The characteristics of cloud fields associated with midlatitude circulation systems in a general circulation model

Cheng-Ta, Chen; Roeckner, Erich . Monthly Weather Review ; Washington Vol. 130, Iss. 3, (Mar 2002): 570.

FULL TEXT

Headnote

(Manuscript received 1 March 2001, in final form 7 August 2001)

Headnote

Cloud fields and concurrent dynamical structures associated with extratropical cyclones in a general circulation model are investigated with emphasis on the cool season (October-March). An ensemble approach is used for constructing the respective anomaly patterns in the storm track region of the northwestern Atlantic. The simulated composite patterns are in many respects similar to those derived from satellite cloud data and operational weather analyses. The results also agree reasonably well with traditional conceptual frameworks for the organization of clouds in the vicinity of warm and cold frontal zones. The vertical structure and wave characteristics of various dynamical, thermal, and hydrological fields reveal the typical patterns found in observed baroclinic wave disturbances such as a westward tilt with height of pressure anomalies and an eastward displacement of the uppertropospheric clouds relative to the center of largest upward motion at 500 hPa. However, this displacement is not as distinct as in the observations. Similar to indications from surface weather reports, the largest precipitation anomalies are simulated westward of the reference site defined by the largest anomaly in cloud water path and cloud optical thickness, respectively. The changes in cloud cover, cloud water. humidity, and temperature during the passage of a synoptic-scale weather disturbance have a distinct impact on the energy budget with a pronounced seasonality in all components except for the longwave radiation. Due to changes in the fluxes of sensible heat, latent heat, and shortwave and longwave radiation, the atmospheric column in most parts of the cyclonic systems is cooled in winter and heated in summer. On the other hand, extratropical cyclones cause anomalous surface heating in winter and cooling in summer. The total effect on the earth-atmosphere system, as identified by the changes in the top-of-atmosphere radiation balance, is a warming during winter and a cooling during summer.

1. Introduction

The evolution of extratropical cyclones and the distribution of cloud and precipitation associated with frontal systems have long been a focus of synoptic meteorology. Studies and conceptual models of the airflow patterns and rainbands associated with the development of midlatitude circulation systems can be found from the early Norwegian school (Bjerknes and Solberg 1926) to more recent review papers and textbooks (e.g., Carlson 1980, 1991; Browning and Monk 1982; Hirschberg and Fritsch 1991; Houze and Hobbs 1982; Cotton and Anthes 1989; Houze 1993). With the aid of recent compilations of satellite and surface cloud climatology, the cloud structure associated with midlatitude synopticscale systems has been revisited from a climatological perspective in the work by Lau and Crane (1995 and 1997, hereafter LC95 and LC97, respectively). They illustrated the cloud information from the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1991) or the ground-based cloud observation from ships and land stations (Hahn et al. 1994). The concurrent atmospheric circulation fields were taken from the operational analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF). The composite picture of ISCCP cloud patterns and the contemporaneous atmospheric dynamics were found to be in good agreement with traditional conceptual frameworks for organization of cloud properties near the midlatitude frontal zone (LC95). The basis of the composite technique is using the daily averaged cloud optical thickness in the Cl dataset produced by ISCCP The sudden increase of cloud optical thickness in the time series typically indicates the passage of an organized cloud system. Since prognostic cloud water schemes are now used in many current general circulation models (Roeckner et al. 1991; Tiedtke 1993; Del Genio et al. 1996; Fowler et al. 1996, and many others), the organization of cloud properties associated with midlatitude circulation systems in the model can be traced in the same fashion as in LC95 thus enabling a comparison between the model simulations and the observations.

The validation of a model cloud simulation of simple statistical properties (e.g., mean, variability) using the atmospheric GCM ECHAM4 is presented in Chen and Roeckner (1997). Although there are some biases in the details, the model simulation generally agrees with the observed spatial distribution and temporal variation in several cloud fields examined. Here we extend the cloud validation work toward the general characteristics of cloud systems associated with midlatitude cyclones using a composite technique similar to LC95. To validate the distribution of clouds surrounding a midlatitude baroclinic system in the forecast model of the ECMWF, Klein and Jakob (1999) create similar composite cloud and flow patterns using short-term forecast results for those specific heavy cloudy events over the North Atlantic as in LC95. The main advantage of this approach is that errors in dynamical forcing are likely to be small so that deviations of simulated clouds from the observed can largely be attributed to deficiencies of the cloud parameterization scheme. In our study, the emphasis is on statistical and dynamical characteristics of clouds and other meteorological variables related to midlatitude weather disturbances as simulated in a GCM of comparatively coarse horizontal resolution (about 300 km). Although the model is forced with observed sea surface temperatures (SSTs), the weather events, due to their stochastic nature, cannot be found at the same time and location as in the observations. Moreover, possible systematic biases in the large-scale forcing of the model will make the interpretation of the results more difficult than in the weather forecast approach. Therefore, a quantitative comparison with the results obtained by LC95 and LC97 is not possible, and we do not attempt to mimic the satellite view of clouds as done by Klein and Jakob (1999) for enabling a direct comparison with ISCCP cloud optical thickness for the time-matched 24-- h forecasts. Nevertheless, the composite technique as applied in this study may provide some useful information on the model's ability to reproduce the observed spatial patterns of clouds and other variables in midlatitude synoptic-scale weather systems. It is very likely that cloud systems simulated in coarse-grid GCMs are different from those in cloud-resolving or cloud ensemble models. The Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) aims to develop cloud system models for studying and parameterizing the physical processes in different cloud systems (e.g., boundary layer, frontal, and convective). The analysis done in this study may provide some insight into the performance of cloud schemes in current GCMs from a cloud system modeling point of view.

The second aim of this study is to study the impact of extratropical cyclones on the top-of-atmosphere radiation budget and the energy budget at the surface and in the atmosphere. As shown by Weaver and Ramanathan (1996) and Tselioudis et al. (2000) on the basis of satellite data and dynamical analyses, extratropical cyclones have a significant impact on the radiation budget. Although the analysis techniques differ from those applied in this study, some qualitative conclusions can be drawn regarding the ability of the model to reproduce the observed features.

A brief description of the model and data used in this study is presented in section 2. The temporal and spatial cloud variability associated with extratropical cyclones is discussed in section 3. Using the composite technique developed by LC95, the concurrent structure of cloud and dynamical fields along the cyclone tracks in midlatitudes are analyzed in section 4. In section 5, we discuss the impact of extratropical frontal cloud systems on the top-of-atmosphere radiation budget and on the energy budget at the surface and within the atmosphere with emphasis on the seasonality of these effects. Section 6 summarizes our results and underlines the issues related to cloud system modeling.

