NWS-HL Cold Season Processes Research and Development

Victor Koren, Eric Anderson, Michael Smith

Hydrology Laboratory
Office of Hydrologic Development

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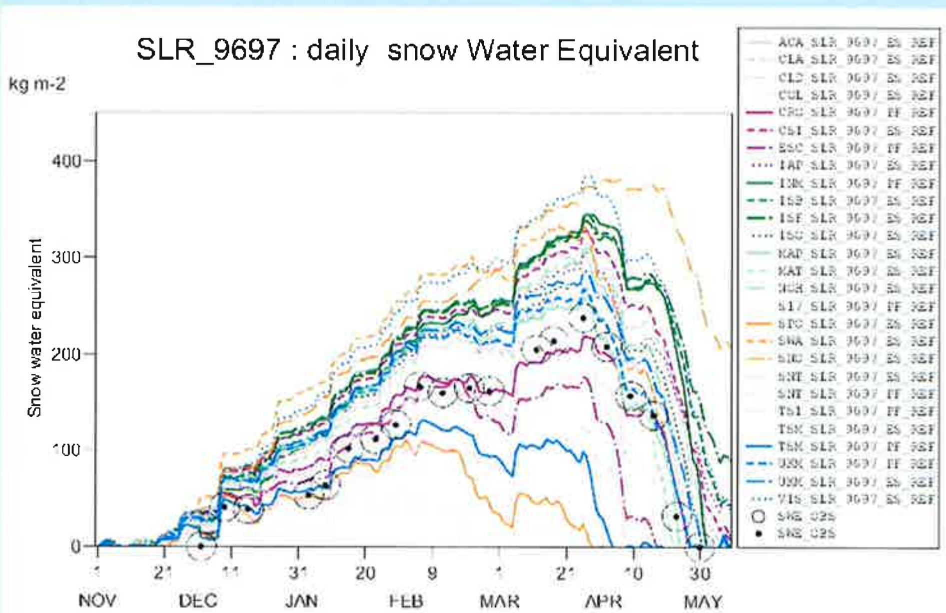
SnowMIP results for Sleeper River (USA) site: 23 energy based models and SNOW-17 (Uncalibrated model results).



Executive Summary

The National Weather Service Hydrology Laboratory (NWS HL) has a rich history of modeling cold season processes. The NWS operational snow model (SNOW-17) is widely recognized as a sound temperature-index model that well represents the physical processes for which it is calibrated. It is used around the world in a number of research and operational settings. A more modest amount of research has been directed to researching the modifications of the rainfall-runoff transformation due to the effects of frozen ground.

The infusion of funding from the Advanced Hydrologic Prediction Service (AHPS) initiative has brought new vigor to HL research and development in cold season hydrologic processes. Several years ago, collaboration between the Office of Hydrologic Development and the Environmental Modeling Center (EMC) of the NWS National Centers for Environmental Prediction (NCEP) has led to the successful implementation of energy budget snow models and physically-based frozen ground components in the land surface component of the NCEP ETA numerical weather prediction model.

More recently, HL has garnered the experience gained from the collaborative work with NCEP to renew its efforts into advanced snow modeling methods for river forecasting. These efforts include participation in the international Snow Model Intercomparison Project (SnowMIP) with two models as well as making several modifications to its current operational temperature index model. A major thrust is planned to evaluate the utility and quality of new and emerging data sets to drive operational energy budget snow models for river forecasting. A pioneering effort to develop an advanced method of computing the effects of frozen ground on the rainfall-runoff process is nearing completion. Research to-date shows that this effort can successfully simulate soil temperature versus depth. Moreover, initial indications are that this approach produces runoff simulations that are equivalent or superior to those generated using the existing conceptual approach which requires seven parameters to calibrate. The beauty of the new approach is that it is truly physically-based and does not require parameter calibration.

Contents

1. Introduction

Figure 1 shows that all of the 13 River Forecast Centers (RFCs) of the NWS have a need to model snow accumulation and melt. Even the RFCs in the southern tier of the US have areas that experience snow accumulation, although obviously snow accumulation and melt are dominant in the intermountain west. Frozen ground effects can also be seen everywhere, although the upper mid-west experiences the most severe cases. In this region, a lack of vegetation during the winder, shallow snow cover, and very cold temperatures produce optimal conditions for the penetration of frost and subsequent modifications to the rainfall-runoff process.

2. Purpose and Scope

The purpose of this document is to provide an overview of the research and development of snow and frozen ground modeling. While past efforts will be discussed, the emphasis of this document is on current and future activities and strategies. This document is not meant to cover topics such as the effects of ice on river flows.

3. Relevant web sites

The reader is directed to the following web sites for HL R&D in snow and frozen ground modeling:

Frozen ground: http://www.nws.noaa.gov/oh/hrl/frzgrd/index.html

Snow Modeling: http://www.nws.noaa.gov/oh/hrl/snow/index.html

4. Modeling of Snow Accumulation and Melt

4.1 Research and Development Strategy

NWS modeling of snow accumulation and melt for river forecasting began in the late 1960's with the development of energy budget algorithms (Anderson, 1968; 1973; 1976). A temperature-index version of this method (hereafter called Snow-17) was implemented in the National Weather Service River Forecast System (NWSRFS) in 1973 and is still in use today at the majority of NWS River Forecast Centers (RFCs). The major reason this temperature index form of the energy budget model was implemented is that the data required to force an energy budget model have not been reliably available and of sufficient quality.

In January, 1996, a major flood occurred in the Northeastern United States. This event was largely due to the rapid melt of above-average snow accumulations combined with intense rainfall (Office of Hydrology, 1998; Anderson and Larson, 1997). During the peak of the snowmelt, extreme conditions prevailed: air temperatures ranged from 13-17^{o} C, relative humidity was above 90 percent, and the peak sustained winds were generally over 10 m/s at open sites. Such conditions were well beyond those for which Snow-17 was calibrated in these regions.

This event and the recommendation from the subsequent disaster survey report (Office of Hydrology, 1998) underscored the need to re-examine the utility of energy budget snow models for river forecasting. HL thus began a dedicated snow research thrust consisting of two phases as shown in Figure 2. Phase 1 is characterized by analysis of the performance of the existing Snow-17 in the Snow Model Intercomparion Project (SnowMIP) as well as exploring several modifications to the algorithm itself. We envision that these modifications will improve the operational performance of Snow-17 in cases involving abnormal conditions for which the model is not calibrated. Phase 2 of the research will focus on the evaluation of new and emerging data sets that could potentially drive an operational energy budget snow model for river forecasting.

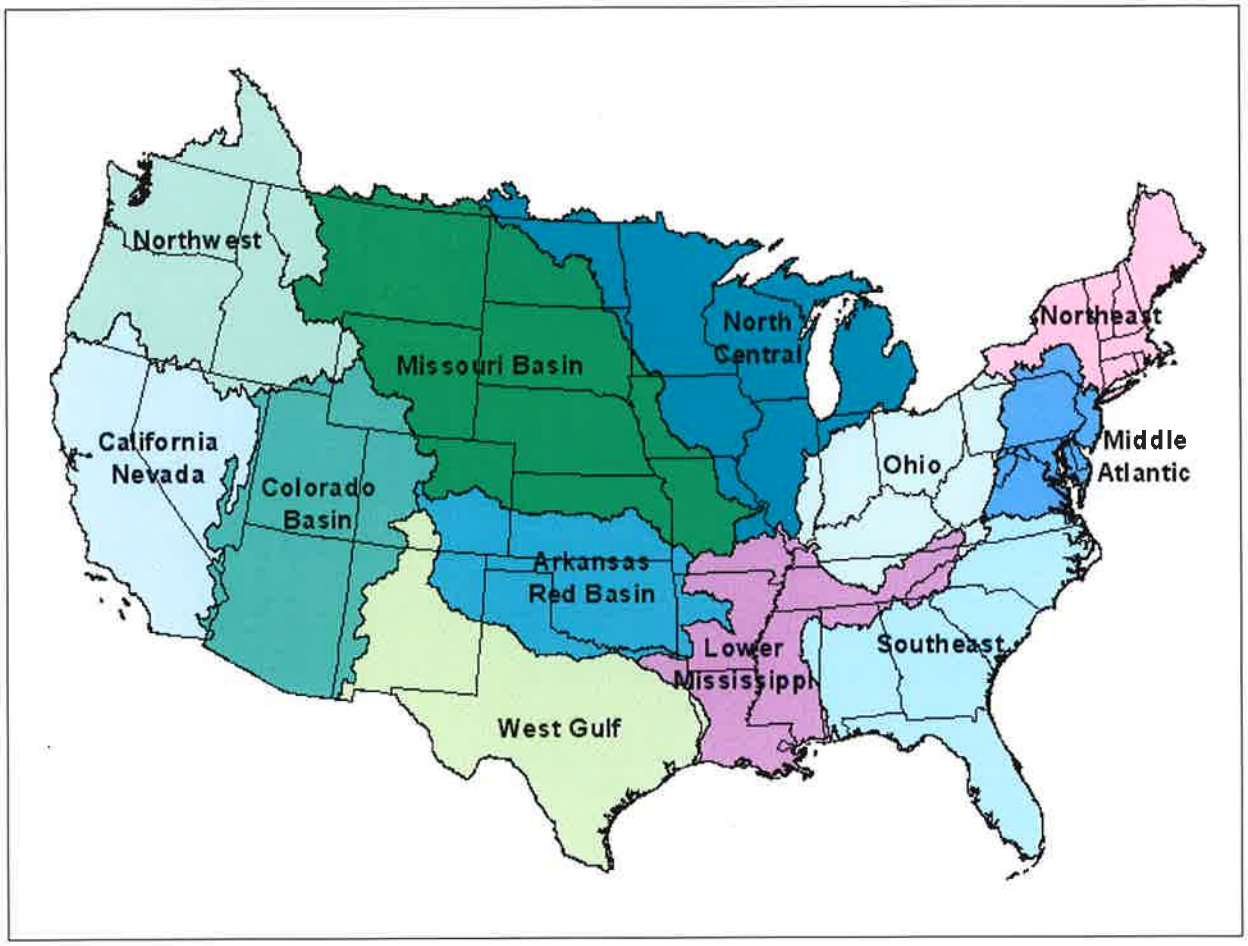


Figure 1. Boundaries of NWS River Forecast Center domains. (Note: Alaska-Pacific RFC domain not shown.

Herein lies one of the major assertions of our snow research strategy: **the physics of snow accumulation and melt are well understood and that robust and reliable energy**

budget models of these processes already exist. Indeed, HL's collaboration with NCEP resulted in the successful inclusion of such a formulation in the land surface component of the Eta model (Ek et al., 2004; Slater et al, 2001; Koren et al., 1999; Schloser et al., 2000) and the participation of HL in the recent SnowMIP project (Koren and Anderson, 2001). Therefore, we believe that Phase 2 should concentrate on the analysis of new and emerging data sources to drive advanced snow models and not the development of new algorithms to model snow accumulation and ablation. Another key component of Phase 2 research is the inclusion of Snow-17 in a distributed model for river forecasting.

