5.8 RELATIONSHIP AMONG ARCTIC CLIMATE VARIABLES BASED ON THE OBSERVATIONS AND MODEL SIMULATIONS OVER SHEBA SITES

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1. INTRODUCTION

Complex exchanges of energy and water among the ocean, sea ice, and atmosphere cause the Arctic climate system to be particularly sensitive to climate change because clouds, snow, and sea ice introduce a host of feedbacks, some of which have powerful global effects. Some of the changes observed during recent decades in the oceanic and terrestrial northern high-latitudes are summarized in Serreze et al. (2000). There is significant warming in the central Arctic, downward trends in sea-ice cover, and negative snow anomalies over both continents. Global climate models (GCMs) exhibit some success in representing high-latitude processes, but obvious shortcomings remain.

Our understanding of the interactions and feedbacks among the components of the Arctic climate system can be significantly advanced by integrating new observations of Arctic climate variables with a global coupled atmosphere-ocean-ice model. Model-only studies are limited by being insufficiently validated against observations, and observation-only studies are often limited by data sparsity and/or by poor spatial and temporal sampling. Recently available Arctic data sets offer new opportunities to evaluate and improve GCM simulations. Even though their record lengths are limited, these observations viewed separately and in concert can be used to improve the accuracy of numerical models by evaluating the realism of their output and analyzing feedback mechanisms and relationships among climate variables. While observations and GCMs individually offer limited ability to study these relationships, the combination of the two constitutes a powerful tool.

In this study we integrate observations with output from simulations of the global climate model of Russell et al. (1995). The preliminary results are presented briefly in this paper. We compare modeled and observed sensitivities and relationships among several different climate variables to determine whether the GCM realistically represents these interactions. These sensitivities are the controlling factors for feedbacks. If the modeled sensitivities differ from reality, so will the feedbacks that involve those variables. The principal objective of this study is to extend observational and model studies by examining the sensitivity among climate variables and the processes and feedbacks that are most important in the high-latitude climate system, including an attempt to quantify some of these relationships.

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2. DATA SOURCES

Output from one global climate model (GCM) and two different observational data sets are used in the analysis. The global synchronously coupled atmosphere-ocean-ice model developed by Russell et al. (1995) has 9 vertical layers in the atmosphere and 13 in the ocean. The horizontal resolution for both the atmosphere and ocean is 4° in latitude by 5° in longitude. The resolution for heat, water vapor, and salt is finer than the grid resolution because those quantities have both means and directional gradients inside each grid cell. Atmospheric condensation and ocean vertical mixing are performed on a 2° x 2.5° resolution horizontal grid. The global model conserves water, includes the important high-latitude feedbacks, and is internally self consistent. Additional information about the model is available at http://aom.giss.nasa.gov/DOC/ATMOCEAN.TXT.

The observations are from the surface heat budget of the Arctic Ocean (hereafter SHEBA) experiment, and satellite retrievals. The SHEBA integrated data set is obtained from http://www.atmos.washington.edu/~roode/SHEBA.html. It includes a wide range of atmospheric and oceanic measurements with daily temporal resolution from rawinsonde soundings, lidar, radar, meteorological surface observations and a microwave radiometer. Satellite observations are from the TIROS Operational Vertical Sounder (TOVS), which has flown on NOAA polar-orbiting satellites since late 1978 and has generated one of the longest and most complete satellite data records in existence. The 20-year global TOVS data set was subsetted for the Arctic region north of 60°N, then the radiances were processed with a version of the Improved Initialization Inversion (“3I”) algorithm (Chedin et al, 1985; Scott et al, 1999) that was modified to enhance accuracy over snow- and ice-covered surfaces (Francis, 1994). Orbital retrievals were gridded on a $(100km)^2$ grid and daily averaged to produce the socalled “Path-P” data set (Francis, 2000; Schweiger et al. 2002). Validation of Path-P is illustrated by comparing temperature and water vapor retrievals with rawinsonde and surface data from some in-situ field programs (Schweiger et al, 2002). Retrieved skin temperatures agree surprisingly well with 2-meter air temperatures (Chen et al, 2002), particularly given the facts that clouds interfere with surface temperature retrievals, they can increase snow/ice surface temperatures substantially when cloud cover changes, and the Arctic is typically very cloudy.