2. Model data

The model data used in this study are taken from the fourth-generation atmospheric GCM developed at the Max Planck Institute for Meteorology (ECHAM4). A detailed model description and the simulation of present-day climate in ECHAM4 have been documented by Roeckner et al. (1996). The validation of the model's simulation of the top-of-atmosphere radiation budget, the mean cloud properties, and their spatial and temporal variability is reported in Chen and Roeckner (1996, 1997). The main characteristics of the model are described as follows.

The model's prognostic variables are vorticity, divergence, logarithm of surface pressure, temperature, specific humidity, and mixing ratio of total cloud water (liquid and ice phase together). Except for the water component, the prognostic variables are represented by truncated series of spherical harmonics with triangular truncation at wavenumber 42 (T42). Nonlinear terms and most of the physical parameterizations are calculated on the associated Gaussian transform grid. The vertical domain extends up to a pressure level of 10 hPa, corresponding to a height of approximately 30 km. A hybrid sigma-pressure coordinate system is used with 19 irregularly spaced levels and with the highest resolution in the atmospheric boundary layer. For the transport of water vapor and cloud water a semi-Lagrangian scheme is used (Williamson and Rasch 1994). Both seasonal and diurnal cycles are simulated. Stratiform clouds are calculated with a prognostic cloud scheme (Roeckner et al. 1996). The total cloud water content is obtained from the numerical solution of the respective budget equation including advective and diffusive transport and sources and sinks due to condensation/evaporation and precipitation formation. The liquid and ice phases are separated according to ambient temperature assuming mixed phase clouds in the temperature range between 233 and 273 K. Ice crystals are removed from the atmosphere by sedimentation. Raindrops are formed by autoconversion within the cloud and grow by accretion when rain is falling through a cloud layer. While cloud water is a prognostic variable, fractional cloud cover is simply diagnosed in terms of relative humidity. Clouds are allowed to form when a specified height-dependent relative humidity threshold is exceeded. The parameterization of cumulus convection (shallow, midlevel, and deep) is based on the bulk mass flux concept of Tiedtke (1989). However, the scheme has been modified with the suggestion by Nordeng (1994). In this modified version, the organized entrainment is related to buoyancy instead of moisture convergence, the organized detrainment is computed for a spectrum of clouds detraining at different heights, and an adjustment-type closure is used for deep cumulus convection instead of the moisture convergence closure applied in the Tiedtke scheme.

The model has been integrated with monthly observed SST and sea ice for the period 1979-93, extended from the Atmospheric Model Intercomparison Project dataset (AMIP; Gates 1992). For the model integration, there are always 30 days in each month. The model data analyzed in this study are for the 7-yr period from October 1986 to September 1993. The length of the period is the same as in LC95. The months of October-March and April-September also represent the cold and warm halves of the annual cycle, respectively. The structure of atmospheric circulation is inferred from the model's daily mean horizontal wind, vertical velocity, temperature, geopotential height, specific humidity, and cloud water content at 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, and 50 hPa interpolated from the hybrid vertical levels. The data grids have a horizontal resolution of roughly 2.8deg in latitude and longitude. In addition to these level data, the daily mean precipitation, total cloud cover, total precipitable water, total cloud water path, and energy fluxes at the surface and the top of the atmosphere as simulated by the model are also obtained for a more complete depiction of interactions among circulation and water and energy cycles.

3. Characteristics of temporal and spatial variability of cloud properties in the extratropics

The cloud variability associated with extratropical synoptic-scale cyclones in the model is examined by using the diagnostic tools developed by LC95 in their observational study. The only difference is that the simulated total cloud water path (CWP, which represents the grid-box mean vertically integrated cloud water content) is used for tracing the passage of thick clouds instead of the cloud optical thickness applied in LC95. Although cloud optical thickness is indeed calculated in the radiative transfer code of the model and affected by both CWP and effective radius, it does not have the same physical meaning as the cloud optical thickness derived from satellite radiance data (e.g., the effective radius of 10 Am is assumed for calculating the ISCCP C I cloud optical thickness). The fractional cloud cover and overlap assumption further complicate the issue of model-satellite comparison (Klein and Jakob 1999). Here we do not attempt to emulate the satellite view from model data. Since the essential aspect of using the cloud optical thickness in LC95 is to identify the passage of a well-organized thick cloud system, the CWP simulated in the model could be used for the same purpose. The uncertainty in using this different physical parameter for tracing clouds is not necessarily larger than developing a methodology to emulate satellite data from model data. Figure la is a Hovmoller diagram for CWP simulated by ECHAM4 over the Atlantic region at 38 deg N during the 1988-89 cool season (October-March). The large CWP associated with the passage of eastward moving circulation systems can be easily traced in the diagram. The similarity between the longitude-time distribution of daily mean CWP in ECHAM4 and of daily mean cloud optical depth derived from ISCCP (see Fig. lb for the same Hovmoller diagram at 38 deg N) suggests that the cloud and circulation systems traced in this model study are not drastically different from those in LC95.

a. Time series and frequency distribution function

Time series of daily mean CWP are shown in Fig. 2 for the selected cool seasons from 1986 to 1993 at a grid point (38 deg N, 65 deg W) situated in the North Atlantic storm track region. There are strong fluctuations in the CWP during the year. Although the background level is relatively high (typically 100 g m^sup -2^), spikes of more than 250 g m^sup -2^ occur from time to time. Similar to the time series of cloud optical thickness in LC95, the occurrence of the events with larger CWP over the Atlantic is rather frequent and erratic, with peak amplitudes spanning a broad range through the cool season. The typical time intervals between the local peak values are about 3-7 days.

Frequency distributions (histograms) of ISCCP cloud optical depth and model-simulated CWP for the 7-yr period over the North Atlantic region are shown in Fig. 3. They are constructed using daily means of the observed cloud optical depth and simulated CWP at 20 model grid points east of the coast of North America (their locations are depicted by the green parallelogram in Fig. 4b) from 1986 to 1993. The histogram shows the number of data points with values of CWP residing in individual "bins" with an interval of 10 g m^sup -2^. Similar to the non-Gaussian characteristics of observed cloud optical depth in the ISCCP dataset (Figs. 3c,d, and LC95), the frequency distribution of CWP (Figs. 3a and 3b) is also positively skewed but with a smaller skewness. The model tends to underestimate the relative frequency of optically thin clouds. This is probably due to the underestimation of the cloud cover in the midlatitudes (Chen and Roeckner 1997). The observed evolutions and fluctuations of thick cloud events are also more abrupt (Fig. 1). However, the simulated seasonal changes in the histograms of CWP are similar to the observed changes in cloud optical depth, showing a shift toward more optically thin clouds during the warm season. These results provide some justification for using CWP in the model as a surrogate for cloud optical depth. Thus, we use a method analogous to that in LC95's study and construct composite pictures of those events with outstanding CWP values. It is suggested that the composite approach is the most appropriate tool for diagnosing the properties common to those pulselike episodes of CWP time series (LC95). A set of reference dates on which the prominent events occurred is selected. The general features of cloud and circulation fields are then obtained from the arithmetic mean of the entire set of reference dates. The following analysis is almost identical to that of LC95. This is done deliberately to enable a comparison. However, the use of satellite or surface cloud observations does not allow a complete three-dimensional description of cloud fields in LC95 and LC97. Here we do not try to mimic the satellite or surface view with some assumptions. The full pictures for cloud-related variables from the model are highlighted instead. This is actually one of the advantages of using the model data.

