Final Report
to
National Aeronautics and Space Administration
Washington, DC 20546

SIMULATION OF BOREAL ECOSYSTEM CARBON AND WATER BUDGETS: SCALING FROM LOCAL TO REGIONAL EXTENTS
Grant: NAG5-2326

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August 1997.

1.0 Overview and Project Objectives:

This project was part of a larger project entitled Simulation of Boreal Ecosystem Carbon and Water Budgets: Scaling from Local to Regional Extents for which Professor Larry Band, University of Toronto was the Principal Investigator. These projects were part of the Boreal-Ecosystem-Atmospheric Study (BOREAS) whose aims were to further our understanding of the exchange of water, energy and carbon within northern boreal forests, and were funded by NSERC (Band) and NASA (Wood). The portion of the project being carried out at Princeton had the following objectives:

1. To develop a coupled water and energy balance model that can predict the partitioning of water and energy between major source, sink and storage elements within the BOREAS Study areas, and

2. Test the model against data collected at BOREAS tower sites during Intensive Field Campaigns (IFCs) and remotely sensed data collected across the BOREAS region.

The project consisted of three elements. The first was the development of model parameterizations identified as being important to the boreal ecosystem. These model improvements are described in section 2.0. The second was an intercomparison of data sets. Understanding the quality of the data is critical to modeling. These results are presented in section 3. The third element of the project is the application of the boreal water and energy model to the tower sites in both the Southern Study Area and Northern Study Area. These results are presented in section 4.

2.0 Water and Energy Balance Modeling

A process based land surface water and energy balance model (Peters-Lidard et al., 1997a) has been applied at the various flux tower sites in both the NSA and SSA. Model improvements have been made to allow for simulations in conditions particular to BOREAS. These improvements include:

• *Inclusion of a moss surface layer.* Moss has a dual effect on the hydrology of boreal forests. Due to its high water retention capacity, moss keeps the underlying soil moisture at or close to field capacity throughout the summer season, and due to its low thermal conductivity keeps the underlying soil layers at a constant, low temperature (Bonan and Shugart, 1989). In addition, a significant portion of the canopy roots can be found in this moss layer. During the BOREAS experiment, the HYD-8 project collected infiltration, drainage and evaporation data for both Feather moss and Sphagnum species which can be used to parameterize the moss module (Price et al., 1997). In the BOREAS region, Sphagnum is the dominate species and can have a thickness of up to 1 m. For Sphagnum, the layer usually supports a very large capillary rise which keeps the surface wet as long as there is water availability. Feather moss tends to be disconnected from its soil layer.

In modeling the hydrologic response of moss, we represent the moss layer as an extra soil layer with special properties; as have others, e.g., Nijssen et al., 1997 and Haddeland and Lettenmaier, 1995. The special properties include lower thermal conductivity, higher heat capacity, higher porosity and lower bulk density. Overstory roots are distributed such that 50% of the overstory vegetation transpiration as is extracted from the moss layer 50% from the underlying soil layer. Drainage from the moss layer into the underlying soil layer is modeled assuming a constant moisture gradient at the moss-soil interface. The moss surface radiation budget is solved through iteration, as described below. This surface temperature is used for the computation of the ground heat flux.

• *Representation of the interaction between canopy cover and under story*. Modeling the complex energy balance of a surface layer that consists of both canopy over- and under-story is very computationally intensive. Most large scale water and energy balance models have a single vegetation which represents both the over- and under-story, and the energy balance is computed for this total layer. For the boreal landscape, it is insufficient. Field work suggests that the ground remains cold under the forest canopy and this coldness reduced transpiration. In addition, the ground under the forest tends to remain frozen later into the spring than does open ground, and this contributes to the spatial variability in water and energy fluxes across the landscape.

A computationally efficient two layer energy balance algorithm was recently developed and implemented into the model. The algorithm solves for each layer independently, using an estimate of the appropriate surface temperature to compute the incoming long wave radiation contributed by the other surface. Incoming solar radiation is attenuated using a Beer's Law relationship based on LAI, and considers multiple reflections of solar radiation between canopy over-story and under-story layers. The two surfaces are solved for alternately and iterated until convergence which occurs with only a few iterations. As an alternative computational option, the incoming long wave radiation for both layers can assumed equal to the incoming atmospheric long wave radiation, and the under-story receiving solar radiation attenuated by the over-story vegetation. Results based on this algorithm were almost identical to results from the more detailed algorithm (correlation >0.90). We expect to use this simpler algorithm in the BOREAS regional area simulations because of the significant reduction in computational effort.

One other improvement is the representation of differences between in-canopy air and dew point temperature and above-canopy air and dew point temperature. The difference between the skin temperature of either layer and the air temperature immediately above it is the driving force for the sensible and latent heat flux from the layer. Using an incorrect air temperature in the solution of the energy balance will result in an error in the latent and sensible heat fluxes. Figure 1 shows these differences for the Young Jack Pine site in the NSA for the period April-August 1994. As one can see, for both air and dew point temperature, during the night and early morning the in-canopy temperature is significantly higher (about $2°$) than the above-canopy temperature. However, during the afternoon, the in-canopy temperature can be up to $5°$ colder than the above-canopy temperature. This can be explained by the extinction of solar radiation in the canopy, which causes the in-canopy temperature in the afternoon to be lower than the temperature above the canopy, and the storage of heat and humidity in the canopy air layer at night. Similar results were obtained for the other flux towers. The diurnal cycle in both air and dew point temperature differences has been represented in the model.

• *Improved ground heat flux parameterization*: Accurate ground heat flux and surface temperature calculations are critical for accurate estimates of the other fluxes in the water and energy balance. Peters-Lidard et al. (1997b) has provided an improved soil heat conductance parameterization that reduces bias and error in the energy balance terms. This parameterization is now used in the model.

• *Sub-grid precipitation*: Including sub-grid precipitation representation within land surface models having model resolutions greater than about $0.5°$ has been shown to be important (Shuttleworth, 1996). An efficient parameterization has been tested and included in our VIC-3L SVAT (Liang et al., 1996a.) We expect to use the rain radar data and gage data collected over the SSA to further our understanding of fractional rain coverage over BOREAS.

