Regional Cloud Cover Change Associated with Global Climate Change: Case Studies for Three Regions of the United States

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ABSTRACT

Land-based observations of cloud cover, for the period 1900–87 and averaged over three geographical regions of the United States (coastal southwest, coastal northeast, and southern plains), show strong positive correlations with one estimate of global mean surface temperature, a finding consistent with prior investigations that suggest cloud cover over land has increased during global warm periods relative to cold periods. It is also found that the strengths of three permanent high/low pressure systems (North Pacific high, Icelandic low, and Azores high) are negatively correlated with global mean surface temperature, suggesting a possible connection between regional cloud cover, for certain locations, and the strengths of adjacent high/low pressure systems. Specifically, for the regions considered it is suggested that the coastal southwest cloud cover is related to changes in the strength of the subtropical North Pacific high, that for the southern plains also to the strength of the North Pacific high, and that for the coastal northeast to the strength of the Icelandic low. Thus the climate-induced change in cloud cover for certain regions appears related, at least in part, to climate-induced change in the strengths of adjacent high/low pressure systems, and plausible physical explanations for this relation are provided for the three regions that have been studied. This does not, of course, provide a direct physical cause-and-effect explanation for the changes in regional cloud cover, because the mechanisms that cause the intensities of the high/low pressure systems to change are not understood.

1. Introduction

Changes in cloud cover associated with global climate change, and how such cloud-cover changes interact with a change in climate (i.e., cloud feedback), remain one of the most challenging aspects of predicting future climate change associated with anthropogenic activities. There have been several studies of cloud-cover changes over land, between warm and cold periods, employing historic records for past decades to more than a century (Lough et al. 1983; Henderson-Sellers 1986, 1989; McGuffie and Henderson-Sellers 1989; Karl and Steurer 1990; Henderson-Sellers 1992; Karl et al. 1993, 1995; Environment Canada 1995). These studies typically indicate that cloud cover over land has increased during warm periods relative to cold periods, and that associated with this increase is a decrease in the diurnal range of surface temperature that is very sensitive to changes in cloud cover (Karl et al. 1993). But there has been no effort at investigating whether these observations of cloud-cover change are related to other aspects of the atmospheric circulation that, themselves, are altered by global climate change. This would seem to be a particularly relevant endeavor, given the importance of understanding how clouds interact with a change in climate. For this purpose we have employed land-based cloud-cover observations averaged over three regions of the United States: the coastal southwest, the coastal northeast, and the southern plains. By additionally utilizing estimates of the secular changes of global mean surface temperature and regional surface pressure, it is found, for the period 1900–87 and for all three regions, that cloud cover increases with increasing global mean surface temperature, consistent with the prior studies discussed above, and that cloud cover decreases with the decreasing strengths of certain permanent pressure systems. We next note that the strengths of three permanent high/low pressure systems, the subtropical North Pacific high, the Azores high, and the Icelandic

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low, all decrease with increasing global mean surface temperature, suggesting a possible link between regional cloud-cover change and the strengths of related high/low pressure systems.

2. Datasets

In that we are investigating cloud-cover change associated with global climate change, we have adopted the global mean temperature anomaly dataset of Jones et al. (1994), which provides information on the change in annual and global mean surface temperature from 1854 to 1993. This dataset is based on corrected land and marine surface temperature measurements. We further employed monthly mean cloud cover averaged over three regions within the United States, utilizing land-based measurements from three meteorological stations within the coastal southwest (Fresno, Los Angeles, and San Diego), 10 stations within the coastal northeast (Boston, Burlington, Concord, Eastport, Hartford, La Guardia, Nantucket, New Haven, Portland, and Providence), and 10 stations within the southern plains (Columbia, Concordia, Dodge City, Fort Smith, Kansas City, Little Rock, Oklahoma City, St. Louis, Springfield, and Topeka). These cloud data were derived from land-based estimates of fractional cloud amount, and the longest periods of record are 1871 through 1987. They contain monthly and annual cloud amount, for all cloud types, as a percentage of sky cover and are available from the Department of Energy's (DOE's) Carbon Dioxide Information Analysis Center (http://cdiac.esd.ornl.gov/cdiac).

