Climatic variability of cloud radiative forcing

By BRYAN C. WEARE*

University of California at Davis, USA

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SUMMARY

Multiple-regression models have been developed relating interannual departures of the Earth Radiation Budget Satellite net, long-wave, and short-wave cloud radiative forcing primarily to variations in the International Satellite Cloud Climatology Project cloud amounts for low, middle and high clouds, and cloud water. These models are used to evaluate the effects of cloud radiative forcing of specified and observed changes in cloud properties.

The calculated changes of cloud forcing due to 16.5% increases in low-, middle- and high-cloud amounts and 25% increases in cloud water are compared with those of a radiative-transfer model. The two methods have results which agree with respect to the signs of the responses and the order of the significance of the independent variables for net cloud forcing. Overall, variations in cloud water have the largest effect on net cloud forcing; those in high cloud have the largest effect on long-wave cloud forcing; those in cloud water make the largest contributions to short-wave cloud forcing.

Using the statistical models forced by one-standard-deviation variations in cloud properties, variations in high cloud are shown to have increased importance relative to the results for the 16.5 and 25% perturbations. In addition, variations in clear-sky planetary albedo and long-wave flux are also found to be important at higher latitudes.

In a small sample of observed short-term climate-change scenarios, compensations amongst the effects of the variables alter the magnitude, and in two cases the sign, of the change in net cloud forcing relative to those resulting from uniform variations of the cloud properties.

KEYWORDS: Climate change Cloud climatology Earth radiation budget Interannual variations

1. INTRODUCTION

Clouds are a major contributor to our uncertainty concerning the nature of climate and climate change. An important tool to aid in the understanding of cloud/climate interactions is the evaluation of cloud radiative forcing derived from the Earth Radiation Budget Experiment (ERBE; Ramanathan et al. 1989) satellite systems. Cloud radiative forcing (CF) may be defined by

\[ CF = E_{ch} - E = f(E_{cl} - E_{ld}) \]  

where \( E \) is the net, emitted infrared, or reflected solar flux, measured at the top of the atmosphere for a month over a 2.5° \times 2.5° grid, \( E_{ch} \) and \( E_{cl} \) are the corresponding mean fluxes for clear and fully cloudy subregions (Dickmann and Smith 1989), and \( f \) is the fraction of a grid covered by cloud. The primary strength of the cloud-forcing concept is that observations depend only on the accurate measurement of total field fluxes \( E \) and the evaluation of clear-sky fluxes \( E_{ch} \), which are relatively homogeneous in space and time.

A number of authors (Ramanathan et al. 1989; Harrison et al. 1990; Stephens and Greenwald 1991; Hartmann et al. 1992; Kiehl 1994) have calculated the mean short-wave (SWCF), long-wave (LWCF) and the net (NCF) cloud radiative forcing for the current climate system. They estimate that the global average SWCF and LWCF are approximately \(-50\) W m\(^{-2}\) and \(+30\) W m\(^{-2}\), respectively. Thus the increased reflection by clouds of short-wave radiation is larger than the enhanced trapping by the same clouds of long-wave radiation. This results in a mean NCF of about \(-20\) W m\(^{-2}\). The magnitude of this NCF is generally larger in high latitudes of the summer hemisphere and near zero in the equatorial zone.

* Corresponding address: Atmospheric Science Program, University of California, Hooland Hall, Davis, CA 95616-8627, USA.
Although there is a good general understanding of mean SWCF, LWCF, and NCF fluxes, there has been much less progress in discerning how these fluxes might vary during a climatic change. This is in part related to the fact that the earlier estimates have been based upon a single year's data and thus cannot give an indication of how cloud radiative forcing might vary during even short-term climatic change. It is also in part because the nature of cloud feedbacks is an immensely complex problem, which requires an understanding of not only the radiative effects of clouds, but also a knowledge of how cloud properties can and do vary during climate change. However, climate models have been utilized a number of times to attempt to understand the nature of possible changes in cloud forcings (e.g. Slingo 1990; Ramaswamy and Chen 1993). However, conclusions based upon these models are hindered by the large uncertainties in the modelling of clouds and their radiative parameters. Recently, Sinha and Shine (1995, hereafter SS95) have used a hybrid approach in which a sophisticated radiative transfer is driven by observed estimates of cloud amount and optical depth. Using this approach SS95 made an assessment of how specified variations in cloud alter the radiation fluxes at the top of the atmosphere.

SS95 prompts several sets of questions. First, do statistical models utilizing observations give results that are similar to those discussed in SS95? Second, what are the results from statistical models if they are forced with observed short-term variations, rather than those specified variations of SS95? Third, what are the observed correlations between the different cloud variables, and how might they modify the overall changes in cloud radiative forcing?

The goal of this paper is to provide preliminary answers to these questions by employing a statistical analysis of a four-year record of top-of-atmosphere fluxes, clouds and other observations. The methodology will follow that of Weare (1995), who used multiple-regression analysis to relate variations in the Earth Radiation Budget Satellite (ERBS) long-wave clear-sky flux and cloud radiative forcing to changes in total cloud amount and top pressure derived from the International Satellite Cloud Climatology Project (ISCCP) estimates and European Centre for Medium-Range Weather Forecasts (ECMWF) analyses of temperature and humidity. In the present paper multiple-regression models are developed relating interannual departures of ERBS NCF, LWCF and SWCF to variations in ERBS clear-sky parameters, ISCCP cloud amounts for low, middle and high clouds and cloud water, and ECMWF precipitable water and upper-tropospheric temperature. These equations are developed for 10° latitudinal strips both separately for land and ocean and for the combination. They then are used to evaluate the effects on cloud radiative forcing of specified and observed changes in cloud properties.

2. Data

Monthly ERBS long-wave and short-wave clear-sky $E_{ch}$ and total $E$ fluxes equatorward of about 60° were provided on a 2.5° grid for the four years 1985–88 through the cooperation of Drs Gerald Potter of the Lawrence Livermore National Laboratory and Robert Cess of the State University of New York at Stony Brook. Data from this single satellite are chosen because they are the result of relatively uniform sampling of the diurnal cycle, and because they are thought to have fewer systematic errors than the combined ERBE three-satellite data (Potter, personal communication). The ISCCP C2 (Rossow and Schiffer 1991) monthly cloud fractions $f$ corresponding to clouds with low, middle and high tops, and the mean cloud water (CW) path for all clouds were obtained from the National Center for Atmospheric Research (NCAR) and transformed to a regular 2.5° grid using the program provided by the ISCCP. The ECMWF analyses of temperature, $T$, and relative humidity, RH, at the 1000, 850, 700, 500, 300 and 200 hPa levels on a
2.5° grid were provided by the NCAR (Trenberth and Olson 1989). Precipitable water was calculated from the ECMWF data as outlined in Weare (1995).