• *Modeling of water bodies.* A large portion of the surface in boreal regions is covered by open water bodies. A one-dimensional energy balance lake evaporation module (Hostetler and Bartlein, 1990) has been included in the model. This module solves the surface energy balance of the lake
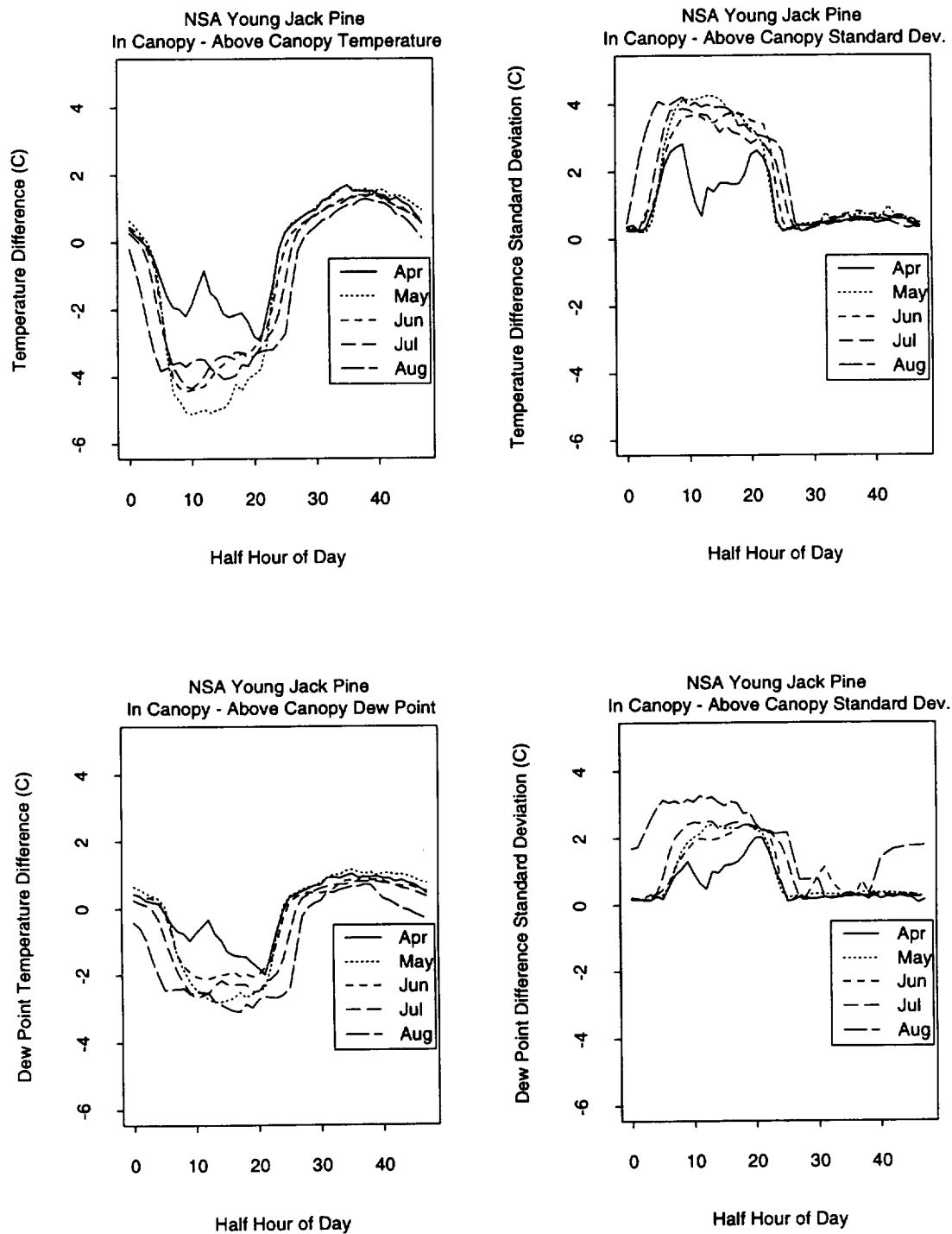

Figure 1. Diurnal cycle of the difference between in canopy and above canopy air and dew point temperatures for the Young Jack Pine tower in the NSA. Times are in GMT. The top part of the figure represents the air temperature differences, the bottom part the dew point temperature differences. The differences are in the left part of the figure, the standard deviations in the right part.

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through iteration for the surface temperature of the lake. The lake model also has a full depth convective mixing scheme, which allows for solution of temperature instabilities in the lake in winter and fall, and an ice formation and accumulation algorithm. We plan to verify the lake model by comparing predicted surface temperatures with those estimated through remote sensing.

• *Extension of the model for simulations in winter time conditions.* Prediction of heat and moisture transfers into the atmosphere during periods with snow cover is best done using an energy-based snow accumulation and ablation model, which uses incoming radiation and surface meteorology as inputs. The two layer energy balance snow accumulation and ablation model of Storck et al. (1995) has been incorporated in the model. This model solves the surface energy balance through iteration for the temperature of the top snow layer. Processes that are included in the model include: (i) interception of snowfall on the canopy, (ii) advection of heat from rainfall-on-snow, (iii) melting and refreezing of snow water in both layers, and (iv) drainage of melt water to the underlying soil layers.

The snow model is linked to a frozen soil model based on the work of Harlan (1973), Guymon and Luthin (1974) and Jame and Norum (1980). Infiltration into and water movement though partially frozen soils is assumed to be governed by Darcy's law, with the relationships controlling the liquid water movement being analogous to those controlling water flow in unsaturated soils. Ice crystals are assumed to form in the center of the pores and are regarded as air bubbles. Heat exchanges due to the melting or freezing of soil water is accounted for in the calculation of the ground heat flux, which is coupled to the improved ground heat flux model of Peters-Lidard et al. (1997b).

