Statistical Estimates of Monthly Mean and Interannual Changes of Radiation Fluxes at the Top of the Atmosphere

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(Manuscript received 31 August 1981, in final form 12 March 1982)

ABSTRACT

Multiple linear regression is used to relate monthly means and year-to-year changes of the monthly mean planetary albedo and infrared flux leaving the atmosphere, as measured by NOAA satellites, to certain meteorological quantities. Physical predictors are selected which are likely to influence cloudiness, such as temperature, relative humidity and wind. Such predictors can be readily obtained from numerical models.

Forty-two months of polar orbiter measurements of radiation fluxes and objective analyses from NMC's operational model were related. Continental and oceanic samples were evaluated separately. Checks on the model consisted of independent tests and comparison with estimation of radiation fluxes in which predictors were functions of latitude, longitude and time of year only. Physical predictors are consistently superior, with the single exception of oceanic albedo, where there was little difference.

In the case of the infrared flux, 93 and 84% of the variance in the monthly means is explained over land and ocean, respectively. The Planck function computed from a humidity (cloud) sensitive radiating temperature is the dominant predictor, with other humidity predictors also useful. Between 60 and 72% of the variance of the albedo is explained; results over land again are superior. Relative humidity and midtropospheric wind speed variables dominate in this case. Greater success with infrared is probably attributable to a failure to adequately estimate the effect of low-topped clouds, which impact the albedo differentially. Over land, patterns of year-to-year changes of visible and infrared fluxes (surrogates for anomalies) are predicted well and are consistent with observed changes in rainfall and cloudiness. Over the oceans the skill for year-to-year changes is low, possibly because low-topped clouds are more common, but also because analyses are poorer there.

1. Introduction

The role of cloudiness change in determining changes of the earth's radiation balance and temperature has received considerable attention. At issue is the degree of balance between two compensating effects (clouds reduce incoming shortwave radiation, but also usually reduce outgoing longwave radiation) and the possible associated temperature change at the earth's surface, if any. Hartmann and Short (1980) and Hunt *et al.* (1980) have produced results and discussions suggesting that cloudiness change has a significant impact on surface temperature change, with decreased cloudiness usually implying warming (the albedo effect). Consistent with that, Ohring and Clapp (1980) and Herman *et al.* (1980) reported imbalance in implied or modeled cloudiness effects on longwave and shortwave radiation, with shortwave dominance. In a modeling study, Stephens and Webster (1981) found the shortwave effect to be predominant for the case of low and middle clouds, especially at high latitudes, but longwave warming to result with high clouds. They conclude that cloud amount, distribution and height must be carefully estimated in climate models.

In contrast, Cess (1976) and Wetherald and Manabe (1980), on the basis of model studies, have inferred that there is little or no sensitivity of surface temperature to cloudiness change. Implicit in this conclusion is the idea that the opposing radiative effects balance out. More recently, Potter *et al.* (1981) concluded that net cloud feedback was possible regionally after redistribution of clouds, but that Cess' conclusion appears to hold globally.

Thus, the issue appears to be very much in doubt, but explicit simulation of clouds and their radiative properties in climate models has proved to be difficult. Stephens and Webster (1981) express concern that a sufficient level of model sophistication is possible for final conclusions to be drawn about cloud-temperature relationships from detailed models.

An alternative method of calculating the radiation balance that permits the treatment of clouds implicitly is that of directly statistically estimating the effects of clouds and cloudiness change on the albedo and infrared flux at the top of the atmosphere. Variables that are themselves associated with cloudiness

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0022-4928/82/071545-10$06.50

and cloudiness change, such as relative humidity, are employed as predictors. This method was first suggested by Möller (1960). In recent years, the existence of a heat budget archive (Gruber and Winston, 1978) allowed Jensenius *et al.* (1978) and Linder *et al.* (1980) to develop regression equations for both the infrared flux and the planetary albedo, as sensed by NOAA polar-orbiting satellites. In this archive, the fluxes are based on partial sampling of the spectrum, introducing some uncertainty, but they are undoubtedly highly correlated with the total fluxes.

Predictors were functions of conventional variables archived or derived from operational objective analyses.[2] Only predictors that bear a physical relationship to cloudiness have been used. Time-invariant predictors, such as latitude, were excluded from consideration, despite their obvious usefulness in explaining the variance in the predictands. Such variables would be of little value for evaluating potential climate change.

Jensenius *et al.* (1978) and Linder *et al.* (1980) developed equations from winter and summer data sets collected every 12 h. Further, their work was limited to a domain consisting of grid points in the United States. For the present paper, the research was expanded to time-mean fields (monthly means have been used) including the oceans, larger continental domains, and all seasons. Equations that can be used to estimate the components of the energy budget with some skill throughout the year over land and water are presented.

In addition, interannual changes in the elements of the radiation balance have also been estimated using this approach. In the absence of a long time-mean archive from which to calculate anomalies, these experiments were designed to discover whether the method has promise for describing the interesting regional departures that occur from time to time. If the regression equations could merely fit the more-or-less latitudinal variations in albedo and infrared flux, their utility for climate modeling would be questionable. The results in Section 4, however, suggest that year-to-year changes on the scale of atmospheric long waves can be modeled in this manner to some extent.