One aspect of the ISCCP cloud observations needs to be emphasized. The reported middle- and low-cloud fractions are the fractions of the sky observed from above which are not obscured by higher cloud. Thus, there is generally much less low cloud in the ISCCP observations than estimated by surface observers (Weare et al. 1996). Furthermore, a consequence of the ISCCP methodology is that cloud optical depths or water contents for middle and high clouds may include contributions from obscured lower clouds. These features of the ISCCP and other satellite cloud observations affect the modelling of radiative fluxes such as in SS95, and this must be borne in mind when interpreting or comparing results.

3. Analysis framework

Following Weare (1995), variations in long-wave cloud forcing may be better understood by analysing (1) for a column with non-overlapping low, middle, and high cloud layers. The dominant contributions to long-wave cloud forcing may be related to observable variables by

\[
d(\text{LWCF}) = f \ dE_{\text{clt}} + (E_{\text{clt}} - E_1) \ df_1 + (E_{\text{clt}} - E_m) \ df_m + (E_{\text{clt}} - E_h) \ df_h \\
- f \ \frac{\partial E_{\text{clt}}}{\partial (\text{CW})} \ d(\text{CW}) - f \ \frac{\partial E_{\text{clt}}}{\partial T_{\text{ca}}} \ dT_{\text{ca}}
\]

(2)

where \( f \) is the total cloud fraction; subscripts 1, m, and h refer to low, middle and high clouds; CW is the mean vertically integrated cloud water; and \( T_{\text{ca}} \) is the mean temperature above the cloud (taken as the 300 hPa temperature). These six terms may be interpreted as variations due to: changes in the clear-sky fluxes \( [1] \), changes due to alterations in the fraction of sky covered by low, middle and high clouds \( [2], [3], [4] \), modifications of the mean emissivity of the cloud due to changes in its water content \( [5] \), and changes in the mean emission temperature of the atmosphere above the cloud \( [6] \). To simplify statistical analysis of the observations, (2) can be rewritten in terms of a multiple-regression estimate of variations of LWCF such that

\[
d(\text{LWCF}) = \beta_1 \ dE_{\text{clt}} + \beta_2 \ df_1 + \beta_3 \ df_m + \beta_4 \ df_h + \beta_5 \ d(\text{CW}) + \beta_6 \ dT_{\text{ca}}
\]

(3)

where the \( \beta \)s are best-fit regression coefficients, and where there is a one-to-one correspondence between the terms in (2) and (3).

Equations (2) and (3) show that changes in cloud forcing are not necessarily related only to changes in the cloud properties themselves as expressed in terms \( [2]–[5] \), but also to changes in the clear-sky fluxes \( [1] \) and upper-tropospheric temperatures \( [6] \). In (3) the coefficient of \( dE_{\text{clt}} \) is positive, with a magnitude of the cloud fraction; those of \( df_1, df_m \) and \( df_h \) are nearly always positive except in the case of an opaque low cloud under inversion conditions; that of \( d(\text{CW}) \) is negative, since greater cloud water is monotonically related to higher emissivities and hence emissions, and that of \( dT_{\text{ca}} \) is generally negative due to the sign of \( [6] \).

A similar set of equations can be derived for the short-wave cloud forcing. Starting with (1), using the far right-hand side,

\[
d(\text{SWCF}) = S \{ f \ d\alpha_{\text{clt}} + (\alpha_{\text{clt}} - \alpha_{\text{clt}}) \ df - f \ d\alpha_{\text{clt}}\}
\]

(4)
where $S$ is the extraterrestrial solar flux, and $\alpha_{clr}$ and $\alpha_{cld}$ are the planetary albedos of the clear and fully clouded portions of the atmosphere respectively. In a manner similar to that of Stephens and Greenwald (1991), $\alpha_{cld}$ may be related to estimates of the reflectivity and absorptivity of a cloudy column by assuming the planetary albedo above a fully clouded region is approximated by

$$
\alpha_{cld} = r_{cld} + r_{cld}^2 r_s + \cdots \approx r_{cld} + (1 - r_{cld} - a_{cld})^2 r_s
$$

where $r_{cld}$, $t_{cld}$, and $a_{cld}$ are the diffuse reflectivity, transmissivity, and absorptivity of the cloudy atmosphere and $r_s$ is the reflectivity of the surface. $r_{cld}$ is primarily a function of the vertical integral of CW, and $a_{cld}$ is mainly a function of the vertical integrals of the concentrations of ozone, aerosols, and atmospheric water vapour, the precipitable water (PW). Assuming that variations in $r_{cld}$ and $a_{cld}$ are primarily related to changes in CW and PW, then variations in the planetary albedo of a cloudy atmosphere may be written as

$$
d\alpha_{cld} = [1 - 2r_s(1 - r_{cld} - a_{cld})] \frac{\partial r_{cld}}{\partial (CW)} d(CW) - 2r_s(1 - r_{cld} - a_{cld}) \frac{\partial a_c}{\partial (PW)} d(PW).
$$

Combining (4) and (6) and dividing cloud amounts into those of low, middle and high clouds, yields

$$
d(SWCF) = \sum \left[ f \alpha_{clr} + (\alpha_{clr} - \alpha_t) d_f + (\alpha_{clr} - \alpha_m) d_f + (\alpha_{clr} - \alpha_h) d_f - [1 - 2r_s(1 - r_{cld} - a_{cld})] \frac{\partial r_{cld}}{\partial CW} d(CW) + 2r_s(1 - r_{cld} - a_{cld}) \frac{\partial a_c}{\partial PW} d(PW) \right]
$$

or

$$
d(SWCF) = \delta_1 d\alpha_{clr} + \delta_2 d_f + \delta_3 d_f + \delta_4 d_f + \delta_5 d(CW) + \delta_6 d(PW).
$$

As with the long-wave, the changes in short-wave cloud forcing are not strictly related to changes only in the cloud properties themselves as expressed in terms {1}–{5} of (7) and (8), but also to changes in the clear-sky albedos {1} and absorption in the cloudy layer by water vapour {6}. In (8) the coefficient of $d\alpha_{clr}$ is positive; those of $df_l$, $df_m$, and $df_h$ are nearly always negative, except in the case of a thin cloud above a relatively bright surface; that of $d(CW)$ is negative, since the sign of the term in (7) is negative, and greater cloud water is monotonically related to higher reflectivities; and that of $d(PW)$ is positive, since absorptivity is monotonically related to PW.