Additional datasets consist of the intensities of the North Pacific high, the subtropical high pressure system situated in the Pacific Ocean off the California coast, the Icelandic low, the low pressure system located in the North Atlantic Ocean south of Iceland, and the Azores high, which is the high pressure system in the subtropical North Atlantic Ocean. These were evaluated by Hameed et al. (1995) from the sea level pressure data of Trenberth and Paolino (1980), and their recent updates to this data, as follows:

$$I_p = \frac{\sum_{i,j=1}^{I,J} (P_{ij} - P_t) \cos\phi_{ij} (-1)^M \delta_{ij}}{\sum_{i,j=1}^{I,J} \cos\phi_{ij} \delta_{ij}},$$

where I_p is the intensity of the system, P_{ij} is the mean sea level pressure (SLP) at grid point (i, j) with ϕ_{ij} the latitude of the grid point, P_t is a threshold mean SLP, $M = 0$ for high pressure systems and 1 for low pressure systems, $\delta_{ij} = 1$ if $(-1)^M (P_{ij} - P_t) > 0$ while $\delta_{ij} = 0$ if $(-1)^M (P_{ij} - P_t) < 0$, and I, J define the study region. In the following, the intensity index I_P is subtracted from the reference value P_t in the case of the Icelandic low and added to P_t in the case of the highs to give the "intensity" of the pressure center. Furthermore, P_t = 1014 mb for the North Atlantic and P_t = 1013 mb for the North Pacific (Hameed et al. 1995), and the study areas chosen are

1) Icelandic low; 40°–75°N, 90°W–20°E;
2) Azores high; 20°–50°N, 70W°–10°E; and
3) North Pacific high; 20°–50°N, 140°E–100°W.

Sensitivity tests were performed with reasonable variations of the study areas and the threshold pressure P_t, which indicated that the qualitative behavior of the interannual variation of the intensity index was not significantly affected by the different choices.

Because the intensity is defined as the area-weighted surface air pressure for the system, then an increase in intensity corresponds to an increase in the strength of a high pressure system and a decrease in the strength of a low pressure system.

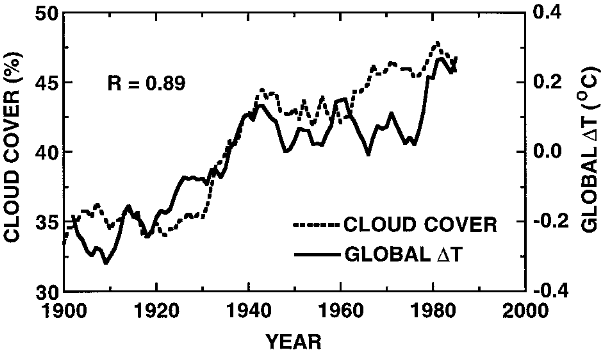

FIG. 1. Annual mean cloud cover for the coastal southwest, and the global temperature anomaly, ΔT, as a function of year. These are 5-yr running means evaluated from the yearly means.

3. Analysis

The annual mean and global mean temperature anomaly data of Jones et al. (1994) are shown in Fig. 1, for the period 1900–87, where ΔT represents the difference between the annual mean and global mean surface temperature from its average value for the period. Here, as with all other quantities in this analysis, the time series is a 5-yr running mean so as to remove short-term fluctuations, such as the quasi-biennial oscillation. As with other datasets of this type, there is a long-term warming trend, imbedded within which are shorter-term periods of cooling. Also shown in Fig. 1 are the annual mean cloud cover data for the U.S. coastal southwest for the same period. Note the strong positive correlation between these two quantities, as evidenced by the linear correlation coefficient (R) of 0.89. This positive correlation is present for each of the three stations (Fresno, Los Angeles, and San Diego) that were used to determine the regional average in Fig. 1, as demonstrated in Figs. 2a–c. Also, as shown in Figs. 2e–h, this positive correlation prevails throughout all seasons of the year. What is intriguing is that the intensity of the North