Section 2 presents some details of the method and the results for the time-mean fields are given in Section 3.

2. Data and method

The radiation budget information is from the near-polar-orbiting NOAA satellites (Gruber and Winston, 1978). Forty-two consecutive months of monthly average radiation data were used. As Stephens *et al.* (1981) point out, this archive is deficient in that it approximates the total infrared energy escaping to space from measurements made by a scanning radiometer in the infrared window region only (10.5–12.5 μm). A regression model is applied in the archive to compensate for the deficiency, but it may not be adequate for detailed atmospheric variations. One approach for checking this is to compare maps from the archive on individual days and months with the observed cloud and rainfall patterns. This has been done, especially in connection with the year-to-year changes discussed in Section 4. General agreement with respect to pattern has been found, which is consistent with the notion that regional anomalies could be modeled by this technique, but considerable uncertainty exists with respect to amplitude.

Further, a similar deficiency exists in the shortwave side of the archive. There, the 0.50–0.70 μm range is taken to represent the entire range of shortwave radiation. No correction is applied, nor are angular variations in reflectance taken into account. Clearly, these factors introduce uncertainty that can only be partially relieved by careful cross-checking with related meteorological fields.

Scanning radiometer data have greater horizontal resolution than those gathered by flat-plate systems. In the present case the data have been interpolated to a 190.5 km mesh, which reduces the horizontal resolution to a scale consistent with that grid size. Nonetheless, the archive on individual days and months displays large gradients. On the whole, the present work may be more accurate with respect to patterns than to amplitudes, as a result of the use of scanning radiometer data.

Predictors were derived from initial analyses of the variables in the Primitive Equation (PE) numerical weather prediction model at the National Meteorological Center (NMC). Monthly averages of meteorological predictors that were identified from daily data and small time-mean samples by Jensenius *et al.* (1978) and Linder *et al.* (1980) as being related to cloudiness and cloudiness change were computed from twice-daily observations for 42 months. See Table 1 for the available predictors.

It should be emphasized that the meteorological predictor fields were averages of grid point data that had been subjected to the various analysis and initialization procedures that are used operationally to obtain fields that are suitable for numerical weather prediction. They are produced by a combination of a "first-guess" forecast and introduction of a limited amount of observations. Many later observations impact only the subsequent first guess. These analyses probably contain rather unreliable information on the divergent part of the motion field, based on careful comparisons made during FGGE (Julia Paegle, 1981, personal communication). Further, they are different over ocean versus land. Over land, no sat-

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[2] After initialization procedures for the operational numerical models were applied.

ellite observations were used, and radiosondes are available, albeit with rather poor coverage. Over the sea, satellite soundings were used but apparently to little effect (Tracton and McPherson, 1977).

The research was divided into studies of continental and oceanic regions. The continental data set consisted of 135 grid points on a 381 km (at 60°N) mesh in North America (Fig. 1). Radiation data were reconciled to meteorological data by selecting every second grid point. The oceanic sample consisted of two roughly equal-sized subsets from the North Atlantic and Pacific Oceans, containing a total of 290 grid points. This resulted in samples of about 10 000 oceanic and 5000 continental observations in the developmental trials.

The regression procedure employed in this work is a "maximum r^2 improvement" technique. At each step of the procedure a model is formed, independent of previous models, that produces the greatest improvement in the fraction of variance explained. The procedure terminates when further substantial improvement is not possible.

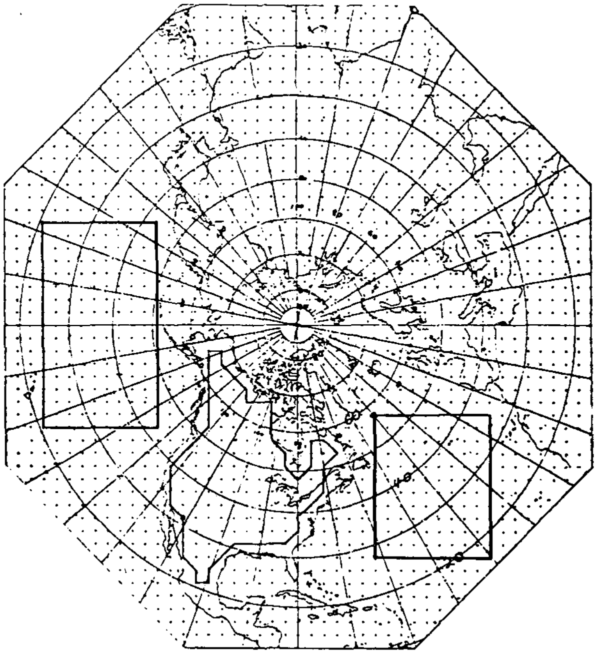

FIG. 1. The continental and oceanic sample regions (within the bold outline) on the PE hemispheric grid.

a. Predictors

The predictors tested on the monthly mean fields are listed in Table 1. The variable P is a Planck function which depends on an effective radiative temperature which will be referred to as TR:

$$\mathrm{TR} = T_s - \frac{(T_s - T_{50} + 25)15}{(\mathrm{DP} + 15)},$$

where T_s is the surface temperature, T_{50} the 500 mb temperature, and DP the 500 mb dewpoint depression. TR is a quantity that represents the temperature of an emitting surface which depends on the dewpoint depression of the middle troposphere. When the troposphere is dry, that is, when DP is large, TR approaches T_s. When DP is small, TR approaches the 500 mb temperature minus a constant, thus representing the temperature of a radiating surface comparable to a cold-topped cloud.