3. Inter comparison of BOREAS data sets.
The accuracy of model-derived water and energy fluxes is dependent upon the accuracy of model inputs, including the specification of model parameters and forcing data. Understanding the accuracy of the data is critical—especially spatially distributed remote sensing-based inputs needed to model BOREAS at regional scales. GOES-derived net radiation was compared to the net radiation from the NOAA Long EZ aircraft along the 'Candle Lake' transect run in the SSA. The results from the Long EZ were averaged up to the 8 km GOES data set and were adjusted for aircraft flight time. The GOES incoming solar radiation was also compared to the incoming solar radiation measured at the various flux towers in both the NSA and the SSA. The comparisons, shown in Figure 2 and 3, show that the GOES-derived data has significantly less spatial variability than that measured by the aircraft, although the GOES estimated solar radiation and the solar radiation measured at the flux towers seem to be in good agreement. Further understanding of these differences in variability is critical since model-derived fluxes, based on GOES radiation forcing, would tend to under-estimate water and energy flux variability. We expect to utilize the work of Gu et al.(1997) and Gu and Smith (1997) as well as our own analysis in these analyses.

Inter comparisons between radar-derived and AES gage measured precipitation were also carried out and are shown in Figure 4. The radar was located just south of the SSA at Paddockwood, Sask. and provided a 2 km. spatial and hourly accumulated precipitation. The low R^2 (0.61) for the rainfall is in part due to rainstorm fractional coverage as well as small scale convective cells that passed over the gages. The radar data will be used to estimate rainfall fractional coverage. Ignoring fractional rainfall results in biased flux estimates (Liang et al., 1997).
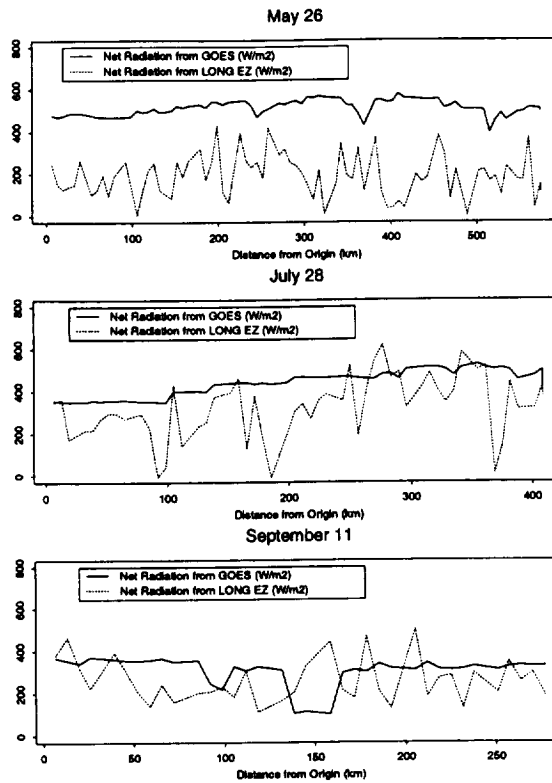
May 26

July 28

September 11

Figure 2: Comparison between GOES-derived and
NOAA Long EZ measured net radiation.
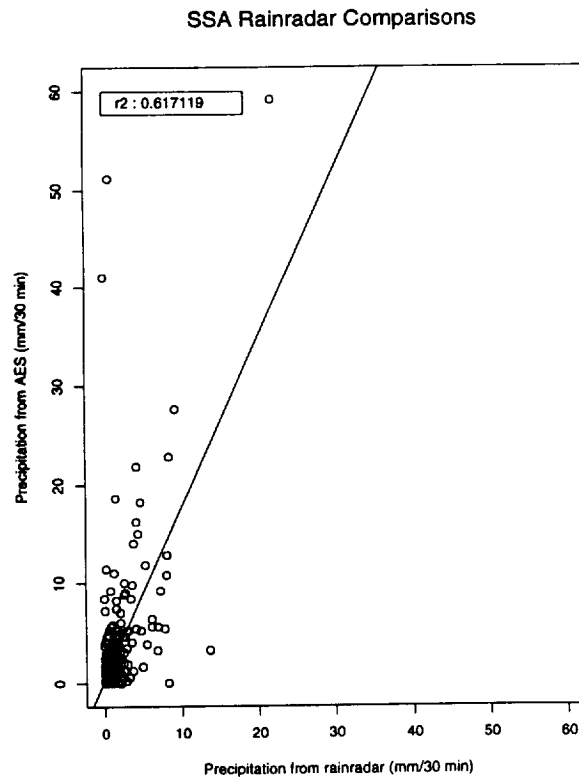
SSA Rainradar Comparisons