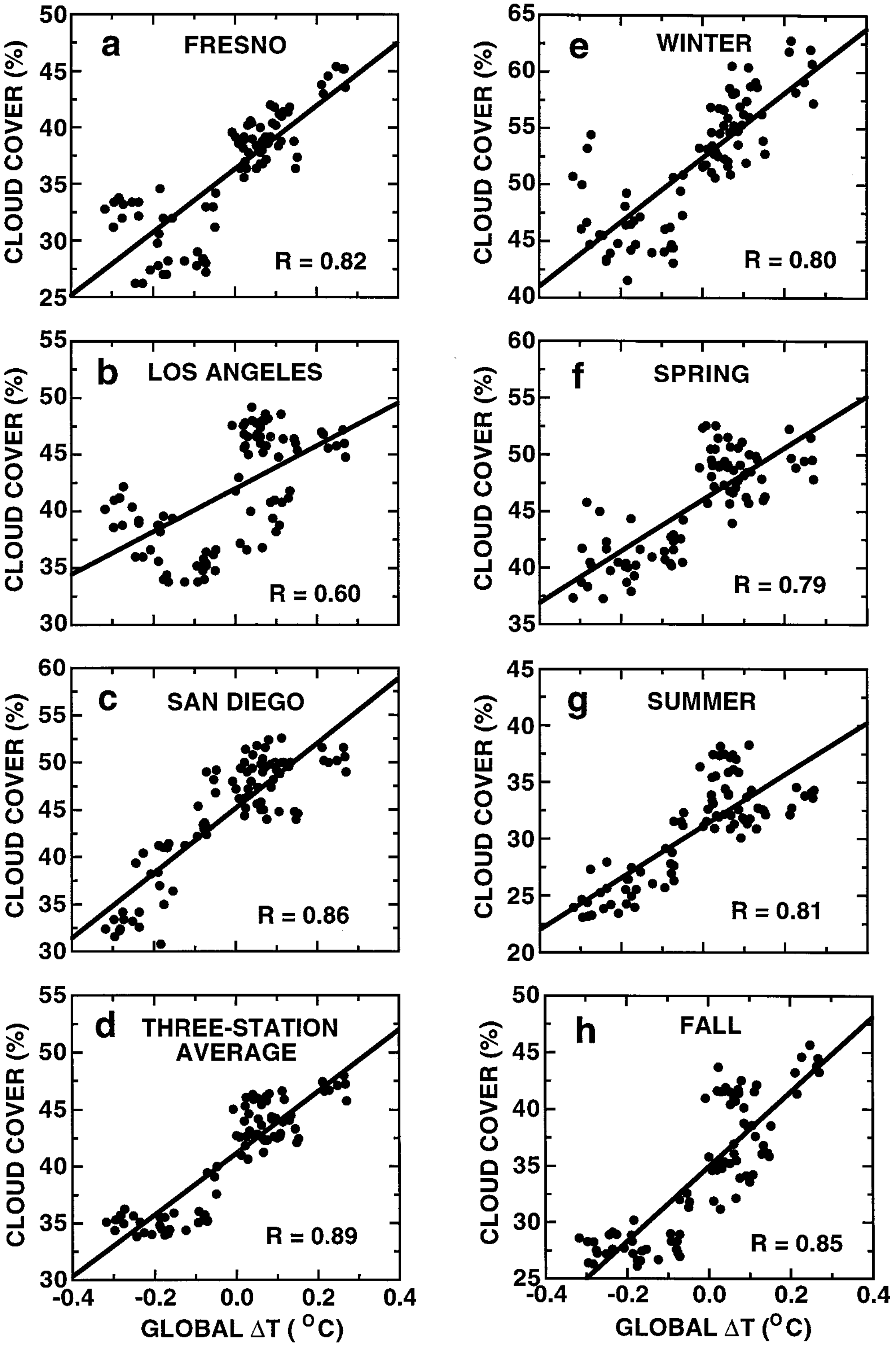

FIG. 2. (a) Annual mean cloud cover for Fresno as a function of the global mean temperature anomaly ΔT. (b) The same as (a) but for Los Angeles. (c) The same as (a) but for San Diego. (d) The same as (a) but for the three-station (Fresno, Los Angeles, and San Diego) average of cloud cover. (e) Winter cloud cover for the coastal southwest as a function of the global mean temperature anomaly ΔT. (f) The same as (e) but for spring cloud cover. (g) The same as (e) but for summer cloud cover. (h) The same as (e) but for fall cloud cover.