TABLE 1. Predictors of IR flux and albedo. Letters in parentheses indicate whether used for land (l), ocean (o), or both (b).

Predictor symbol	Units	Description
T_s (l)	K	Surface temperature
T_{85} (o)	K	850 mb temperature
P (b)	W m^2 μm^{-1}	Planck function dependent on TR
R1 (b)	%	Relative humidity from 100 mb deep boundary layer
R2 (b)	%	Relative humidity from boundary to ~700 mb
R3 (o)	%	Relative humidity from ~700 to 500 mb
$\underline{\mathrm{DP}}$ (l)	K	Dewpoint depression from R3
$\overline{\mathrm{RH}}$ (l)	%	Mean relative humidity from three layers
MAXRH (b)	%	Maximum relative humidity of three layers
H10 (b)	m	1000 mb heights
DH10 (o)	m	12 h 1000 mb height change
S20 (l)	m s^{-1}	200 mb wind speed
S30 (o)	m s^{-1}	300 mb wind speed
S85 (o)	m s^{-1}	850 mb wind speed
VS20 (l)	m s^{-1}	magnitude of 200 mb south wind
VS30 (o)	m s^{-1}	magnitude of 300 mb south wind
VS85 (o)	m s^{-1}	magnitude of 850 mb south wind
N30 (o)	%	Percentage of days in month with a south wind at 300 mb
N85 (o)	%	Percentage of days in month with a south wind at 850 mb
SNO (l)	—	Snow cover fraction for each month
TR (b)	K	Effective radiative temperature

Humidity predictors include those which come directly from the analyses, the average for the three moisture-carrying layers, corresponding to approximately 1000–900, 900–700 and 700–500 mb, and the maximum value of the three layers for each grid point.

The link between cloudiness and dynamic forcing is made by use of height and wind predictors. One thousand millibar height and height change as well as surface air and 850 mb temperatures were available directly from the analyses. Wind predictors were taken from horizontal components given in the analyses. The component from south was employed, for these Northern Hemisphere data, as a measure of dynamical forcing associated with thermal vorticity advection. Previous work had shown this approach

TABLE 2. Results from continental studies. Experiments are: (A) physical predictors with variable coefficients; (B) physical predictors with constant coefficients only; (C) nonphysical predictors. The numbers are values of the explained variance in percent.

	A		B		C	
	Developmental test	Independent test	Developmental test	Independent test	Developmental test	Independent test
IR flux	93.0	93.2	89.6	91.2	82.6	82.3
Albedo	70.8	71.8	68.1	68.6	64.9	62.8

to be more reliable than calculation of the dynamical variables themselves.

Finally, a snow cover variable is available directly from the archive and is simply a measure of the fraction of time each month that snow is on the ground at each grid point. It was used as a predictor of albedo over land only.

To test the possibility that there may exist annual variations of the relative contributions of each predictor to the estimation of IR and albedo, predictors were also tested whose coefficients varied annually in a sinusoidal manner (Fromm, 1980). Results with annually varying coefficients were compared to the alternative approach of using constant coefficients only.

b. *Testing procedures*

From the available 42 months of data spanning the period July 1974–December 1977, six months were extracted as a test sample. These months were chosen to represent every season equally, although the choice was constrained by the size of the available data set; data from an entirely separate period would provide a better test.

One test of the physical equations is a comparison with equations having only functions of latitude, longitude and time of year as predictors. Linear latitude variables, sinusoidal longitude and time of year variables, and combinations were employed in developing regression equations against which the skill of the physical predictors was rated.

c. *Interannual differences*

It is doubtful whether skill in fitting monthly means by itself is sufficient proof that the regression equations are useful for climate studies. It may simply indicate an ability to reproduce climatological normals. The predictors must have the quality that they are sensitive to deviations from some norm in order to justify confidence in their usefulness for climate change assessment. Because the normal radiation components are unknown, an alternative way of assessing that ability is to relate year-to-year changes in the energy budget components to changes in the set of predictors. If it can be shown that there is skill in such experiments, confidence in the validity of the method should be enhanced.

Accordingly, equations for the interannual changes in the monthly mean values of the radiation balance components from 1975 to 1976 and from 1976 to 1977 were developed, with interannual changes of the meteorological variables in Table 1 as predictors. The continental and oceanic domains were the same. An independent test set consisted of six months of changes, July 1974–July 1977, August 1974–August 1977, and so on, through December.

