crane, 1995, 1997; Hahn et al., 2001). Satellite-based determinations of cloud radiative properties and precipitation show the same association of cloud properties and vertical structure, cloud radiative effects and precipitation in different weather conditions (Tselioudis et al., 2013). The sense of the feedback of cloud processes on the atmospheric circulation has been diagnosed in three different ways.

Vonder Haar and Suomi (1971) used the early satellite determinations of the mean meridional distribution of TOA net radiative heating (SW absorption minus LW emission) to infer the poleward energy transport by the combined atmosphere-ocean circulations that is required to balance the meridional gradient. Sohn and Smith (1992) expanded this analysis to two dimensions to determine not only the poleward transport but the land–ocean exchanges. Zhang and Rossow (1997) separated the mean poleward energy transport into its atmospheric and oceanic components by differencing the mean meridional net TOA radiative and total surface (SRF) fluxes (and reviewed other previous estimates). They showed explicitly that the zonal, annual mean cloud radiative effects increase (decrease) the required equator-to-pole energy transport by the atmosphere (ocean). As discussed below, the positive feedback on the atmospheric circulation results from the cloud-radiative effect (mostly decreased LW cooling) reinforcing the atmospheric heating by precipitation, particularly enhancing tropical convection, whereas extensive cloud cover at high latitudes inhibits surface cooling and the consequent deep convection in the ocean (cf. review of atmosphere-ocean coupling processes by Webster (1994)). Zhang and Rossow (2023) examined a transient change in mean meridional radiation over a decade and found that the changed cloud radiative effects implied a negative (positive) feedback on the atmospheric (oceanic) poleward circulation. These results suggest that, while the time-averaged cloud radiative effects are a positive feedback on the global atmospheric circulation, they can act as a negative feedback in transient events that may be induced by slower changes of the ocean circulation (see discussion of observed ocean changes that occurred during this particular period in Zhang and Rossow (2023)).

Peixoto and Oort (1992) updated the observational basis for estimating the average energy exchanges in the atmospheric general circulation: the exchanges between zonal mean and eddy available potential energy and zonal mean and eddy kinetic energy could be calculated from monthly mean conventional weather observations (profiles of temperature, humidity, horizontal winds), but the generation of available potential energy could only be inferred in the long-term average by assuming an equilibrium balance with dissipation. Romanski and Rossow (2013) directly calculated the separate contributions to the daily generation of available potential energy by radiative heating/cooling (see also Stuhlman and Smith (1988)), precipitation and surface sensible heat flux using (mostly) global satellite observations. Their results showed that the main driver of the mean atmospheric circulation is the surface sensible heat flux (as expected) but that the circulation is strengthened by precipitation heating – a cloud feedback – and weakened overall by radiation. In the case of the eddy circulation, the main driver is precipitation (i.e., storms) with the sensible heat flux acting as a weak negative forcing and overall radiation as a stronger negative forcing. However, these results also show that the cloud modifications of radiation increase the generation of both zonal mean and eddy available potential energy. In other words, the cloud effect on atmospheric radiative cooling (decreased cooling) strengthens both the mean and larger-scale eddy circulations, a positive feedback.

