

## Arctic Cloudiness: Comparison of ISCCP-C2 and *Nimbus-7* Satellite-derived Cloud Products with a Surface-based Cloud Climatology

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### ABSTRACT

One surface-based and two satellite arctic cloud climatologies are compared in terms of the annual cycle and spatial patterns of total monthly cloud amounts. Additionally, amounts and spatial patterns of low, middle, and high cloud type are compared. The surface-based dataset is for the years 1951–81, while the satellite-based data are for 1979–85 and 1983–86. The satellite cloud amounts are generally 5%–35% less than the surface observations over the entire Arctic. However, regional differences may be as high as 45%. During July the surface-based cloud amounts for the central Arctic are about 40% greater than the satellite-based, but only 10% greater in the Norwegian Sea area. Surprisingly, (ISCCP) cloud climatology and surface observations agree better during winter than during summer. Possible reasons for these differences are discussed, though it is not possible to determine which cloud climatology is the “correct” one.

### 1. Introduction

Products from the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer 1991, hereafter RO91) are designed to provide information for studying the effects of cloud cover on the radiation balance of the earth. While specific experiments have been designed to validate the ISCCP products against the surface and aircraft observations [e.g., FIRE (Wylie and Menzel 1989)], no such experiments are currently planned in the polar regions. Validation of ISCCP products in the polar regions, where the problems of cloud detection are enhanced, has been limited to the intercomparison with cloud information derived from satellites using more sophisticated algorithms that employ a greater number of channels (Rossow 1991; Key and Barry 1989). To our knowledge, ISCCP data for the polar regions have not yet been compared to the rather sparse collection of surface-based cloud observations currently available. In this paper we compare the monthly cloud statistics from the ISCCP-C2 dataset with monthly cloud statistics from an atlas of global cloud cover compiled by Warren et al. (1986, 1988; hereafter WAR). In addition to the comparison with surface observations, the ISCCP-C2 cloud product is also compared with cloud statistics from the *Nimbus-7* Global Cloud Climatology of Stowe et al. (1988; hereafter C-MATRIX), which is based on satellite ra-

diances from the Temperature Humidity Infrared Radiometer (THIR) and the Total Ozone Mapping Spectrometers (TOMS) on board the *Nimbus-7* satellite. This comparison provides insight into the dependence of satellite cloud climatologies on the type of algorithm used.

The motivation for making these comparisons comes from a larger project in which we attempt to produce a monthly climatology of the surface and top-of-the-atmosphere radiation budgets from the ISCCP-C2 dataset. Unfortunately, given the limited knowledge of the spatial and temporal distribution of clouds in the arctic regions, none of the datasets can be considered to represent “true” cloud information. Therefore, this intercomparison tries to establish the range of differences between the three datasets, which may serve as an error estimate in subsequent sensitivity studies.

### 2. Data

#### a. Datasets

The ISCCP-C2 dataset is a compilation of monthly statistics (RO91) derived from the daily ISCCP-C1 cloud product. For the polar regions where the geostationary satellites do not provide coverage, cloud information in the ISCCP dataset is derived from the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA polar orbiting satellites. Cloud statistics are retrieved from the imagery using a sophisticated algorithm based on channel 1 (0.58–0.68  $\mu\text{m}$ ) and channel 4 (10.3–11.3  $\mu\text{m}$ ) radiances. The algorithm employs a combination of temporal and spatial statistical tests and radiative analyses to retrieve cloud

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amount, cloud top height, and cloud optical thickness, to name only a few of the parameters. While the ISCCP-C1 dataset of daily parameters retains more detailed information on cloud height/optical thickness statistics, ISCCP-C2 monthly statistics are given for a number of cloud classes based on height and optical depth. Throughout the remainder of this paper, "cloud type" refers to the height categories low, middle, and high. A detailed description of the ISCCP dataset and algorithms can be found in RO91. To date, the ISCCP-C2 dataset covers the period from July 1983 through December 1990, even though only data for the period 1983 through December 1986 were used in the present study.

WAR have recently published global cloud climatologies for land and ocean areas. Surface observations contained in the Fleet Numerical Oceanography Center (FNOC) synoptic reports for the period from 1971 to 1981 were analyzed and compiled into a land-area atlas. Cloud observations from ships contained in the Comprehensive Ocean-Atmosphere Data Set (COADS) (Woodruff et al. 1987) for 1951–1981 form the basis for the ocean-area atlas. Summary statistics used in both atlases are also available on digital media from the Carbon Dioxide Information Analysis Center (CDIAC) (Hahn et al. 1988). The atlases contain monthly statistics of total cloud amount, cloud type as well as base height for the lower cloud types, along with quality control statistics. Since there is no direct overlap between the ISCCP and the WAR datasets, only monthly statistics were compared. Interannual variability of monthly cloudiness is small, in the range of 5% for July and up to 8% in January of the four ISCCP years, so that errors due to nonoverlapping climatologies should be of a lower magnitude than the other potential error sources discussed later.

The *Nimbus-7* C-MATRIX product for the period 1979–1985 is available in the form of monthly statistics. The C-MATRIX is derived from radiances in the 11.5- $\mu\text{m}$  thermal channel of the THIR sensor and from the 0.36- $\mu\text{m}$  and 0.38- $\mu\text{m}$  channels of the TOMS sensor. The algorithm incorporates concurrent temperatures and snow/ice cover data from the Air Force 3D neph-analysis. Total cloud amount and cloud amounts in three altitude categories are determined. A bispectral threshold method yields two independent estimates of clouds, one based on IR radiances and the other based on the UV reflectivity, which are then combined to yield composite estimates. At night, which in the polar region is the winter period, only the IR estimates are used. Due to the high UV reflectivity of snow and ice covered areas the TOMS part of the algorithms is not used when pixels are completely snow/ice covered. The C-MATRIX algorithm displays a unique feature that is relevant to the retrieval of polar cloud cover: when climatological inversions are present (from the Air Force 3D analysis) and the surface is colder than 280 K, any pixel with a temperature near the precomputed

threshold will be assigned a low cloud label. This particular step is designed to allow computation of cloud amounts in areas where low warm clouds frequently occur and contrasts the ISCCP procedure, which always assumes clouds to be colder than the surface. This part of the algorithm relies on the accuracy of the atmospheric temperature analysis, which reportedly produces large errors over Antarctica and Greenland. Comparisons of C-MATRIX results with manual classification indicate a random error of daily estimates ranging between 7% and 16% (Stowe et al. 1988). Apparently, no specific efforts were directed toward validation in the polar regions, and cloud estimates in the polar regions are described as "uncertain."