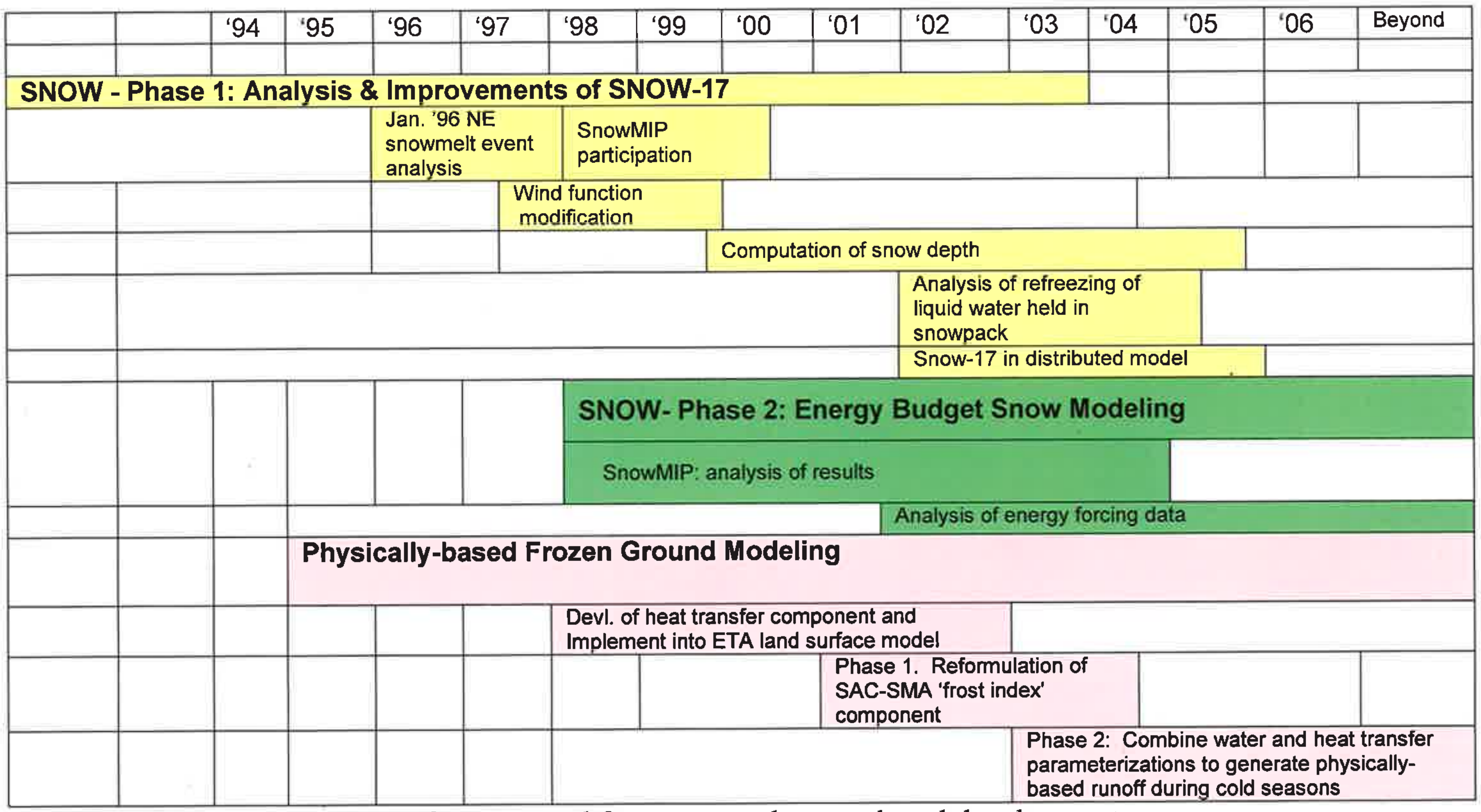


Figure 2. Major plan elements for snow and frozen ground research and development.

In a parallel thrust, HL is actively developing a physically-based approach to model the effects of frozen ground on the rainfall-runoff transformation. Again, this effort is based on the successful collaboration with NCEP in the development of their land surface component (e.g., Ek et al., 2004; Koren et al., 1999).

4.1.1 Phase 1 Snow Modeling: Internal HL R&D

As shown in Figure 2, this phase contains several efforts to modify the existing Snow-17 model. These include procedures to aid in real time manual updating during abnormal events as well as generating new output fields to aid in calibration and forecasting. Finally, we are engaged in efforts to understand a potential bug in the refreezing of liquid water.

Wind Function Modification

This effort resulted from Recommendation 1.2 of the disaster survey report for the large flood event that occurred in the Northeastern United States in January, 1996 (OHD, 1998). This specific recommendation called for a run-time modification to be added to the NWSRFS operational code so that the forecaster can adjust the wind function (Snow-17 UADJ parameter) during rain-on-snow events. As seem in Figure 3, variations in the UADJ parameter can have a large effect on the snow pack.

Computation of Snow Depth

In addition to computing snow water equivalent, Snow-17 has been modified to produce a time series of computed snow depth. This time series is very helpful in the calibration phase since observed snow depth data are available in some places. This modification was delivered to the field at the beginning of FY04

Refreezing of liquid water in the snow pack.

In the course of examining Snow-17 in a variety of modes, a potential anomaly in the algorithm has been identified. Apparently, the existing Snow-17 does not refreeze liquid water held in the snow pack. In some cases, this may have considerable effect on the snowpack melt rates. Figure 4 shows the effects of this anomaly and a preliminary attempt to correct it.

Adoption of Snow-17 in a Distributed Model

A cross-cutting effort between snow and distributed modeling will be the inclusion of Snow_17 into the distributed model within the NWS Hydrology Lab Research Modeling System.

4.1.2 Phase 1 Snow Modeling: Collaborative Research

4.2.1.a. Snow Model Intercomparison Project.

Complementing HL's internal research, a significant emphasis was placed on collaborating with other research partners. This was primarily achieved by participating in SnowMIP (http://www.cnrm.meteo.fr/snowmip/). This successful project was organized by the International Commission on Snow and Ice (ICSI), a commission of the International Association of Hydrologic Sciences (IAHS). SnowMIP activities were coordinated through

Météo-France: National Center for Meteorological Research. Participants submitted uncalibrated simulations from 26 models. The overall goal of SnowMIP was to meet the need to have a more general comparison of snow models. The following objectives were identified (Etchevers et al., 2002):

- To define a common method to compare a large variety of models,
- To estimate the impact of the different physical parameterizations
- To identify the key processes for each application.

HL viewed SnowMIP as an accelerated venue through which advances to the NWS snow modeling capability could be identified. HL participated in SnowMIP with two models: the Snow-17 temperature-index model and the energy budget snow model incorporated into the land surface component of the NCEP numerical weather prediction model (Koren and Anderson, 2001). This energy budget snow model was developed by Victor Koren of HL (Koren et al., 1999). Hereafter, this latter model will be referred to as the NCEP land surface model (LSM). In this way, HL could measure the strengths of both algorithms against observed data and 24 other models of various complexity.

Findings from HL's participation in SnowMIP.

HL gained valuable experience from the comparisons resulting from SnowMIP:

- Model complexity does not guarantee accuracy. This is clearly seen in Figure 5, which shows the wide disparity amongst energy budget models in computing snow-water equivalent.
- Temperature index models provide practical and reasonable results, however they are sensitive to weather conditions, specifically wind and solar radiation conditions.
- Energy based models are sensitive to input data errors, specifically wind, solar radiation and albedo treatment.
- Most critical problem is understanding of data uncertainties to define the most reliable data sources

4.1.2.b North American Land Data Assimilation System

Additional analysis of Snow-17 and the NOAH LSM snow model was gained through HL's participation in the North American Land Data Assimilation System (NLDAS) project (Mitchell et al., 2004). NLDAS was designed to evaluate four land surface models as candidates for a 4-dimensional data assimilation system for numerical weather and seasonal climate prediction models. In the 3-year CONUS executions of the models, the NWS Snow-17 model performed rather well as stated by Mitchel el al. (2004):

> 'The VIC and (Snow-17) models provided the best simulations of snowpack water content compared to SNOTEL observations……The (Snow-17) snowpack simulations performed rather well, as its simple temperature-index based snow pack model bypasses

energy balance and albedo and thereby bypasses positive feedback loops that haunt snowpack simulations in models with surface energy balance.'

This conclusion further underscores the sensitivity of energy budget snow models to input forcing and the subsequent need to examine the quality and robustness of input data as called for in Phase 2 snow R&D.

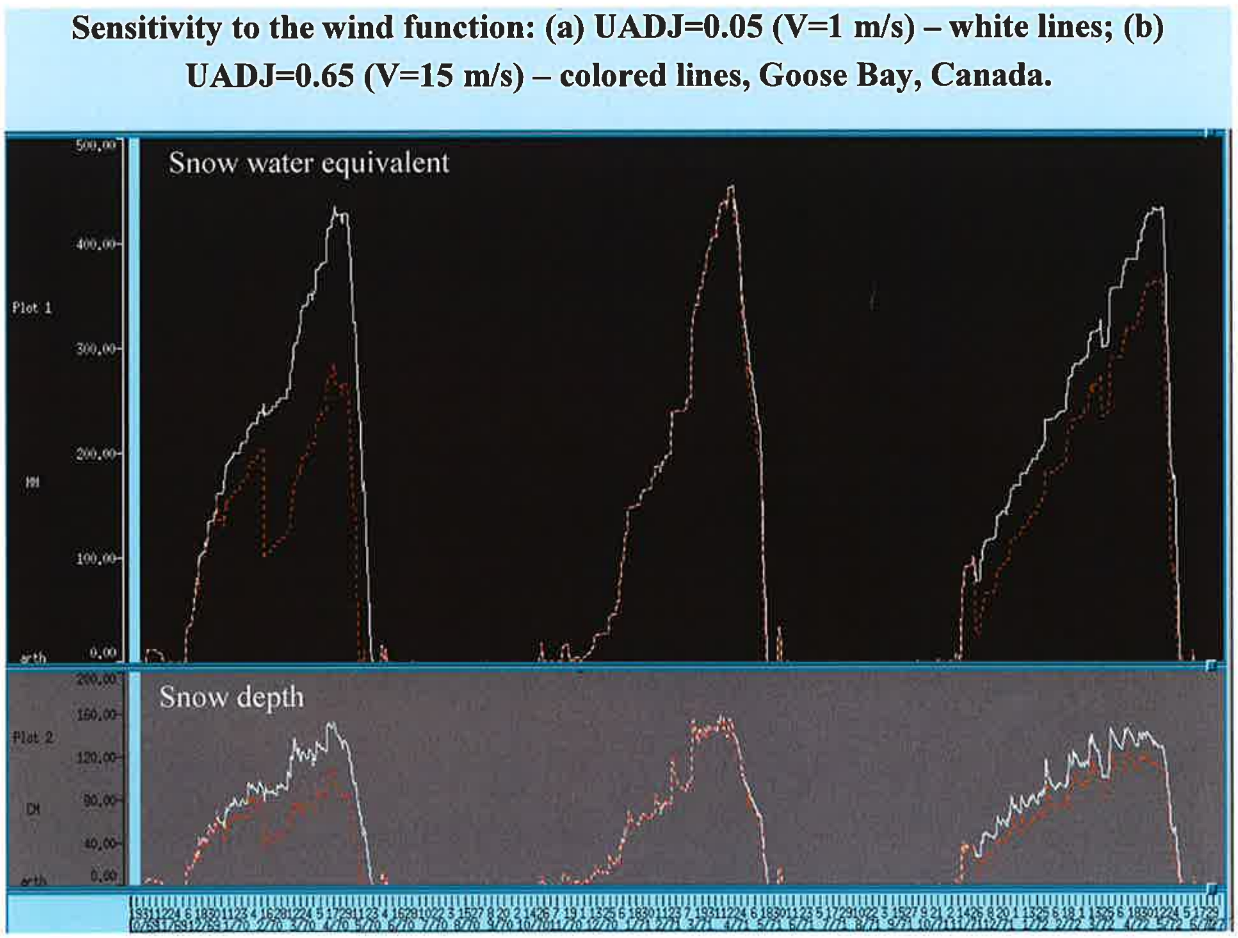


Figure 3. Snow water equivalent and snow depth for two values of the Snow-17 wind function parameter UADJ.