Finally, the variations in the net cloud forcing may be expressed as the combination of those described above, such that

$$
d(NCF) = \beta_1 dE_{clr} + \delta_1 d\alpha_{clr} + (\beta_2 + \delta_2) d_f + (\beta_3 + \delta_3) d_f + (\beta_4 + \delta_4) d_f + (\beta_5 + \delta_5) d(CW) + \delta_6 d(PW)
$$

where the interpretation of the $\beta$s and $\delta$s are those of (3) and (8). In this equation $\beta_1$ and $\delta_1$ are both positive, $(\beta_2 + \delta_2)$ is likely to be negative since low clouds have emission temperatures comparable with those of the surface, $(\beta_3 + \delta_3)$ could be either positive or
negative, \((\beta_i + \delta_i)\) is most likely positive since high clouds are very cold relative to the surface, and \((\beta_s + \delta_s)\) may be either positive or negative.

The regression coefficients in (3), (8) and (9) have been calculated employing singular-value decomposition (Press et al. 1986). The accuracy of the regression estimates depends upon the assumption that the underlying relationships are linear, and that the data utilized span the full possible range of variability. In order to maximize the possibility of the latter the calculated regression models used individual monthly grid-point departures from the four-year monthly means for all data in 10° latitudinal strips. Thus, these models are based upon interannual anomalies which are functions of both time and longitude. In most cases data for all calendar months were combined. These conditions assure that important latitudinal dependencies are resolved at the same time that there is a sampling from a wide range of cloud situations corresponding to different longitudes and times. The regression equations calculated in this manner are based on several thousand individual data points and are judged significant at much greater than the 99% level using a chi-squared test (Press et al. 1986). It also should be noted that the resulting regression coefficients account for correlations between the 'independent' variables, and hence are estimates of the influence of each variable independent of all of the others.

4. INTERANNUAL VARIATIONS IN CLOUD FORCING

(a) Regression results

Equations (3), (8) and (9) and the ERBS, ISCCP, and ECMWF departures from four-year means are used as the bases of multiple-regression analyses of LWCF, SWCF, and NCF. Table 1 summarizes the explained variances and regression coefficients utilizing data for all months over both land and sea in each 10°-latitudinal zone. In the case of the NCF the last two terms in (9) have been excluded. Regression equations including those terms are nearly identical. The models for the long-wave, short-wave, and net cloud forcing explain 64–91%, 25–83% and 21–39% of the variance at each latitude. Generally, the smallest values of explained variance are at the highest latitudes, and the largest values are near the equator. Smaller explained variances in the southern hemisphere for net and short-wave cloud forcing may be related to the fact that SWCF variability itself is relatively small compared with ERBS uncertainties over the Southern Ocean. The relatively small values for NCF are attributable to the fact that there is generally a great deal of compensation between the LWCF and the SWCF, such that interannual variations often have magnitudes comparable with the estimated uncertainties (Harrison et al. 1990). Evidence of the rather noisy nature of interannual variations of ERBS NCF is given by the fact that the dominant empirical orthogonal function of such variations (not shown) explains only about 6% of the variance. The fractions of the interannual variance explained in these models are similar to those discussed in Hartmann et al. (1992), who relate ERBE total-sky fluxes to daily variations in the fractions of five cloud types in order to estimate clear-sky fluxes from extrapolations to zero cloud fractions. The rather low fraction of explained variance for NCF is also consistent with SS95, who show differences between calculated total scene net fluxes and ERBE measurements (their Fig. 2(c)) which are large fractions of the ERBE estimates of net cloud radiative forcing (Ramanathan et al. 1989).

Separate regression analyses have also been carried out using interannual departures for each calendar month. The variances explained by these twelve models (not shown) are up to about 25% larger than those illustrated in Table 1. However, because these monthly models are based upon fewer data points, the statistical significance is generally comparable with that for the all-month models described in Table 1. The regression coefficients (not shown) of these twelve monthly models exhibit moderate seasonal variations, especially
### TABLE 1. EXPLAINED VARIANCE AND REGRESSION COEFFICIENTS

**ΔLWCF—Eq. (3), land and sea**

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Explained variance (%)</th>
<th>$E_{clt}$</th>
<th>$f_i$</th>
<th>$f_m$</th>
<th>$f_h$</th>
<th>Cloud water</th>
<th>$R_{500}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°-50°S</td>
<td>64.01</td>
<td>0.82</td>
<td>0.11</td>
<td>0.23</td>
<td>0.62</td>
<td>0.10</td>
<td>-1.05</td>
</tr>
<tr>
<td>50°-40°S</td>
<td>68.10</td>
<td>0.78</td>
<td>0.14</td>
<td>0.40</td>
<td>0.82</td>
<td>0.16</td>
<td>-1.02</td>
</tr>
<tr>
<td>40°-30°S</td>
<td>77.78</td>
<td>0.63</td>
<td>0.17</td>
<td>0.47</td>
<td>1.02</td>
<td>0.19</td>
<td>-0.99</td>
</tr>
<tr>
<td>30°-20°S</td>
<td>82.88</td>
<td>0.22</td>
<td>0.19</td>
<td>0.39</td>
<td>1.15</td>
<td>0.24</td>
<td>-0.48</td>
</tr>
<tr>
<td>20°-10°S</td>
<td>82.71</td>
<td>0.22</td>
<td>0.19</td>
<td>0.38</td>
<td>1.29</td>
<td>0.46</td>
<td>-0.25</td>
</tr>
<tr>
<td>10°S-0°</td>
<td>91.30</td>
<td>0.40</td>
<td>0.16</td>
<td>0.58</td>
<td>1.27</td>
<td>0.39</td>
<td>-0.57</td>
</tr>
<tr>
<td>0°-10°N</td>
<td>90.76</td>
<td>0.50</td>
<td>0.18</td>
<td>0.55</td>
<td>1.24</td>
<td>0.44</td>
<td>-0.52</td>
</tr>
<tr>
<td>10°-20°N</td>
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<td>0.11</td>
<td>0.59</td>
<td>1.16</td>
<td>0.48</td>
<td>-0.69</td>
</tr>
<tr>
<td>20°-30°N</td>
<td>85.32</td>
<td>0.33</td>
<td>0.15</td>
<td>0.47</td>
<td>1.14</td>
<td>0.31</td>
<td>-0.64</td>
</tr>
<tr>
<td>30°-40°N</td>
<td>77.91</td>
<td>0.64</td>
<td>0.22</td>
<td>0.46</td>
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<td>0.26</td>
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<tr>
<td>40°-50°N</td>
<td>72.71</td>
<td>0.80</td>
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<td>0.42</td>
<td>0.85</td>
<td>0.31</td>
<td>-1.35</td>
</tr>
<tr>
<td>50°-60°N</td>
<td>67.40</td>
<td>0.78</td>
<td>0.08</td>
<td>0.32</td>
<td>0.62</td>
<td>0.24</td>
<td>-1.21</td>
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</tbody>
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**ΔSWCF—Eq. (8), land and sea**