3. Results

a. *Continental studies*

The results of the analysis for the North American grid are summarized in Table 2. Results are given for albedo and IR flux for three types of experiments: (A) physical variables with annually varying types of coefficients; (B) physical variables with constant coefficients only; and (C) functions of latitude, longitude and time of year. Infrared estimation is considerably more successful than that of albedo; this is probably related to the difficulty of constructing a reliable predictor for low clouds, which have a small impact on the IR variation but significantly alter the albedo. Further, the possible misrepresentation of the albedo by the 0.5–0.7 μm observations could be a factor.

A comparison of results of tests with and without annually varying coefficients (A and B) reveals that the use of annually varying coefficients produces some improvement over constant coefficients but the increase is small. IR estimation is superior by 0.9 percentage points while albedo is better by 3.2 percentage points in the independent test case. Whether this increase is significant is not clear.

However, comparing the results of both approaches using physical predictors with that which did not (A or B with C), it is clear that the physical predictors represent a considerable increase of skill ($\sim$11 and 7 percentage points in independent tests of IR and albedo, respectively) over non-physical variables. A slight but consistent tendency of an increase of explained variance in the independent physical tests and decrease in the non-physical case, is possible evidence of the ability of the physical variables to capture changing meteorological conditions which affect the energy budget. In fact, the independent tests, such as they are, suggest no overfitting

TABLE 3. Results from oceanic studies. Experiments are: (A) physical predictors with variable coefficients; (B) physical predictors with constant coefficients only; (C) nonphysical predictors. The numbers are values of the explained variance in percent.

	A		B		C	
	Developmental test	Independent test	Developmental test	Independent test	Developmental test	Independent test
IR flux	87.6	85.9	86.1	84.5	56.1	56.0
Albedo	68.6	60.7	66.3	63.1	63.1	60.4

within the sample studies for the physically-based equations.

The equations for the North American IR results are

$$\mathrm{IR} = 179.0 + 6.2P - 0.206\cos\left(\frac{2\pi}{p}t\right)T_s - 0.321\mathrm{R1} - 0.161\sin\left(\frac{2\pi}{p}t\right)\mathrm{S20} + 2.4\cos\left(\frac{2\pi}{p}t\right)P + 0.346\cos\left(\frac{2\pi}{p}t\right)\mathrm{R2}, \quad (1)$$

$$\mathrm{IR} = 170.1 + 7.18P - 0.28\mathrm{R1} - 0.364\mathrm{S20}, \quad (2)$$

for flux (W m^{-2}) and where the predictors and their units are given in Table 1. Eq. (1) has time-varying coefficients of period p = 12 months, while (2) has constant coefficients.

Inspection of (1) and (2) reveals that IR flux is estimated by humidity-related variables (including the Planck function with humidity-adjusted radiative temperature), surface temperature, and 200 mb wind speed. The Planck function with temperature TR is by far the most dependable predictor of IR flux; it accounts for ~87% of the variance by itself.

Eqs. (3) and (4) were obtained to estimate North American albedo:

$$\mathrm{Albedo} = 12.2 - 0.804\mathrm{DP} + 9.64\mathrm{SNO} + 0.375\mathrm{R1} + 0.074\cos\left(\frac{2\pi}{p}t\right)\mathrm{R2} + 3.75\sin\left(\frac{2\pi}{p}t\right)\mathrm{SNO} - 0.390\cos\left(\frac{2\pi}{p}t\right)\mathrm{VS20}, \quad (3)$$

$$\mathrm{Albedo} = -15.4 + 1.30\overline{\mathrm{RH}} - 0.645\mathrm{R2} + 0.017\mathrm{H10} + 0.194\mathrm{S20} + 13.6\mathrm{SNO}. \quad (4)$$

The albedo is expressed in percent and the predictors and their units are given in Table 1. Eq. (3) has time-varying coefficients of period p = 12 months, while (4) has constant coefficients. Variables selected include the dewpoint depression near 500 mb, relative humidity variables, snow cover, 1000 mb heights and 200 mb wind speed. With the exception of snow cover for albedo and temperature for IR, similar variables, all plausibly related to cloudiness or cloudiness change, appear in all of the physical equations for both IR flux and albedo.

b. *Ocean studies*

The results of the regression analysis over the oceans are summarized in Table 3. The over-ocean results seem consistent with, but somewhat inferior to, those over land. Once again, IR results are clearly better than visible. Overall, the contribution of annually varying coefficients appears not to be significant, with the constant coefficients actually better in the independent albedo test. Also, the physical variables out-perform the nonphysical variables and the physical equations hold up fairly well under independent test. However, the drop of explained variance from developmental to independent test is not small in the case of albedo estimates with annually varying coefficients. Further, in the case of albedo, the physical predictors are not much superior to the non-physical variables. Generally, physical predictors do better for IR over albedo, better over land than over ocean, and never lose to simple time/space fits.