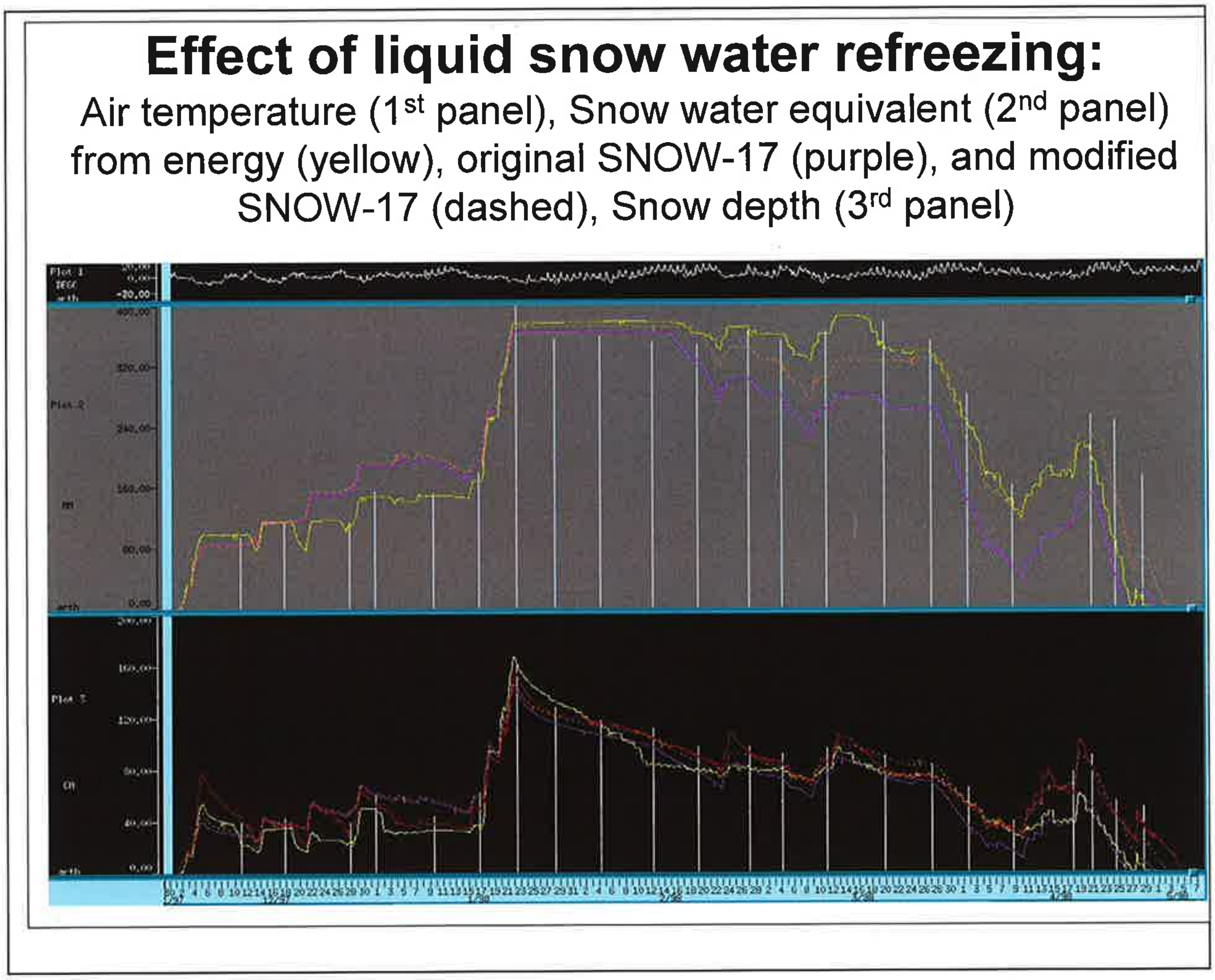


Figure 4. Effect of potential anomaly in Snow-17 liquid water refreezing algorithm. A potential 'fix' to the anomaly shows closer agreement to the observed values. Observed are white vertical lines in top pane.

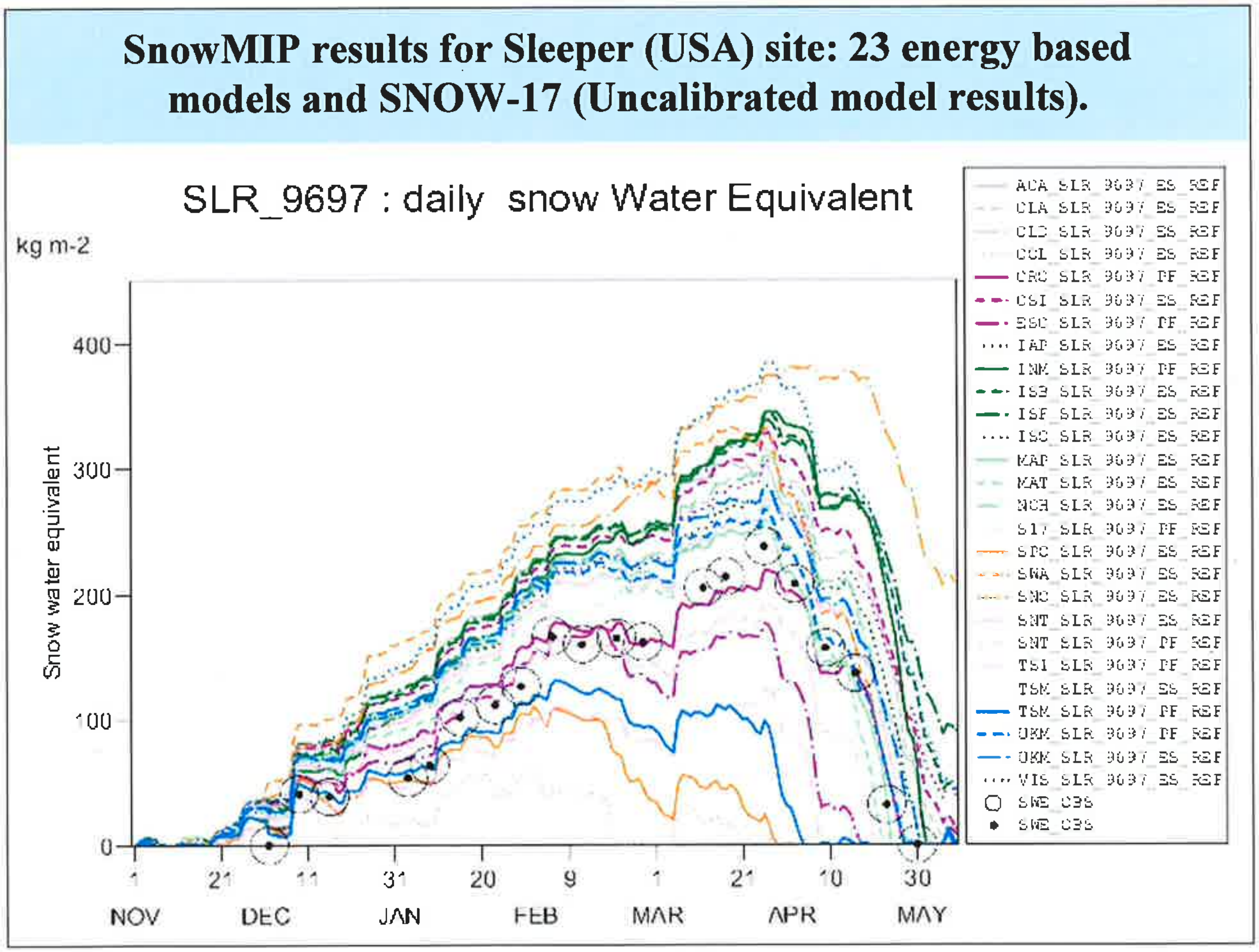


Figure 5. Simulation of snow-water equivalent by 23 energy-budget snow models in SnowMIP.

4.1.3 Phase 2: Evaluation of Data to Support Operational Energy Budget Model

The experience gained from SnowMIP and the NLDAS projects confirmed that the major issue for advanced snow modeling for river forecasting is not a new algorithm for snow accumulation and ablation. Rather, we see as the major need the extensive analysis of new and emerging sources of temperature, wind, solar radiation, relative humidity, dew point, etc that are needed to force an energy budget model. At present, HL is actively trying to hire a specialist to plan and accomplish this task. Data sources to be examined include output fields from numerical weather prediction models, satellite-bases observations, and products from the National Operational Hydrologic Remote Sensing Center (NOHRSC).

5. Modeling of Frozen Ground Effects

5.1 Research and Development Strategy

NWS modeling of frozen ground effects on the rainfall-runoff process began in the late 1960's with the development of a conceptual modification to the Sacramento Soil Moisture Accounting Model (SAC-SMA) (Anderson and Neuman, 1984). This approach used the concept of a frost index which modified the runoff generated by the SAC-SMA. As a conceptual model, this approach requires the calibration of 5 parameters.

As stated earlier, a successful collaboration between the Office of Hydrologic Development and NCEP resulted in the development of a heat-transfer component of the NCEP land surface model. As reported by Koren et al. (1999) and Mitchell et al. (2002), this parameterization proved to be a valid component that reduced biases in certain computed values.

Capitalizing on this successful collaboration, HL began to develop an advanced approach to modifying the SAC-SMA for the effects of frozen ground. The goal of this research is to develop a physically-based heat transfer component for the SAC-SMA that requires minimal calibration. Two requirements are identified for this component:

- Simple enough to run with sparse and noisy data
- Matches the complexity of the SAC-SMA

As shown in Figure 2, this work consists of two phases. In Phase 1, a physically-based heat transfer component is developed, while in Phase 2, the SAC-SMA model is modified to include the heat-transfer component and the effects of frozen soil on the generation of runoff.

5.2 Modeling of Frozen Ground Phase 1: Heat Tranfser Component

Work in this phase was directed at modeling the heat transfer in a column of soil as shown in Figure 6. Two hurdles were overcome to develop a scheme suitable for the SAC-S MA First, the SAC-SMA model does not contain an explicit definition of soil layers, although it defines upper and lower tension and free water storages that could be transformed in to a number of soil layers. This hurdle was overcome by recalculating the SAC-SMA storages in to their representative soil layers using soil porosity data. As such, the total of the SAC-SMA tension and free water storages is disaggregated into 4 layers as shown in Figure 7. The transformation between the SAC-SMA soil layers and the heat transfer component occurs every time step.

The second hurdle to be overcome is that the heat transfer component in Figure 6 requires the depth of snow above the soil surface, and the current version of Snow-17 only computed snow water equivalent. Thus, Snow-17 was modified to compute this value. A secondary result of this modification was that the resultant time series of computed snow depth are valuable for calibration of Snow-17.

Test results showed that the heat transfer component successfully computes soil temperature at various depths. Figure 8 shows the computed and observed soil temperatures for a site in Iowa. Good agreement can be seen between the computed and observed soil temperatures, validating the heat transfer parameterization.

The SAC-SMA storages, represented as totals of tension and free water, plus a water content below wilting point, are recalculated into required number of soil layers using soil texture data. Three-four layers are usually used with much higher resolution in the upper zone. At each time step, SAC-SMA liquid water storage changes due to rainfall/snowmelt are estimated, and then are transformed into soil moisture states of the heat transfer model. The heat transfer model splits the total water content into frozen and liquid water portions based on simulated soil temperature profile. Estimated new soil moisture states are then converted back into SAC-SMA model storages. The time step of the frozen ground component may be a fraction of the SAC-SMA time step.