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Explained variance (%)</th>
<th>$\alpha_{clt}$</th>
<th>$f_i$</th>
<th>$f_m$</th>
<th>$f_h$</th>
<th>Cloud water</th>
<th>Precipitable water</th>
</tr>
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<tbody>
<tr>
<td>60°-50°S</td>
<td>25.25</td>
<td>2.17</td>
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<td>-0.79</td>
<td>-0.50</td>
<td>-0.65</td>
<td>-1.39</td>
</tr>
<tr>
<td>50°-40°S</td>
<td>31.12</td>
<td>1.59</td>
<td>-0.55</td>
<td>-0.92</td>
<td>-0.66</td>
<td>-1.14</td>
<td>-0.22</td>
</tr>
<tr>
<td>40°-30°S</td>
<td>53.38</td>
<td>0.92</td>
<td>-0.74</td>
<td>-0.92</td>
<td>-0.98</td>
<td>-1.62</td>
<td>-0.12</td>
</tr>
<tr>
<td>30°-20°S</td>
<td>68.61</td>
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<td>-0.56</td>
<td>-0.64</td>
<td>-1.01</td>
<td>-1.72</td>
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</tr>
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<td>-0.44</td>
<td>-0.48</td>
<td>-1.11</td>
<td>-2.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10°S-0°</td>
<td>82.80</td>
<td>2.27</td>
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<td>-0.45</td>
<td>-1.09</td>
<td>-1.99</td>
<td>0.07</td>
</tr>
<tr>
<td>0°-10°N</td>
<td>82.64</td>
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<td>-0.54</td>
<td>-0.96</td>
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<td>10°-20°N</td>
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<td>-0.32</td>
<td>-1.06</td>
<td>-1.76</td>
<td>-0.05</td>
</tr>
<tr>
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<td>67.66</td>
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<td>-0.55</td>
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<td>-1.81</td>
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<td>2.10</td>
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<tr>
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<td>0.01</td>
</tr>
<tr>
<td>50°-60°N</td>
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<td>-0.79</td>
<td>-0.67</td>
<td>-1.03</td>
<td>0.68</td>
</tr>
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**ΔNCF—Eq. (9), land and sea**

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Explained variance (%)</th>
<th>$E_{clt}$</th>
<th>$\alpha_{clt}$</th>
<th>$f_i$</th>
<th>$f_m$</th>
<th>$f_h$</th>
<th>Cloud water</th>
</tr>
</thead>
<tbody>
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<td>60°-50°S</td>
<td>21.54</td>
<td>0.70</td>
<td>1.92</td>
<td>-0.20</td>
<td>-0.56</td>
<td>0.01</td>
<td>-0.53</td>
</tr>
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<td>50°-40°S</td>
<td>23.84</td>
<td>0.71</td>
<td>1.44</td>
<td>-0.39</td>
<td>-0.55</td>
<td>0.10</td>
<td>-0.99</td>
</tr>
<tr>
<td>40°-30°S</td>
<td>28.40</td>
<td>0.51</td>
<td>0.74</td>
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<td>-0.50</td>
<td>0.00</td>
<td>-1.44</td>
</tr>
<tr>
<td>30°-20°S</td>
<td>28.84</td>
<td>0.05</td>
<td>0.55</td>
<td>-0.39</td>
<td>-0.32</td>
<td>0.09</td>
<td>-1.47</td>
</tr>
<tr>
<td>20°-10°S</td>
<td>25.07</td>
<td>0.27</td>
<td>1.12</td>
<td>-0.25</td>
<td>-0.08</td>
<td>0.18</td>
<td>-1.51</td>
</tr>
<tr>
<td>10°S-0°</td>
<td>26.62</td>
<td>0.42</td>
<td>1.62</td>
<td>-0.21</td>
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<td>0.16</td>
<td>-1.56</td>
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</tr>
<tr>
<td>10°-20°N</td>
<td>22.23</td>
<td>0.27</td>
<td>1.60</td>
<td>-0.23</td>
<td>0.26</td>
<td>0.08</td>
<td>-1.28</td>
</tr>
<tr>
<td>20°-30°N</td>
<td>25.43</td>
<td>0.15</td>
<td>1.11</td>
<td>-0.30</td>
<td>-0.18</td>
<td>0.26</td>
<td>-1.49</td>
</tr>
<tr>
<td>30°-40°N</td>
<td>31.22</td>
<td>0.57</td>
<td>1.67</td>
<td>-0.29</td>
<td>-0.32</td>
<td>0.20</td>
<td>-1.30</td>
</tr>
<tr>
<td>40°-50°N</td>
<td>39.22</td>
<td>0.78</td>
<td>1.61</td>
<td>-0.19</td>
<td>-0.36</td>
<td>0.14</td>
<td>-1.04</td>
</tr>
<tr>
<td>50°-60°N</td>
<td>35.38</td>
<td>0.78</td>
<td>1.93</td>
<td>-0.13</td>
<td>-0.32</td>
<td>0.03</td>
<td>-0.67</td>
</tr>
</tbody>
</table>

For explanation of headings see text.
at higher latitudes for the short-wave and net cloud forcing. However, the annual means of these coefficients in all cases are similar to the values illustrated in Table 1.