The equations for IR over oceans (both Pacific and Atlantic) are

$$\mathrm{IR} = 185.9 + 5.58P - 0.390\mathrm{S30} - 0.069\mathrm{VS30} - 15.0\cos\left(\frac{2\pi}{p}t\right)\mathrm{S85} + 0.21\mathrm{R3}, \quad (5)$$

$$\mathrm{IR} = 204.4 + 4.63P - 0.408\mathrm{S30} - 0.96\mathrm{VS30}. \quad (6)$$

As before, the variables and units are in Table 1, and (5) refers to time-varying coefficients, while (6) has constant coefficients.

The estimation of IR flux is again dominated by the Planck function with humidity (cloud) sensitive radiation temperature TR. Jet-stream level wind speed and south wind are also important contributors with a minor contribution from 850 mb wind speed with a time-varying coefficient, as well as from another humidity variable. The role of time-dependent coefficients appears to be especially weak over the oceans.

With respect to albedo over the oceans, the respective equations for time-varying and constant

TABLE 4. Variances explained (%) by predictors of interannual changes. Values in parentheses refer to a subset having predicted departures larger than one standard deviation (based on developmental standard deviation value).

	Developmental		Test	
Predictand	Land	Ocean	Land	Ocean
IR flux	65 (76)	41 (58)	52 (64)	40 (62)
Albedo	49 (64)	14 (25)	28 (52)	13 (20)

coefficients are

$$\text{Albedo} = 4.1 + 0.72\text{S30} + 1.5\text{VS85} + 0.15\text{R3} - 0.26\cos\left(\frac{2\pi}{p}t\right)\text{S85}, \quad (7)$$

$$\text{Albedo} = -13.0 + 0.23\text{S30} + 0.61\text{VS30} + 1.2\text{N85} + 0.15\text{R3} + 0.26\text{MAXRH}. \quad (8)$$

Once more, the predictors and units are given in Table 1.

In contrast to the overland albedo and to all IR experiments, albedo over the ocean is estimated predominantly with predictors related to high- and low-level winds. Relative humidity predictors enter the equations but are not as important as they are for land equations. The disparity may be due to the scarcity of radiosonde observations leading to poor analyses, rather than a physical difference in the relationship of radiation to the predictors from land to ocean. However, it is also possible that the low-cloud problem is more severe over the oceans, where the boundary layer is nearly always moist.

4. Interannual differences

The results for estimating radiative quantities obtained for monthly mean grid fields were superior to day-to-day estimates reported by Jensenius *et al.* (1978) or Linder *et al.* (1980). However, that may be due to the ability of the methods to specify only the climatological mean distribution of the radiation fluxes. Such a result might not be very useful for modelers of climatic change.

A more stringent test of the method consists of applying it to the estimation of interannual changes of fluxes. Presumably, the year-to-year change of monthly mean albedo or IR could be of climatological interest, similar to an anomaly field. Such changes could be associated with larger scale changes of flow pattern between years. Table 4 shows the results of such a study, conducted separately over land and water. The equations related changes of monthly mean radiation fluxes between 1975 and 1976 or between 1976 and 1977 to corresponding changes of the types of variables found earlier to be associated with the fluxes themselves. An independent test set consisted of changes from July through November 1974 to the corresponding months of 1977. The table shows, as before, that results are better for infrared than visible radiation, and better over land than over ocean. Recalling that these are year-to-year changes, the estimation skills for IR and visible radiation fluxes are considerable, and in the IR case, are very stable on the independent test. However, a test of the estimation of net radiation changes (not shown) was quite poor, especially over the ocean, probably as a result of compensation error.

TABLE 5. Observed means of interannual changes (W m^{-2}).

	1974–75	1975–76	1976–77
Infrared flux	+2.87	−0.39	−0.72
Absorbed visible flux	+6.84	+9.61	−4.06
Change of net flux	+3.97	+9.99	−3.34

Also given in Table 4 are values in parentheses. These show the percent of variance explained after observations had been excluded for which the value of the predictand was less than one standard deviation from zero. The screening of these "small change" observations in the test case was done with respect to the predicted value of the predictand. The skill of estimation of large changes is apparently greater than that of all changes. Inspection of the independent test results reveals that the equations that estimate the large changes exhibit at least as much stability as those estimating all changes. Hence, the increase of skill cannot be attributed to an overfitting of coefficients to a smaller data sample. Of course, a modeler will not know *a priori* whether large changes of radiation fluxes will occur, only when large changes are predicted. While for these cases, the skill of estimation is better than for all cases, it would not be as good as that implied by the numbers in parentheses in Table 4.

The predictors leading to the results reported in Table 4 in the case of IR flux changes were interannual changes is the cloud-sensitive radiation variable *P*, in mean humidity, in 1000 mb in height, and in wind speed at 300 mb. For albedo changes, interannual changes in mean relative humidity and 300 mb winds accounted for the explained variance.