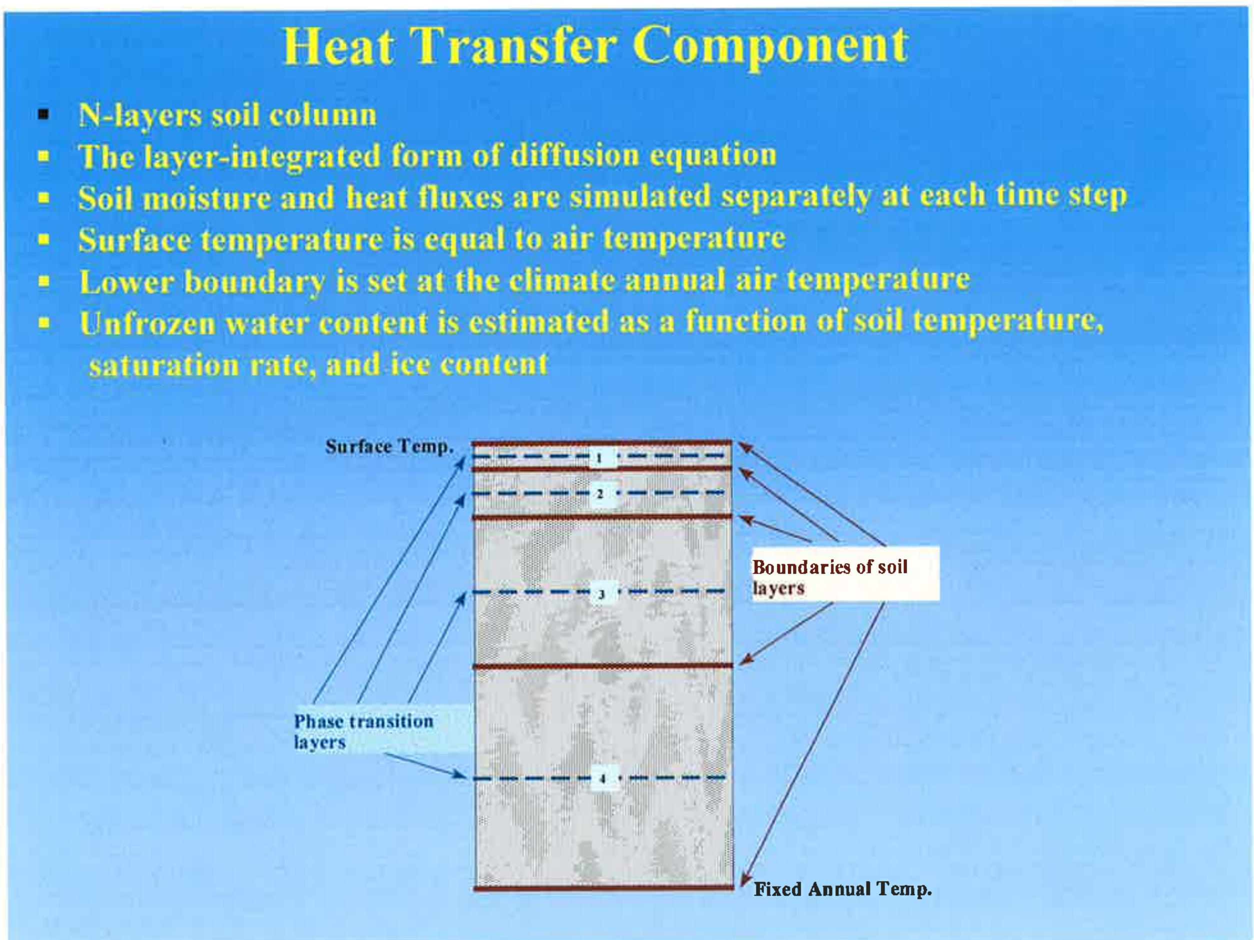


Figure 6. Schematic of the soil layers and heat transfer component.

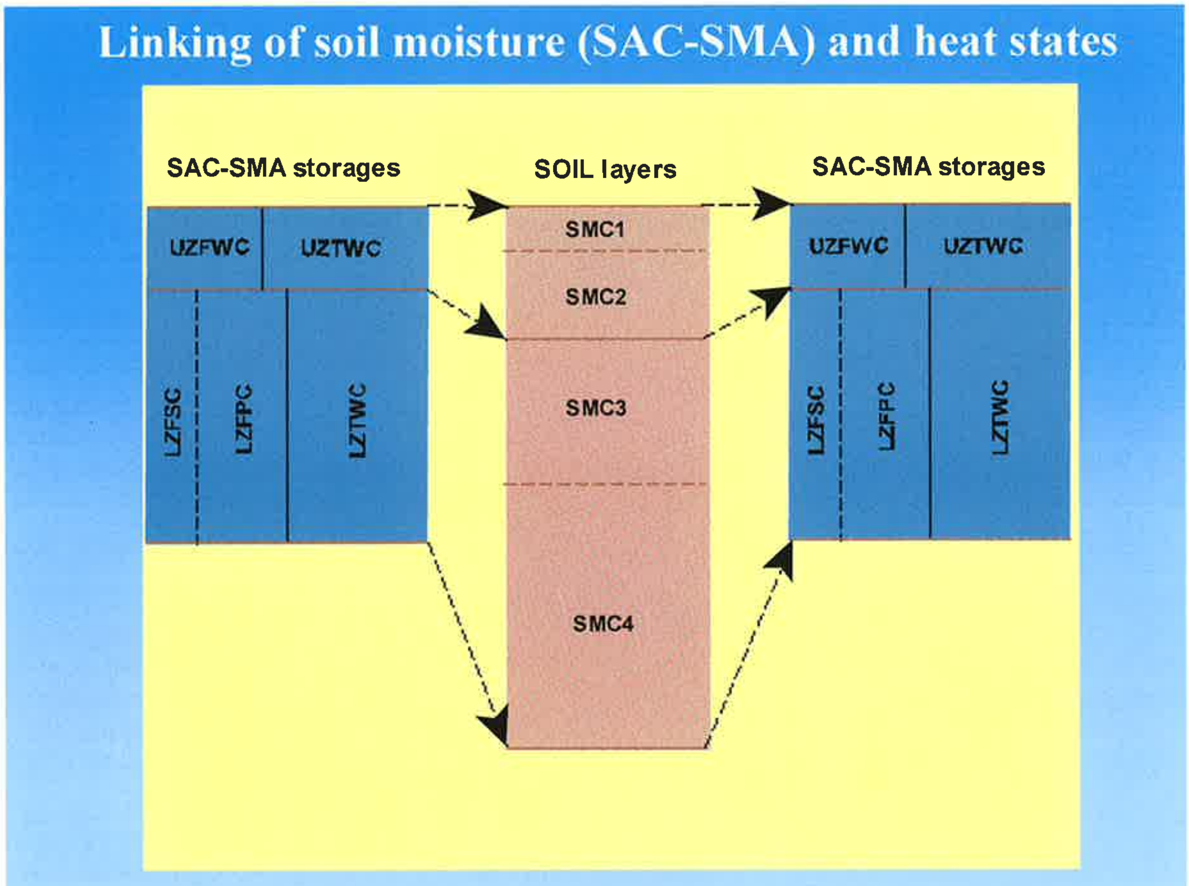


Figure 7. Schematic of the transfer of SAC-SMA storages to the four soil layers of the physically-based heat transfer component.

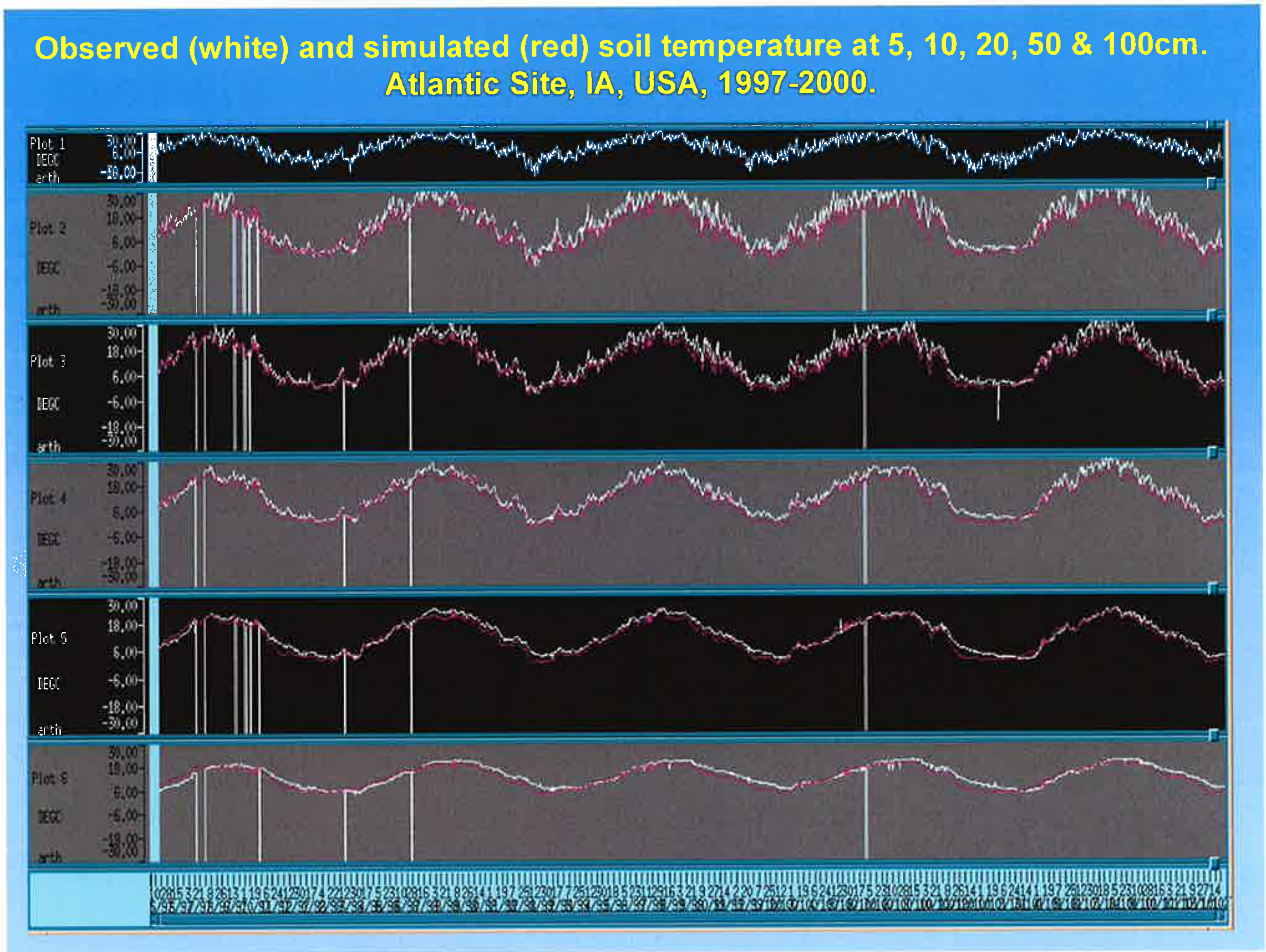


Figure 8. Comparison of computed and observed soil temperatures at various depths.

5.3 Phase 2: Implementation of heat transfer component into water balance model

In this phase, the SAC-SMA is modified so that the heat transfer component computes the amount of frozen water in the soil and thus in the SAC-SMA. The amount of frozen water is then used to adjust the amount of runoff computed from the SAC-SMA. Very recent results shown in Figure 9 indicate that the physically-based methodology produces runoff volumes that are as good or superior to those from the calibrated conceptual approach of Anderson and Neuman (1984). This is a significant development because the physically-based approach requires no calibration while the conceptual formulation specifies seven parameters to be calibrated.