(b) Perturbations proportional to means

In order to better understand these results, the coefficients from the all-month and monthly regression models have been utilized to calculate the specified changes of 16.5% increases of the mean low, middle and high-cloud fractions and a 25% increase in cloud water and ice, which are simulated in the model described in SS95. Figure 1 illustrates for each latitude zone the estimates of changes in the NCF due to the cloudiness perturbations derived from the all-month regressions. Table 2 shows the annual mean global changes for NCF, LWCF and SWCF as calculated in SS95 (Tables 2 and 4) and from the all-month regression results summarized in Table 1. The changes for NCF using the individual calendar-month regression models for the four sample months used in SS95 (January, April, July and October (IAGO)), and annual means, are shown in Fig. 2.

Table 2 and Fig. 2 illustrate fair agreement between the statistical and SS95 radiative-transfer model estimates, given the vast differences in methodologies. First, in all cases there is agreement as to sign for all terms. Second, both methods give the same ordering of importance for the contributions to the net radiative cloud forcing: cloud water is most important, low cloud is next, followed by middle and high cloud. Third, as shown in Fig. 2, both methods have comparable magnitudes of seasonal variability. Note, however, that the mean results for the current statistical models using all months together (Fig. 1 and Table 2) differ by up to about 10% from the means based upon an average of the IAGO months used by SS95 or all 12 calendar months.

A careful consideration of the differences between the results from these two methodologies should be useful in understanding the inherent uncertainties in either or both. Altogether, the best agreement between the present results and those of SS95 is for the long-wave fluxes. However, even for the LWCF there is a sizable disagreement concerning the role of changes in high-cloud amount; the regression results suggest about twice the sensitivity of that of SS95. The largest differences in all of the results are for the short-
TABLE 2. Predicted change in cloud radiative forcing arising from the specified increases of the listed independent variables

<table>
<thead>
<tr>
<th></th>
<th>Increases relative to mean values</th>
<th>25% cloud water</th>
<th>16.5%</th>
<th>16.5%</th>
<th>16.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>f_i</td>
<td>f_m</td>
<td>f_h</td>
<td></td>
</tr>
<tr>
<td>Contribution to net cloud radiative forcing (W m⁻²)</td>
<td>Eq. (9)</td>
<td>-5.72</td>
<td>-1.35</td>
<td>-0.69</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>SS95</td>
<td>-3.94</td>
<td>-3.61</td>
<td>-2.17</td>
<td>0.73</td>
</tr>
<tr>
<td>Contribution to long-wave cloud radiative forcing (W m⁻²)</td>
<td>Eq. (3)</td>
<td>1.43</td>
<td>0.78</td>
<td>1.23</td>
<td>2.62</td>
</tr>
<tr>
<td></td>
<td>SS95</td>
<td>1.37</td>
<td>0.38</td>
<td>1.01</td>
<td>1.35</td>
</tr>
<tr>
<td>Contribution to short-wave cloud radiative forcing (W m⁻²)</td>
<td>Eq. (8)</td>
<td>-7.12</td>
<td>-2.13</td>
<td>-1.87</td>
<td>-2.14</td>
</tr>
<tr>
<td></td>
<td>SS95</td>
<td>-5.31</td>
<td>-3.99</td>
<td>-3.18</td>
<td>-0.61</td>
</tr>
</tbody>
</table>

Sinha and Shine (1995, SH95) values are derived from their Tables 2 and 4. For explanation of headings see text.

Figure 2. Estimated monthly and annual mean changes in the cloud radiative forcing of the net radiation at the top of the atmosphere (NCF) arising from a 25% increase in cloud water (CW) and 16.5% increases in low- (f_i), middle- (f_m), and high-cloud amounts (f_h). Data bars are always in the same order as legends.

wave fluxes. Although both sets of results suggest that the changes in CW are by far the most important, the current results show a sensitivity nearly 2 W m⁻² larger than SS95. Furthermore, the SS95 results suggest that SWCF is less sensitive to variations in high clouds and more sensitive to variations in low and middle clouds. The differences for CW and low and middle-cloud amount terms in NCF are similar to those of SWCF. The relatively small difference in the predicted contribution of high-cloud changes in NCF is the result of a near compensation between the relatively large differences in the short-wave and long-wave fluxes.

The differences between the regression results and those of SS95 may be due to errors in the regression models, the SS95 radiative-transfer modelling assumptions, or both. As
stated previously, the largest uncertainties in the regression results can be attributed to possible errors in the observed interannual variations in the ISCCP and ERBE variables, or to the possibility that the 'true' relations between cloud properties and cloud radiative forcing are not linear. The largest errors in the SS95 results are likely to be related to the uncertainties in the mean cloud properties described by the ISCCP analysis, and in fundamental modelling assumptions such as cloud overlap.

To test the possibility that important nonlinearities are contributing to the differences, a series of scatter plots were made (not shown). These relate an ISCCP cloud variable to the residual of an observed cloud-forcing departure minus the departure predicted by a regression model, which excludes the chosen ISCCP variable (Eqs. (3), (8) and (9) without the term involving the targeted ISCCP variable; see Weare (1995)). Visual inspections of a number of these plots provides no evidence that the relationships diagnosed in Eqs. (3), (8), and (9) are not approximately linear.

With the remaining possible uncertainties in the regression model and those in the radiative-transfer model in mind, some of the differences between the current results and SS95 will be tentatively explored. The first is the relatively large sensitivity of the SWCF and NCF regression results to variations in CW amount. Weare (1993) has suggested that ISCCP CW estimates are relatively highly correlated with those of total cloud cover. This may be a consequence of the ISCCP methodology and not a feature of the real atmosphere. An artificially large correlation between CW and one or more of the cloud fractions could increase the apparent influence of CW relative to that of the cloud fractions. This is consistent with the comparison with SS95. On the other hand the differences might also be attributable to one of the several problems encountered by SS95 in accurately modelling mean total-scene short-wave fluxes.

The most interesting difference between the results concerns the role of high-cloud variations. The regression results are much more sensitive to high-cloud variations in both the long wave and short wave. This may be related to the conclusion in SS95 that their mean high-cloud ice estimates are probably too low and/or that the ISCCP mean high-cloud top temperatures are likely too high. The first factor would reduce the effect of changes in the fraction of high clouds on the SWCF by reducing the average reflectivity of high clouds. At the same time the overestimated cloud-top temperatures would reduce the effects of these cloud changes on LWCF by lessening the difference between emission from a cloud top and that from the surface or lower clouds. These influences are consistent with the reduced sensitivity to changes in high cloud exhibited by SS95 for both the short-wave and long-wave fluxes. An alternate explanation might be that the ISCCP estimates of variations in high-cloud amounts are too small, leading to overestimates of the effects of high clouds in the current regression models. However, this seems less likely since high clouds of moderate or larger optical depths and relatively easy to detect using the ISCCP methodology.