Figure 4: Comparison between radar-estimated and gage
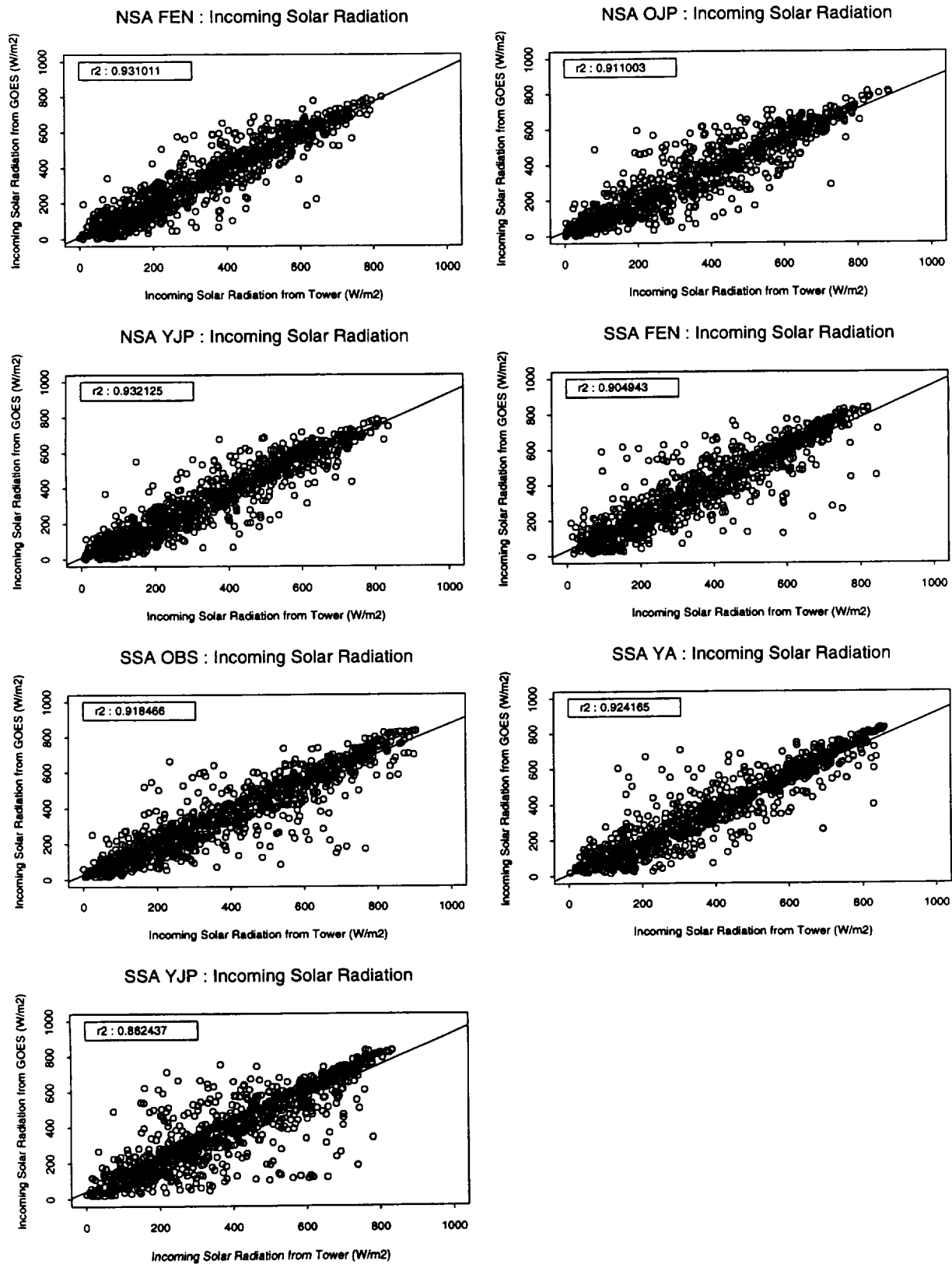estimated precipitation for 13 May-23 Sept. 1994.

Figure 3: Comparison between GOES estimated and flux tower measured incoming solar radiation.

4. Modeling results.

4.1. Modeling during summer time conditions.
The water and energy balance model, enhanced with the model improvements described above, was run over the various flux tower sites in the BOREAS study region. Figures 5, 6, 7 and 8 show the comparisons between modeled and observed latent, sensible and ground heat fluxes and net radiation. The high correlation coefficients (average r^2 for latent heat flux is 0.83, for sensible heat flux 0.90, for ground heat flux 0.87 and for net radiation 0.94) suggest that the model can successfully represent, at the tower scale, the important process that govern the exchanges of water and energy with the boreal land-atmosphere system. The correlation coefficients (~90 %) are consistent with measurement inter comparisons across sensors (Gu and smith, 1997). Figure 9 presents IFC averaged Bowen Ratio (BR) and evaporative fractions (EF; evaporation/precipitation) for different tower sites and IFCs, which again shows that the model is capable of modeling water and energy exchanges within the boreal forest. Note that some Efs are greater than 1.0 suggesting that over the IFC period the soil-vegetation system is utilizing soil water for evapotranspiration.

Figure 10 shows both the time series and the scatter plot of the comparisons between simulated and observed lake temperatures at the Beaver Pond site in the NSA. Good agreements are obtained.

4.2. Modeling during winter time conditions.
Again utilizing data provided by the tower investigators, together with data from the Saskatchewan Research Council (SRC) meteorological station located near the Old Jack Pine tower in the SSA, simulations were run over the entire winter season of 1994-1995, with the purpose of testing out the snow model. Figure 11 shows the observed and simulated snow height over this simulations period. Simulated snow water equivalent was converted into snow height by assuming an increase in snow density of 0.004 g/cm3/day (Anderson, 1976) and a second-power relationship between density of freshly fallen snow and air temperature based on data in Gray (1970). A correlation coefficient of 0.93 was obtained, which proves that the model can accurately represent the snow accumulation and melt processes.

5.0. Conclusions
An energy driven processes based water and energy balance model has been developed for application in BOREAS. An algorithm representing the influence of a moss layer on the hydrology in boreal forests has been incorporated in the model. The radiation exchange between canopy and under story is represented in the model. A module to simulate the energy and water balance of open water bodies has been added to the model. The model has been enhanced with an algorithm that simulated the effect of frozen soil on the transport of water and energy in the soil column. An energy driven snow melt and accumulation module has been added to the model.

Using these enhancements, simulations have been done for the tower flux sites in the BOREAS study region, and good agreements between observed fluxes, temperatures and snow heights have been obtained.

Comparisons have also been done between various BOREAS data sets. For the comparisons between gage observed and rain radar estimated precipitation poor correlations (61%) were obtained, suggesting the importance of small convective cells passing over the gages. Good comparisons between GOES estimated and flux tower observed solar radiation have been obtained.