An analysis of distributions of cloud top pressure and optical thickness in the ISCCP dataset showed a small number of characteristic patterns or regimes, called weather states (Jakob and Tselioudis, 2003; Rossow et al., 2005). Tselioudis et al. (2013) showed that these weather states exhibit characteristic cloud vertical structures and are associated with large-scale upwelling motions and precipitation or downwelling motions and little precipitation. Tselioudis et al. (2021) also compared a later version of the observational results with climate model distributions. Rossow et al. (2016) further showed that each climate zone is occupied only by a specific small subset of these weather states. In the cloudy zones (tropics, midlatitudes) the cloud radiative effects by one type (storms) reduce atmospheric LW cooling (a heating) to amplify atmospheric heating by their associated precipitation. This heating is offset by the stronger LW cooling of the fair weather state. Some weather states, dominated by low-level clouds, appear to slightly enhance the atmospheric radiative cooling, especially at higher latitudes. In the subtropics only radiative cooling by low cloud and fair weather states predominates. In the review of model feedback processes by Sherwood et al. (2020), the variety of model cloud feedbacks (cloud effect on TOA net flux related to surface temperature) in specific dynamical regimes is discussed, but separately with no consideration of the dynamic connection/interaction of these regimes. In contrast, Stephens et al. (2024) review the dynamic interaction of tropical and subtropical cloud properties and processes (radiation, precipitation) that leads to a "pattern" or "non-local" dependence between clouds and surface temperature. The weather state analyses show the dynamic connection of these regimes in that the sense of cloud radiative effects on the atmosphere are correlated with precipitation heating and the sign of vertical motions. That is, upwelling regions are generally associated with precipitation and less LW cooling because of higher-level clouds, whereas downwelling regions are associated with an absence of precipitation and more LW cooling (even enhanced by lower-level clouds). This correlation relationship at low latitudes is demonstrated clearly by Jakob et al. (2019), who also show the dynamical connection of cloud processes and feedbacks with the large scale circulation (also Needham and Randall (2021) who also note the correlation with column relative humidity). In other words, these studies show that the vertical and horizontal energy transports by the atmospheric circulation are amplified by the cloud radiative (and precipitation) effects.

These observational analyses suggest that cloud feedbacks (radiation, precipitation) **on the atmospheric circulation** are generally positive, that they amplify weather systems and the general circulation of the atmosphere (as opposed to a net negative influence on the planetary energy budget). The results of Zhang and Rossow (1997) also suggest a negative cloud radiative feedback on the oceans related to their inhibition of surface cooling at high latitudes. However, the longer-term feedback on a forced climate change (including other feedback processes, some of which are coupled to cloud processes) and the consequences for the surface temperature are still uncertain because the observed transient behavior in the available short data records may not reflect the fully coupled atmosphere-ocean response on decadal and longer time scales. While these studies provide a clear "sense" of the cloud feedbacks on the atmospheric circulation for shorter time scales, more work is needed to better quantify the magnitude and coupling of these effects and to compare the detailed dynamical results with weather and climate model representations. The precise consequences **in equilibrium** of the changes in atmosphere-ocean circulations on global mean surface temperature remain uncertain.

5. Possible analyses for further progress

Fig. 1 presents a more complete concept of cloud feedback on the atmospheric circulation (the system). The red arrows for radiation interacting with the atmospheric circulation indicate the direct nature of radiative heating/cooling: solar radiation is the direct forcing, some of it directly heats the atmosphere but most of it heats the surface and is communicated to the atmosphere as sensible heat Romanski and Rossow (2013). The system response is LW cooling and the general circulation, which redistributes energy (temperature) and water. The clouds produced by the atmospheric motions then feedback on the circulation by precipitation heating and their effects on radiative cooling. The main analysis difficulty is that all the relationships in Fig. 1 between clouds and their atmospheric heating/cooling effects are local in space and time, whereas the relationships of radiation and precipitation with the atmospheric circulation are non-local because it is the space–time contrasts in heating/cooling that drive the motions. Moreover, these relations are scale dependent in that the intensity of the response to heating varies with scale and the responses at different scales are coupled (e.g., convection interacts with the larger-scale Hadley circulation). Hence, the analysis approach illustrated by Aires and Rossow (2003) to examine small time-scale relationships would work for the cloud relationships indicated by blue arrows in Fig. 1, but cannot work directly for the heating relations to the atmospheric circulation without a representation of the space–time scale dependence and scale coupling.