The third important area of disagreement illustrated in Table 2 is in the role of changes in low- and middle-cloud amounts on SWCF and NCF. The SS95 results suggest stronger sensitivity to both. SS95 discuss a possible reason for the greater sensitivity of their results. They show that their estimated middle- and low-cloud albedos are too large relative to ERBE observations, which implies that the mean ISCCP CW amounts are too large. If these mean CW amounts were underestimated, this would lead to an overestimate of the influence of changes in low- and middle-cloud amounts. Alternatively, the possible artificial correlation between interannual variations of CW and cloud fractions, mentioned in reference to differences in sensitivity to CW changes, could lead in the regression results to an underestimate of the sensitivity to changes in middle and/or low clouds. In addition, the disagreement in Table 2 concerning the role of middle clouds on NCF may also be
partially due to the fact that, as shown in Fig. 1, this term is weakly positive in the tropics and negative elsewhere, and that the regression model ‘global means’ only account for the variations between 60°S and 60°N.

The regression result showing that increases in middle-level cloud amounts in the tropics leads to increases in NCF is itself contrary to SS95. Table 1 shows that this result is associated with a broad, weak maximum in the $f_{m}$ coefficients for LWCF and a minimum of those coefficients for SWCF. Possibly, relatively shallow convective clouds lead to weakly positive NCF.

(c) Perturbations proportional to observed standard deviations

Figure 3 shows for both land and ocean the predicted changes in NCF, LWCF and SWCF due to observed one-standard-deviation increases in each of the variables on the right-hand sides of (3), (8), and (9). For NCF (Fig. 3(a)), variations of both of the clear-sky terms, $E_{cr}$ and $d_{cr}$, make substantial contributions, especially at the higher latitudes. Those of the precipitable water and the 300 hPa temperature are relatively small at all latitudes. Figure 3(a) also shows, as does Fig. 1, that the largest contribution to variations in NCF is nearly always attributable to changes in CW. However, in contrast to the results shown in Fig. 1, variations in high-cloud amount contribute on average nearly as much as those of low-cloud amount.

Figure 3(b), illustrating the results for LWCF, shows a dominance of variations in high-cloud amount at all but the highest latitudes. The next most important variable is generally middle cloud. At high latitudes the variations in the clear-sky long-wave flux are often more important than any single cloud parameter. This latter dependence may be due to true variability of the surface in conjunction with cloud changes, or to errors in the ERBE clear-sky identification scheme (Weare 1995). The patterns comparable with those in Fig. 3(b) derived separately for ocean and land grids (not shown) are qualitatively very similar.

Figure 3(c) shows that the contributions to SWCF are relatively complex. The most important term is due to variations in high-cloud amount. At first this would appear to contradict the conventional thought that variations in low clouds tend to be most important for SWCF. This contradiction is resolved by the fact that the ISCCP high-cloud amounts are relatively very variable. Variations in CW are slightly less important to alterations in short-wave forcing. Low- and middle-cloud variations make still smaller, but comparable, contributions. Variations in the clear-sky albedo are especially important in the high latitudes of the northern hemisphere. This contribution may be due to real interactions between clouds and snow cover, or be an artifact of errors in the ERBE clear-sky retrievals.

Results for NCF calculated separately for the portions of the latitudinal strips covered by land and sea (ignoring the precipitable water and 300 hPa temperature terms) are shown in Fig. 4. This figure illustrates that there are some substantial qualitative differences between variations over land and sea. In particular the influence of low-cloud amounts is generally much larger over sea than land. This is primarily attributable to the larger differences over the sea between clear and cloudy planetary albedos. Another factor may be the greater uncertainties in the ISCCP low-cloud estimates over land, where surface albedos are often large and variable. Furthermore, over land, increasing low-cloud amount contributes to a weak increase, rather than decrease, in NCF over much of the globe. This suggests that over land increases in low cloud actually contribute to a larger heating due to an increased greenhouse effect than cooling due to an increased cloud albedo. This implies that the ISCCP low clouds over land are relatively dark and cold in comparison with their oceanic counterparts. Colder continental clouds may be due partially to the fact that the ISCCP cloud determination algorithm uses a larger temperature threshold over land than
Figure 3. Estimated changes using the parameters in Table 1 in the cloud radiative forcing at the top of the atmosphere arising from a one-standard-deviation increase in cloud water (CW), low-cloud amount ($f_l$), middle-cloud amount ($f_m$), high-cloud amount ($f_h$) and the other parameters described in Eqs. (3), (8), and (9). (a) Net cloud radiative forcing (NCF), (b) long-wave cloud radiative forcing (LWCF) and (c) short-wave cloud radiative forcing (SWCF).
Figure 4. Estimated changes using the parameters in Table 1 in the cloud radiative forcing of the net radiation at the top of the atmosphere (NCF) arising from a one-standard-deviation increase in cloud water (CW), low-cloud amount ($f_l$), middle-cloud amount ($f_m$), high-cloud amount ($f_h$), clear-sky long-wave flux ($E_{clr}$), and clear-sky planetary albedo ($\alpha_{clr}$). (a) Only grid points over ocean and (b) only grid points over land.

sea. The inference that the ISCCP continental clouds are darker is partially verified by the fact that over most of the northern hemisphere the ratio of thick 'stratus' to thin 'cumulus' is about 10% greater over sea than land. The magnitudes of the differences between land and sea are consistent with SS95 (see their Fig. 5). However, SS95 do not show small positive changes in net radiation over low latitude land areas.

Figure 4 suggests that middle-level clouds are generally more important over ocean than land in middle latitudes. This is in general agreement with SS95 (see their Fig. 6) which shows that the changes in net radiation due to variations of middle cloud over sea are slightly larger than those over land at the same latitude. Furthermore, the current results show that increases in middle-level cloud amounts over ocean more clearly lead to a modest positive variation in cloud forcing in the tropics but a moderate negative change at the highest latitudes. In this sense middle-level clouds tend to act like high clouds in the tropics, intercepting long-wave radiation more effectively than reflecting short-wave
radiation, and like low clouds at higher latitudes, reflecting short-wave radiation more effectively than intercepting long-wave radiation. Finally, Fig. 4 indicates that the dominant clear-sky term at high latitudes is that related to $E_{cr}$ over ocean and to $\alpha_{cr}$ over land. This suggests that interannual variations in surface albedo over land, possibly associated with snow cover, are making substantial contributions to changes in the observed NCF.