### b. Gridding

The ISCCP and WAR datasets are presented on equal area grids with different longitudinal and latitudinal resolutions. The ISCCP grid consists of 2.5° latitudinal bands, with increasing longitudinal resolution resulting in a data cell size of approximately 280 km  $\times$  280 km. The WAR dataset offers approximately half the resolution with 5.0° latitudinal bands. Subsets of grid points north of 62.5° were extracted from both datasets. Prior to comparison, the ISCCP dataset was remapped and averaged to the WAR grid by weighting individual ISCCP grid box values according to their areal overlap with the WAR grid boxes. Thus, no additional errors were introduced through the remapping procedure. The combined datasets were then mapped to a polar azimuthal projection. Prior to contouring the irregular grid (decreasing number of points with increasing latitude), the data were interpolated to a regular grid using a standard interpolation procedure. Since data points are relatively evenly distributed, no significant errors are expected to be introduced in this step. The C-MATRIX presents clouds statistics on the Earth Radiation Budget (ERB) grid, similar to the one used for the ISCCP product but with a resolution of 165 km  $\times$  165 km and different latitude segments. Regular grids presenting the data in a polar projection were constructed from the C-MATRIX product with the same procedure.

### c. Cloud overlap

The retrieval of cloud-type amounts from surface as well as satellite observations is a problematic issue. The difficulty in determining cloud-type amounts arises from the fact that the amounts of clouds obscured by higher/lower clouds (when viewed from above/below) cannot be determined accurately. Surface observations used by WAR only contain amounts for total cloud cover and the lowest unobscured cloud type. When present high and middle cloud are noted, but their amounts are not contained in the synoptic code. Total cloud amount for high or middle cloud,  $A_U$ , is calculated from the total and lower-level cloud amounts (if

present),  $A_T$  and  $A_L$ , assuming random overlap such that

$$1 - A_T = (1 - A_U)(1 - A_L). \quad (1)$$

This equation is used to calculate upper-level cloud amounts only when two cloud levels are reported and when lower-level cloud amount is less than or equal to 6 octas. When more than two cloud levels are present, or when the sky is totally obscured by a lower cloud, higher and middle cloud amounts are taken to be the same as for the cases where it is observed or calculated using (1). Thus, the accuracy of the upper-level WAR cloud amounts depends on the validity of two assumptions: (i) random overlap and (ii) that upper-level cloud amounts in cases where they cannot be calculated (i.e., when all three types are present or when the lowest cloud amount is 7–8 octas) are equal to the mean amount in cases where they can be observed or inferred from (1). Satellite-derived cloud-type information suffers from a similar problem in that lower-level clouds may be completely or partially obscured by higher-level clouds. In order to obtain cloud-type statistics from the ISCCP dataset that can be compared to surface observations, we have applied a correction for cloud overlap. Again assuming random overlap, total low and middle cloud amounts,  $A_L$  and  $A_M$ , can be shown to be related to the observed high, middle, and low cloud amounts  $A'_H$ ,  $A'_M$ , and  $A'_L$  (i.e., those areas not obscured by clouds above) according to

$$A_M = \frac{A'_M}{1 - A_H} \quad (2)$$

$$A_L = \frac{A'_L}{1 - A_M - A_H - A_M A_H}. \quad (3)$$

ISCCP cloud-type amounts were adjusted with (2) and (3) for comparability with the WAR dataset. We note, however, that the correction of cloud-type observations for obscured cloud types is to be considered approximate for both surface and satellite observations, and significant errors related to the random overlap assumption can occur (Tian and Curry 1989). While we have included a comparison of cloud-type amounts, the focus of the following analysis is on total cloud cover.

### 3. Annual cycle of cloud amounts for the entire Arctic

In this and the following section, cloud amounts for the entire Arctic and regional differences between the datasets are described. Discussions of the possible reasons for these differences are for the most part deferred until section 5.

#### a. Total cloud amount

Figure 1 shows the annual variation of total cloud amounts in the ISCCP-C2 and WAR datasets for the region north of 62.5° latitude. Two separate cloud amounts are given for the ISCCP-C2 set: (a) the cloud amount reported as total in the ISCCP-C2 dataset, and (b) marginal cloud amount. Marginal cloud amounts reported are derived in the ISCCP procedure through the application of a different threshold and represent the first derivative of cloud amount with respect to the threshold (RO91). After the computation of a clear-sky composite, which is considered to represent clear-sky thermal and visible radiances for a particular analysis cell over a period of 5, 15, or 30 days, the ISCCP

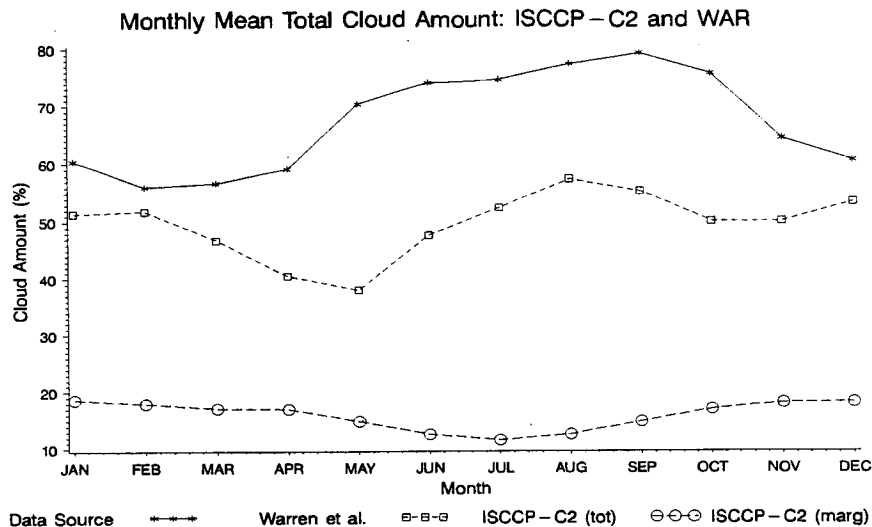


FIG. 1. Annual cycle of total cloudiness in the Arctic (north of 62.5° latitude) from the ISCCP-C2 and WAR datasets. ISCCP data are for 1983–1986; WAR data cover the period 1951–1981.

algorithm proceeds to label pixels as cloudy or clear according to a bispectral decision matrix. This decision matrix is conservative in the assignment of pixels to the cloud category but retains information on how well the decision criteria were met through the assignment of intermediate categories summarized in the marginal cloudiness. The total cloud includes the marginal cloud. These marginally cloudy pixels display radiances that are near the clear-sky radiances and occur primarily in areas of broken cloudiness and where the contrast between cloudy and clear conditions is low. Such conditions prevail in the polar regions, and the marginal cloud amount is presented as an indicator of the level of uncertainty in the thresholds. As can be seen from Fig. 1, this level of uncertainty is greater during winter.

To highlight the conservative approach we point out that for a pixel to be labeled definitely cloudy when only IR information is available (arctic winter), it needs to be colder than the surface composite by twice the threshold for the particular surface type (3.5 K for sea ice). Pixels with temperatures colder than clear-sky composite temperatures by only the threshold amount will be labeled marginally cloudy. Thresholds for the visible band are similarly conservative and require definitely cloudy pixels over snow and ice covered surfaces to be 12% more reflective than clear sky and 6% for marginally cloudy pixels.