b. Composite charts

As an illustration of the basic analysis procedure used in the present study, we first describe how a composite pattern can be constructed with reference to the time series of CWP at the selected location. For each 6-month cool season in the 7-yr record analyzed, the nine dates (about 5% of the sample) with largest CWP values at the

North Atlantic point are identified. This yields a total pool of 63 "key" dates for constructing the composite patterns. To avoid situations in which the peak values occur too close to each other, the separation of key dates is at least 4 days. If a pair of key dates fails to meet this criterion, the date with lower amplitude is eliminated from the set and is replaced by another peak with ranking just below the original nine-member set. The composite chart of CWP, as constructed by arithmetic averaging over the 63 members of key dates (here-- after referred to as day 0) obtained from the above method, is shown in the middle panel of Fig. 4. To describe the temporal evolution of individual features in these patterns, the composite procedure has been applied to the data for the day before day 0 (hereafter referred to as day -1: see Fig. 4a), and the day after day 0 (day + 1; see Fig. 4c). For all patterns shown in Fig. 4, the composite signals are presented as departures from the local background level, which is estimated by averaging the CWP values corresponding to days -2, - 1, + 1, and +2. Since the CWP values increase to uncommonly large amplitudes on day 0 (see Fig. 2), these data points are specifically excluded from the computation of the background level (LC95). The presentation of the results as deviations from the respective background value allows for the identification of the relevant patterns much more clearly than does showing the full fields. This applies, in particular, to variables where the anomalies are relatively small compared to the background value (e.g., temperature, geopotential height, zonal wind, etc.).

The area of enhanced CWP centered at the reference site on day 0 (Fig. 4b) has a south west-northeast orientation just as that in the observed cloud optical depth enhancement (LC95). The shape of this feature resembles the familiar cloud shield associated with a typical midlatitude frontal system often seen in the satellite imagery. The reduced CWP zones located on the two sides of the enhanced CWP area show a similar southwest-- northeast orientation although the reduction in CWP is much weaker (note the negative extreme mark as N in the same figure). The characteristic wavelength and the propagation speed of this composite pattern are approximately 4000-5000 km and 10 m s^sup -1^, respectively. The wavelength is estimated by the distance between the two centers of reduced CWP in Fig. 4b. The propagation speed of this wavelike pattern is estimated by dividing the distance between the center of maximum CWP, which moves from the North Carolina area on day -1 (denoted as P^sub -1^ in Fig. 4a) to the North Atlantic on day + 1 (P^sub +1^ in Fig. 4c). These wave structures are similar to those in LC95.

c. Temporal coherence, degree of waviness, and propagation vector

As in LC95, individual composite patterns identical to those shown in Fig. 4 have been computed for the whole globe. For a given reference site P^sub o^, the positive extremes in the composite chart on day -1 (e.g., P^sub -1^ in Fig. 4a) and on day +1 (e.g., P^sub +1^, in Fig. 4c) are identified. A propagation vector is then assigned to the grid point P^sub o^. The east-west and north-south components of the vector are represented by the zonal and meridional movement of the distance from P^sub -1^ to P^sub +1^ divided by the 2-day period. As an indicator of how well the primary cloud signal is maintained during this 2-day period, the average of the magnitude of the composite CWP values at P^sub -1^ and P^sub +1 is also evaluated. It is hereafter referred to as the "temporal coherence" for the site P^sub o^. According to this definition, the temporal coherence at Po is relatively large if positive CWP anomalies with respect to the background value can be identified throughout the 2-day period.

Another measure for the composite pattern of CWP at a given reference site P^sub o^ is the "degree of waviness." It is provided by the absolute value of the negative extremes appearing in the composite chart of CWP on day 0 (e.g., point N in Fig. 4b). A site with large value of this parameter would indicate that enhanced CWP at the site is paired with a prominent region of reduced CWP in its vicinity. This coexistence of extremes with opposite sign implies that the overall composite pattern possesses a strong wavelike character.

The near-global distributions of the temporal coherence, degree of waviness, and propagating vectors, as computed using the method outlined above, are presented in Fig. 5 for the 6-month period of October-- March. In the Northern Hemisphere, the occurrences of highly coherent features are mainly over the east Asia-- western North Pacific and eastern North America-westem North Atlantic sectors (Fig. 5a). These locations are also characterized by a high degree of waviness (Fig. 5b). The propagation vectors undergo a gradual transition from a predominantly southeastward orientation to a northeastward orientation as they pass through the area (Fig. 5c).

The propagation speed over the western portions of the North Pacific and North Atlantic is typically 9-12 m s^sup -1^ (gray shading in Fig. 5c). All these main features simulated in the model and constructed using the CWP composite pattern are similar to the results of LC95 using a composite chart of observed cloud optical depth. The propagation speed in the model is somewhat slower than in the observation. These features over much of the extratropical North Pacific and North Atlantic are manifestations of organized baroclinic waves traveling along the wintertime "storm tracks" (LC95). They are also reasonably well represented in the climate model. One noteworthy difference between the results in LC95 and the present study is the contrast between the mean background values and the temporal coherence values. The mean and temporal coherences of observed cloud optical depth over the storm track region are about 7 and 20, respectively. The mean and temporal coherences of simulated CWP over a similar region are about 120 and 70 g m^sup -2^, respectively. This means that, when large CWP events pass over the reference site, the relative enhancement of CWP from the background is much smaller than the relative enhancement of cloud optical depth in LC95. The relatively large background CWP is an indication that cloud water in the model atmosphere is not removed efficiently enough after the passage of an extratropical disturbance. Thus, the large CWP events tend to last longer and propagate farther along the track. Locally, over the western North Atlantic, there are only a few dates with daily mean CWP less than 60 g m^sup -2^. Klein and Jakob (1999) also point out that the simulated high-top thin clouds appeared to be more abundant than observed to the northeast of the near-surface low center, and that the optical depth of low-top clouds to the east of the high-- top cloud shield appeared to be too large. Their study also indicates, although the general geographic location of cloud is well simulated, that the contrast in optical depth between high-top cloud and low-top cloud is too small.

The weaker temporal coherence and waviness in the Tropics is in good agreement with the results presented in LC95. Even the northeastward orientation of propagating vectors from the east of Hawaii to Mexico aligned with the upper-level stationary trough in that region during winter is well reproduced in the model (see Fig. 4a in LC95). This feature has been related to cloud "plumes" linking the convective zone in the tropical eastern Pacific to the subtropical jet stream over North America (McGuirk et al. 1988; LC95).