Zelinka et al. (2023) combine their radiative kernel analysis (which accounts for the variation of cloud effects on TOA radiative fluxes with cloud properties, but see Zhang et al. (2021)) with the weather state concept, which begins to associate cloud-radiative effects with dynamic regimes. Although this analysis still defined cloud-radiative feedback as the ratio of equilibrium changes of TOA fluxes and surface temperature, they found that model differences are largest for the "dynamic" component of their feedback (i.e., weather state dependence) with contrasting behavior at low and high latitudes. Combining this approach for cloud radiative effects with observations of precipitation and the large-scale vertical motion regimes might reveal systematic relationships between weather-scale and seasonal-scale behavior. In other words such an analysis might identify emergent (Klein and Hall, 2015) dynamic relations in observations that could also be compared to model representations. This is similar to compositing cloud radiative effects by dynamic regimes (e.g., Tselioudis and Jakob (2002), Bony and Defresne (2005), Tselioudis and Rossow (2006)), but combining radiative effects and precipitation with measures of the atmospheric (and oceanic) circulation to capture and quantify the full cloud feedback loop.

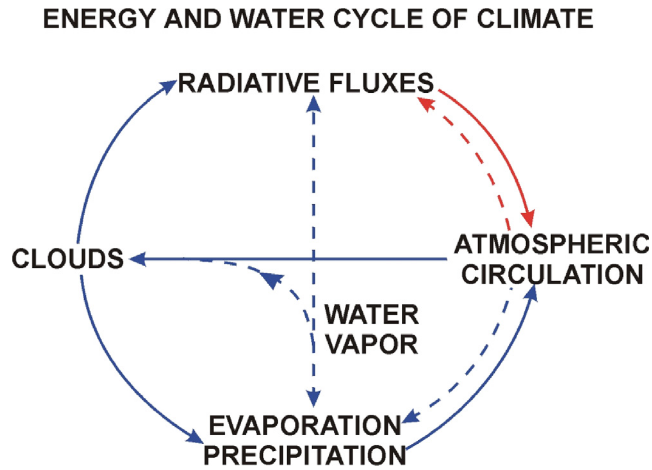

Fig. 1. Schematic of the feedback interactions between the atmospheric circulation and cloud processes that affect radiative heating/cooling and precipitation heating.

The neural-network-based analysis technique proposed by Aires and Rossow (2003) might succeed if the connections between changes in cloud-related heating/cooling and the general circulation are formulated in non-local terms and calculated from observations. Following Romanski and Rossow (2013), the daily changes in the generation of zonal and eddy available potential energy could be related to the changes of the large-scale circulation in the form of zonal and eddy kinetic energy in a multi-variate analysis. However, these relations are probably time-lagged and scale dependent. The advantage of the neural-network-based analysis is that the individual contributions to the generation of available potential energy can be input separately and the time-lagged and scale dependence can be treated with multiple inputs from different times and locations. Another approach might be to apply such an analysis to inputs averaged over different space–time scales. For instance, averaging the generation rate and kinetic energy changes on a scale of about two weeks (to be tested) might be enough to average out most of the synoptic variations but still capture the changes in the global-scale circulation. Such an approach might also reveal connections to changes in oceanic circulation on longer time scales. This kind of scale separation approach might account for the non-local nature of the relationships in Fig. 1 for the global circulation and its seasonal variations. The objective of this analysis would be to develop detailed statistical relationships among the components in Fig. 1 but accounting for their non-local nature.