3. RESULTS

In this section we examine and compare relationships among climate variables at SHEBA sites in the Arctic using in-situ measurements, satellite observations and

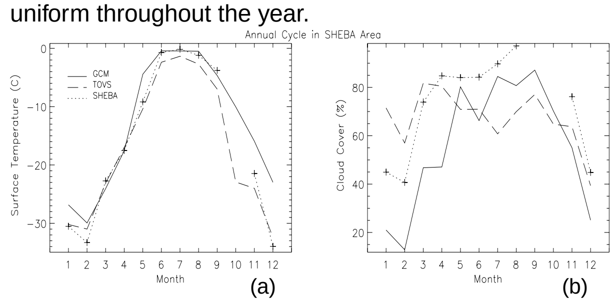
GCM output. The different sources of observations are denoted by TOVS and SHEBA. The climate variables include surface air temperature (skin temperature if from satellite), fractional cloud cover, and downward longwave flux (hereafter DLF). Although DLF is calculated internally by the model, it is not stored, only the net thermal radiation emitted by the surface is stored. For this paper, DLF is calculated as the Stephen-Boltzman constant times ground temperature raised to the fourth power minus net radiation emitted by surface.

We first compare the annual cycles for each climate variable and the interannual variability of TOVS retrievals and GCM output. Then we compare the ranges in magnitude of the climate variables for the different data sets. Finally, we examine relationships between pairs of climate variables to see how daily changes in one variable are related to changes in another.

There are some differences among the variables to be compared in this section. One potential reason for differences between TOVS temperature and the other temperatures is that TOVS obtains skin temperature rather than the surface air temperature, and the skin temperature in winter can be one to two degrees colder than the surface air temperature. The SHEBA variables are obtained at a point, while the TOVS and GCM values are averaged over areas of several grid boxes with resolution of 100 x 100 km^2 and 5° x 4°, respectively. Observations from the SHEBA experiment are for one year only (October, 1997 to September, 1998). We use the same periods for TOVS and GCM corresponding to SHEBA. It is important to note that the one-year model record for this period is not meant to correspond to the actual climate of that one year, but our examination of several other model years shows that this period is representative of the climatology of the decade surrounding it. TOVS observations are at the same time as SHEBA, and ideally, should correspond with each other.

3.1 *Annual cycles and interannual variability*

Figure 1 shows the annual cycle of the three climate variables at the SHEBA site for TOVS, GCM and SHEBA. Figure 1a shows that the annual range of surface air temperature is large with a maximum near 0°C in summer for both model and observations. In winter the model's surface air temperature is warmer than TOVS and SHEBA temperatures. The largest discrepancy among data sources occurs for cloud cover (Fig. 1b). The amplitude of the model's annual cycle is much larger than that of either TOVS or SHEBA, with largest differences in the winter. The criterion for the presence of a cloud in the model is when the amount of condensate in the water column generates an optical depth greater than one; when it's less than one, no cloud is assumed to be present. This leads to the thinnest clouds being missed in the model diagnostics and the winter cloud coverage being lower than the in situ observed cloud cover from the SHEBA experiment. For the model, cloud cover ranges between 20-80%, for SHEBA between 40-90%, and for TOVS between 40-80%. The model's annual cycle shape is more similar to the SHEBA observations with a minimum in winter and maximum in summer than it is to TOVS which is fairly uniform throughout the year.



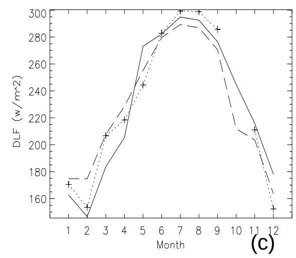


Fig. 1 Annual cycles of (a) surface air temperature, (b) fractional cloud cover, and (c) downward longwave flux (DLF) for SHEBA, TOVS, and GCM at the SHEBA site. All are based on one year (October, 1997 - September 1998).

An important climate variable for the Arctic energy budget is DLF. Figure 1c shows that the amplitudes of the annual cycles are in good agreement with maxima near 300 Wm^{-2} in summer and minima of 160 Wm^{-2} in winter. This suggests that this component of the model's energy budget is being simulated well although given big differences in cloud fraction, perhaps for the wrong reason. DLF obtained from TOVS is also in good agreement with the in situ observations. The amplitude of the annual cycle for TOVS is somewhat lower than for SHEBA as it is about 10 Wm^{-2} too low in summer and too high in winter. This is expected given the much coarser spatial resolution of TOVS retrievals and consequent reduction in variability. The similarity of the DLF cycle to the surface temperature cycle is consistent with other observations that these variables are closely related.