4. Cloud fields and atmospheric circulation associated with extratropical disturbances

a. Procedure for combining composite charts for neighboring sites

To enhance the representativeness of the composite patterns in describing the cloud and circulation fields associated with the passage of large CWP, an array consisting of 20 reference sites has been chosen for the North Atlantic. The selected sites are located within the green parallelogram in Fig. 4b. These particular grid points are selected by the same considerations used in LC95. They lie in the path of higher temporal coherence of CWP with a well-defined direction and speed of propagation and relatively high degree of waviness. Thus, their locations are not exactly the same as in LC95 due to differences in the detailed geographic location of temporal coherence discussed in the previous subsection.

For each reference site P^sub o^, a composite chart is constructed following the procedure outlined in section 3b. The composite data for each Po from the 20 selected sites over the North Atlantic are then aligned to a common Cartesian coordinate system. The origin of this system corresponds to the location of P^sub o^. The x and y axes of this system represent the zonal and meridional displacements (as measured in degrees of longitude and latitude) from P^sub o^, respectively. The entire sample of the composite patterns is then combined by arithmetically averaging the 20 composite values at the same coordinates in this common system. Thus, the final composite picture is constructed from a total of 63 X 20 = 1260 patterns. The above procedure has been applied to various variables analyzed later. It should be emphasized again that the composite patterns for all variables examined in this study are based on key dates determined from the time series of CWP at individual sites. The merged composite data to be shown in this and the following sections are expressed as departures from a background level, which is defined as the average over the composite data for days -2, -1, 0, +1, and +2 relative to the key dates. Again, this procedure follows LC95 to allow a direct comparison with their results.

b. Composite patterns of cloud fields, precipitation, and the near-surface circulation

The distribution of surface pressure (contours), 1000hPa horizontal wind (vectors), and CWP (color shades), as constructed by merging the corresponding composite charts on day 0 for the 20 reference points in the North Atlantic during the cool season, is displayed in Fig. 6. It is evident that the outstanding episodes of large CWP at the reference site are accompanied by well-defined patterns of surface pressure and atmospheric circulation, very similar to those obtained from observations (see Fig. 6a in LC95 and Fig. 4 in LC97). Composite charts for precipitation (large scale and convective), column-- integrated water vapor and total cloud cover are shown in Fig. 7. Compared to the CWP pattern (Fig. 6), the total cloud cover is slightly extended in the northeastern direction (Fig. 7d). Large-scale precipitation (Fig. 7a) is almost in phase with CWP while the convective precipitation (Fig. 7b) is shifted southwestward relative to the reference point. These precipitation patterns resemble those obtained by Klein and Jakob (1999) from ECMWF Re-Analysis (ERA) forecast data. Also the ERA peak anomalies of 8 mm day^sup -1^ for large-scale precipitation and 4.3 mm day^sup -1^ for convective precipitation are very similar to those shown in Figs. 7a,b. Although the amounts are different, the fractional rates of increase are similar for both types of precipitation (about 120%). The southwestward extension of the precipitation anomalies relative to the reference site is also consistent with surface weather reports (LC97). A quantitative validation of simulated rainfall anomalies is not possible due to the lack of rainfall measurements over this oceanic region. Positive anomalies in precipitable water are simulated in a southwest-northeast-oriented band (Fig. 7c), with the largest increase between the reference point and the low surface pressure center (cf. Fig. 6). This northeastward extension of the anomalies can be related to advective effects due to the position of the wintertime upper-level quasi-stationary trough along the east coast of North America (Schubert et al. 1990). The maximum enhancement of total precipitable water is about 40% above the background level.

The spatial patterns of CWP, cloud cover, precipitable water, and precipitation in the composite charts (Figs. 6 and 7) are closely related to the atmospheric circulation. The largest increase in the respective variables is simulated between the surface low with a cyclonic circulation in the southwestern sector and the high pressure center with a clockwise flow pattern in the northeastern sector. Within the central part of the positive anomaly patterns, close to the reference site, southerly airstreams originating from lower latitudes prevail. Suppressed CWP, cloud cover, precipitable water, and precipitation are found, on the other hand, in regions with northerly flow in the rear of the cyclone and also eastward of the major high pressure system.

c. Composite patterns of atmospheric circulation and dynamical forcing at different altitudes

Figure 8 shows the composite pattern of horizontal wind vectors (arrows) and cloud water content (color shades) at 200 (panel a), 500 (panel b), and 1000 hPa (panel c). Superimposed on the vector fields in Fig. 8 are contours depicting horizontal advection of absolute vorticity (panel a), negative pressure velocity (panel b), and horizontal temperature advection at the corresponding levels (panel c). All patterns are based on the key dates identified by fluctuations in CWP at the 20 reference sites in the North Atlantic for the cool season, and represent departures of the composite values on day 0 from the average over the 5-day periods centered on the key dates.

Comparison between the vector patterns in the three panels in Fig. 8 reveals that both the cyclonic and anticyclonic centers are displaced about 12deg westward with increasing altitude. Accordingly, the area of enhanced CWP, cloud cover, precipitable water, and precipitation shown in Fig. 7 is located toward the east side of the trough at about -20deg relative longitude in the upper troposphere. This is consistent with the observed location and direction of the upper-level jet maximum along the cloud edge in satellite pictures and the region of heaviest precipitation at the cloud edge (e.g., see Carlson 1991, Figs. 12.15 and 12,16). For the enhanced cloud water content (color shades) at day 0 (shown in Fig. 8), a slight eastward displacement with increasing altitude is simulated in the middle and upper troposphere. A possible explanation for this shift is the effect from the enhanced eastward motion in the upper level. The cloud water content in the boundary layer (Fig. 8c) is noisier than that in the free atmosphere. There is actually a suppressed cloud water content at the reference site where the CPW enhanced the most. Since the change in cloud cover is very small near the surface (not shown), the most plausible explanation is that anomalous precipitation generated at higher levels leads to a reduction of cloud water at lower levels because the accretion of raindrops falling through low-level clouds becomes more effective.

The contour fields in Fig. 8 indicate the contribution of various dynamical forcing mechanisms to the vertical velocity, which is, as will be shown in the following analyses, a principal governing factor of the cloud water and precipitation distribution in the model. In conventional quasigeostrophic analyses (e.g., see Holton 1992, chapter 6), the midtropospheric rising motion is associated with the rate of increase with height of positive vorticity advection (mainly due to positive vorticity advection in the upper troposphere) and warm advection (strongly associated with a surface warm front). Conversely, subsidence is forced by negative upper-level vorticity advection, and by cold advection. From the patterns found in Fig. 8b, it is evident that the circle region of enhanced cloud and precipitation coincides well with the area of rising motion at 500 hPa in the model. The strong dynamical forcing is linked directly to the simulated large-scale condensation. This feature is different from the observational study in which the high-top thick clouds are located more toward the east of the maximum increase in vertical velocity (LC95, their Fig. 7). The advective effect exerted by the enhanced eastward motion in the upper troposphere was used to explain the eastward displacement of the cloud shield in LC95. However, as pointed out by Klein and Jakob (1999), the use of asynoptic datasets in LC95 might be able to explain the differences between ISCCP data (daily mean value for sunlit hours is roughly at 1500 UTC) and ECMWF analyses (daily mean value is averaged from data at 0000 and 1200 UTC). Therefore, the observed spatial displacement between cloud and maximum ascent is artificially exaggerated.