However, poor agreements have been obtained between net radiation observed by the NOAA Long EZ aircraft and GOES estimated net radiation. It is suggested that the aircraft can observe significantly more spatial variability than the GOES satellite. A serious effort in the future to further understand these differences in variability will me made.
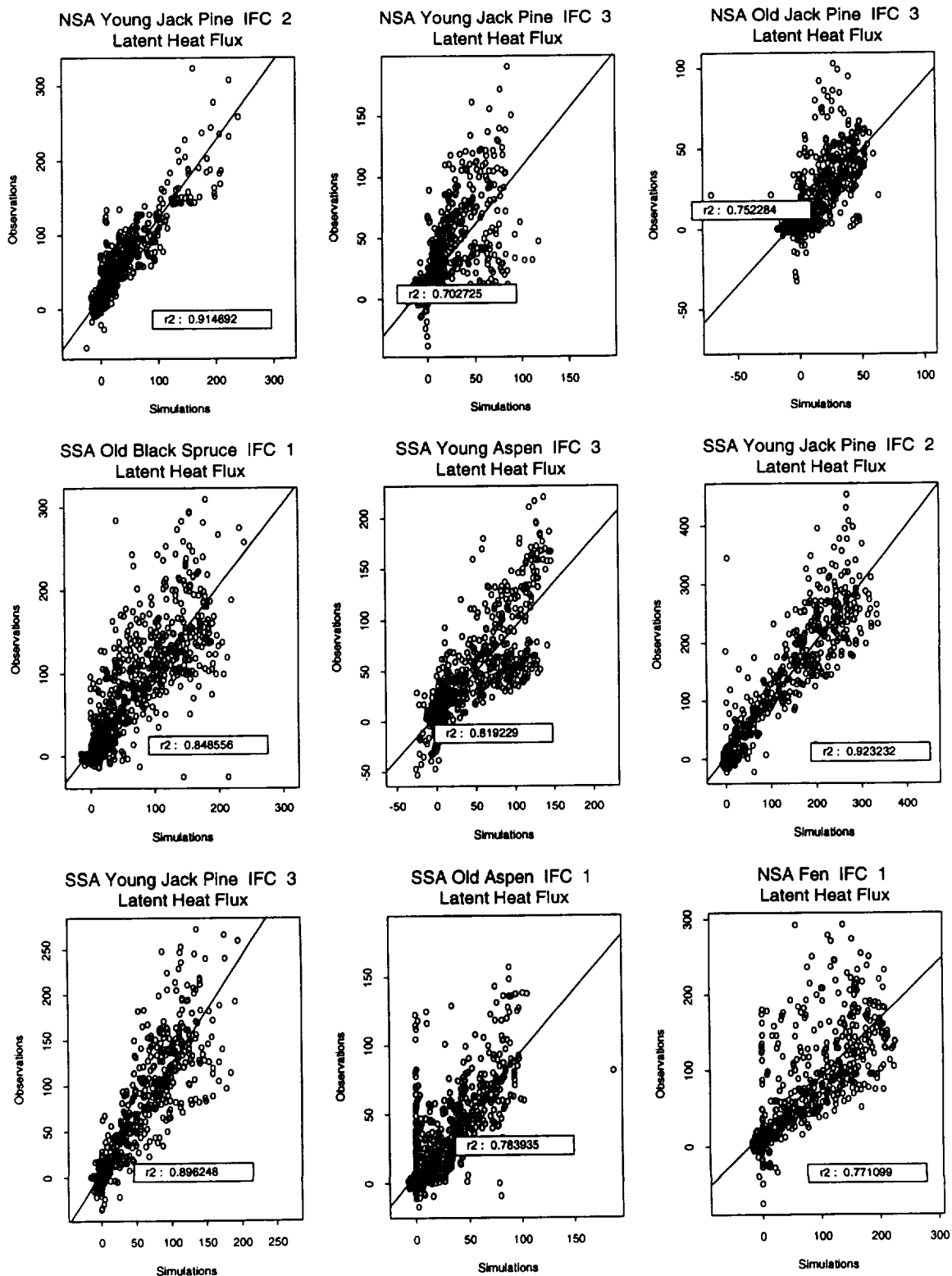

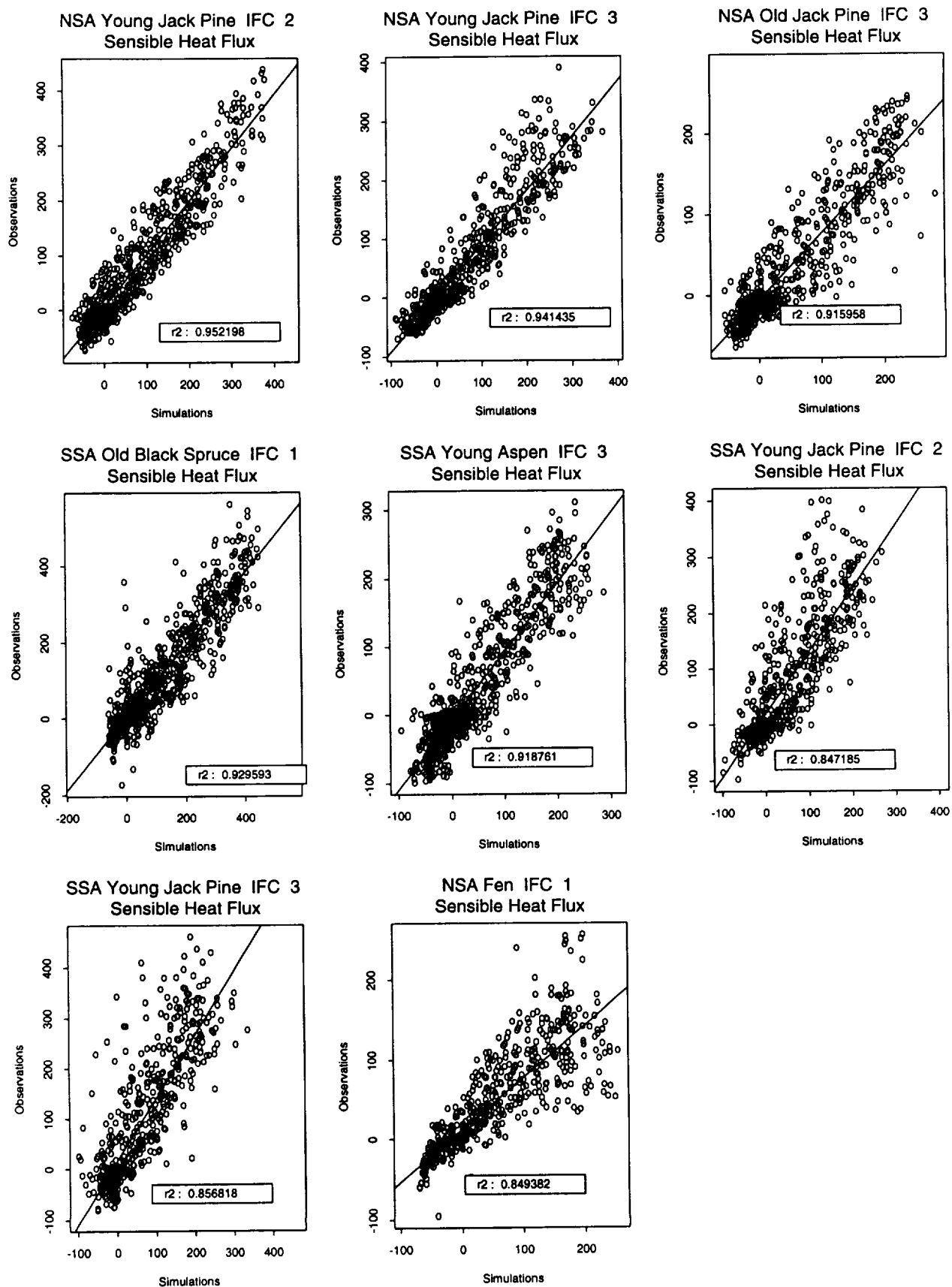Figure 5: Comparison between observed and simulated latent heat fluxes for the various towers and IFCs in 1994.