A comparison of the annual cycle of cloud amounts in Fig. 1 shows substantial differences between the ISCCP and WAR results. Surface observations report 20%–35% greater cloud amounts than the ISCCP dataset from April through October. During winter ISCCP cloud amounts are lower than those reported by surface observers by less than 10%. Marginally cloudy pixels account for 10% of the total cloud amount during summer and up to 20% during winter. Despite the dif-

ferences in total cloud amount, the annual cycle of cloud amounts from the WAR and ISCCP datasets parallel from spring through fall. Cloud amounts in the WAR dataset begin to increase from April, with a peak during September. ISCCP cloud amounts begin to rise in May with a peak in August and September. The smaller differences during winter may be related to systematic biases that may be negative for cloud amounts from surface observations (absence of light, unreported ice crystal precipitation) and positive for satellite-derived datasets during winter. A detailed discussion of possible sources of error will follow the comparisons.

Mean cloud amounts from the C-MATRIX dataset for the entire Arctic (Fig. 2) parallel the annual cycle of cloudiness from surface observations very well, with the month of lowest cloudiness just one month earlier in March. As in the ISCCP dataset, C-MATRIX cloud amounts are lower than WAR cloud amounts throughout the year and match surface observations better during winter. As will be shown later, however, there are important regional differences between the C-MATRIX and WAR results.

A comparison of the datasets under investigation here and the statistics from Huschke (1969, hereafter HU69) and Curry and Ebert (1992) shows an interesting feature. The annual cycle from HU69, which is based on surface observations, resembles the WAR dataset differing only in the amplitude of the annual cycle with about 10% greater cloud amount during summer and about 10% lower cloud amounts during winter. Curry and Ebert (1992) modified HU69 statistics to account for up to 50% cover of radiatively important ice crystal precipitation (or ice crystal haze or "diamond dust") that frequently occurs in the central Arctic regions during the winter (Ohtake 1982; Curry et al.

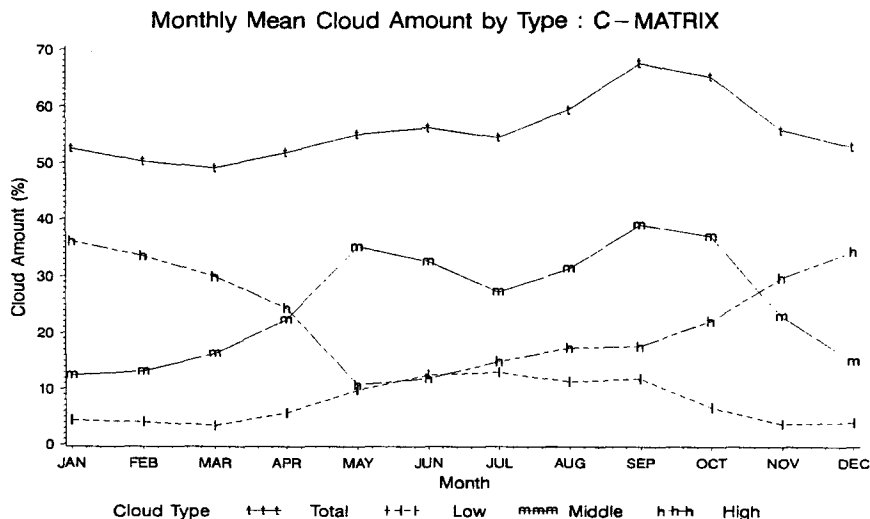


FIG. 2. Annual cycle of total cloudiness in the Arctic by cloud type from the C-MATRIX dataset. C-MATRIX data are for 1979–85.

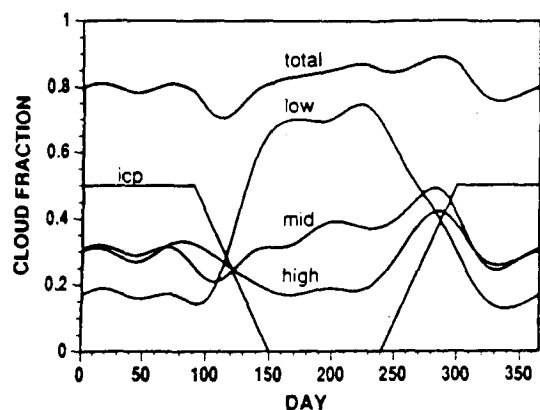


FIG. 3. Annual cycle of total cloud amount and cloud types including ice-crystal precipitation. From Curry and Ebert (1992).

1990) but will not be reported as clouds by a surface observer (Fig. 3). Their modified annual cycle follows the ISCCP cloud amount more closely, even though differing in absolute amounts. The difference in total cloud between winter and summer when ice crystal haze is included is much smaller, and the minimum in cloud cover occurs during March/April. This fact might provide some evidence to support the hypothesis that the ISCCP data includes ice crystals in its cloud statistics. We will address this hypothesis in detail later.

#### b. Cloud types

Cloud types in the ISCCP-C2 dataset are defined by altitude as low (1000–680-mb), middle (680–440-mb) and high (440–50-mb) clouds (Table 1). In the C-MATRIX dataset, low clouds are defined to occur within the lower 2 km, and middle clouds between 2 and 4 km for areas north of 60° latitude. Based on the mean January pressure–altitude relationship from radiosonde measurements taken over Russian ice islands in the northern Canada Basin, C-MATRIX low, middle, and high cloud classes correspond roughly to 1000–800 mb, 800–600 mb, and 600–50 mb (Table 1). Low-lying stratus clouds, which commonly occur in the lower 2-km Arctic troposphere with thicknesses of several hundred meters and top heights between 500 m and 1000 m (Tsai and Jayaweera 1984), are unfortunately grouped with other substantially higher clouds in the ISCCP low category.

Figure 4 shows the annual cycle of cloud types in the ISCCP dataset. The annual cycle of cloud types from the C-MATRIX dataset was given in Fig. 2. Middle cloud amounts form the largest category in the ISCCP data, in the range of 18%–32%, with the greatest amount during winter. Low-lying clouds form the next largest category of clouds, ranging from 10% to 20%, with the maximum in June. The smallest category is formed by high clouds, which does not exceed 10%,

and interestingly parallels the total and middle cloud amounts in its annual cycle.

Comparison of cloud-type statistics between the ISCCP and the C-MATRIX datasets is difficult because of the different cloud-type definitions. Thus, it is not surprising to see that high cloud amounts in the C-MATRIX dataset are similar to those in the middle category of the ISCCP dataset, in the range of 10%–35% with maxima in December and January and a minimum in May. On the other hand, low cloud amounts from the ISCCP dataset do not seem to match middle clouds in the C-MATRIX dataset as one would expect. Middle cloud amounts in the C-MATRIX dataset range from 10% to 40%, with maxima in May and September. Low cloud amounts in the C-MATRIX dataset, while lower throughout the year, resemble low cloud amounts in the ISCCP-C2 dataset. This is probably an indication that low cloud amounts in the ISCCP-C2 dataset mostly originate from a cloud type that occurs at less than 2-km height and thus is comparable to the C-MATRIX low cloud amounts.