The composite chart of the 500-hPa negative pressure velocity (Fig. 8b) from the model appears to receive more contributions from the upper-level vorticity advection than from the temperature advection (cf. the contours in Figs. 8a and 8c). The longitudinal phase of major features in the contour pattern in Fig. 8b is approximately given by the average of the corresponding phases deduced from Figs. 8a and 8c. The enhancement of cloud water content at that level coincides very well with the change in vertical velocity. Comparing the contours for dynamical forcing and vertical velocity with LC95, it is found that the positive temperature advection near the reference site at 1000 hPa is weaker than in the observations. However, the simulated anomalous vertical velocity is actually larger. Since the simulated upper-level vorticity advection is very similar to the analyses of LC95 (cf. their Fig. 7a), the larger vertical velocity in the model is possibly triggered by a too large diabatic heating rate. The surface trough axis (Fig. 6) is aligned with the boundary between sectors of warm advection to the east and cold advection to the west (Fig. 8c). This is a distinct feature of extratropical frontal systems. There is also a strong upper-tropospheric warm air advection slightly to east of the surface low center (not shown). This warming by temperature advection in the upper troposphere is generally larger than the cooling by vertical motion and advection in the lower troposphere. The deepening of the surface low by the warming and the enhanced vertical circulation is important for the development and evolution of extratropical cyclones as shown in an observational study by Hirschberg and Fritsch (1991).

The moisture advection pattern near the surface is similar to that for temperature advection, with moist advection in the enhanced CWP region and dry air advection in the cold advection region (not shown). The composite pattern for maximum convergence of moisture flux at 1000 hPa is quite similar to the pattern of enhanced CWP. In the middle and upper troposphere, the dominant anomalous moisture transport at the reference site is northeastward. The moisture divergence (convergence) to the west (east) of the maximum CWP and vertical velocity is consistent with the general eastward tilting with height of moisture and cloud water and the movement of the cloud system.

d. Composite patterns along vertical cross sections

To provide a more detailed description of the vertical structure of the features described in the preceding subsections, composite pictures of selected variables are compiled at each of the available pressure levels following the same procedure described previously. The vertical cross sections of these composite data are then taken along selected line segments (highlighted in green in Fig. 8c). The line segment AB, which passes through the principal surface high and low centers, is intended to depict the vertical variation in a plane along the moving direction of the disturbance. The north-south-oriented segment CD is used to outline the relevant features along the meridional planes corresponding to the warm sector of the composite circulation system.

The contours and shades in Fig. 9 describe the composite patterns of cloud cover and cloud water content (contours and shades; panel a), temperature and moisture (contours and shades; panel b), and geopotential height and meridional wind (contours and shades; panel c) in the vertical plane along the segment AB. In constructing these fields, averages are taken over grid points lying within one grid-size distance from the segment AB. For the wind fields, the results are projected on the vertical plane along the line. These projected wind vectors (arrows) are reproduced in all three panels in Fig. 9. The patterns for temperature, geopotential height, and negative pressure velocity can be directly compared to LC95 (their Fig. 8). These composite patterns, which are reasonably well captures by the model, exhibit the familiar structure characteristics of a baroclinic wave (LC95; Lim and Wallace 1991). Due to the limitations of satellite measurement, only the top cloud layer can be seen. Therefore, a direct comparison for cloud cover and water content is not possible. However, LC95 provide some information on the approximate cloud-top altitudes and optical thicknesses. According to Fig. 9a, the vertical extents of the departures in cloud cover and cloud water content are well overlapped with the largest values located in the middle troposphere. The maximum enhancement in cloud water content is extended slightly higher than that for cloud cover. There is an eastward displacement with increasing altitude for the composite patterns shown in Fig. 9a. The largest positive anomalies for cloud fields are located in the region of strongest ascent between the low center near the surface and the ridge in the upper troposphere (Fig. 9c). LC95 also indicate a systematic reduction of both cloud-top altitude and cloud optical depth from the upper-level ridge to the west. Above the surface low pressure center, there is an increase in cloud cover and water content and weak westerly flow prevails. The maximum ascending motion is located ahead of the surface low. Behind the surface low, there are slight increases in cloud cover and water content in the atmospheric boundary layer. The cloud enhancement occurs preferentially ahead of the surface low center where ascending, warm, moist, and southerly air currents develop. Although the composite pattern for the uplifted moisture field is greater in the lower troposphere (Fig. 9b), the background temperature profile (colder temperatures in the upper troposphere) leads to large positive cloud anomalies in the middle troposphere (Fig. 9a). On the other hand, there is a significant reduction of cloud water near the surface, which is probably caused by enhanced accretion of raindrops falling through low-level cloud layers (see the discussion of Fig. 8c).

The meridional cross sections in Fig. 10 show the distribution of cloud cover and cloud water content (contours and shades; panel a), temperature and moisture (contours and shades; panel b), and geopotential height and zonal wind (contours and shades; panel c) taken along segment CD over the warm sector. The wind vectors (arrows) are again repeated in all three panels. The most notable feature in the circulation along the meridional plane in the warm sector is the warm air current originating from the lower troposphere in lower latitudes and reaching much higher altitudes as it advances poleward. The enhancement in cloud fields in the warm sector is well correlated with the vertical ascending motion. The region of increased vertical velocity in the warm sector is accompanied with a warm and moist ambient atmosphere (Fig. 10b). The cyclonic and anticyclonic flow patterns are found in the composite chart along the warm sector in the lower and upper troposphere, respectively. The structure of temperature and circulation in the warm sector in the model is very similar to the observed composite in LC95.