Figure 6. Comparison between observed and simulated sensible heat fluxes for the various towers and IFCs in 1994.
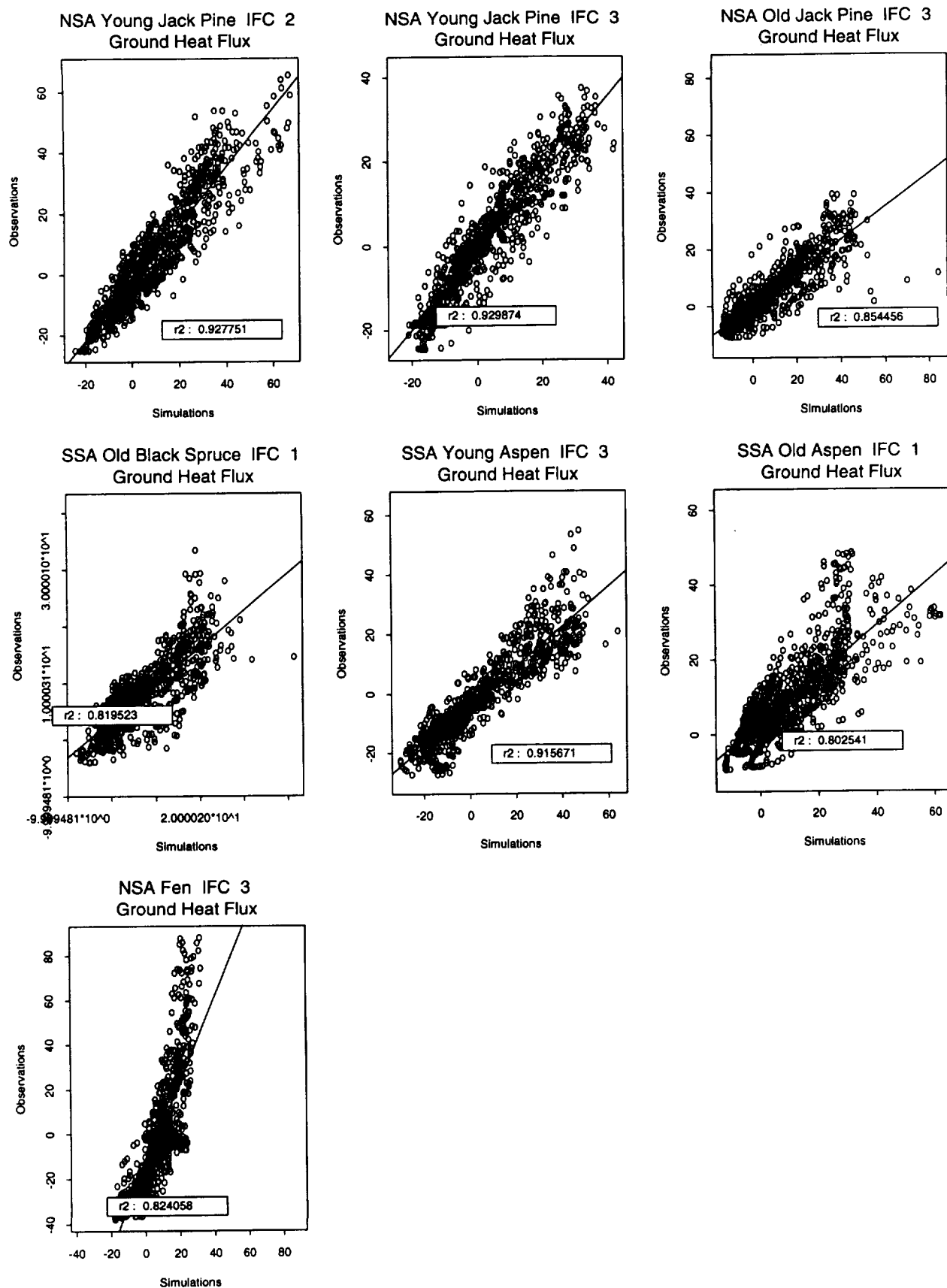
Figure 7: Comparison between observed and simulated ground heat fluxes for the various towers and IFCs in 1994.
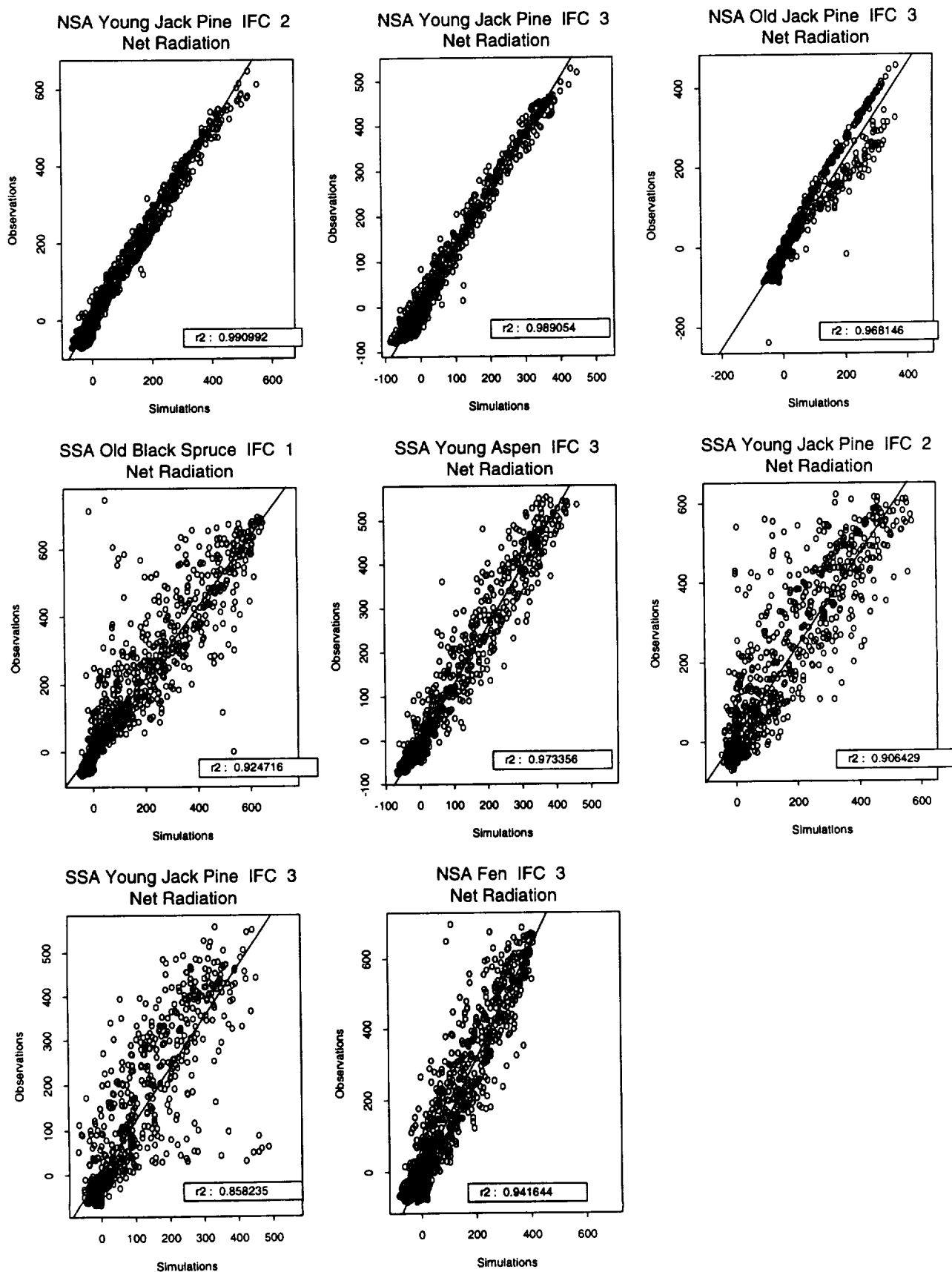