Table 2 summarizes the seasonal statistics of cloud types from the ISCCP and the WAR dataset. ISCCP statistics are given with and without correction for overlap. The differences between WAR and the adjusted ISCCP middle cloud amounts are within 7%, where ISCCP cloud amounts are lower except for the winter season. As with the total cloud amounts, ISCCP low cloud amounts are lower than WAR by 10%–15%, with the greatest differences occurring in summer and fall. This difference is attributable to the fact that low-lying stratus clouds have a low temperature and brightness contrast with the surface and may be missed by the ISCCP algorithm. The fact that ISCCP cloud-type statistics adjusted for overlap are in better but not complete agreement with surface observations (except for the winter season) indicates that overlap alone may not account for the differences in cloud-type amounts. The largest differences between ISCCP and WAR cloud-type amounts are found in the high category. Differences are in the order of 20% throughout the year. Even though we have included the cumulonimbus category (Cb) in the high cloud amount, the Cb category for basinwide statistics represents only 5% of the high cloud amount in the WAR statistics and less than 5%

TABLE 1. Lower altitudinal bounds of ISCCP and C-MATRIX cloud types.

Z (km)	p (mb)	ISCCP	C-MATRIX
6	440	High	High
5			
4	600		
3	680		
2	800	Middle	Middle
1			
0	1000	Low	Low

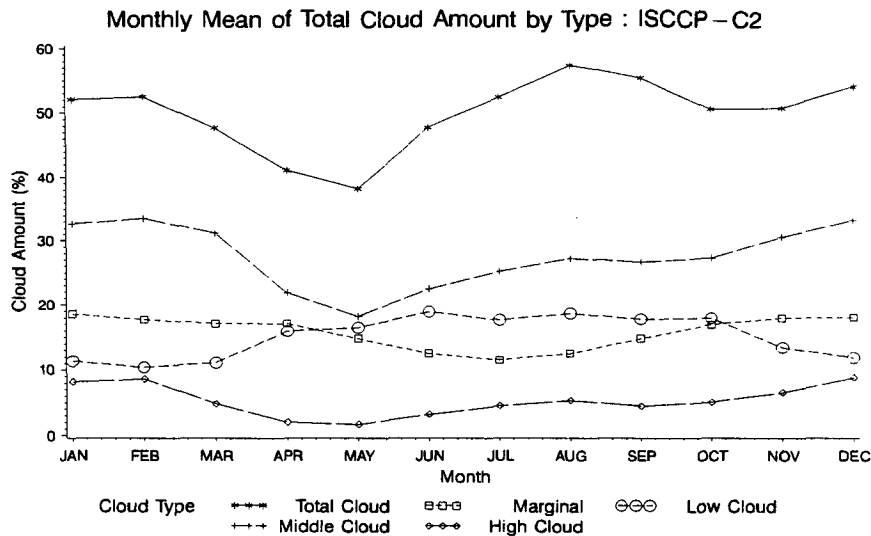


FIG. 4. Annual cycle of arctic cloud types in the ISCCP dataset.

in the ISCCP dataset (Cb is not a category in the ISCCP but "deep convective" is). According to the surface observations in WAR, high cirrus clouds account for approximately 20% of the high cloud amount. The annual cycle of high clouds also differs between WAR and ISCCP. ISCCP high cloud amounts are largest in winter, while there is little variation in the WAR dataset.

While the differences in low cloud amount between surface observations and satellite-derived statistics can be explained by the similarity of the spectral signatures of low clouds and the surface, difference in high cloud amounts are more difficult to explain, since high clouds are substantially colder than the surface and are easily identified, particularly in summer. We note, however, that WAR do not report observed high or middle cloud amounts. Unless high clouds are the only cloud present, high and middle cloud statistics in WAR are computed

from reported low and total cloud amounts using the random overlap assumption when possible. Although even a thin high cloud would be correctly identified as cloud in the detection part of the ISCCP algorithm, a bias of the ISCCP radiative transfer analysis to overestimate cloud optical depth over snow-covered areas might lead to an incorrect calculation of cloud height with the result that thin, high cloud would be labeled as middle or low cloud. The fact that differences in low cloud amount between ISCCP and WAR are too small to explain the differences in total cloud amount, while middle cloud amounts are in agreement, would support the foregoing hypothesis.

A comparison of both satellite datasets with the HU69 monthly cloud statistics reveals large discrepancies. HU69 uses a cloud-typing scheme based on aircraft statistics described by Henderson (1967) in which a cloud distribution model (CDM) is selected depending on current total cloud cover and the synoptic weather situation. This CDM is used to account for clouds not visible to the observer due to the sky being obscured by fog or lower-lying clouds. Depending on the CDM, low clouds are defined to be located between 335 m and 1524 m, middle clouds between 3048 m and 4572 m, and high clouds range from 6400 m to 7620 m. HU69 low cloud amounts during summer reach values of over 70%, while neither ISCCP nor C-MATRIX low cloud amounts ever exceed 25%. ISCCP middle cloud amounts agree more favorably with HU69. The annual variation of C-MATRIX middle cloud amounts, while substantially lower, seems to parallel HU69 low cloud amounts. High cloud amounts from the HU69 and C-MATRIX also match reasonably well, with minima in the summer when HU69 reports less than 20% and C-MATRIX shows approximately 10%.

TABLE 2. Comparison of seasonal ISCCP-C2 and WAR cloud types in the Arctic.

Cloud type	Season	WAR	ISCCP	ISCCP (adjusted for overlap)
High	DJF	24.7	8.5	8.5
Middle	DJF	32.2	33.1	36.0
Low	DJF	26.5	11.2	17.9
High	MAM	28.1	2.8	2.8
Middle	MAM	29.0	23.7	24.5
Low	MAM	29.6	14.5	19.7
High	JJA	26.4	4.3	4.3
Middle	JJA	32.4	24.9	26.1
Low	JJA	41.2	18.4	26.4
High	SON	27.0	5.3	5.3
Middle	SON	36.5	28.2	29.7
Low	SON	39.0	16.4	24.7

Total Cloud Amount in : JUL Source: WARREN



Total Cloud Amount in : JUL Source: ISCCP



Total Cloud Amount in : JUL Source: C-MATRIX



#### 4. Spatial patterns of cloud amount

##### a. Total cloud amount

The comparison of cloud amounts averaged over the entire Arctic has revealed some significant differences but has also indicated some encouraging parallels. Here we describe spatial patterns for two months: January and July.