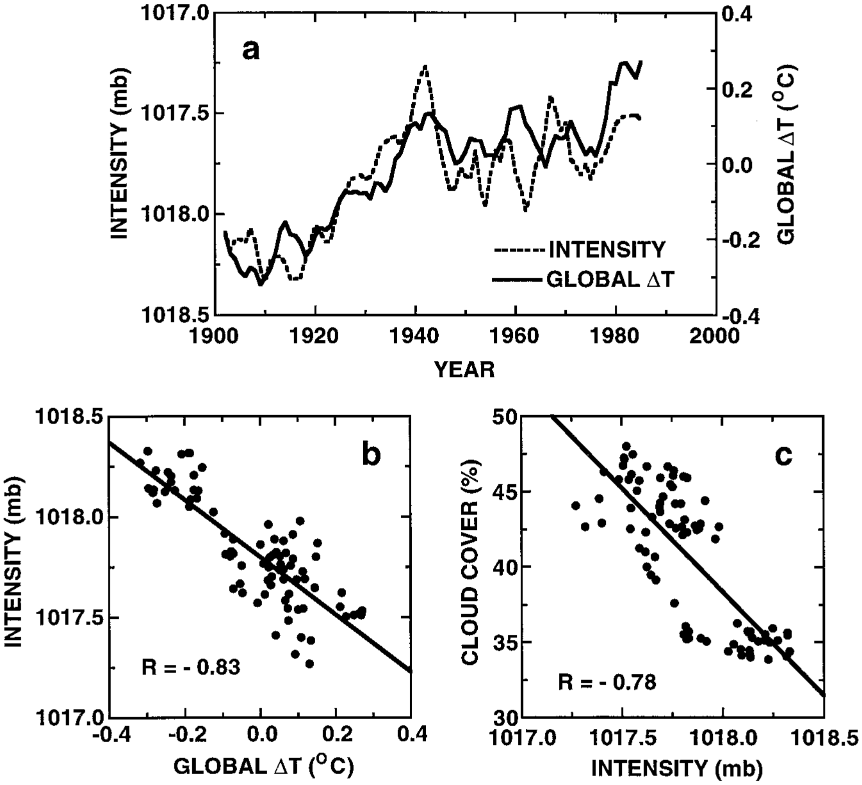

FIG. 3. (a) Annual mean intensity of the North Pacific high, and the global temperature anomaly ΔT as a function of year. These are 5-yr running means evaluated from the yearly means. (b) Annual mean intensity of the North Pacific high as a function of the global temperature anomaly ΔT. (c) Annual mean cloud cover for the coastal southwest as a function of the intensity of the North Pacific high.