5. Impact of midlatitude cloud system on the local energy budget in the model

Using the model data to highlight the simulated atmospheric characteristics and cloud systems associated with extratropical synoptic-scale disturbances similar to those in observational studies (e.g. LC95) has the advantage of easy evaluation of model performance. In addition, the abundant variables produced in the model integration with a consistent dynamical and physical framework provide an opportunity to investigate other physical processes associated with passages of the synoptic-scale cloud systems. Here we will show an example by discussing the impact of these midlatitude frontal systems on the energy fluxes at the surface and the radiative fluxes at the top of the atmosphere. In previous sections, we have discussed the composite patterns of horizontal temperature advection and moisture flux near the reference site. Synthesis of this information could lead to a better understanding of the local changes in energy fluxes following the movements of these systems in the model. It should be emphasized again that the composite patterns only reveal the common impact of extratropical cyclones on the energy budget.

a. Surface energy fluxes

The same procedure as described in section 4a for constructing the composite patterns based on the reference point in the North Atlantic during the cool season (October-March) is applied to the model variables examined here for both the cool and the warm season (April-September). Figure 11 shows net shortwave radiation (panel a), net longwave radiation (panel b), latent heat flux (panel c), sensible heat flux (panel d), and total surface energy flux (i.e., the sum of these four components; panel e) at day 0 as departures from the respective background levels for the cool season. Positive (negative) values indicate anomalous surface warming (cooling). A comparison with Figs. 6 and 7 confirms that the anomalous surface fluxes are closely related to the anomalies in CWP, cloud cover, precipitable water, and precipitation. Both the surface cooling through a reduction in shortwave radiation (Fig. 11a) and the surface warming through an increase in downwelling longwave radiation (Fig. IIb) are collocated with the increase in CWP (Fig. 6). However, one should note that increases in both temperature and moisture (cf. Figs. 7, 9, and 10) contribute to the anomalous longwave radiative heating of the surface as well. This is also suggested by the slight westward displacement, relative to the CWP anomaly, of the anomalies in longwave radiation and precipitable water (cf. Fig. 7c). As will be shown later, the shortwave radiative response is seasonally dependent. During the cool season analyzed here, the largest decrease is about 30 W m^sup -2^ while in the warm season the response is more than doubled (about 70 W m^sup -2^).

The latent heat flux is reduced in a southwest-northeast-oriented band (Fig. 11c). The response pattern is governed by low-level increases of specific humidity (cf. Figs. 9b and 10b), which tend to reduce the moisture gradient in the surface layer. Further contributions to the reduced latent heat flux are increased static stability in the surface layer, and changes in wind speed may contribute as well. Although the changes in latent flux are larger than those of the other components, about 40 W m^sup -2^ in the center, its fractional change is comparatively small, about 20%, because the background flux in the cool season is relatively large. It is noteworthy that the positive moisture anomaly in the warm sector of the system is maintained through horizontal advection while the moisture supply through latent heat flux, or surface evaporation, is actually reduced in this region. Similar to the latent heat flux, the sensible heat flux is reduced in the warm sector of the system, which leads to anomalous heating of the surface (Fig. 11d). The main reason for this reduction is the warming of the atmospheric boundary layer so that the vertical temperature gradient becomes smaller. Secondary effects are a reduction of the heat transfer coefficient due to increased stability and, possibly, changes in wind speed. The maximum change (about 35 W m^sup -2^) is slightly smaller than the change in latent heat flux but larger than the changes in radiation. There is no phase shift with respect to the reference site, but the pattern shows a southwest to northeast orientation similar to that of the latent flux. The changes in total surface heat flux are shown in Fig. 11e. A comparison with Fig. 6 reveals that the anomalous surface heating is closely connected with the dynamical system. The largest surface warming is simulated slightly westward of the surface low. The largest surface cooling, predominantly due to increases in sensible and latent heat fluxes, is found eastward of the respective surface highs in regions characterized by cold air advection. It is important to note that this response is typical for the cool season.

In the warm season, the reduction in solar radiation (Fig. 12a) is roughly doubled compared to the cool season and by far the most important contribution to the change in the total surface energy budget. However, the fractional rate of change is almost independent of season (about -50% in the center of the anomaly). All other components contribute positively to the surface energy budget through enhanced downwelling longwave radiation (Fig. 12b) and reduced turbulent fluxes of both latent heat (Fig. 12c) and sensible heat (Fig. 12d). However, compared to the cool season, the changes in the turbulent fluxes are very small while those in the longwave radiation are almost independent of season. During the warm season, the change in total surface energy flux (Fig. 12e) is negative, with a peak value of about -35 W m^sup -2^ in the center of the cyclone, while a positive change of up to about 60 W m^sup -2^ is simulated during the cool season (cf. Fig. 11e).

b. Radiative fluxes at the top of the atmosphere

Figure 13 shows the composite patterns for the anomalies in shortwave (panel a), longwave (panel b), and net radiation (panel c) at the top of the atmosphere during the cool season. The reduction in shortwave radiation due to increases in cloud cover and CWP has a similar pattern as that at the surface (cf. Fig. 11a), but the magnitude is somewhat smaller. The slight phase lag relative to the reference point is due to the vertical tilting of cloud cover and cloud water content (cf. Fig. 9a).

On the other hand, due to the larger cloud cover, cloud water content, and moisture in extratropical cyclones, the outgoing longwave radiation is reduced so that more heat is trapped in the earth-atmosphere system (Fig. 13b). In contrast to the shortwave anomaly there is no phase shift relative to the reference site. Since the longwave heating is slightly larger than the shortwave cooling within the cyclonic system, the net effect is a moderate heating of about 15 W m^sup -2^ near the reference site whereas there is a net cooling to the east of the surface highs in areas with northerly flow (cf. Fig. 6). A comparison of the total flux anomaly at the surface (Fig. lIe) and the net radiative anomaly at the top of the atmosphere (Fig. 13c) reveals that the former is significantly larger (by about 50 W m^sup -2^). The difference between the top-of-atmosphere anomaly and that at the surface is therefore negative, which means that the changes in vertical energy fluxes during the cool season lead to a cooling of the atmospheric column (Fig. 13d), which has to be compensated by horizontal energy flux convergence. As is to be expected, there is a pronounced seasonality in the shortwave anomaly that roughly doubles in the warm season with peak values of about -60 W m^sup -2^ (Fig. 14a) while the longwave anomaly (Fig. 14b) is practically independent of season (cf. Fig. 13b). The net radiative flux anomaly (Fig. 14c) is negative in the warm season, with peak values of about -20 W m^sup -2^, while it is positive during the cool season (cf. Fig. 13c). The pronounced seasonality in the anomalies of shortwave radiation and turbulent heat fluxes at the surface is also reflected in the net atmospheric heat flux. Due to the changes in the vertical energy fluxes, the atmospheric column in most parts of the cyclonic systems is cooled in winter (Fig. 13d) and heated in summer (Fig. 14d). One the other hand, extratropical cyclones cause anomalous surface heating in winter (Fig. 11 le) and cooling in summer (Fig. 12e). These results are qualitatively similar to those obtained by Tselioudis et al. (2000) who used ISCCP data and the National Centers for Environmental Prediction (NCEP) reanalysis data for estimating the impact of dynamical regimes on the radiation budget. According to this observational study, more sunlight is reflected in the low pressure regime than in the high pressure regime (up to 20 W m^sup -2^ in January and up to 50 W m^sup -2^ in July). On the other hand, there is no indication for a seasonality in the longwave differences between dynamical regimes, with peak values of about 35 W m^sup -2^ in both seasons. As a result, the total flux difference is positive in winter (up to 15 W m^sup -2^) but negative in summer (up to -40 W m^sup -2^). Although the agreement with our results is striking, we have to note that different techniques were used to identify the dynamical regimes. In our study, the deviation from a background value produced by a well-developed cyclone (about 5% of the whole sample) is calculated while Tselioudis et al. (2000) consider a larger part of the frequency distribution to define low and high pressure regimes and calculate the anomalies as differences between these regimes.