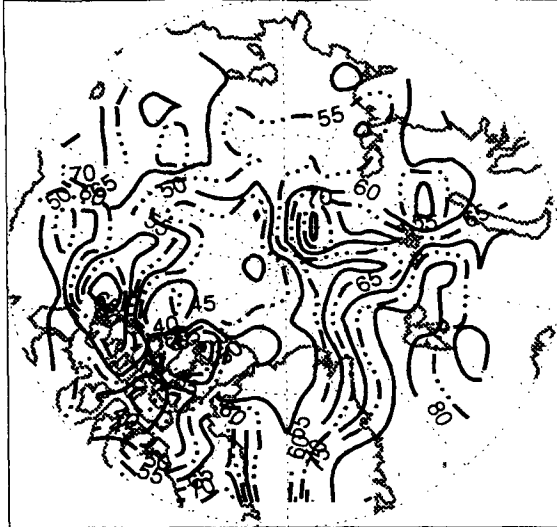
Comparison of the spatial patterns of the WAR and ISCCP datasets show that summer cloud amount differences observed for the entire Arctic are mainly due to large differences over the central Arctic basin (Fig. 5). WAR cloud amounts over the central Arctic are 40% larger than satellite-derived total cloud amounts. C-MATRIX cloud amounts are in very good agreement with ISCCP cloud amounts except over Greenland. Significantly lower cloud amounts over Greenland are reported in WAR and ISCCP datasets, with the ISCCP cloud amounts being roughly 30% lower than WAR cloud amounts. The lower cloud amounts over Greenland also agree with observations by Barry et al. (1987), manually derived from Defense Meteorological Satellite Program (DMSP) satellites for the summers of 1979 and 1980. There are three issues that may account for these differences: 1) Stowe et al. (1988) suggest a potential problem with the surface temperatures over Greenland used in the C-MATRIX, 2) the land atlas from which clouds amounts over Greenland are derived (Warren et al. 1986) indicates that there are no observations over north central Greenland, and 3) the ISCCP retrieval uses a larger threshold over permanently ice-covered land areas (8 K), which emphasizes the characteristic of the ISCCP algorithm to underestimate total cloudiness.

A particular feature that is obvious in all three datasets is the area of large cloud amounts over the Barents and Norwegian sea sectors. This cloudiness is associated with a major storm track, as shown in Barry et al. (1987). ISCCP and C-MATRIX cloud amounts over land areas of the Eurasian sector of the Arctic are lower than those in the WAR data by about 10% and 20%, respectively. A band of decreased cloudiness stretching from Greenland along the North American coast into the Beaufort Sea during July is somewhat less pronounced in the WAR data. In a study currently underway using a manual analysis method and DMSP imagery for an 11-year period, reduced cloud amounts over the Beaufort sea in June have also been observed (M. Serreze, personal communication). These cloud amounts are still significantly larger than those reported in the ISCCP dataset.

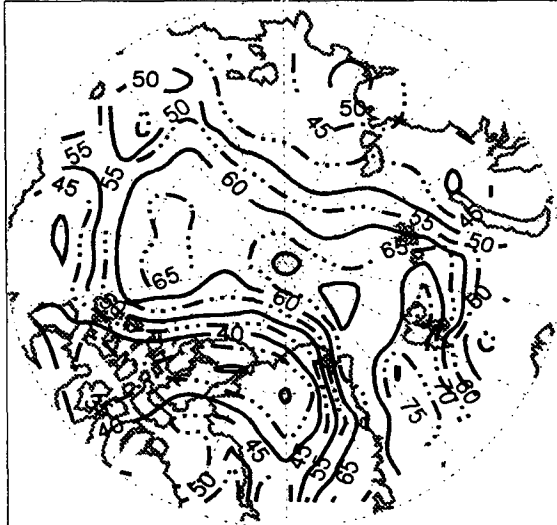
A comparison of January total cloud amounts (Fig. 6) shows a reversed pattern of differences. WAR surface

FIG. 5. WAR, ISCCP, and C-MATRIX total cloud amounts (%) in July. ISCCP total cloud amounts incorporate marginally cloudy pixels.

Total Cloud Amount in : JAN Source: WARREN



Total Cloud Amount in : JAN Source: ISCCP



Total Cloud Amount in : JAN Source: C-MATRIX



observations now report cloud amounts near 50% for the central Arctic, while ISCCP cloud amounts are on the order of 60%. C-MATRIX cloud amounts over the central Arctic are substantially larger and show a marked increase over summer cloudiness. This difference highlights the more conservative approach chosen in the ISCCP algorithm. Similarities again are the very cloudy areas in the Norwegian and Barents sea sectors, where cyclones enter the Arctic and the "cloud low" over Greenland extending to the Canadian Archipelago. In the ISCCP dataset this cloud low is much more pronounced than in the WAR dataset. The C-MATRIX dataset again differs over Greenland. Differences in cloud amounts over Eurasian and North American land areas between the ISCCP and WAR are within 10%. C-MATRIX cloud amounts over these land areas are lower than WAR cloud amounts by about 15%.

A detailed comparison of fall and spring cloud patterns is not presented here, but it is interesting to note that WAR and ISCCP cloud patterns are rather similar during April and to a lesser degree during October. C-MATRIX cloud amounts for the central Arctic begin to decrease later (May) and increase earlier. This agreement may be fortuitous as it reflects the transition from typical winter and summer patterns in the two datasets, which seem to display reversed direction of biases.

#### *b. Cloud types*

Due to the general difficulties in comparing cloud-type amounts from surface and satellite observations, the comparison of cloud-type spatial patterns will focus on the ISCCP and C-MATRIX datasets. We note that for the comparison with C-MATRIX unadjusted ISCCP cloud-type amounts are used and that a comparison to surface observations has to be limited to seasonal statistics. In January the ISCCP dataset shows low-level clouds concentrated in the area of cyclonic activity in the Norwegian-Barents area with low cloud amounts as high as 55%. Middle clouds amount to roughly 25%, and high level clouds make up less than 10% of the cloud cover in this area. Owing to the different definition of cloud levels in the C-MATRIX dataset (Table 1), middle-level clouds form the largest group in the Norwegian-Barents seas area. Low cloud amounts are 15%–20%, and high clouds make up roughly 20% of the total. This is in contrast to the cloud-type analysis by WAR. Due to insufficient data, only seasonal patterns for cloud types are presented by WAR. In their analysis, cloudiness in this area is also dominated by middle and low clouds, but a substantial fraction of the total cloudiness is attributed to high clouds, mainly those of the Cb type (up to 28%) (re-

FIG. 6. WAR, ISCCP, and C-MATRIX total cloud amounts in January. ISCCP total cloud amounts incorporate marginally cloudy pixels.



member Cb is used as high cloud in this context). While the occurrence of Cb clouds has been noted by Vo-winkel (1962, hereafter VO62) and attributed to convection over relatively warm waters, climatologically, the frequency of occurrence is surprising, and it is difficult to imagine not detecting this cloud type in the satellite analyses. Cumulonimbus clouds are defined by their shape and vertical extent, where the cloud top is generally at the tropopause. Mean monthly profiles from the NP-26 ice island (not shown) indicate that the troposphere is located at about 9-km height during January and at about 10-km height during July in the central Arctic area. Those heights are more than twice the height of the upper limit of the low cloud category of the ISCCP dataset. Given the fact that a misclassification of satellite-derived cloud tops to this degree is unlikely, we conclude that the surface observations of cloud type are in error. In contrast to the Norwegian-Barents sea area, most of the central Arctic is dominated by middle-level clouds (approximately 60%) according to the ISCCP dataset, with less than 10% low clouds, even after adjustment for overlap. C-MATRIX cloud types present a similar picture, except that due to the different cloud classification scheme, central Arctic winter cloudiness is mostly represented by the high category. Cloud types dominating the central Arctic in the WAR dataset are stratiform clouds with the lower stratus type dominating.