Pacific high exhibits a similarly strong correlation with global ΔT, in this case a negative correlation, as shown in Figs. 3a (note that the intensity axis is reversed) and 3b. We are unaware of other studies demonstrating such a relationship between the strength of a permanent high/low pressure system and global mean surface temperature. Correspondingly, the regional cloud cover is negatively, and strongly, correlated with the intensity of this high pressure system as demonstrated in Fig. 3c, suggesting that a climate-induced change of the intensity of the North Pacific high might in part be the cause of the substantial cloud-cover change exhibited in the coastal southwest. Alternatively, the correlation in Fig. 3c could be coincidental and an artifact of both quantities responding to ΔT in ways that are unrelated to one another, as will be further discussed with respect to the southern plains. There are, however, two plausible mechanisms by which the coastal southwest cloud cover could be negatively correlated to the intensity of the high pressure system. One is that an intensification of a subtropical high will, with the possible exception of marine stratocumulus clouds, lead to a reduction of cloudiness as a consequence of increased subsidence. The second mechanism is that intensified anticyclonic motion about the high would result in an increase in colder, and thus drier, air being drawn northwesterly to the coastal southwest, affecting cloud cover for this region. Thus there exist reasonable physical mechanisms by which the coastal southwest cloud cover could be related to the strength of the North Pacific high.

That there is a connection between cloud cover, for some regions, and the strength of an adjacent high/low pressure system is also suggested by cloud cover changes in the coastal northeast in relation to changes in the intensity of the Icelandic low. Figures 4a–c briefly summarize the salient results for this connection, analogous to Figs. 2d, 3b, and 3c for the coastal southwest. From Fig. 4a there is again a strong positive correlation between cloud cover and global ΔT, and as for the coastal southwest this positive correlation is present for all seasons, with the respective winter, spring, summer, and fall correlation coefficients being 0.61, 0.74, 0.72, and 0.66. And the intensity of the Icelandic low is positively correlated with global ΔT as shown in Fig. 4b, meaning that the strength of the low diminishes with increasing ΔT, analogous to the negative correlation in Fig. 3b that indicates a reduction in the strength of the North Pacific high with increasing ΔT. Correspondingly, the cloud cover for the coastal northeast is negatively correlated with the intensity of the Icelandic low (Fig. 4c), and