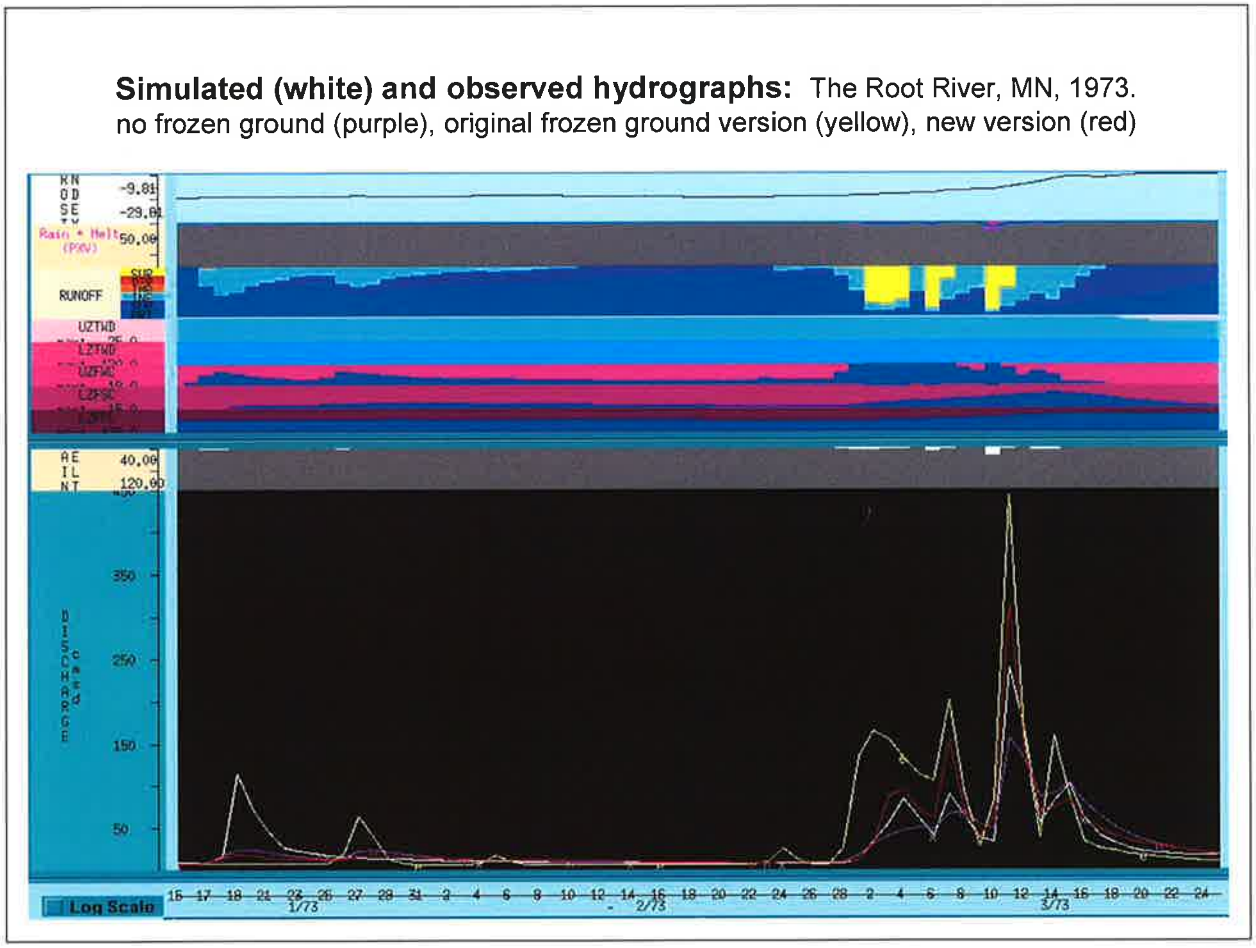


Figure 9. Hydrograph simulation using Sacramento model with three options: 1. no frozen ground component (purple); 2. original conceptual frozen ground component (yellow); 3. new physically-based frozen ground component (red). The physically-based component shows better agreement with observed discharge (white).

6. References

Anderson, E.A., 1976. A point energy and mass balance model of a snow cover. NOAA Technical Report NWS 19, U.S. Department of Commerce. February, 150 pp.

Anderson, E.A., 1973. National Weather Service River Forecast System- Snow Accumulation and Ablation Model. NOAA Technical Memorandum NWS HYDRO-17, U.S. Department of Commerce, November.

Anderson, E.A., 1968. Development and testing of a snow pack energy balance equations. Water Resources Research. Vol. 4, No. 1, 19-37.

Anderson, E.A., and Larson, L, 1997. The role of snowmelt in the January, 1996 floods in the Northeastern Unites States. Internal HL document.

Anderson, E.A., and Neuman, P.J., 1984. Inclusion of frozen ground effects in a flood forecasting model. The 5th North. Res. Basins Symp. And workshop, Vierumaki, Finland, March 19-23.

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, **V. Koren**, G. Gayno, and Tarpley, 2004. Implementation of Noah land-surface model advances in the NCEP operational mesoscale Eta model. GCIP3 Special Issue, JGR, 2004, *accepted.*

Etchevers, P. and numerous co-authors, 2002. SnowMIP, an Intercomparison of snow models: first results. Extended abstract, conference of the ISSW, August, 8 pp.

Koren, V., J. Schaake, K. Mitchell, Q.-Y. Duan, F. Chen, and J. Baker, 1999. A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, JGR, Vol. 104, No. D16, 1999, 19569-19586.

Mitchel, K.E., Lohman, D., Houser, P.R., Wood, E.R., **Schaake, J.C**., Robock, A., and others including **Victor Koren** and **Qingyun Duan**, 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. GCIP3 Special Issue, Journal of Geophysical Research-Atmospheres, accepted for publication.

Office of Hydrology, 1998. Northeast Floods of January, 1996. Natural Disaster Survey Report. U.S. Department of Commerce, March.

Schlosser, et al. (including **V. Koren**), 2000. Simulations of a Boreal Grassland Hydrology at Valdai, Russia: PILPS 2(d). *Monthly Weather Review, Vol. 128, No. 2, 301-321, 2000.*

Slater, A.G., and many co-authors including **Koren, V., Schaake, J., and Duan**, P.-Y, 2001. The representation of snow in land surface schemes: Results from PILPS 2(d). Journal of Hydrometerology, Vol. 2, No. 1, February, 7-25.

Appendix 1

Papers and Publications from Cold Season Process Research

Peer-Reviewed Papers in Scientific Journals (HL scientists in bold)

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, **V. Koren**, G. Gayno, and Tarpley, 2004. Implementation of Noah land-surface model advances in the NCEP operational mesoscale Eta model. GCIP3 Special Issue, JGR, 2004, *accepted.*

Koren, V., J. Schaake, K. Mitchell, Q.-Y. Duan, F. Chen, and J. Baker, 1999. A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, JGR, Vol. 104, No. D16, 1999, 19569-19586.

Mitchell, K., M. Ek, D. Lohmann, **V. Koren**, **J. Schaake, Q. Duan**, P. Grunmann, G. Gayno, Y. Lin, E. Rogers, D. Tarpley, C. Peters-Lidard, 2002. Reducing near-surface cool/moist biases over snowpack and early spring wet soils in NCEP Eta model forecasts via land surface model upgrades, *16th Conference on Hydrology, January, 2002, Orlando, FL, AMS, paper J1.1, pp. J1-j6.*

Mitchel, K.E., Lohman, D., Houser, P.R., Wood, E.R., **Schaake, J.C**., Robock, A., and others including **Victor Koren** and **Qingyun Duan**, 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. GCIP3 Special Issue, Journal of Geophysical Research-Atmospheres, accepted for publication.

Schlosser, et al. (including **V. Koren**), 2000. Simulations of a Boreal Grassland Hydrology at Valdai, Russia: PILPS 2(d). *Monthly Weather Review, Vol. 128, No. 2, 301-321, 2000.*

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Presentations at conferences

Koren, V., 2003. Parameterization of soil moisture-heat transfer processes for conceptual hydrologic models. AGU-EGS-EUG Assembly, April 9-14, 2003, Nice, France.

Koren, V., Duan, Q.-Y, and Schaake, J., 1999. Validation of a snow-frozen ground parmeterization of the ETA Model. Paper J1.3, Preprints, 14th Conference on Hydrology, American Meteorological Society meeting, 10-15 January, Dallas, Texas. 410-413.

Koren, V. , Qing-Yun Duan, Q.-Y., and Schaake, J.C., 1995. Modeling the effect of frozen ground on snowmelt/rainfall-runoff processes. Proceedings of the International GEWEX Workshop, Banf, Alberta, Canada, 22-26 May, 1995, IGPO Publ. Series No 15, 78-82.

Koren, V., 2002. Importance of snow measurements on the river flood modeling/prediction, WCRP Workshop on Determination of Solid Precipitation in Cold Climate Regions, Fairbanks, Alaska, June 9-15, Proceedings of the workshop on a CD-ROM, 2002.

Koren, V., Q. Duan, J. Schaake, 1995. A simple frozen ground model for snowmelt/rainfall-runoff simulation. Abstract on AGU Fall Meeting, December 11-15, San Francisco, California, Supplement to Eos, No 7, 1995, H41C-3.

Koren, V., K. Mitchel, **Q.-Y. Duan, J. Schaake**, and F. Chen, 1998. Snow-Frozen Ground Parameterization in the Mesoscale Eta Model. Abstract on the GCIP Mississippi River Climate Conference, June 8-12, 1998, St. Louis, Missouri.

Koren, Victor, Eric Anderson, Michael Smith, 2000. Conceptualization of Heat Transfer Processes for Storage-Type Hydrological Models. AGU Fall Meeting, San-Francisco, California, December 2000, H52E-09, F408.

Koren, V., E. Anderson, 2001. Effect of Weather Conditions on Snowpack Simulations: Results from Energy Balance and Temperature Index-Based Models. IAMAS Conference, Innsbruck, Austria, July 2001.

Koren, V., 2003. Parameterization of soil moisture-heat transfer processes for conceptual hydrologic models. AGU-EGS-EUG Assembly, April 9-14, 2003, Nice, France.

Mitchell, K., M. Ek, D. Lohmann, **V. Koren**, **J. Schaake, Q. Duan**, P. Grunmann, G. Gayno, Y. Lin, E. Rogers, D. Tarpley, C. Peters-Lidard, 2002. Reducing near-surface cool/moist biases over snowpack and early spring wet soils in NCEP Eta model forecasts via land surface model upgrades, *16th Conference on Hydrology, January, 2002, Orlando, FL, AMS, paper J1.1, pp. J1-j6.*

Mitchell, K., **J. Schaake**, D. Tarpley, F. Chen, Y. Lin, M. Baldwin, E. Rogers, G. Manikin, A. Betts, Z. Janjic, **Q. Duan**, **V. Koren**, 1999. Recent GCIP advancements in coupled land-surface modeling and data assimilation in the NCEP mesoscale Eta model. *14th Conference on Hydrology, 10-15 January 1999, Dallas, TX, AMS, 4B.1, 261-264.*

Mitchell, K., Y. Lin, E. Rogers, C. Marshall, M. Ek, D. Lohmann, **J. Schaake**, D. Tarpley, P. Grunmann, G. Manikin, **Q. Duan**, **V. Koren**, 2000. Recent GCIP-sponsored advancements in coupled land-surface modeling and data assimilation in the NCEP Eta mesoscale model. *15th Conference on Hydrology, 10-15 January 2000, Long Beach, CA, AMS,* 180-183.

Etchevers, P., et al., (including **V. Koren**), 2002. SnowMIP, an intercomparison of snow models: first results, *ISSW Meeting*, 2002.

Appendix 2

Reflections on Future Directions in Snow Modeling for the Hydrology Program of the National Weather Service

Eric Anderson

November 2003

Executive Summary

Introduction

Presentations and discussions at the recent Snow Hydrology workshop held at the Northeast RFC made it clear that there are a variety of efforts, proposals, and thoughts regarding future snow modeling efforts within the NWS Hydrology Program. It is clear that some consensus is needed so that the resources of OHD, NOHRSC, and the RFCs can be properly utilized to provide the greatest benefit and so that there are not duplicated or wasted efforts. Since I was the developer of the SNOW-17 model and have played a major role in the direction of snow modeling within the Hydrology Program up to this time, I thought it might be helpful to express my thoughts and insights, for what they are worth, on this subject.