In the Norwegian-Barents sea area cloud-type patterns between summer and winter are similar. An increase in cloud heights is reflected in the decrease in the low-level group and an increase in the middle-level group. This result also contrasts the observations in WAR where summer cloudiness in this area is dominated by low stratiform clouds, related to the advection of warmer air over cool ocean surface. As in winter, the central Arctic is dominated by middle clouds. Because of the greater temperature difference between the cloud deck and the surface (absence of an inversion), the number of marginally cloudy pixels is about 15%, as opposed to 25% during the winter. C-MATRIX cloud patterns, considering the different cloud height classification scheme, are similar. There is one noteworthy difference between the ISCCP and the C-MATRIX dataset. The ISCCP and WAR "cloud low" over Greenland in summer (described above), which is mainly due to a depression in middle cloud amounts, contrasts with an extreme C-MATRIX "cloud high" due to intense high cloudiness. Given the agreement between the ISCCP and WAR datasets in this area and the fact that fewer clouds over Greenland have also been observed in the manual classification by Barry et al. (1987), it is the authors' conclusion that the C-MATRIX cloud statistics over Greenland are in error due to incorrectly modeled surface temperature, as suggested by Stowe et al. (1988). Physical reasons, such as the high elevation of Greenland and the related low

temperatures and reduced moisture availability, as well as orographic effects, further support ISCCP and WAR statistics.

The fact that ISCCP and WAR total cloud amounts are often in better agreement than the cloud-type patterns points to insufficiencies in the random overlap assumption. In fact, Tian and Curry (1989), in a comparison of overlap assumptions using the Air Force 3D nephanalysis dataset, find that while the random overlap assumption seems to be valid on the average, there are cases where the assumption of random overlap underestimates total cloud cover because it overestimates overlap between clouds. The random overlap assumption was found to perform the poorest for grid sizes greater than 90 km when there were only two layers of intermediate amounts (30%–70%). With regard to the problem of deriving high or middle cloud statistics from total and low cloud amounts as done by WAR, this would lead to an overestimation of high and middle cloud amounts.

## 5. Discussion

In this section we discuss possible reasons for the large differences between satellite and surface observations. Systematic biases expected from either type of observation are briefly discussed.

### *a. Biases in surface observations*

At this point it is important to point out that the good agreement of cloud climatologies based on surface observations (WAR, HU69, VO62) does not necessarily lend more credence to surface-based climatologies. For example, a comparison of the WAR July total cloud pattern with VO62 shows a striking similarity. This similarity of the pattern in spite of the sparsity of data in the Arctic regions is due to the fact that both analyses rely in part on the same data sources. The COADS dataset, which is the source for WAR ocean dataset, incorporates data from drifting stations, as do the VO62 and HU69 cloud climatologies (S. Woodruff, personal communication). The differences between statistics from these datasets therefore reflect processing methods, error checking procedures, and spatial and temporal coverage.

Biases in surface observations are discussed at length in Warren et al. (1986, 1988) and are briefly summarized here. The difficulties in objectively quantifying cloud cover from the surface are exacerbated at nighttime. In other regions of the world this may lead to biases in the diurnal cycle of the cloud cover; in the Arctic problems of cloud observations from the surface will introduce biases in the seasonal cycle. It is difficult to quantify this bias. In an ongoing study, C. Hahn (personal communication) finds that nighttime cloud cover shows a positive correlation with the amount of

moonlight. Her preliminary results for lower latitudes indicate that the difference may amount to more than 5%. This nighttime bias is further affected by a difference in the sampling frequency between nighttime and daytime observations. Surprisingly, the number of observations contained in the 85°–90° latitude band of the WAR dataset is greater during winter than during summer: 3200 3-hour periods (1952–81) with at least one cloud report for December, January, February, and only 2300 such reports during June, July, August. In the 80°–85° latitude band the sampling bias is more toward daytime (summer) with 4700 versus 8200 observations. Geographical biases, introduced by the presumably uneven distribution of surface observations in the Arctic region, may further account for some of the differences between surface and satellite observations. It is difficult to judge the effect of geographical biases without an accurate knowledge of the spatial patterns of cloudiness.

#### *b. Biases in satellite observations of cloud amounts*

The problems of cloud detection in polar regions have been discussed at length elsewhere (e.g., Key and Barry 1989; McGuffie et al. 1988; Crane and Barry 1988; Arking 1987). The problem is related to the spectral similarity of ice surfaces and overlying cloud cover in the spectral bands of satellite sensors used in the analyses and to frequent low-level temperature inversions. The ISCCP algorithm attempts to overcome the spectral similarity problem by constructing a reference surface reflectivity and temperature through the use of temporal and spatial statistics. The C-MATRIX algorithm instead uses surface temperatures from a forecast model to construct background radiative temperatures. In both cases the surface temperatures are then compared to individual image pixels to retrieve cloud amounts. The ISCCP algorithm uses a bispectral threshold during summer (day) and a single IR threshold during winter (night). Over sea ice pixels with brightness temperatures at least 7.0 K lower than the surface and VIS reflectivities of at least 12% greater are labeled definitely cloudy. In order for a pixel to be assigned marginally cloudy status, the thresholds are relaxed to half their value and only one of them has to be passed. At night, or in the arctic winter, this means that a pixel needs only to be colder by 3.5 K to be included in the cloud statistics. The C-MATRIX algorithm employs a single IR threshold over snow and ice regions, requiring a pixel to be 6 K colder than the surface (in the absence of a climatological inversion). The requirement that pixels have a lower temperature than surface pixels poses a particular problem in the polar regions where low-lying clouds just above a surface inversion layer may have temperatures very close to those of the surface. The design of the algorithm is therefore conservative and should underestimate

cloudiness. Recent estimates with an updated version of the ISCCP algorithms that employs the 3.7- $\mu\text{m}$  near-IR channel show that cloud amounts in the polar regions are underestimated by about 10%–20% (Rossow 1991). While during the summer this underestimation in the ISCCP data is plausible when compared with surface observations, the relatively close agreement during winter is suspicious.

#### *c. Systematic differences between surface and satellite observations*

Systematic differences between satellite and surface-based cloud amounts as a result of differing viewing geometries depend on cloudiness, cloud type, and illumination conditions. Investigations into the direction of the biases produce conflicting results. Earlier studies (Barnes 1966; Malberg 1973) found that surface observers tended to overestimate cloud cover. Underestimation of cloud cover by surface observers compared to Meteosat imagery is reported by Seze (1987). Henderson-Sellers et al. (1987), in a comparison of ISCCP results for Europe with surface observations, found that ISCCP cloud cover tended to be greater than that reported by surface observers. Through the use of a sky camera Henderson-Sellers and McGuffie (1990) were able to eliminate the subjective element of the observer and found that there is actually little difference between surface and satellite computed cloud cover.

Another problem with satellite observations is that of resolution. Broken cloudiness at subresolution scales may cause a pixel to either exceed the threshold or remain below it. Thus, resolution-related biases would depend on the general cloudiness of the area. In the Arctic, where cloud amount is large throughout the year, subpixel cloud amounts are also expected to be large, resulting in a systematic overestimation of total cloud cover.