(d) Sample short-term climate variations

Although Figs. 1–4 are useful for determining the relative importance of variations of the different cloud variables, they are insufficient for determining the actual variations of the cloud radiative forcing during an actual short-term climate change. This is because simultaneous variations of the cloud variables are unlikely to be equal or necessarily of the same sign. To explore this problem the correlations between the dominant term CW in the net cloud forcing and the three cloud fractions have been calculated for each latitude. These correlations (not shown) are only weakly functions of latitude and have values of about $-0.2$, $0.3$, and $0.5$ for low, middle and high cloud, respectively. This suggests that positive cloud-water variations are likely to be accompanied by small low-cloud amount decreases and middle- and high-cloud amount increases.

In order to better understand the relationships in observed short-term climate changes, CW, $f_l$, $f_m$, and $f_h$ were separately analysed using empirical orthogonal function (EOF) analysis. Figure 5 shows the most important functions and their associated time coefficients. The plotted EOFs have been normalized such that the product of a spatial weighting and a time coefficient is the predicted departure in units of a grid-point’s interannual standard deviation for that place and time. Although these EOFs explain less than 20% of the total variance, they do pass the North et al. (1982) test for significance and thus represent one significant mode of variation. Clearly, these EOFs are dominated by responses to the 1986/87 El Niño/Southern Oscillation (ENSO) with relatively large changes in the equatorial central Pacific during the first three months of 1987.

In order to approximate the actual NCF during a short-term climatic change, the departures of CW, $f_l$, $f_m$ and $f_h$ during early 1987 in the three regions with relatively large EOF spatial weights, near (5°S, 160°W), (25°N, 50°W), and (5°S, 30°W), were estimated from Fig. 5. For these points NCF is then calculated in two ways. In Method I, the average departure in standard-deviation units for all four cloud variables is multiplied by the corresponding changes in net cloud forcing of a one-standard-deviation, $\sigma$, change as shown in Fig. 4(a) and then summed.

Method I

$$\Delta\text{NCF} = \left( \frac{\Delta f_l + \Delta f_m + \Delta f_h + \Delta \text{CW}}{4} \right) \times \left\{ \sigma_{f_l}(\beta_2 + \delta_2) + \sigma_{f_m}(\beta_3 + \delta_3) + \sigma_{f_h}(\beta_4 + \delta_5) + \sigma_{\text{CW}}(\beta_5 + \delta_5) \right\} \quad (10)$$

where the $\Delta x$ notation refers to departures in units of standard deviations as inferred from Fig. 5. In Method II the departures at each point are multiplied by the one-standard-deviation changes at each point and summed.

Method II

$$\Delta\text{NCF} = [\Delta f'_l \sigma_{f_l}(\beta_2 + \delta_2) + \Delta f'_m \sigma_{f_m}(\beta_3 + \delta_3) + \Delta f'_h \sigma_{f_h}(\beta_4 + \delta_5) + \Delta \text{CW} \sigma_{\text{CW}}(\beta_5 + \delta_5)]. \quad (11)$$

Method I corresponds to a uniform departure (in standard-deviation units) of all four cloud variables, whereas Method II corresponds to an estimate associated with the relative changes that are actually observed.
Figure 5. Dominant empirical orthogonal functions (times 10) and associated time, (a) low-cloud amount \( (f_l) \), (b) middle-cloud amount \( (f_m) \), (c) high-cloud amount \( (f_h) \) and (d) coefficients of cloud water (CW) based upon (e) interannual departures for 1983–88. These functions explain about 12, 10, 9, and 18% of the total variance, respectively. All functions have been normalized such that the product of a function value at a given location, times a time coefficient for a given time, equals the predicted departure in units of the total standard deviation of departures for each point.
Table 3 summarizes the results together with estimates of the ERBS changes for the same regions and time based upon the dominant NCF interannual EOF (not shown). EOF estimates of the ERBS NCF changes are utilized because the directly observed NCF departures are quite noisy and, therefore, lead to estimates which are very sensitive to the choice of specific region and time. Unfortunately, this relatively large random variability gives rise to a dominant EOF which explains only about 6% of the total variance. Thus care must be taken in interpreting these results. Most interesting are the results for the two equatorial sites for which the two methods give rise to net cloud forcings of the opposite sign. In both cases the Method II value is in relatively good agreement with the observed change. At these equatorial sites differences between the results for Method I and II are mainly due to the fact that for the observed variations the changes in cloud water are relatively small, whereas those in high-cloud amount are relatively large. Thus in these cases the changes in the greenhouse effect weakly dominates over the albedo effect, leading to a weak positive radiative feedback (Stephens and Greenwald 1991). At the other location the two methods give net cloud forcing results with the same sign, but the magnitude for Method II, which is in better agreement with the observation, is smaller.
TABLE 3. Predicted and observed changes in net cloud forcing (NCF) for January–March 1987