Issues

The main snow modeling issues as I see them, are as follows:

- X How to make improvements to the application of the SNOW-17 model to overcome existing operational deficiencies,
- X How to best utilize energy budget computations, and
- X How should distributed modeling be utilized for snow.

Discussion

There are a number of considerations to take into account before making decisions about the future direction of snow modeling efforts for the NWS Hydrology Program.

- X There are 3 main steps that are required in order to successfully implement SNOW-17, the temperature index snow model currently used by the RFCs, for operational river forecasting:
  - B The model must be properly calibrated using an extended period of consistent historical data -- calibration expertise has improved though there is still room for progress,
  - B The data used operationally to drive the model must be unbiased as compared with the data used for calibration B differences in data networks and the algorithms to compute MAT make it likely that a bias exists in many cases which limits operational effectiveness, and
  - B Objective procedures are required that utilize all relevant real time observations to adjust model states and computations to reduce random errors and overcome model limitations B procedures exist for updating water equivalent in the west, but not east of the Rockies, and there are no techniques to quantify rate adjustments during periods of abnormal melt which often occur during extreme snowmelt events.
- X It is generally agreed to by most snow hydrologists that the science of snow cover energy exchange is quite well understood. Most of this science is included in the distributed energy-and-mass-balance snow model that is part of the Snow Data Assimilation System (SNODAS) being implemented by the NOHRSC.

X The problem in trying to apply an energy budget snow model is not the science, but obtaining good estimates of all the required data and modifying those estimates to account for elevation, slope, aspect, and vegetation cover. Calibration primarily involves adjusting coefficients and parameters related to the input data.
X An energy budget model will provide improved estimates of snowmelt over those obtained with a temperature index model if the data used to drive the model are unbiased and of sufficient quality and an adequate calibration has been performed.
X The expertise and resources, both human and computational, to apply a procedure like SNODAS are considerable -- it is probably unrealistic to attempt the implementation of such a system at each RFC that utilizes a snow model.
X It would be difficult to make changes to the algorithms used by SNOW-17 that would result in improvements over a wide range of conditions without overly complicating the model.
X Objective updating procedures could be developed to utilize SNODAS results to not only adjust SNOW-17 estimates of water equivalent, but also melt rates, areal snow cover, depth, and internal states.
XThe SNOW-17 model could be applied in a distributed manner. Research is required to determine how to adequately define the spatial variation of the input data and how to derive or calibrate the model parameters. Improved simulations are possible at the beginning and end of the melt season though overall the gain is likely to be minimal as compared to a lumped application (utilizing elevation zones in mountainous regions) when snowmelt is the dominant source of runoff.

Conclusions

My personal recommendations for future efforts in snow modeling for the NWS Hydrology Program are:

1. An energy-and-mass-balance snow model based on the best science should be utilized,
2. The energy-and-mass-balance snow model should be developed, applied, and maintained at a central location rather than being an integral part of the RFC forecast system -- the most logical place is the NOHRSC,
3. The energy-and-mass-balance snow model should be used to provide objective updates to the states and internal computations of the index snow model run at the RFCs rather than providing direct input to runoff models -- the development of such updating procedures should be a joint effort between OHD and NOHRSC,
4. OHD should conduct research on applying the SNOW-17 model in an distributed manner,
5. There should be considerably more effort by the RFCs and OHD devoted to making sure that the data used operationally for the SNOW-17 model is unbiased as compared to that used for calibration,
6. Changes should not be made to SNOW-17 unless they are clearly needed and will improve results over a wide range of climatic conditions -- the focus should be on developing objective updating procedures and utilizing the model in a distributed manner, and
7. Continued training should be provided to the RFCs on all aspects of snow modeling.

Introduction

Presentations and discussions at the recent Snow Hydrology workshop held at the Northeast RFC made it clear that there are a variety of efforts, proposals, and thoughts regarding future snow modeling efforts within the NWS Hydrology Program. From a modeling viewpoint, these range from modifications to the SNOW-17 model that is currently used by the RFCs to the use of a full energy-and-mass-balance model. As far as modeling a watershed the aim appears to be to move toward a distributed application of whatever snow model is used. In addition there is the question of whether a distributed energy budget model could and should be run at the RFCs as part of their forecast system or whether such a model should be run centrally with results used to modify the index model used by the RFCs. It is clear that some consensus is needed regarding the future direction of the snow modeling efforts so that the resources of OHD, NOHRSC, and the RFCs can be properly utilized to provide the greatest benefit and so that there are not duplicated or wasted efforts.

Since I was the developer of the SNOW-17 model and have played a major role in snow modeling within the Hydrology Program up to this time, I thought it might be helpful to express my thoughts and insights, for what they are worth.

Background

Prior to the 1970's the forecasting of snowmelt by the RFCs utilized various index procedures. None of the RFCs used a procedure that did a full accounting of the precipitation during periods of snow cover nor did any of the procedures explicitly account for ripening or areal depletion. Degree-day methods were used with the melt factor varying seasonally or based on the portion of the estimated volume of snowmelt that had already occurred. The seasonal variation in degree day factors implicitly included ripening of the snow cover and areal depletion. The potential snowmelt volume was based on either seasonal streamflow volume regression estimates or snow survey measurements. Coefficients and their variation over time were generally derived from analyzing past events, but no formal calibration or verification of the procedures using an extended period of historical data was conducted. Curves and coefficients utilized by these early procedures were typically refined over time based on forecast experience.

In 1973 the Snow Accumulation and Ablation model described in NOAA Technical Memorandum NWS HYDRO-17 (Anderson, 1973) became part of the newly developed National Weather Service River Forecast System (NWSRFS). This model has commonly been referred to as the SNOW-17 model. SNOW-17 is a conceptual model of the snow accumulation and ablation process. Most of the physical processes that determine the amount of snow that is accumulated and the energy exchange that takes place within the snow cover are include, but in a simplified manner. The development of the SNOW-17 model relied on various studies of the physics that control snow accumulation and ablation, including energy budget studies, to determine the processes to include and the functional form of many of the equations used in the model even though only air temperature was used to compute surface energy exchange. Air temperature, certainly at that point in time, was by far the most easily obtainable data, both historically and in real time, to use to estimate snow cover energy exchange and to compute surface melt. It is also relatively straight forward to extrapolate air temperature from measurement sites to locations where direct measurements are not available. There was some effort made to include other indices, such as dew-point, wind, and sky cover data, in the surface energy exchange computations, however, this was unsuccessful. The conclusion was that rather than trying to find an empirical equation involving multiple meteorological variables that would consistently improve snowmelt computations over an equation utilizing only air temperature, the next step should be to use the full energy budget equation to define how all the variables determine snow cover energy exchange. Of course the use of energy budget equations to obtain improved results depends on the availability and quality of the necessary data.

As opposed to prior applications of computing snowmelt based on air temperature, typically degree day methods, the SNOW-17 model utilizes separate equations to compute melt depending on whether rain is occurring. The non-rain melt equation includes a seasonally varying melt factor. The seasonal variation is primarily needed because of the variation in the amount of solar radiation available for melt per increment of temperature above a base value. The rain-on-snow melt equation relies on several assumptions so that the form of the energy budget equation can be utilized. The main reason for the two equations is that melt during rain-on-snow doesn=t exhibit a seasonal variation, whereas melt during non-rain periods does. The initial version of the SNOW-17 model, as described in HYDRO-17, was modified somewhat over several years based on subsequent snowmelt studies, primarily the development of a detailed energy-and-mass- balance model of a snow cover (Anderson, 1976). The Anderson (1976) report includes a comparison of the SNOW-17 model and the energy balance model at a research location with high quality measurements of the needed variables. The most current description of the SNOW-17 model is in Section II.2 of the NWSRFS User=s Manual.

The SNOW-17 model is now used by all RFCs that perform snow computations. The model has been calibrated at many locations, though regional parameters are still used in some cases. The model has been solely applied in a lumped manner, though in mountainous regions watersheds are generally subdivided into several elevation zones to account for large differences in the amount of snow and the timing of melt. In general, the operational results produced by the model have been a big improvement over past procedures. The use of the SNOW-17 model also allows for the generation of extended probablistic predictions of a variety of hydrologic variables using ensemble techniques that was impossible with prior methods of dealing with snow. The biggest complaints that have been brought to my attention involve the timing of snowmelt and the computation of melt during extreme or abnormal meteorological situations. A number of offices have indicated a tendency for melt to occur too early at the beginning of the snowmelt season during operation use, but haven=t indicated a similar tendency when calibrating the model. Several offices also have difficulty in adjusting model estimates of melt during periods of extreme or abnormal meteorological conditions, especially periods with high dew-points and high winds. Situations when the normal relationship between air temperature and melt breaks down have been documented, however, currently no objective procedure is available to assist the RFCs in determining the magnitude of the adjustment factor to apply and how the modification should vary over time when these situations occur. There have also been some problems involving the diurnal variation of streamflow during snowmelt periods. This problem is primarily the result of determining improper soil moisture model parameters during a calibration that uses only mean daily flow data to check the model simulation.

Issues

The main snow modeling issues for the future and some of the questions that arise for each issue, as I see them, are as follows:

1. How to make improvements to the application of the SNOW-17 model to overcome existing operational deficiencies. Is additional training needed? How to insure that operational data are unbiased compared to that used for calibration? What improved procedures can be developed for objectively determining the values of run-time modifications (MODS) to update water equivalent, areal snow cover, and snowmelt computations. Are additional MODS needed for use with SNOW-17 (the ability to change the heat deficit or to allow actual wind data to be used during rain-on-snow events have been mentioned)? Should changes be made to the SNOW-17 model itself (there has been talk of using additional indices to compute melt or modify how the refreezing of liquid water is calculated)?

2. How to best utilize energy budget computations. Should an energy budget snow model be available for use within the RFC=s forecast system or is it more reasonable to run an energy budget snow model centrally and use the results to update an index model used by the RFCs? What is the quality of the data values needed to drive an energy balance model in order to obtain consistently improved results over an index model? Are meteorological forecasts of the needed energy variables sufficiently accurate and if so, for how long into the future can they be used to provide better melt estimates? How would an energy budget model be calibrated and how long of a period of record is needed? How would the data needed for calibration be obtained? Would an extended period of historical energy budget input data be needed for ensemble predictions? Do the RFCs have the resources, both human and computational, to process, quality control, run, monitor, and analyze the data analysis, modeling, and assimilation procedures required to properly utilize energy budget snowmelt computations?

3. How should distributed modeling be utilized for snow. Does an energy budget snow model have to be run in a distributed mode? How would parameter values be determined for the SNOW-17 model if it is run in a distributed manner (would distributed calibration utilizing an extended historical period of record be necessary or can parameters for a distributed application be derived from a lumped calibration, possibly with a short period of distributed data to fine tuned the results)? Under what conditions could improved results be

anticipated by utilizing distributed modeling for watersheds with significant snowmelt contributions? How would a distributed application be utilized for extended ensemble predictions?

Before addressing many of these issues and offering my opinions, there is a need to provide some discussion of each of the two main snow modeling approaches; index methods represented by the SNOW-17 model and energy budget computations. Some of the future snow modeling issues will be addressed within this discussion.

SNOW-17 Model

There are 3 main steps that are required in order to successfully implement SNOW-17, or any index snow model, for operational river forecasting. These are:

1. The model must be properly calibrated using an extended period of consistent historical data. Recommended procedures for analyzing and processing the historical data and for applying and calibrating conceptual models, including the SNOW-17 model, are fully described in chapters 2 through 7 of the Calibration Manual by Anderson (2002). The main objective of the historical data analysis process is to generate consistent input time series for the model that have the true physical scale (i.e. they are as unbiased as possible compared to what actually occurred in nature) and have minimum random variation given the available data network. The objectives of the model calibration process are to produce simulations with a minimum amount of bias given the limitations of the model and the spatial scale of the computations, to have each model parameter embody what it was designed to physically represent, and to have the spatial variation of parameter values be consistent with physiographic factors.