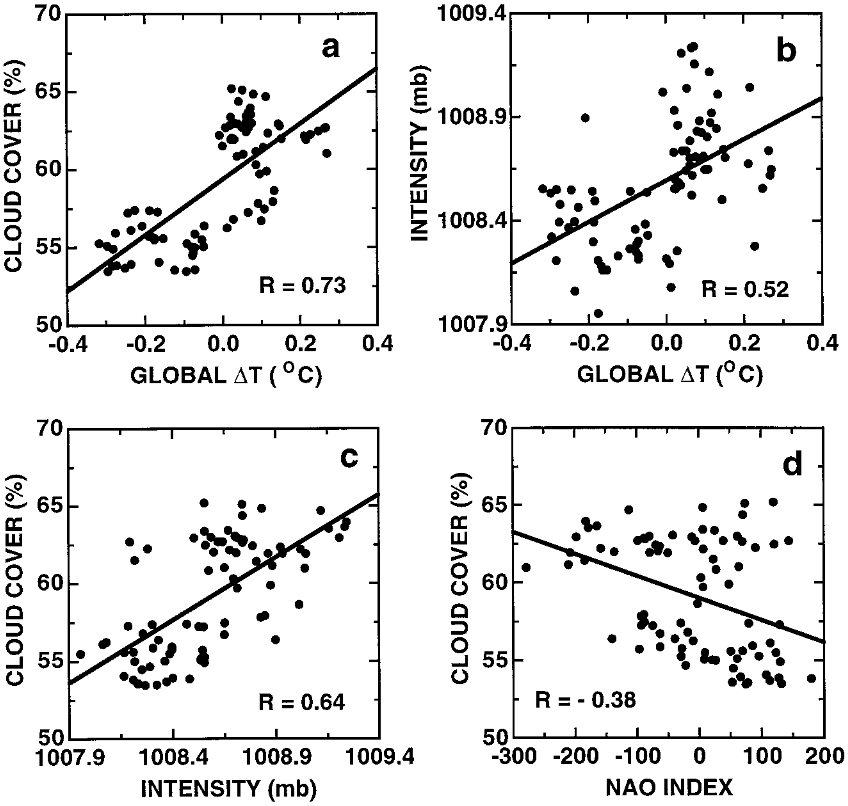

FIG. 4. (a) Annual mean cloud cover for the coastal northeast as a function of the global mean temperature anomaly ΔT. (b) Annual mean intensity of the Icelandic low as a function of the global temperature anomaly ΔT. (c) Annual mean cloud cover for the coastal northeast as a function of the intensity of the Icelandic low. (d) Annual mean cloud cover for the coastal northeast as a function of the North Atlantic Oscillation (NAO) index (Hurrel and van Loon 1995).

there is a possible explanation for this correlation. As the intensity of the low pressure system increases, its strength decreases, and the ensuing reduction in cyclonic motion about the low would result in a decrease in colder, and thus drier, air drawn northeasterly into the region, causing changes in cloud cover. Thus, like the coastal southwest, there is a plausible explanation for the observed correlation.

One might extend this argument to suggest that the coastal northeast is additionally impacted by the Azores high, the intensity of which is negatively correlated to ΔT with $R = -0.58$, but an argument can be made that such is probably not the case. To demonstrate this, consider the two-variable regression

$$\text{cloud cover} = a_0 + a_1 I_p(\text{Icelandic low}) + a_2 I_p(\text{Azores high}), \qquad (1)$$

where I_p denotes the intensity of the respective systems, while $a_1 = 7.68$ and $a_2 = -1.04$ from the regression. What is important is that the magnitude of a_2 is much less than that of a_1, while the intensity ranges for the two systems are comparable, indicating that for the coastal northeast it is the Icelandic low that is the dominant system. This is consistent with a minimal increase in R from 0.64 for the one-variable regression (Fig. 4c) to 0.65 for the two-variable regression. Furthermore, the slope in Fig. 4c is 8.09, comparable to the value for a_1 (7.68) given above.

Traditionally, variations of climate in the North Atlantic region have been interpreted in terms of fluctuations of the North Atlantic Oscillation (NAO) index, which is the anomaly of the pressure difference between the Azores high and the Icelandic low (Hurrel and van Loon 1995) and may be considered to represent the strength of zonal flow across the North Atlantic. Figure 4d shows that the correlation between the coastal northeastern cloud cover and the NAO index explains only 14% (R^2) of the cloud-cover variations as compared with 41% by the Icelandic low itself (Fig. 4c). This result thus suggests that further progress in deciphering the causes of cloud variations in this region can be obtained by focusing on the physical interaction of the Icelandic low system with the flow regime over the northeastern United States.

The third region is the southern plains, which also exhibits a strong positive correlation of cloud cover with

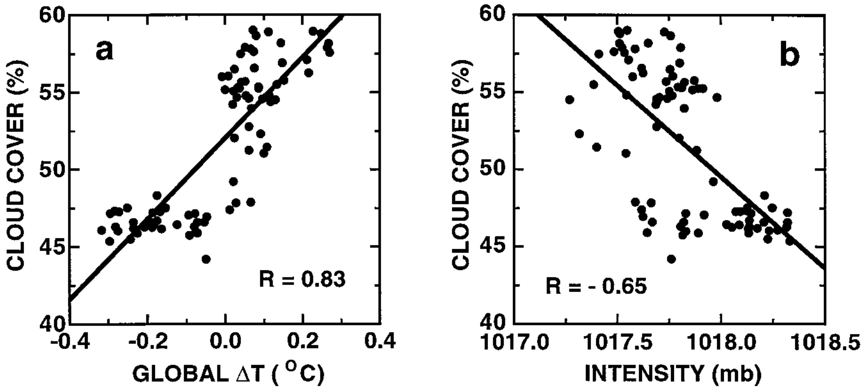

FIG. 5. Annual mean cloud cover for the southern plains as a function of the global mean temperature anomaly ΔT. (b) Annual mean cloud cover for the southern plains as a function of the intensity of the North Pacific high.