#### *d. Is ISCCP winter cloudiness realistic?*

We previously noted the similarity between ISCCP cloud amounts and those reported by Curry and Ebert (Fig. 3) and speculated that the ISCCP algorithm might indeed report the ice-crystal precipitation assumed by Curry and Ebert. The ISCCP retrieval is generally expected to give an underestimate of the cloud amount, so that the similarity between the ISCCP and surface-based amounts in winter is unexpected. The occurrence and detection of ice-crystal precipitation could account for this higher than expected winter cloud amount in the ISCCP dataset. Two reasons make this hypothesis questionable.

First, in order to be labeled as clouds, pixels affected by ice-crystal precipitation would have to exhibit brightness temperatures below the surface temperature by at least the threshold corresponding to the particular

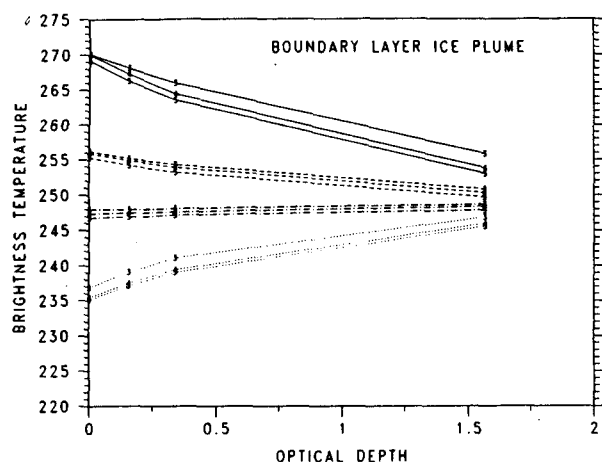


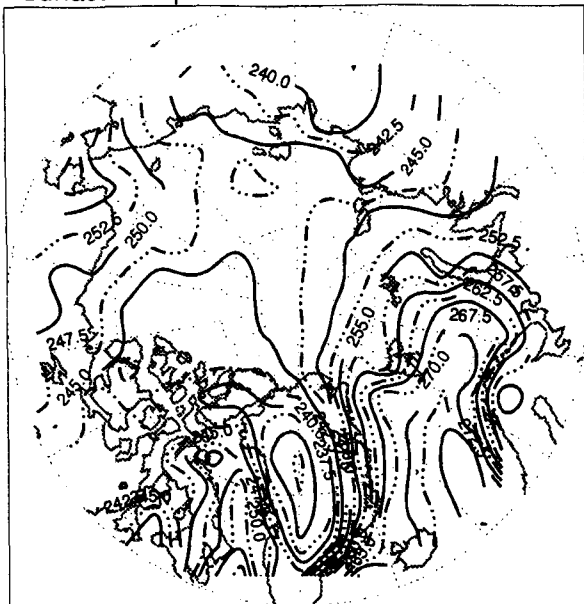
FIG. 7. Brightness temperatures as a function of ice-crystal plume optical depth for the three AVHRR thermal channels (3.7, 11, and 12.5  $\mu\text{m}$ ) and for four surfaces (from the top down in the figure): open water (270 K), 5-cm-thick ice (256 K), 15-cm-thick ice (247 K), and 200-cm-thick ice (236 K). The top of the plume is near the top of the mean January inversion, which has a temperature of approximately 250 K. Simulated sensor scan angle is  $30^\circ$ .

surface type. This threshold over sea ice is 3.5 K. In the presence of a low-level inversion, which is persistent in the central Arctic region (Serreze et al. 1992a), such low brightness temperatures are unlikely for all but an extremely thick layer of ice-crystal precipitation that would extend above the inversion. To verify this assumption a number of radiative transfer calculations were conducted. A boundary-layer ice plume with varying optical depth over a range of surface temperatures was modeled with LOWTRAN 7 (Kneizys et al. 1988). Mean January temperature and humidity profiles from the ice island dataset were used. For simplicity the ice plume was modeled as a low-lying cirrus cloud using the standard cirrus model available in LOWTRAN. Single scattering properties of this cloud model differ somewhat from those generally used for ice-crystal precipitation (e.g., the mode radii of the cirrus model is larger than that of ice-crystal precipitation), but the effect of scattering is small in the infrared, and therefore, these differences are considered of minor importance. The top of the ice-crystal layer was near the top of the inversion, where the temperature is approximately 250 K. As is apparent from Fig. 7, an ice plume confined to the boundary layer will increase brightness temperatures over cold surfaces and decrease brightness temperatures over warm surfaces. However, ice crystal plumes do not have to be confined to the low-level inversion layer but can under certain conditions penetrate the inversion. To test the effect of an extreme case of ice-crystal precipitation, several model runs were conducted using the assumption of a 4-km thick ice-crystal precipitation layer with a varying op-

tical depth over an ice surface with an assumed surface temperature of 245 K and emissivity of 1.0. The scan angle was varied between  $30^\circ$  and  $70^\circ$ . At a scan angle of  $53^\circ$  (near the maximum for the AVHRR) an optical thickness of 16 was necessary to lower brightness temperatures sufficiently below the surface temperature so that the ISCCP algorithm would detect the ice plume as cloud. Although optical depths in that range are possible (Curry et al. 1990), this case has to be considered extreme with respect to the height of the plume. Serreze et al. (1992b), in a theoretical study of convection heights over open leads, found that in 90% of all cases over leads less than 100-m wide the convection height was below the median inversion height of 1200 m. The maximum observed plume height (Schnell et al. 1989) of 4 km is expected to occur over 10 000-m wide leads in less than 8% of their cases. In light of these arguments, it seems unlikely that the occurrence of ice-crystal precipitation is responsible for the unexpectedly large winter cloud amounts in the satellite record.

The second possible explanation for the large winter cloud amounts in the ISCCP dataset is that the clear-sky composites do not represent the radiative properties of the surface but rather represent the radiative properties of a persistent low cloud or ice-crystal precipitation layer. In this case, it is possible that reported cloud amounts actually represent clear-sky fractions plus middle and high cloud. This hypothesis assumes the failure of the clear-sky composite logic in the ISCCP dataset and incorrectly modeled, warmer than actual conditions in the C-MATRIX algorithm. To investigate this hypothesis ISCCP and C-MATRIX surface temperatures are compared to mean monthly profiles from the NP-22 and NP-26 ice islands, buoy temperatures from the Arctic Ocean Buoy Program (Colony and Muñoz 1986), and surface temperatures from an atlas (Gorshkov 1980). Figure 8 shows ISCCP surface temperatures in January. In the central Arctic these temperatures are approximately 245 K, similar to the temperature reported by the buoys (Fig. 9) and the atlas (not shown). The spatial pattern of ISCCP surface temperatures also matches that of the buoys with lower temperatures toward the Canadian Archipelago and increasing temperatures toward the Bering, Norwegian, and Barents sea areas. On the other hand, mean January profiles from the two ice islands for the periods 1979–83 and 1983–87 indicate near-surface air temperatures of 239.5 K and 241.8 K. The differences in the profiles between cloudy and clear conditions show temperatures as much as 10 K higher for cloudy conditions (Fig. 10). This difference, however, was determined for NP-26 during 1986–87 since no cloud observations were available for the other years. It appears that these winters were colder than usual. Since ISCCP surface temperatures should reflect clear-sky temperatures, the match with buoy and atlas temperatures—