Table 5 gives the observed changes of radiation fluxes for three pairs[3] of years over the land grid. The changes of IR flux are small compared to the changes in absorbed visible flux, so that the changes in net radiation are primarily produced by changes in albedo, at least in the polar-orbiter archive. The changes in IR flux are likely to be associated with changes in cold-topped cloudiness. Hence, Table 5 implies that high cloudiness was relatively constant from year to year. This means that the large changes

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[3] 1974–5: July to November only.

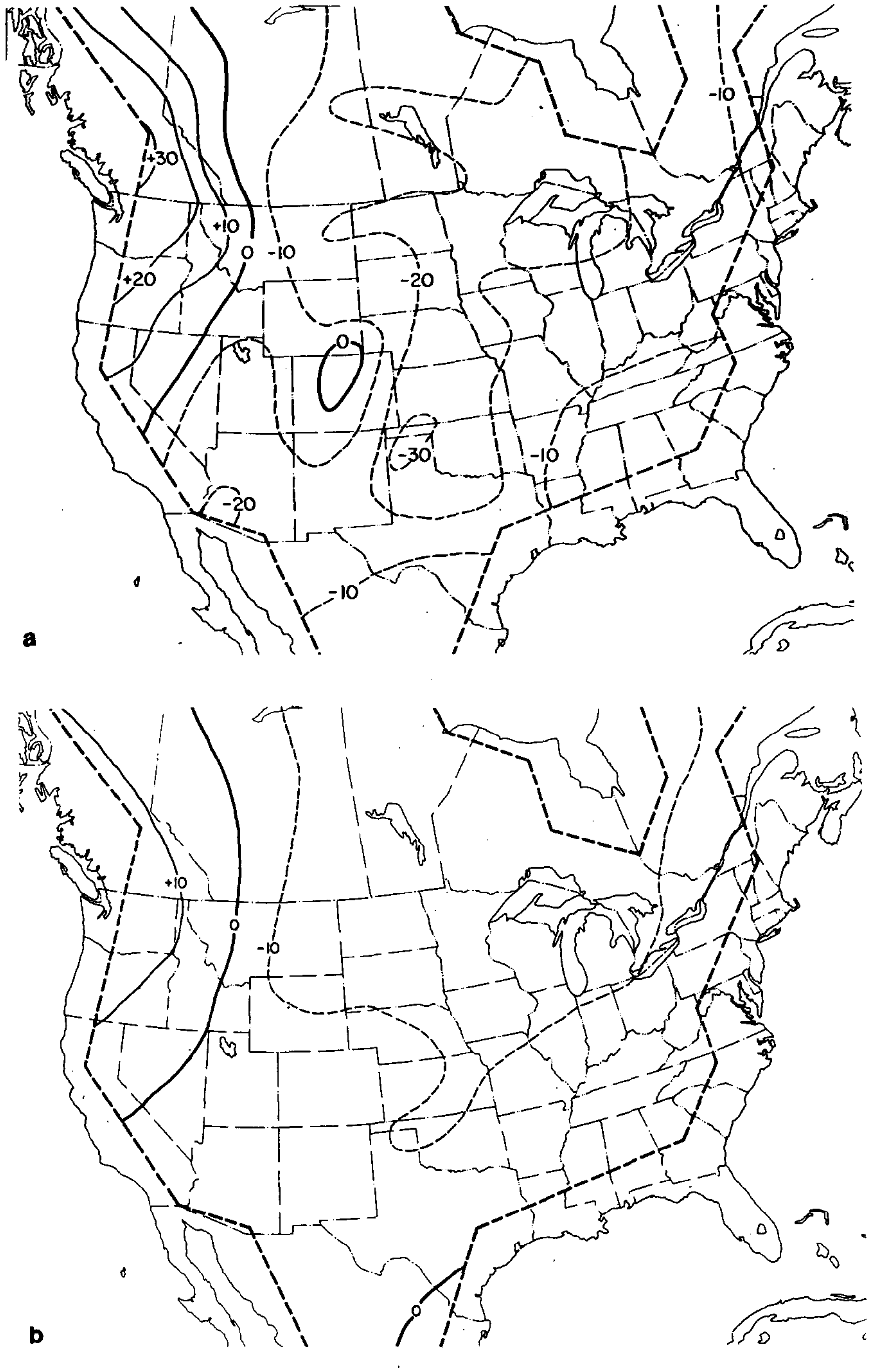

FIG. 2. The observed (a) and predicted (b) change of monthly mean infrared flux from August 1976 to August 1977 for a portion of the continental sample region (within the bold broken line). The contour interval is 10 W m^{-2} with increases in solid isopleths, decreases in light broken isopleths.

in albedo[4] must have come from large changes in low cloudiness (or of snow cover). However, large changes in albedo occur also in summer, suggesting the importance of changes of clouds.

Figs. 2–3 show changes of infrared flux and albedo, predicted and observed, from August 1976 to August 1977. The large-scale patterns of the changes of vis-

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[4] There was some instrumental degradation during this time, but these changes are considerably larger.