The connection of cloud changes and their heating/cooling to short-term circulations (weather) can be made directly using the available observations by tracking weather systems (both fair and foul). Following air parcels in such a Lagrangian diagnosis of the cloud-related energy (and water) exchanges can determine the cloud feedbacks over the lifecycle of different weather systems. In other words, the time derivatives of cloud-related processes and changes of atmospheric properties can be evaluated directly. In the tropics, convective storms can be tracked by their cloud features (e.g., Machado et al. (1998), Fiolleau and Roca (2013)) or by precipitation features (Takahashi et al., 2021). These two could be combined with cloud and atmospheric properties to characterize storm intensity and duration. Another approach is to anchor observations on a specific event in time to form a statistical composite life cycle (e.g., Masunaga (2012, 2013), Inoue and Back (2017)). The dynamics of convective systems (at least isolated plumes) can be inferred this way (Masunaga and Luo, 2016). Combining these analyses would suggest the feedbacks by examining the changes from before to after the event in atmospheric conditions and motions. In the extratropics, surface pressure anomalies in a reanalysis can be tracked (e.g., Bauer et al. (2016)) and the cloud structure composited (Govekar et al., 2011). Direct tracking of air parcels using the reanalysis winds is also possible (e.g., Tuinenburg and Staal (2020)). Composite lifecycles can also be used (e.g., Tselioudis and Jakob (2002)). While recent studies examine the effects of precipitation on the development and evolution of extratropical synoptic cyclones (e.g., Marcheggiani and Spengler (2023)), combining the tracking results with satellite-based results for clouds, radiation and precipitation (Polly and Rossow, 2016) sets the stage for a more complete cloud feedback investigation where the reanalysis winds provide the dynamic component. The principal question to be answered in all these investigations is whether cloud-related heating/cooling only changes the energy transports by storms or whether it also changes the storm strengths and/or durations: the former is a feedback on the large-scale circulation, while the latter is a feedback on the weather-scale circulation.

6. Conclusions

The observational data products now available provide global weather-scale and long-term (decadal) quantitative information about cloud characteristics, their related radiative effects and precipitation, together with the properties of the atmosphere including its general circulation. Diagnostic studies to date show that the cloud-radiative feedback amplifies the cloud-precipitation feedback on the atmospheric circulation from weather-to-annual time scales. That is, cloud feedbacks on the atmospheric circulation at these time scales are positive. Further diagnostic studies, such as suggested above, can better detail and quantify these weather-to-seasonal-scale feedbacks of cloud processes. Analysis on even longer time scales (seasonal-to-interannual) can also be applied to determine the effects on the ocean circulation (energy and water exchanges and surface winds). Evaluating the fidelity of climate model representations of cloud processes and directly assessing their feedbacks on these time scales are now possible with available data products employing a more complete feedback concept.

Given that the available data record is too short for a direct observational determination of cloud-climate feedbacks, such an analysis effort would still serve to enhance and evaluate the realism of modeled climate-change forecasts. In any case, some of the data records are now more than 40 years long and suggest that "something" is happening to the clouds (e.g., Tselioudis et al. (2024)). Since about 1980, the global mean surface temperature has increased. Precipitation in the tropics at least has increased, mostly in the form of organized convective systems (Tan et al., 2015), and the tropical convective zone has narrowed (Wodzicki and Rapp, 2016). There has been a poleward shift of the midlatitude cloudiness (Tselioudis et al., 2016). These changes amount to an expansion of the subtropical zone dominated low-level cloudiness, as discussed by Jakob et al. (2019) and Stephens et al. (2024). There has also been a general decrease of global cloud cover (Rossow et al., 2022), mostly in the optically thin low and middle level clouds with a smaller decrease of cirrus (see Fig. 4 in Zhang and Rossow (2023)). The former changes cause an increase of SW heating, only partially offset by the effect of the cirrus decrease (Tselioudis et al., 2024; Zhang and Rossow, 2023). In light of the above discussion, these cloud-related changes suggest a positive feedback on the atmospheric circulation.

Whether or not these transient cloud-related changes are a good representation of cloud feedbacks on equilibrium climate, their precise contribution to the increase of global mean surface temperature is still uncertain because the response of the atmospheric circulation as well as the ocean circulation to changes in **surface** energy/water fluxes still must be accounted for. In other words, the observed changes in surface temperature depend, not only on changes in the planetary energy budget, but also on changes in the atmosphere-ocean circulations and their energy exchanges and transports.

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