The strong impact of extratropical disturbances on the shortwave radiation budget at the top of the atmosphere was also found by Weaver and Ramanathan (1996) who analyzed Earth Radiation Budget Experiment (ERBE) data in the North Pacific for July 1985. It was shown that the large shortwave cloud radiative forcing of about 150 W m^sup -2^ in the monthly mean is predominantly caused by traveling cyclones.

6. Discussion and summary

Following a composite technique to depict the synoptic-scale organization of cloud properties associated with midlatitude weather systems (LC95 and LC97), we have constructed anomaly patterns of GCM-simulated cloud fields in conjunction with the concurrent 3D atmospheric structure and dynamical processes near selected reference sites in the northwestern Atlantic. The main focus is on the cool season when the baroclinicity is higher and the weather disturbances are more frequent than in the warm season. The composite procedure is based on the timing of distinct episodes with large cloud water path. It is adopted from LC95 with the intention of easy comparison with the already published results. The only difference is that we employ the total cloud water path to trace the movement of the prominent cloud events instead of cloud optical thickness used in LC95. Compared to traditional model validation techniques that compare geographical distributions of simulated and observed means and variances, for example, the ensemble approach used in this study has several advantages. First, the reference sites at which the analysis is centered can be selected according to the preferred location of the respective phenomenon in the model, which is not necessarily identical to that which one would select from the observations. Thus, the impact of possible dynamical model biases on simulated cloud patterns can be minimized. Second, the method allows for validation of the simulated fields of clouds and related variables in conjunction with a certain class of atmospheric phenomena such as baroclinic wave disturbances or tropical cyclones, for example. This process-oriented approach aids in identifying possible reasons for deficiencies in cloud simulation. Finally, the time- and space scales involved in the analysis procedure seem to be more appropriate for investigating rather short-lived cloud processes than the standard techniques, which involve averaging over a wide range of scales.

As in the observations the simulated cloud variations over the northwestern Atlantic are closely linked to the passage of baroclinic waves as clearly evident from the atmospheric structure. For example, the vertical distribution of geopotential height anomalies with the typical westward tilt with altitude is comparable to the observed pattern (LC95) not only in structure but even in amplitude. This good agreement suggests that we picked a similar sample as LC95 so that the dynamical forcing should be similar as well. The composite charts show also a slight eastward displacement in upper-tropospheric cloud anomalies relative to the center of upward motion at 500 hPa. However, this vertical tilt in the cloud pattern is not as distinct as in the observations. As pointed out by Klein and Jakob (1999), part of this difference can be attributed to the use of asynoptic data in LC95 so that not all is necessarily due to systematic model biases. Similar to indications from surface weather reports (LC97), the largest precipitation anomalies are simulated westward of the reference site defined by the largest anomaly in cloud water path and cloud optical thickness, respectively. The distribution of vertical velocity in the model can be explained by the dynamical forcing at different vertical levels. However, the near-- surface temperature advection in the model is smaller than in the observations. Nevertheless, the underestimation of the forcing does not lead to weaker enhancement in ascending motion near the reference site. This indicates a possible problem related to the diabatic heating produced during prominent cloud events. The vertical cross sections along the wave propagating direction and along the warm sector reveal a more complete 3D structure of various fields and their interrelations. Most of these features are in good agreement with the classical model of an extratropical cyclone (Bjerknes and Solberg 1926) and more recent depictions of clouds and airflow patterns associated with the development of extratropical cyclones (Carlson 1980; Hirschberg and Fritsch 1991; Anderson et al. 1995). The detailed characteristics associated with frontal systems (e.g., frontal boundary, comma-shaped cloud shield, mesoscale rainbands) cannot be seen in the final composite picture due to coarse model resolution and, moreover, due to the superposition of many different events with varying structure and life cycles. However, the virtue of these composite patterns lies in their representativeness of those characteristics that are common to prominent cloud episodes that have occurred in the model.

The second objective of this study is to investigate the impact of well-developed extratropical cyclones on the energy fluxes. In the cool season, the surface is heated over the surface low pressure center with an elongated extension from southwest to northeast. The largest contribution to the maximum heating slightly south of the low center is from the reduction in sensible and latent heat flux. At the top of the atmosphere, the cloud enhancement leads to a reduction in absorbed shortwave radiation, cooling the earth-atmosphere system, and a reduction in outgoing longwave radiation, which has the opposite effect. Since the latter effect is slightly larger, the earth-atmosphere system is heated over the surface low. However, compared to the net surface heating, the top-of-atmosphere change is relatively small so that the atmospheric column experiences a cooling due to changes in vertical energy fluxes. This cooling has to be compensated by horizontal energy flux convergence within the column. There is a marked seasonal dependence of these energy flux changes at both the surface and the top of the atmosphere, and there is even a sign reversal in the warm season when the change in shortwave radiation (strongly negative over the low pressure center) becomes the dominant term in the energy budget. These results are qualitatively similar to those obtained by Tselioudis et al. (2000) who used ISCCP satellite observation and NCEP reanalysis data for estimating the impact of dynamical regimes on the radiation budget. However, we have to note that different techniques are used to identify the dynamical regimes. Tselioudis et aL (2000) consider a larger part of the mean sea level pressure frequency distribution to define low and high pressure regimes and calculate the anomalies as differences between these two regimes while we compute the deviation from a background value produced by a well-developed cyclone (about 5% of the whole sample).

The results presented here are encouraging in the sense that even a coarse-resolution model is able. to realistically capture anomalies in cloud and radiation associated with the passage of well-developed cyclones, at least qualitatively. This is probably related to the fact that cloud formation can reasonably well be simulated when the dynamical forcing is relative large. In other regimes, such as stratocumulus formation under a subsidence inversion, climate models tend to systematically underestimate cloud formation. This applies also for the model used in this study (Chen and Roeckner 1996, 1997). Moreover, it is shown in these earlier studies that total cloud cover over the extratropical oceans during summer is too low by about 20% and the shortwave cloud radiative forcing in these regions underestimated by about 20 W m^sup -2^. Since the simulated longwave cloud radiative forcing is close to the observations, it is concluded that a lack of low and middle clouds is the main source of error. From the results presented here it is very unlikely that these biases are caused by insufficient cloudiness in well-developed cyclones. More likely they are due to biases in the frequency distribution of dynamical regimes and/or insufficient cloud formation under weaker dynamical forcing.