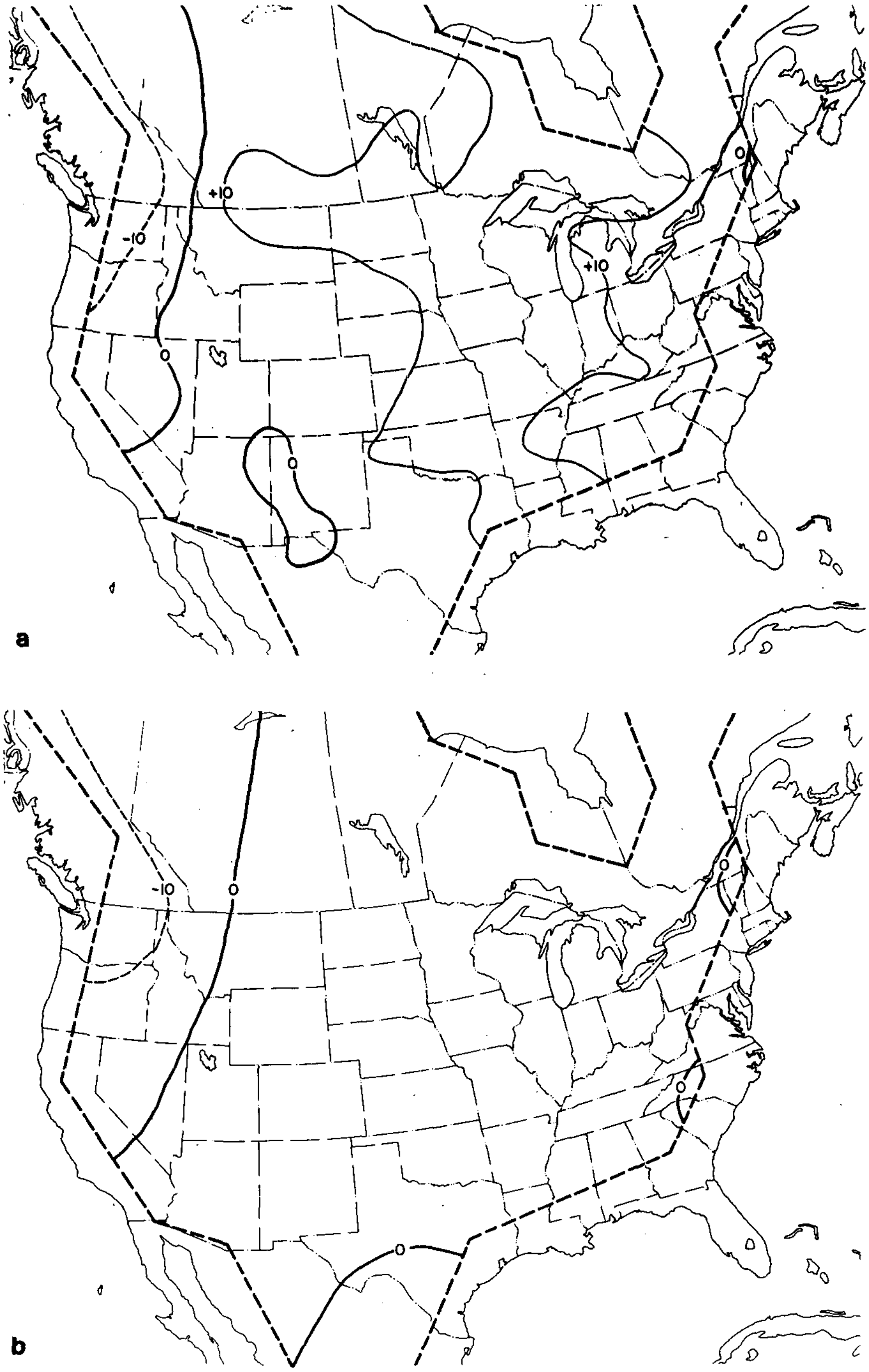

FIG. 3. The observed (a) and predicted (b) change of monthly mean albedo from August 1976 to August 1977 for a portion of the continental sample region (within the bold broken line). The contour interval is 10% with increases in solid isopleths, decreases in light broken isopleths.

ible and infrared changes are estimated quite well, as can be seen from the isopleths of zero change. But the magnitude of the predicted changes are numerically smaller than those of the observed changes, in the case of albedo, much smaller. Some of these differences could be attributable to the spectrum being only partially measured by scanning radiometers.

It is noteworthy that August 1977 featured near record-breaking wetness and cloudiness in the United States Midwest (Dickson, 1977), while August 1976