<table>
<thead>
<tr>
<th></th>
<th>CW</th>
<th>$f_i$</th>
<th>$f_m$</th>
<th>$f_b$</th>
<th>Method I</th>
<th>Method II</th>
<th>ERBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x'$ (from Fig. 5)</td>
<td>$5^\circ S, 160^\circ W$ (Pacific)</td>
<td>0.06</td>
<td>0.08</td>
<td>-0.11</td>
<td>0.69</td>
<td>-0.63</td>
<td>0.08</td>
</tr>
<tr>
<td>$\sigma_s (\beta_i + \delta_i)$ (from Fig. 4(a))</td>
<td>-3.84</td>
<td>-1.31</td>
<td>0.90</td>
<td>0.78</td>
<td>-0.63</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>$\Delta$NCF (W m$^{-2}$)</td>
<td>-0.63</td>
<td>0.08</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta x'$ (from Fig. 5)</td>
<td>$25^\circ N, 50^\circ W$ (Atlantic)</td>
<td>0.09</td>
<td>0.04</td>
<td>-0.11</td>
<td>0.28</td>
<td>-0.41</td>
<td>-0.27</td>
</tr>
<tr>
<td>$\sigma_s (\beta_i + \delta_i)$ (from Fig. 4(a))</td>
<td>-4.29</td>
<td>-2.11</td>
<td>-0.95</td>
<td>1.67</td>
<td>-0.41</td>
<td>-0.27</td>
<td>-0.15</td>
</tr>
<tr>
<td>$\Delta$NCF (W m$^{-2}$)</td>
<td>-0.41</td>
<td>-0.27</td>
<td>-0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta x'$ (from Fig. 5)</td>
<td>$5^\circ S, 30^\circ W$ (Atlantic)</td>
<td>-0.04</td>
<td>-0.04</td>
<td>0.06</td>
<td>-0.28</td>
<td>0.26</td>
<td>-0.24</td>
</tr>
<tr>
<td>$\sigma_s (\beta_i + \delta_i)$ (from Fig. 4(a))</td>
<td>-3.84</td>
<td>-1.31</td>
<td>0.90</td>
<td>0.78</td>
<td>0.26</td>
<td>-0.24</td>
<td>-0.05</td>
</tr>
<tr>
<td>$\Delta$NCF (W m$^{-2}$)</td>
<td>0.26</td>
<td>-0.24</td>
<td>-0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For explanation of headings see text.

than that from Method I. These sample results suggest that for actual variations in clouds there is considerable compensation, especially between the affects of changes in cloud water and those in high-cloud amount.

The results in Table 3 emphasize the fact that NCF is not only the result of large compensations between SWCF and LWCF, but is also the result of subtle compensations of the individual cloud parameters. Thus to evaluate cloud radiative forcing fully during climate change it is necessary not only to understand how variations of cloud forcing are related to changes in cloud parameters, but also to understand exactly how those cloud parameters are interacting amongst themselves.

5. Discussion

Multiple-regression models have been developed relating interannual departures of ERBS net, long-wave, and short-wave cloud radiative forcing to variations in ERBS clear-sky parameters, ISCCP cloud amounts for low, middle and high clouds and cloud water, and ECMWF precipitable water and upper-tropospheric temperature. These models are then used to evaluate the effects on cloud radiative forcing of specified and observed changes in cloud properties. Important conclusions include:

(i) The fraction of interannual variance explained by the regression models of net, long-wave, and short-wave cloud radiative forcing is comparable with that of published models for intramonth variance.

(ii) The coefficients of these models nearly always have signs consistent with the theoretical framework describing cloud-forcing variations.

(iii) The estimated changes of cloud forcing due to 16.5% increases in low-, middle- and high-cloud amounts and 25% increases in cloud water agree with modelled estimates made by Sinha and Shine (1995) with respect to the signs of the responses and the order of the significance of the dependent variables for net cloud radiative forcing.

(iv) A one-standard-deviation variation in cloud water has the largest effect on net cloud forcing; one in high-cloud fraction has the largest effect on long-wave cloud forcing; those in both cloud water and high-cloud amount together make the largest contributions to short-wave cloud forcing.
(v) Variations in clear-sky planetary albedo and long-wave flux are important contributors to changes in cloud forcing at higher latitudes.

(vi) The dominant factors contributing to changes in net cloud forcing differ somewhat over land and sea. Over much of the globe, low-cloud increases contribute to weak increases in net cloud forcing over land, whereas over sea they lead to moderate decreases. At high latitudes clear-sky albedo changes are much more important than clear-sky long-wave flux changes over land, whereas the opposite is true over sea.

(vii) In a small sample of observed short-term climate-change scenarios compensations amongst the effects of the variables alter the magnitude, and in two cases the sign, of the estimated change in net cloud forcing relative to that resulting from uniform variations of the cloud properties.

These conclusions are clearly dependent upon the stability of the statistical results and the quality of the data utilized. All of the results discussed are found to be very robust with respect to small changes in input data. Tests involved running separate regression analyses using data over only oceans or land. All of these models give results which are consistent with those presented. In addition nearly all of the regression models were run for the shorter time period 1985–87 rather than 1985–88. These results are also very similar to those presented. The results are also found to be insensitive to the substitution of 500 hPa temperatures for the 300 hPa temperatures used in the long-wave and net cloud forcing models, and to the inclusion or deletion of the 300 hPa temperature and precipitable water in the net cloud forcing models. Finally, for a number of cases, scatter diagrams, relating important independent variables and the residuals of regression analyses utilizing all other independent variables (see Weare 1995), show the most important relationships are strongly linear (not shown) as assumed in the regression analysis.

The quality of the data and the possible impact of their uncertainties on these analyses are more difficult to assess. The ERBE clear-sky and cloud radiative forcing fluxes have been evaluated by a number of authors (e.g. Harrison et al. 1990; Hartmann and Doelling 1991). In general they find that there are random uncertainties of less than 5 W m$^{-2}$ and similar, or perhaps slightly larger, systematic uncertainties. Results illustrated in Figs. 3 and 4 suggest that the biases may be larger at high latitudes, especially over land. The small fraction of variance explained by the most important EOF of interannual variation of the cloud forcing of net radiation (not shown) suggests that research should be undertaken to understand better and reduce the uncertainties in, interannual variations of ERBE NCF.

The uncertainties in the ISCCP cloud estimates have also been explored by a number of authors (e.g. Rossow and Schiffer 1991; Weare 1993; Rossow and Gardner 1993a,b; Kobayashi 1993). Overall, these authors find that mean low-cloud amounts may be underestimated and that the cloud-water estimates are quite uncertain at latitudes poleward of about 50°. However, for this analysis the important uncertainties are those associated with departures from long-term means. In this regard Klein and Hartmann (1993) find measurable trends in the ISCCP cloud water and cloud-top temperature associated with the use of three different NOAA$^*$-series satellite sensors. However, these trends are generally insignificant in the present analysis (see Fig. 5) because the utilized data are almost all from the period of the NOAA-9 satellite, which are free of discernible trend.

Future work should include efforts to lengthen the data records in order to test the generality of the results better and to provide further examples comparable with those illustrated in Table 3. Additionally, work needs to be carried out to assess the quality of the observed interannual variability derived from the ISCCP and ERBE observations. Extensions of these results should include the utilization of different cloud-parameter data, such

$^*$ National Oceanic and Atmospheric Administration
as cloud water path estimated from microwave radiometer measurements (Prabhakara et al. 1982) and cloud drop-size distributions derived from multichannel ISCCP observations (Han et al. 1994).

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