Surface Temperature in : JAN Source: ISCCP



Surface Temperature in : JAN Source: C-MATRIX

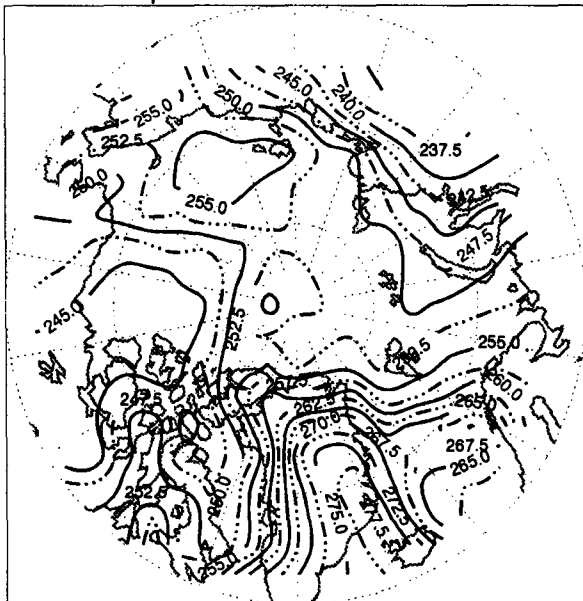


FIG. 8. ISCCP and C-MATRIX surface temperatures during January. Descending orbit C-MATRIX temperatures are given.

taken over clear and cloudy conditions—would seem to indicate that ISCCP clear-sky composite temperatures are too high by more than 5 K and support the hypothesis that ISCCP clear-sky composites in the Arctic are in error. Buoy temperatures are expected to be higher than the skin temperature since the buoys are often covered by snow, and the temperatures are somewhere between that of the snow-ice interface and

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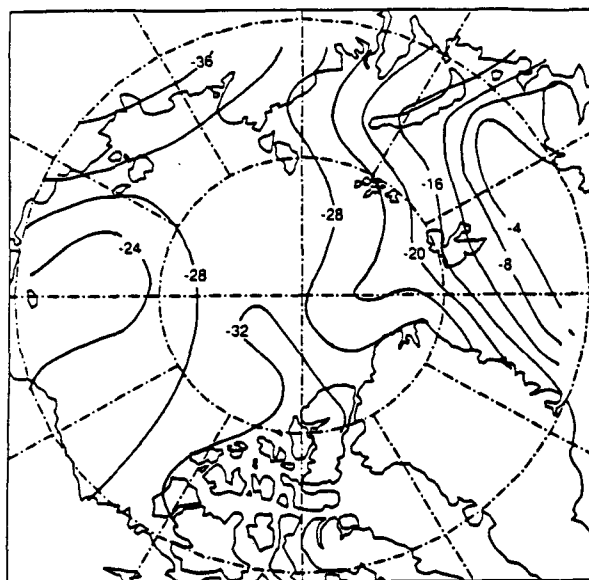


FIG. 9. Mean buoy (near-surface) temperatures from the Arctic Ocean Buoy Program during January 1979-86 (I. Rigor and R. Colony, personal communication). Temperatures are in degrees Celsius.

the skin temperature measured by the satellite. A traceback through the ISCCP algorithm logic, however, shows that in order for cloudy pixels actually to be registered as clear pixels and thereby to influence the clear-sky composite temperatures, clouds have to be extremely persistent and show a temporal variation over two days of less than 1.1 K. This low temporal variability in cloud-top temperatures seems unlikely so that one would not expect to find cloudy pixels labeled as clear.

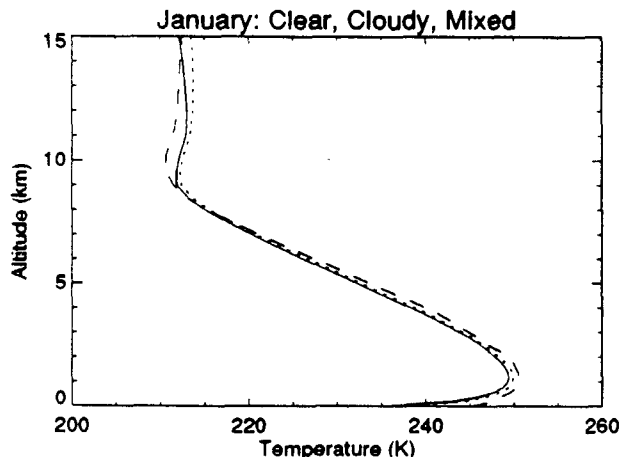


FIG. 10. Mean January profiles of atmospheric temperatures for 1986-87 from the NP-26 ice island. Solid lines represent clear conditions, long dashed lines give profiles for cloudy conditions, and short dashes give mean temperature profiles over all conditions.

While both of the foregoing arguments have to be discounted separately, the possibility that elements of each hypothesis together might account for the unexpectedly small differences between WAR and ISCCP exists. As argued above, ISCCP surface temperatures seem high in comparison with other climatologies. Thus, given overestimated surface temperatures (due to cloud contamination?), the ice-crystal hypothesis becomes more credible. It is therefore plausible that the ISCCP algorithm would report low-level ice-crystal "cloudiness," but for the wrong reasons.

## 6. Summary and conclusions

One surface-based and two satellite Arctic cloud climatologies were compared in terms of the annual cycle and spatial patterns of total monthly cloud amounts. Additionally, amounts and spatial patterns of low, middle, and high cloud types from the two satellite climatologies were compared. The surface-based dataset is for the years 1951–81, while the satellite-based data are for 1979–85 (C-MATRIX) and 1983–86 (ISCCP-C2). The satellite cloud amounts are generally 5%–35% less than the surface observations over the entire Arctic. Regional differences, however, may be as high as 45%. During July the surface-based cloud amounts for the central Arctic are 40% greater than the satellite-based values, but only 10% greater in the Norwegian Sea area. In winter the ISCCP climatology in the central Arctic agree (unexpectedly) to within 10% of the surface observations. While satellite-derived cloudiness during summer seems to reflect the conservative approach of the ISCCP algorithm and probably represents an underestimate, there is considerable uncertainty with respect to the winter cloudiness. Ice-crystal precipitation could account for the unexpectedly high winter ISCCP cloud amounts.

Except for the central Arctic a reasonable agreement in spatial pattern of cloudiness is seen in the datasets. The surface-based climatology is in general agreement with the ISCCP data over Greenland but not with the C-MATRIX dataset. The comparison of cloud-type information emphasized the general problem of multilevel comparisons between satellite and surface observations and points to potential problems in the random overlap assumption used by WAR. Unfortunately, it is not possible at this time to determine which cloud climatology is the "correct" one. The large differences between the data sources indicate the urgent need for a more comprehensive validation program of satellite-based cloud algorithms specifically designed for the Arctic.

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