Acknowledgments. The authors would like to thank Drs. Ngar-Cheung Lau and Steven Klein for examining a preliminary draft of the manuscript and for offering many invaluable suggestions. We are also grateful to the helpful comments by the anonymous reviewers. The ISCCP datasets are produced through an effort led by W. B. Rossow at the NASA Goddard Institute of Space Studies. The further processed data tapes have been provided to us by Mark W. Crane at the NOAA/Geophysical Fluid Dynamics Laboratory. This research was supported by the National Science Council, Republic of China, under Grants NSC 89-2111-M-003-006 and NSC 90-2111-M-003-001, and by the Program of Grants for Project-based Personnel Exchange with Germany, NSC-- DAAD Joint Research Collaboration.

References

REFERENCES

References

Anderson, R. A., T N. Carlson, and J. R. Grant, 1995: Synoptic-scale cloud and moisture patterns. Images in Weather Forecasting-- A Practical Guide for Interpreting Satellite and Radar Images, M. J. Bader et al. Eds., Cambridge University Press, 70-137.

Bjerknes, J., and H. Solberg, 1926: Life cycle of cyclones and polar front theory of atmospheric circulation. Geofys. Publ., 3, 1-18.

Browning, K. A., and G. A. Monk, 1982: A simple model for the synoptic analysis of cold front. Quart. J. Roy. Meteor. Soc., 108, 435-452.

Carlson, T. N., 1980: Airflow through midlatitude cyclones and the comma cloud pattern. Mon. Wea. Rev., 108, 1498-1509.

References

-, 1991: Mid-latitude Weather Systems. Harper-Collins, 507 pp.

Chen, C.-T, and E. Roeckner, 1996: Validation of the Earth radiation budget as simulated by the Max Planck Institute for Meteorology general circulation model ECHAM4 using satellite observations of the Earth Radiation Budget Experiment. J. Geophys. Res., 101, 4269-4287.

-, and -, 1997: Cloud simulations with the Max Planck Institute for Meteorology general circulation model ECHAM4 and comparison with observations. J. Geophys. Res., 102, 93359350.

Cotton, W. R., and R. A. Anthes, 1989: Storm and Cloud Dynamics. Academic Press, 883 pp.

References

Del Genio, A. D., M.-S. Yao, W. Kovari, and K. K.-W. Lo, 1996: A prognostic cloud water parameterization for global climate models. J. Climate, 9, 270-304.

Fowler, L. D., D. A. Randall, and S. A. Rutledge, 1996: Liquid and ice cloud microphysics in the CSU general circulation model. Part 1: Model description and simulated microphysical processes. J. Climate, 9, 489-529.

Gates, W. L., 1992: AMIP: The Atmospheric Model Intercomparison Project. Bull. Amer. Meteor. Soc., 73, 1962-1970.

Hahn, C. J., S. G. Warren, and J. London, 1994: Edited synoptic cloud reports from ships and land stations over the globe, 19821991. Carbon Dioxide Information Analysis Center Rep. NDP026B, 47 pp. [Available from Data Support Section, National Center for Atmospheric Research, PO. Box 3000, Boulder, CO 80307.

References

Hirschberg, P A., and J. M. Fritsch, 1991: Tropopause undulation and development of extratropical cyclones. Part II: Diagnostic analysis and conceptual model. Mon. Wea. Rev., 119, 518-550.

Holton, J. R., 1992: An Introduction to Dynamical Meteorology. 3d ed. Academic Press, 511 pp.

Houze, R. A., Jr., 1993: Cloud Dynamics. Academic Press, 573 pp. and P Hobbs, 1982: Organization and structure of precipitating cloud systems. Advances in Geophysics, Vol. 24, Academic Press, 225-315.

Klein, S. A., and C. Jakob, 1999: Validation and sensitivities of frontal clouds simulated by the ECMWF model. Mon. Wea. Rev., 127, 2514-2531.

Lau, N.-C., and M. W. Crane, 1995: A satellite view of the synopticscale organization of cloud properties in midlatitude and tropical circulation systems. Mon. Wea. Rev., 123, 1984-2006.

-, and -, 1997: Comparing satellite and surface observations of cloud patterns in synoptic-scale circulation systems. Mon. Wea. Rev., 125, 3172-3189.

References

Lim, G. H., and J. M. Wallace, 1991: Structure and evolution of baroclinic waves as inferred from regression analysis. J. Atmos. Sci., 48, 1718-1732.

McGuirk, J. P, A. H. Thompson, and J. R. Schaeffer, 1988: An eastern Pacific tropical plume. Mon. Wea. Rev., 116, 2505-2521.

Nordeng, T E., 1994: Extended versions of the convective parameterization scheme at ECMWF and their impact on the mean and transient activities of the model in the tropics. ECMWF Tech. Memo. 206, Reading, United Kingdom, 61 pp.

Roeckner, E., M. Rieland, and E. Keup, 1991: Modelling of cloud and radiation in the ECHAM model. Proc. ECMWF/WCRP Workshop on Clouds, Radiative Transfer and the Hydrological Cycle, Reading, United Kingdom, ECMWF, 199-222.

-, and Coauthors, 1996: The atmospheric general circulation model ECHAM4: Model description and simulation of present-day climate. Max-Planck-Institut fur Meteorologie Rep. 218, Hamburg, Germany, 90 pp.

References

Rossow, W. B., and R. A. Schiffer, 1991: ISCCP cloud data products. Bull. Amer. Meteor. Soc., 72, 2-20.

Schubert, S., C.-K. Park, W. Higgins, S. Moorthi, and M. Suarez, 1990: An atlas of ECMWF analyses. Part I-First moment quantities. NASA Tech. Memo. 100747, 258 pp.

Tiedtke, M., 1993: Representation of clouds in large-scale models. Mon. Wea. Rev., 121, 3040-3061.

Tselioudis, G., Y. Zhang, and W. B. Rossow, 2000: Cloud and radiation variations associated with northern midlatitude low and high sea level pressure regimes. J. Climate, 13, 312-327.

Weaver, C. P, and V. Ramanathan, 1996: The link between summer cloud radiative forcing and extratropical cyclones in the North Pacific. J. Climate, 9, 2093-2109.

Williamson, D. L., and P J. Rasch, 1994: Water vapor transport in the NCAR CCM2. Tellus, 46A, 34-51.

AuthorAffiliation

CHENG-TA CHEN

Department of Earth Sciences, National Taiwan Normal University, Taipei, Taiwan

AuthorAffiliation

ERICH ROECKNER

Max Planck Institute for Meteorology, Hamburg, Germany

AuthorAffiliation

Corresponding author address: Dr. Cheng-Ta Chen, Department of Earth Sciences, National Taiwan Normal University, No. 88, Section 4, Ting-Chou Rd., Taipei 116, Taiwan.
E-mail: chen@rain.geos.ntnu.edu.tw

DETAILS

LINKS

Linking Service