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Figure 8: Comparison between observed and simulated net radiation for the various towers and IFCs in 1994.
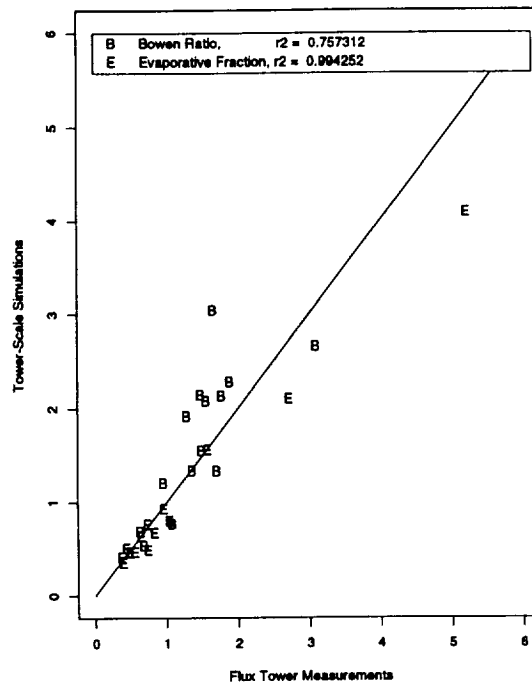
Figure 9: IFC-averaged model-estimated and measured
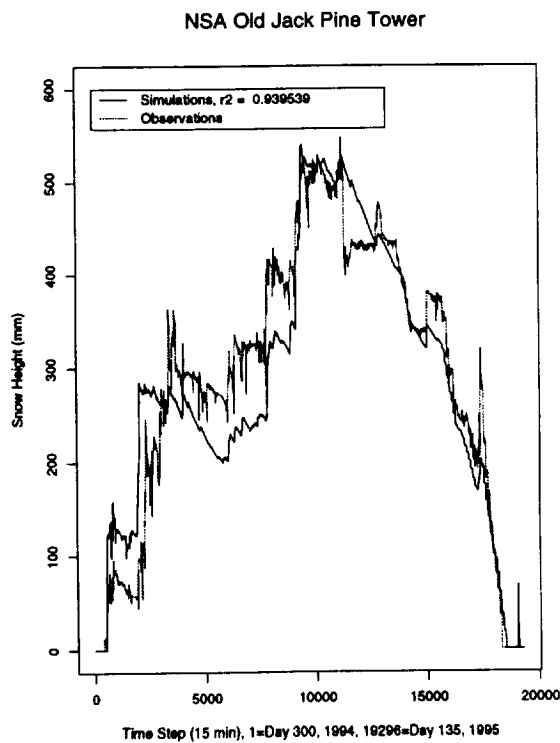Bowen ratios and evaporative fractions for tower-sites.