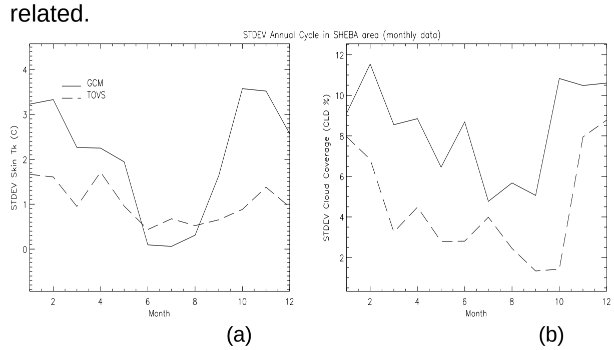
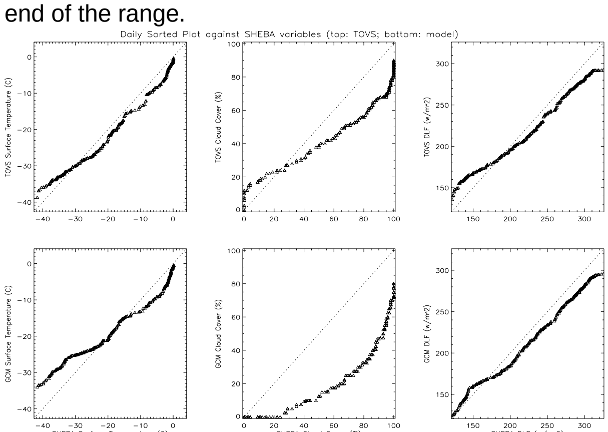


Fig. 2 Surface temperature and cloud cover as in Figure 1, except the standard deviation of the variables for TOVS and GCM based on 19 year records (1980-1998).

In addition to comparing monthly means of the climate variables as in Figure 1, it is important to understand the variability and covariability of the parameters. We can examine both the variability within a given month or the interannual variability. Figure 2a and 2b shows that over SHEBA site the model's interannual variability from 1980 to 1998 in both surface temperature and cloud cover has a much stronger seasonal cycle than does TOVS. There is a seasonal cycle in the variability for both variables, with the highest variability in winter and lowest in summer. Surface temperatures are close to the melting point during summer in the Arctic, and the variability is small.

3.2 *Rank-ordered plot*

To examine how well the ranges of the variables differ among the three data sources, we next examine the rank-ordered plots shown in Figure 3. The top panel shows the relation between TOVS and SHEBA. For each of the three variables - temperature, cloud cover, and DLF - TOVS values have a smaller range than SHEBA measurements. This is a consistent result because if cloud cover were large, we would expect DLF to be high and temperature to be high. For the model in the lower panel, the poorest agreement is for cloud cover. The model has no clouds when the observations are between 0 and 20% and always has less than observed. The model's DLF is somewhat lower than the observed, which would be consistent with the model's reduction in cloud cover and surface temperature too low in the high end of the range.



(a) (b) (c)

Fig. 3 Rank-ordered comparison at SHEBA site of TOVS (top) and GCM (bottom) climate variables against SHEBA variables for (a) surface air temperature, (b) cloud cover, and (c) downward longwave flux. Points on the plot are obtained by ordering all SHEBA points for one year from highest value to lowest value and then plotting against the corresponding ordered TOVS and model values.

3.3 *Relationships between daily changes*

This component of the study is based on daily data from the three sources. Figure 4 shows the comparison of the daily changes during the one-year SHEBA experiment for SHEBA, TOVS, and GCM. Each point represents the day-to-day change in one variable versus the corresponding change in the second variable. For example, Fig. 4a indicates that the daily change in DLF is highly linearly correlated (greater than 0.8 for SHEBA and the GCM) with the daily change in surface air temperature for the three data sources. Furthermore, these same panels quantify the relationship and show that for SHEBA, the DLF changes by 6.03 Wm^{-2} for every 1 degree change in surface air temperature and 6.89 Wm^{-2} per degree for the GCM. For TOVS, the change in DLF is much smaller (1.85 Wm^{-2} per degree). The agreement between the GCM and SHEBA observations is quite high and this is encouraging when examining climate feedbacks.

Figure 4b shows that daily changes in DLF and cloud cover are highly correlated for both SHEBA observations and the GCM with DLF increasing by 0.60 and 0.64 Wm^{-2} for each 1% increase in cloud cover. Another feature of the model's relationship is that there is much less scatter about the regression line. The range of the model's daily changes is smaller than that of SHEBA for each of the variables. For SHEBA the daily changes in DLF exceed 60 Wm^{-2} while for the model they only reach 40 Wm^{-2}. Similarly for cloud cover there are many days when the in situ observed cloud cover changes by more than 50%, while the model's daily changes are much less. This is likely due to a point measurement at SHEBA being compared with a grid-box averaged value from the model. The figure is consistent with the well known behavior that a larger cloud cover emits more DLF to the surface, thus increasing surface temperature. For TOVS, the correlation between DLF and cloud cover is very low.