ΔT, as demonstrated in Fig. 5a. As with the two other regions, this positive correlation is present throughout all the seasons of the year, and the annual mean cloud cover for this region is positively correlated with the intensity of the North Pacific high as shown in Fig. 5b. But this also emphasizes that cloud cover versus intensity correlations could be very misleading, with a strong correlation not necessarily implying that a connection between the two quantities really exists. Indeed, a strong positive correlation between cloud cover and ΔT guarantees a positive correlation between cloud cover and the intensity of the North Pacific High, because the latter is also positively correlated with ΔT (Fig. 3b). This argument, of course, applies to the two other regions as well. And the same point can be made with respect to southern plains cloud cover and the intensity of the Azores high, for which a positive correlation exists with $R = 0.44$. Thus by this logic one might arguably claim that the southern plains cloud cover is not related to the intensities of either the North Pacific high or the Azores high, or alternatively that it depends on the intensities of both high pressure systems. The application of (1), however, with I_p (Icelandic low) replaced by I_p (North Pacific high), and with cloud cover referring to that for the southern plains, provides quite a different interpretation. In this case $a_1 = -11.10$ while $a_2 = -0.81$, thus providing a degree of confidence that the intensity of the North Pacific high is impacting the southern plains cloud cover, since $a_2/a_1 = 0.07$. Moreover, $R = 0.64$ for the two-variable regression, virtually the same as in Fig. 5b for the one-variable regression, while the one- and two-variable negative slopes (respectively 11.84 and 11.10) are likewise quite similar. That the two-variable regression indicates a dependence of southern plains cloud cover on the intensity of the North Pacific high tends to minimize the possibility that the correlation shown in Fig. 5b is coincidental, because if this correlation were coincidental it is doubtful that the two-variable regression would demonstrate such a strong preference for a dependence on the intensity of the North Pacific high versus the that of the Azores high.

Trewartha (1981) notes that the source of atmospheric moisture in the southern plains region has been a source of controversy. Wexler (1943) suggested that the anticyclonic winds of the Azores high carry moisture from the Gulf of Mexico into the southern plains region. Other investigators, such as Hales (1974), have maintained that while the Gulf of Mexico serves as a source of moisture in this region, most of the moisture reaching the central and eastern sections of the southwestern interior region originates from the Pacific. The more dominant role of the Pacific air masses in influencing moisture and cloud cover in that region is consistent with the regression described above. Lydolph (1985) has also suggested that air over western Arizona, Nevada, and adjoining states is often capped by a subsidence inversion produced by the eastward extension of the North Pacific High.

4. Concluding remarks

This study suggests that secular changes in the strengths of three permanent high/low pressure systems, the North Pacific high, the Icelandic low, and the Azores high, are in part related to secular changes in global climate, that is, changes in global mean surface temperature. The strengths of all three systems diminish with increasing global temperature. Although these relations are purely statistical, they suggest the usefulness of pursuing physical cause and effect mechanisms. It is further suggested, but not conclusively proven, that the climate-induced change in cloud cover for certain regions is related to the climate-induced change in the strengths of adjacent high/low pressure systems, and plausible physical explanations for this relation exist for the three regions that have been studied. This does not, of course, provide a direct physical cause and effect explanation for the changes in regional cloud cover, because we do not understand the mechanisms that cause the changes of the strengths of the high/low pressure systems. But the suggestion of this study is that regional climate change, at least for certain locations, might be related to changes in the strengths of certain high/low pressure systems, and given the importance of understanding regional climate change, it would seem that this is an area of research that should be pursued.

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