NSA Old Jack Pine Tower

Time Step (15 min), 1=Day 300, 1994, 19296=Day 135, 1995

Figure 11: Comparison between observed and simulated
snow height for the NSA Old Jack Pine tower during the
1994-1995 winter season.

NSA Beaver Pond
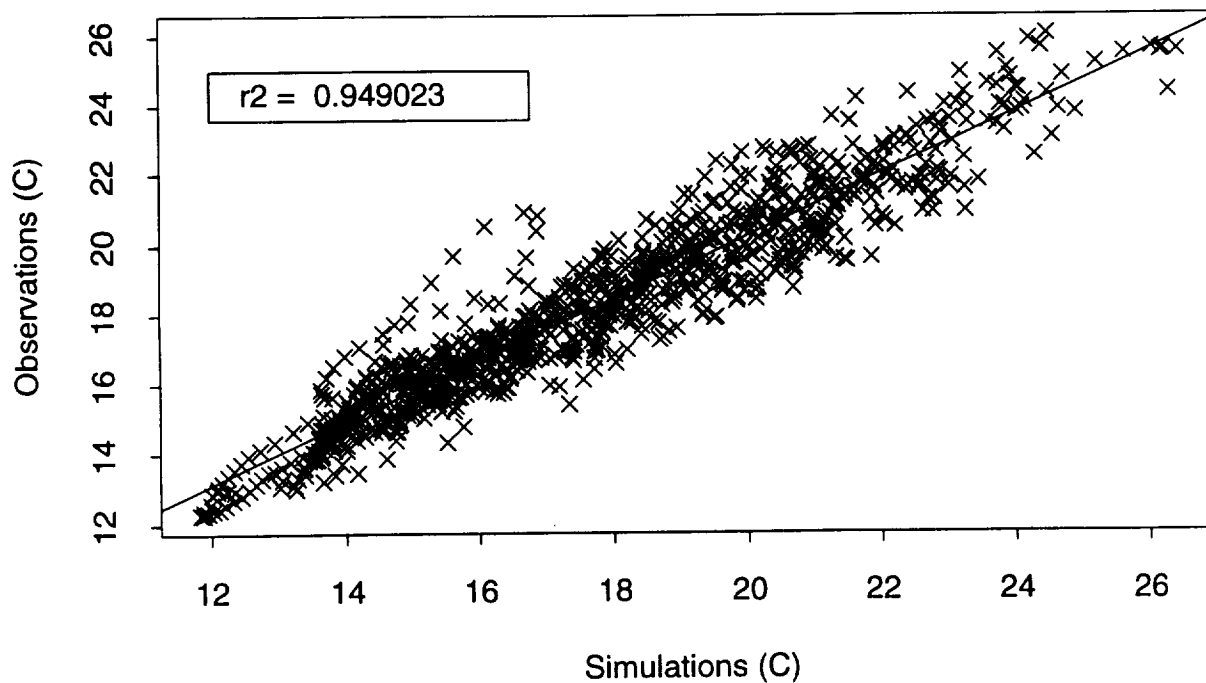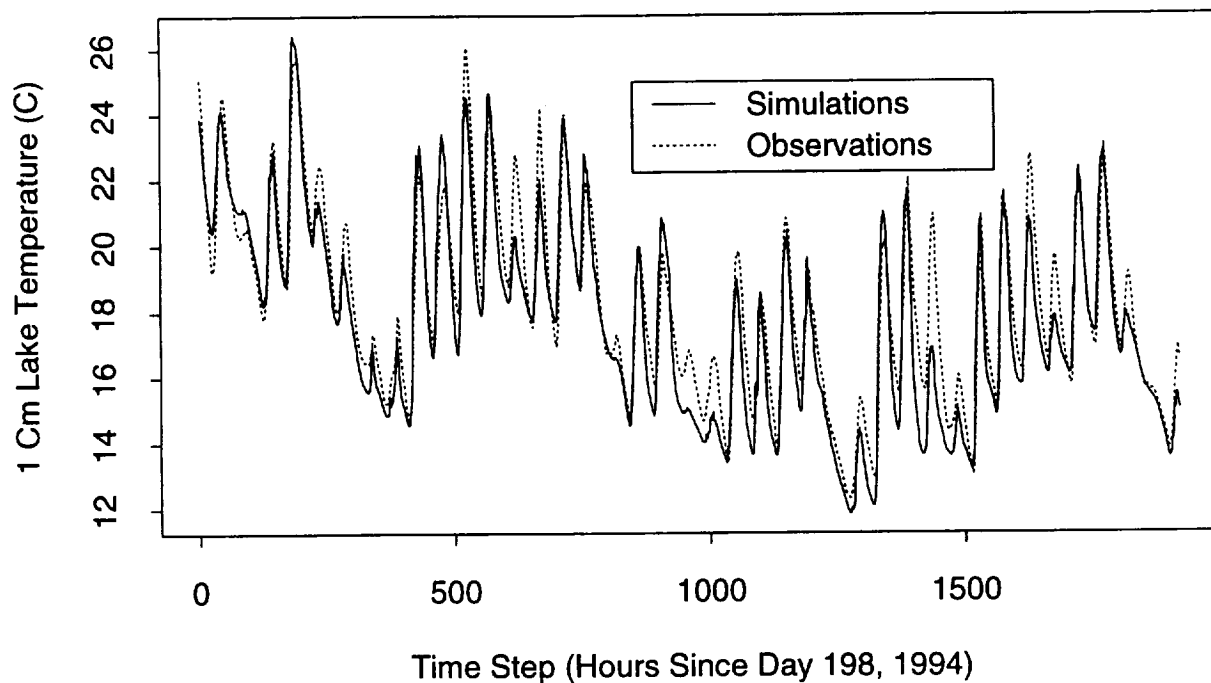## Simulations from Day 198 through 238,1994.

Figure 10: Comparison between observed and simulated lake temperatures at the NSA Beaver Pond Site. Top: time series of the simulations. Bottom: scatter plot of the results.

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