2. The data used operationally to drive the model must be unbiased as compared with the data used for calibration. Different station networks and different methods of computing the input variables used by the model operationally, as compared to the historical network and data processing procedures, can easily create a bias. Care must be taken to insure that any bias is minimal. Chapter 8 of the Calibration Manual discusses some of the ways that bias can occur in the operational data feed to the models and various steps and techniques that will minimize the bias. Besides direct comparisons of time series, the possibility of a bias can often be deduced by comparing the operational simulations with those obtained during calibration. In general, the historical simulation should reasonably define the variation that can be expected in operational results and thus, if the operational simulations are frequently outside of anything that occurred during calibration, it is likely that the operational data are biased as compared to that used historically. For example, the timing of snowmelt is going to vary from one historical year to another, but if the operational simulation shows melt occurring much earlier or later than any of the historical years, it is very likely that there is a bias in the temperature data being used operationally. This is especially true if the operational simulation shows the same trend for several years in a row. Insuring that the data used operationally are unbiased as compared to that used for calibration is somewhat time

consuming and not very glamorous, but it is absolutely essential to obtaining the full benefits of any model.

3. Objective procedures are required that utilize all relevant real time observations to adjust model states and computations to reduce random simulation errors and overcome model limitations. Objective adjustment procedures typically utilize the model simulation along with predictions generated from additional observations to produce a more optimal estimate for use by the model. Such procedures are essential in order to maximize forecast accuracy and minimize uncertainty. In addition, the proper tools must be available for the forecasters to subjectively interact with the model and data in order to resolve differences between simulated and observed values.

From my perspective there has been mixed success within the NWS Hydrology Program at meeting the objectives of each of these steps. Because of this, the full benefits of using the SNOW-17 model have not yet been achieved. There are successes and failures for each of the steps as discussed below.

Step 1. The knowledge and expertise needed to properly generate the historical time series and determine SNOW-17 model parameter values has increased at the RFCs over time, however, there is still room for improvement. Mountainous terrain, which is common in many of the regions where snowmelt runoff is significant, makes the historical data analysis process more complex. In many mountainous regions there is a lack of good data at higher elevations where most of the snow occurs and a majority of the runoff is generated. If one is not careful, it is easy to produce precipitation and temperature time series that don=t conform to the physical scale that occurs in nature. Great care must also be taken to insure that precipitation and evaporation estimates are spatially consistent and produce a proper water balance. Chapter 6 of the Calibration Manual provides recommendations for generating historical time series that are physically realistic and spatially consistent. This documentation, rather than just notes from training sessions or workshops, should assist in having more RFC personnel understand and use the recommended data analysis procedures when generating historical time series for use in model calibration and ensemble streamflow predictions (ESP).

I believe that more RFC personnel are becoming adept at SNOW-17 model calibration. At some offices there wasn=t a good understanding of the structure of the snow model and how to determine the proper value for each of the parameters. This resulted in the use of regional parameter values or unrealistic and spatially inconsistent values when calibration was attempted. While this situation has improved, my impression is that it still exists at some level. Hopefully the documentation in chapter 7 of the Calibration Manual will help though there is undoubtedly a need for continued training on the snow model through workshops and other methods. The ability to know how to isolate the effect of each of the model parameters is one skill that particularly needs to be improved. A good understanding of the structure of a model, its limitations, and how to determine parameters values are essential to successful operational application and there is no better way to learn about a model than by performing calibrations.

Step 2. The existence of bias between the data used operationally to run the snow model and the data used for calibration is a major concern that hasn=t been properly addressed at headquarters or by most RFCs. In general, biased data are the result of differences in operational and historical data networks and variations in methods of generating the values. Differences in the two networks require that the long term means at all stations are known so that it can be determined that the long term mean areal estimates produced by each network are the same. This is not only true in mountainous regions, but also in non-mountainous areas. It is true for both the precipitation and temperature data used by the snow model. RFCs in mountainous regions, especially in the west, have made more of an effort to establish a good estimate of the long term mean for stations that were not part of the historical network prior to using the data operationally. This needs to be done everywhere. Very little effort has been expended at most offices to make comparisons between operational estimates of precipitation and temperature and those used during calibration (comparisons have been made between radar based estimates of precipitation and estimates derived from historical gage data as part of the distributed modeling research, but these have largely involved regions where snow is not important). The checks outlined in chapter 8 of the Calibration Manual should be followed and frequent comparisons made between the operational and historical time series.

There is also a potential bias problem in NWSRFS that involves temperature estimates. Historical MAT time series are generated solely from maximum and minimum temperature observations, whereas in the Operational Forecast System (OFS) both instantaneous and max/min data are utilized. Historically the time of the max and min are based on the observation time for each station and a fixed diurnal variation is used to compute 6 hourly MAT values. Operationally the instantaneous data determines when the max and min occur and the diurnal variation in temperature (a further discussion of this problem is in Chapter 6-4 of the Calibration Manual). These differences in data and processing methods certainly have the potential to create a significant bias. Since the SNOW-17 model is very sensitive to a temperature bias (see Figure 6-1 in the Calibration Manual), this problem could significantly alter the timing of snowmelt in an operational simulation as compared to what was obtained during calibration. Even though the problem has been identified and requests made by some RFCs to have it fixed, nothing has been done. Unfortunately, as far as I am aware, no one has quantified the magnitude of this potential difference between historical and operational MAT time series and the factors that may determine how the bias may be affected by region and historical data observation times. If the magnitude of the bias were known, there might be a greater chance of having someone work on a solution. Even though it should be clear that a significant temperature bias could exist operationally and would affect the timing of melt, there has been a tendency when the timing of snowmelt is off (typically too early as mentioned previously) to call for changes to the model structure or request that a MOD be added to OFS that would allow the user to change the heat deficit in SNOW-17 (generally to increase the heat deficit to delay runoff from the snow cover). In many of these cases I=m sure that the heat deficit would have to be set to a value well outside the range of anything that was encountered during calibration and that the MOD would have to be used multiple times to delay snowmelt by a sufficient amount. While a MOD to change the heat deficit may be a good idea, it is very likely that bias temperature data are the primary cause of the operational snowmelt timing problems. This problem needs to be resolved.

Step 3. The primary focus to date regarding objective updating procedures for use with the SNOW-17 model has been water equivalent. First, some western RFCs developed regression equations for updating water equivalent using relationships between historical simulated water equivalent and one or more snow course sites. This concept was taken further with the development of the Snow Updating and Estimation System (SEUS) [Day(1990)]. The National Operational Hydrologic Remote Sensing Center (NOHRSC) was given the responsibility to support the operational implementation of SEUS. However, after a couple years the key personnel working with SEUS left the NOHRSC and this implementation effort stalled. More recently Riverside Technology Inc. (RTi) developed a snow updating system for the Bonneville Power Administration (BPA), referred to as **snowupdate**. This system is now used by the Northwest RFC (NWRFC) and I believe some other western RFCs. **Snowupdate** is sort of a simplified versus of SEUS. All of these procedures to objectively update model estimates of water equivalent are based on having a long record of measurements at snow course sites at regular intervals and thus are restricted to use in the western states and Alaska.

In the east and upper midwest such water equivalent measurements are generally not available. Most measurements of water equivalent in these regions are made at irregular intervals and typically only during years with significant snow cover. Within the past few years the NOHRSC has developed the Snow Data Assimilation System (SNODAS) [Carroll et. al. (2001)]. SNODAS is a distributed, energy-and-mass-balance snow model and data assimilation system. One of the aims of SNODAS is to assimilate all available measurements of the amount of snow (point water equivalent and depth observations as well as aerial gamma flight line derived values) with model estimates to derive an improved estimate of the spatial variation in water equivalent. The intention is to give RFCs, especially those in the east and midwest, a mean areal value that can be used to update the SNOW-17 model estimate. In order to make such a update objective, several years of overlapping areal estimates from both SNOW-17 and a stable SNODAS configuration must be available. Currently the SNODAS estimates have only been used in a subjective manner to replace SNOW-17 computed values in eastern basins where the SNOW-17 values are highly suspect.

Other than water equivalent, no objective updating procedures exist for SNOW-17. MODs are available in the OFS to update the areal extent of snow cover, the non-rain melt rate, and the wind function during rain-on-snow events, however, there aren=t any objective methods for determining the values to use. These MODs are currently used in a subjective manner by comparing simulated and observed hydrograph response and looking at satellite snow cover observations. It is especially important to develop objective means of adjusting the melt rate since it is clearly known that there are meteorological situations when the relationship between air temperature and melt varies considerably from the average relationship determined via calibration. In many cases these situations are associated with extreme snowmelt events. It is difficult during such events to decide on the proper melt adjustments based primarily on a hydrograph comparison since other problems, such as errors in precipitation amount, antecedent conditions, or ice jams, are typically also occurring and the melt rate adjustments vary over time as meteorological conditions change.

Besides the currently available MODs in the OFS for the SNOW-17 model, there may be a need for a MOD that would adjust the heat deficit. Several RFCs have requested such a MOD though in many cases the perceived need is likely the result of a temperature bias between the operational input and that used for calibration as discussed previously.

Energy Budget Snow Models

It is generally agreed to by most snow hydrologists and others involved in studying the physics of snow that the science of snow cover energy exchange is quite well understood. Most of this science is included in the snow model that is used by SNODAS. SNODAS is based on the SNTHERM.89 model developed by Jordan (1991). The early development of SNTHERM drew extensively from the energy-and-mass-balance model developed by Anderson (1976). These energy-and-mass-balance snow models are one-dimensional models that represent the energy exchange and mass changes in a snow cover at a point. In order to apply such models to watersheds they must be applied in a distributed mode. This is not only because snow conditions vary considerably spatially, but because of large spatial variations in the input variables and how they are affected by vegetation and terrain. It is physically unrealistic to apply an energy budget snow model on a lumped basis to a watershed.

The problem with trying to use an energy-and-mass-balance model is not the science, but is how to obtain the data needed to run such a model. An energy budget snow model requires estimates of air temperature, dew point, wind speed, incoming solar radiation, albedo, incoming atmospheric longwave radiation, and precipitation. At research sites high quality measurements of all these variables are generally available, however, the situation is much different when an energy budget model is being applied over a large region. At each point where the model is run estimates of these variables must be generated by interpolating and extrapolating available measurements. In addition, adjustments must be applied for the effect of the terrain (slope, aspect, elevation) and vegetative cover on each variable. Also, direct measurements of some of the variables (e.g. albedo and incoming longwave, and perhaps even incoming solar, radiation) are generally not available and thus the values must be estimated from other data. SNODAS is run hourly using 1 km, gridded, meteorological input data downscaled from mesoscale numerical weather prediction (NWP) model analyses with the snow cover divided into three layers. Digital elevation data are used to assign the elevation and derive the slope and aspect of each grid cell. Each grid cell is also assigned forest cover and type information, derived from remotely sensed data, and soils information. Updating of the SNODAS model is done periodically (based on comparisons by the NOHRSC staff between computed and observed snow cover amounts and available resources) using all available measurements of water equivalent and depth . My understanding is that satellite areal extent of snow observations are not currently used directly in the updating process, but a manual comparison is made between model and observed snow cover. The assimilation of the observations into the model is an interactive process.

Some comments on energy budget snow models in general and the SNODAS application in particular are relevant at this point. The comments on SNODAS are based on knowledge of the algorithms and on infrequent comparisons of simulated values with SNOTEL data and personal observations primarily for an area in the central Colorado mountains (Summit County and surrounding area).