We expect that there could be significant differences in the relationships shown in Fig. 4 if winter and summer are examined separately. The results (not shown) indicate that the correlations for all of the relationships shown in Fig. 7 are higher in winter, except for the relationship between DLF and cloud fraction for the SHEBA observations for which there is almost no change between the annual and winter relationships. One of the interesting features here is that the change in DLF per unit change in surface temperature in winter is now larger for the model than for SHEBA observations (7.8 Wm^{-2} vs. 5.3 Wm^{-2}). Compared to their annual values, the model has increased and SHEBA has decreased. For TOVS the change is much smaller than either for the SHEBA observations or the model. Because there is no solar radiation during winter, we expected that the correlation between surface temperature and DLF would be higher in winter.

4. DISCUSSION

A standard way of validating GCMs is to compare the climate variables that they simulate with the same observed variables. Figures 1 and 2 show such comparisons for monthly means and standard deviations of surface air temperature, cloud cover, and downward longwave flux. The GCM output is consistent with both in-situ measurements and satellite retrievals except for cloud cover, in part, because of the differences in the way clouds are defined in the three sources. However, when trying to understand feedbacks in the climate

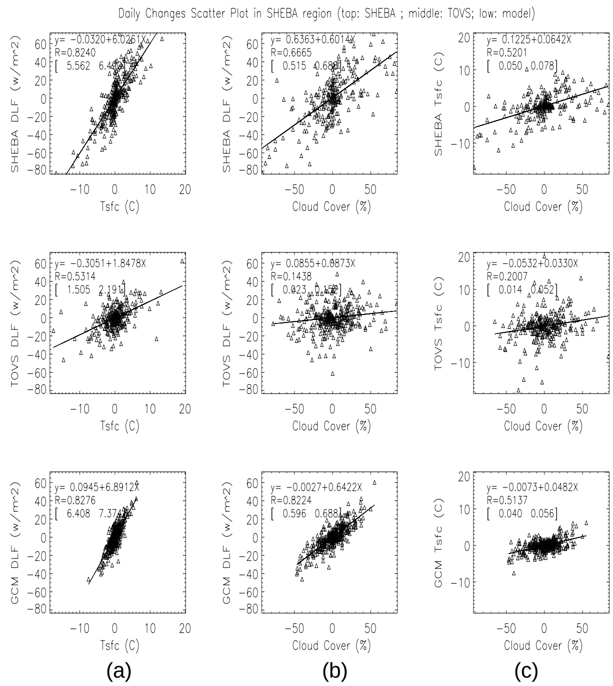


Fig. 4 Relationships at SHEBA site between daily changes of pairs of climate variables for SHEBA (top), TOVS (middle), and model (bottom) for (a) surface air temperature and downward longwave flux (b) fractional cloud cover and downward longwave flux, and (c) surface air temperature (T_{sfc}) and cloud cover. Each point represents the day-to-day change in one variable with the corresponding change in the second variable for the same days. The points are for one year (Oct., 1997 - Sep, 1998) for SHEBA, TOVS, and model.

system, it is important that the relationships between changes in different climate variables be accurately represented in the model. In the Arctic, feedbacks play an important role in controlling climate change. Thus the model's ability to provide plausible scenarios of future climate change depends on whether or not the GCM can simulate the correct relationships among climate variables. To address this point, we compare the relationships between each pair of the three variables (surface temperature, cloud cover, and DLF) to evaluate the GCM's performance. The results are encouraging.

In summary, the highest correlations (above 0.9) occur for the relationship between DLF and temperature in winter for both the model and the SHEBA data and between DLF and cloud cover for the model. The correlations for TOVS aresomewhat lower. In winter the change in DLF per unit change in temperature is lowest for TOVS (2.0 Wm^{-2}) and highest for the model (7.8 Wm^{-2}) as compared to the in situ value of 5.3 Wm^{-2}. In summer the correlations between DLF and cloud cover are high for the model and SHEBA data, but the linear correlation for TOVS is low and shows no relationship between the two variables. This raises some concern about the consistency of the TOVS retrievals of clouds and/or DLF in summer because we generally would expect DLF to increase when cloud cover increases.

All three sources of data indicate a high correlation between temperature and cloud cover in winter. Not only are the correlations high, the magnitudes of the responses are similar too, ranging between 0.06 and 0.09 °C/percent change in cloud cover. The relationship is much weaker in summer and the magnitude of the response is negative and small. In summer the temperature decreases by 0.0 to 0.03 °C for each 1% increase in cloud cover. There are several reasons for the differences between these relationships in summer and winter. First, there is no solar radiation in winter. More cloud cover reduces the longwave radiation to space and reemits longwave radiation back to the surface. Second, the surface temperature over the Arctic Ocean is confined to near the melting point of water in summer due to the existence of sea ice, and doesn't change much. This constraint of the surface temperature to be near zero in summer accounts for why the high correlation between DLF and cloud cover is not accompanied by a similar response between cloud cover and surface temperature.

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