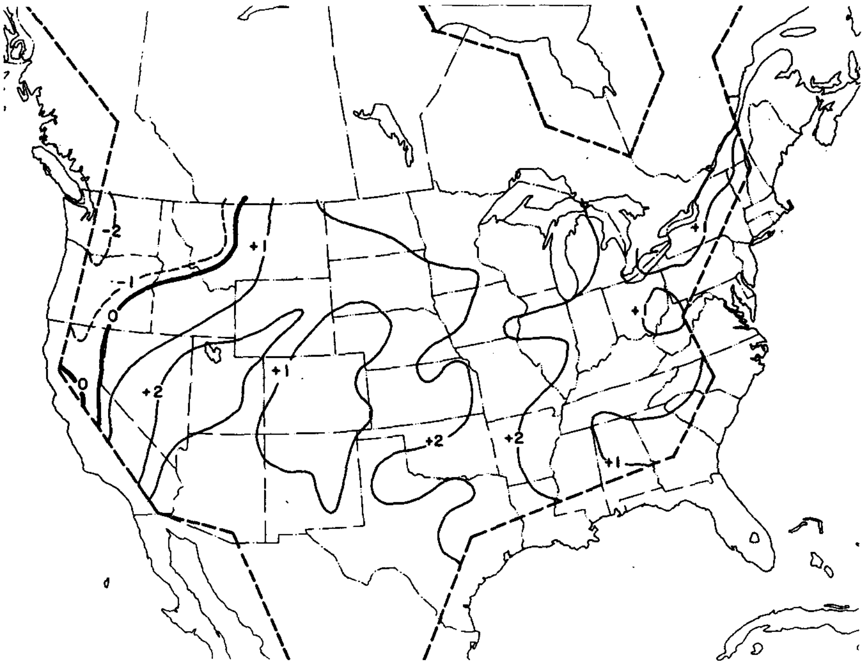

FIG. 4. The observed change of monthly mean cloud cover from August 1976 to August 1977 for the United States only. The contour interval is one-tenth of cloud cover with increases contoured as solid lines, decreases as light broken lines.

was dry with normal sunshine (Dickson, 1976). Fig. 4 shows the observed cloudiness change (U.S. Department of Commerce, 1976, 1977). According to the data in this archive, the IR flux decrease was ~20 W m^{-2} near the Midwest cloudiness increase maximum, while the decrease of absorbed shortwave radiation was ~50 W m^{-2}. This implies a decrease of net radiation on a rather large scale associated with increased cloudiness during August 1977 relative to August 1976. The regression equations show some skill in modeling these types of changes, but the errors, especially with albedo, result in unsatisfactory results for the net radiation.

5. Summary and conclusions

Multiple linear regression was employed to relate monthly mean radiation budget variables, infrared flux and albedo, to meteorological variables that are linked with clouds, such as relative humidity and wind. The approach is to be considered an alternative to the complex task of explicit cloud modeling in climate simulations. Radiation measurements from NOAA polar-orbiter satellites and initial analyses from an operational numerical model comprised the predictand and predictor data samples, respectively. Regression experiments are carried out separately over Northern Hemispheric midlatitude oceanic and continental domains. Between 84 and 93% of the variance of the IR flux can be explained while somewhat less (60–72%) is explained in the case of albedo. Performance over continents exceeds that over oceans, perhaps because of diminished quality of the operational analyses and a greater likelihood of low cloudiness over oceans.

The stability of the equations is tested in several ways. They were subjected to tests on independent samples. They were compared with attempts to develop relations between the same predictands and nonphysical predictors such as latitude, longitude and time of year. Finally, year-to-year changes of the predictands were correlated with similar changes of the predictors to assess their sensitivity to deviations from a type of norm. The observed interannual changes of IR flux and albedo were mapped, analyzed and compared with observed cloudiness changes as well as with predicted values of the predictands.

The equations which estimate the monthly means hold up well under an independent test, explaining very close to the same fraction of variance as in the developmental test. Some reservations exist, however, about the choice of an independent sample too close in time to the developmental sample; further tests are needed. Also, the equations with "physical" predictors show considerably more skill than those using "nonphysical" predictors in both developmental and independent tests, in all save the over-ocean albedo case.

Analysis of year-to-year changes indicates that meteorological predictors identified by the work have some ability in describing the regional patterns of year-to-year change in the radiation balance components, taken separately. This is especially true of the infrared and, as in other experiments, is more true over land than over ocean. There is also some reason to believe that the approach works somewhat better for the large changes. However, the net radiation, which is usually the sum of two quantities of similar magnitude, but opposite sign, is not yet well specified.

There is some evidence, however, that the regional patterns of interannual radiation changes (or possibly anomalies) could be determined by models having skill in specifying changes in the meteorological predictors, which themselves are related to cloudiness changes. Errors in the approach appear to be related to poor specification of low-topped clouds, and deficiencies in the current analysis of moisture—especially over oceans. Further, inaccuracies in scanning radiometer sampling could be involved.

At the present time, the statistical model presented in this paper is some distance from being a practical tool for the climate modeler. Studies must be initiated in tropical and arctic regions. Also, the effect of the diurnal variation of clouds on the radiation budget must be evaluated. Nonetheless, the method holds some promise, especially for regional studies of the effect of cloudiness change on the climate.

Finally, our conclusions are based on radiation measured in narrow bands. It would be useful if analogous studies could be performed in the future if broad band radiances are archived.

Acknowledgment. This work was supported by the U.S. Department of Commerce, National Earth Satellite Service, Earth Satellite Laboratory under Contract 04-6-158-44013. Special thanks go to Mr. Harry Henderson, who helped solve a difficult data problem.

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