1. All models require some calibration even if they include detail representations of all the relevant physical processes (often referred to as deterministic models) and are being driven by high quality measurements of all input variables. In general, people think of calibration as being associated with conceptual or black-box type models, but even point applications of deterministic models require some calibration since no model contains a totally complete reproduction of what occurs in nature. However, the more physically complete a model, the easier it should be to at least know what each parameter or coefficient represents and thus have a better understanding of the range of realistic values. The wind function is the main element of an energy budget snow model that typically requires some calibration even at a research site. The wind function varies with the roughness of the snow surface, the stability of the atmosphere, and other factors affecting the air flow at a particular location. Even a theoretically based wind function that accounts for stability requires some calibration since the changing properties of the snow surface are not being modeled nor are other unique aspects of the wind flow at a given site. SNODAS uses a bulk transfer representation of the wind function which accounts for stability and fixed values from the literature for the parameters and coefficients involved. Figures 5.12 through 5.17 in Anderson (1976) illustrate how different, yet reasonable, values of the wind function parameters and coefficients can affect model results.

2. While some limited calibration is required for an energy budget snow model at a point with very high quality data, considerably more calibration is needed when applying such a model to an area. Partly this is due to assumptions and simplifications that must be made to account for the spatial variability in physiographic factors when running the model in a distributed mode, but mostly it is caused by uncertainties in determining the input variables for the model, especially when there are few, if any, direct measurements of these quantities. In this situation calibration primarily involves parameters that control the derivation of the input variables used by the model and not those of the model itself. Without some kind of calibration it is impossible to know whether the results are unbiased. For an energy budget snow model the main difficulties are in getting the proper wind speed and radiation components. The wind speed supplied to the model typically has to be derived for some level in the atmosphere from available measurements, adjusted to the elevation of the area being modeled, modified for terrain effects based on wind direction, aspect, and slope, and altered to account for the effect of the vegetation. Radiation incoming from the atmosphere

in many cases is computed based on sky conditions rather than direct measurements. Adjustments to these radiation estimates for terrain effects are fairly straight forward, but the modification of the radiation terms for the effect of vegetation contain more uncertainty. In addition, for areal applications, the albedo of the snow is not measured but estimated. Albedo can be estimated from surface grain size or density (which also must be computed since they are not measured) or in some cases a constant albedo is assumed. The current SNODAS configuration uses universal coefficients based on logical assumptions to estimate and adjust the data being used to drive the energy budget model at each grid point. A constant albedo of 0.70 is currently used though algorithms to vary the albedo based on snow surface conditions are being considered. While such coefficients and assumptions may result in a somewhat realistic build up and ablation of a snow cover, it is highly likely that the results at most specific locations contain a bias and could be significantly improved by some level of calibration.

3. The largest source of error in the current SNODAS application appears to be the precipitation field used by the model. This is especially true in mountainous regions. In the part of Colorado that I have examined, the estimated storm amounts are generally very low and there are problems with the orographic distribution. Updating the modeled amount of snow through assimilation with observations (only done once in Colorado) can partially correct the problem for the point in time when the data are assimilated, however, errors in the overall pattern of snow distribution cannot be totally removed by updating with the existing snow data network. Large errors in the amount and distribution of the snow cover make it very difficult to determine the reasonableness of the computations during ablation periods. A better estimate of the precipitation field is needed. In order to obtain a reasonably accurate, dynamic estimate of the amount and spatial distribution of precipitation in mountainous regions for use with any distributed model a procedure involving orographic modeling at the proper scale, along with the assimilation of gage measurements and other relevant observations, is likely needed.

4. An energy budget model will definitely provide improved estimates of snowmelt and snow cover outflow over those that can be obtained with a temperature index model, however, this is only true when the data used to drive the energy model are unbiased and of sufficient quality and model coefficients have been calibrated to remove any bias in the results. The differences between the two models should be greatest for locations where there is a large variability in the meteorological conditions during melt periods. Differences should be greatest at open sites where the relative magnitude of the terms in the surface energy balance equation can vary considerably from one period to another (e.g. solar radiation may dominate for several clear days which are followed by a warm, cloudy, windy, humid period where most melt is the result of latent and sensible heat transfer). Differences should be smallest for a very dense, conifer forest where there is little penetration of solar radiation and wind movement is minimal and thus most of the energy is due to longwave exchange between the forest and the snow which is nearly linear with temperature. The SNOW-17 model produced results that were quite similar to an energy budget model at a open, research site in Vermont [Anderson(1976)]. Differences occurred during periods with high winds and high dew points and during a cool, clear period when the snow surface was well aged (melt undercomputed

by SNOW-17) and during a period with little wind but abnormally warm temperatures (melt overcomputed by SNOW-17). Of course, all the SNOW-17 parameters had to be calibrated to the location, whereas only the wind function coefficient needed calibration for the energy budget model.

5. In order to use an energy-and-mass-balance snow model as an integral part of an RFC forecast system (i.e. provide direct rain plus melt input to a rainfall-runoff model) would require a detailed calibration. To perform such a calibration over a large region would be a major effort and undoubtedly require the development of some new strategies. The calibration should involve comparisons between model results and point or flight line measurements of the amount of snow, satellite observations of areal cover, and any other available measurements of snow properties, in addition to performing streamflow simulations in conjunction with the RFC=s rainfall-runoff and channel system models. As previously mentioned, the calibration of an energy budget snow model would primarily involve making changes to parameters that control the gridded data values being feed to the model. In order to perform such a calibration a sufficiently long historical period of record would be required. I would guess that 3-5 years with a significant snow cover might be sufficient for the snow component though a longer record would likely be needed to properly calibrate the full suite of models. This is a shorter period than generally needed to calibrate a temperature index procedure due to the physical nature of the model, but involves generating historical estimates of many more types of data. The period should ideally contain snow covers of different magnitudes and a variety of melt scenarios. It would also be critically important that the methods for determining the model input variables and their spatial variation be consistent throughout the period. Calibrations could be performed for individual watersheds, but to make sure that the parameters were spatially consistent, it is most likely that a strategy would have to be devised that covered a large area involving many watersheds. Obviously the operational use of a calibrated energy budget snow model would require that the real time data estimates be generated in a manner that was consistent with those used during calibration. Changes in how the real time data were determined would lead to the need to recalibrate the model.

A comparison of SNODAS computed water equivalents and observed values at SNOTEL sites was possible in Colorado for the 2003 melt season after the April 1st assimilation produced a reasonable magnitude for the snow cover. SNODAS uses coefficients and parameters based on literature to adjust input data fields and perform energy exchange computations. There is currently no calibration. Almost all of the SNOTEL sites that I examined showed the computed ablation of the snow cover to be anywhere from 5 to 15 days later than the measurements indicated. This indicates to me that some level of calibration is needed. SNODAS could likely produce more realistic overall simulations of snow cover accumulation and ablation by making improvements such as providing better estimates of some input data fields (e.g. precipitation), adding a method to vary albedo with snow surface conditions, and tweaking some of the coefficients that control how the NWP data are downscaled and modified for terrain and vegetation. Such improvements hopefully will occur over time as SNODAS evolves into a stable configuration. However, if one is going to use the results from an energy-and-mass-balance snow model like SNODAS to directly provide unbiased input (i.e. rain+melt) for operational streamflow simulations, a full calibration is required. Without a full calibration the alternative would be to use the results from a stable (i.e. changes not being made to the data or model algorithms) energy budget model as input to objective procedures that would provide updates to a calibrated temperature index model.

6. It is my understanding that the resources required to run SNODAS are considerable. This is both the computer resources to process the needed data, run the model, and archive results and the human resources needed to interact with and monitor the input data, model results, and assimilation of snow observations. SNODAS currently only simulates with observed data. Ideally an expansion can be made at some time to produce snow cover simulations involving forecasts of meteorological data fields at least for a few days into the future.

Discussion of Issues

The two preceding sections discussed the two basic types of snow models and expressed opinions regarding some of issues affecting the future of snow modeling within the NWS Hydrology Program. This section will provide a further discussion of these issues.

How to Improve the Operational Application of SNOW-17

1. An attempt to add other variables, such as dew point and wind speed, as indices to computing snowmelt is a waste of time in my opinion. It would be quite difficult to determine how to combine such variables with air temperature to produce an improved estimate of snowmelt on a consistent basis. Granted during certain extreme events high dew points and high wind speeds combine to produce abnormally large amounts of melt, however, it would be difficult to come up with an empirical formulation that would not only improve the results during such situations but work well during all other periods. Based on my experience, improvements to the computation of snowmelt beyond using air temperature requires the use of an energy budget approach in some manner. This could be done by the direct computation of snowmelt using an energy budget model or the adjustment of SNOW-17 estimates based on energy balance computations.

2. Air temperature has been shown in many studies to be a good estimate of daily snowmelt, however, as far as the diurnal variation in melt, the estimates are not as good. In general, more melt is generated per increment of temperature above a base value during daylight hours than at night. Thus typically a temperature index model will produce a more damped diurnal melt pattern than actually exists though this depends on the density of the forest cover and the meteorological situation. Six hourly computations of melt, even if not showing the full daily amplitude of the melt pattern, definitely have more value than calculating melt on a daily basis, however, hourly melt computations with a temperature index model would likely produce only marginal improvements over 6-hour estimates. In some fast responding watersheds hourly runoff estimates are needed during high intensity rainfall events in order to properly simulate streamflow. The SNOW-17 code has been designed to be able to use

hourly precipitation time series with 6-hourly temperature data. This allows the variation in rainfall intensity to be preserved on an hourly basis without having to generate hourly temperature estimates.

During active melt periods significant surface melt is occurring during the day while in many cases there is heat loss at night resulting in the refreezing of liquid water and lowering of the temperature near the surface of the snow cover. At an open site with calm winds and clear skies the heat loss is undoubtedly greater than the air temperature would indicate. Under such conditions there would be a heat loss even when the air temperature was above freezing at night due to a negative longwave radiation exchange. However, if the site is forested or the sky is overcast or it is windy, the energy balance is much different and heat exchange computed by a temperature index model should be much more reasonable. There have been suggestions that the SNOW-17 algorithms that control the refreezing of liquid water need to be modified. The evidence for this is based on comparisons with observed data at open sites that frequently have calm, clear nights during active melt. Changes could undoubtedly be made that would improve results at these sites, but most likely negatively affect the results at other locations. It is my opinion that one has to recognize that there are limitations to a temperature index model and not overly complicate the model or go beyond the information contained in the data by trying to figure out how meteorological conditions and thus the energy balance are varying based solely on air temperature. If straightforward changes can be made that apply universally without adding additional parameters, that is fine, but the complexity of the SNOW-17 model is very close to the limit of what is reasonable when solely using air temperature to compute surface energy exchange.

3. MODs are currently available to make the majority of the adjustments that are needed when using the SNOW-17 model operationally for river forecasting. The changes that need to be made most frequently to the model are to update the amount of water equivalent (.WECHNG MOD) and to varying the surface melt computations (.MFC and .UADJ MODs). A MOD is also available to change the areal extent of the snow cover (.AESCCHNG). As mentioned earlier, there are objective procedures for updating water equivalent at least in regions with snow course records taken at regular intervals, however, there aren=t any objective techniques for updating water equivalent in regions with only depth data or infrequent water equivalent observations nor are there objective procedures for determining appropriate values for updating melt computations or areal snow cover. Possible approaches are discussed under the next section on How to Utilize of Energy Budget Computations. As far as other run time adjustments, it was previously indicated that there are requests for a MOD to update the heat deficit. Considerations for updating the heat deficit based on SNODAS output are discussed in the next section

There has also been a suggestion that .UADJ MOD values could be computed based on actual wind observations during rain-on-snow events. The idea is to compute the average wind speed during such events based on the calibrated value of the UADJ parameter and the wind function used to obtain initial estimates of the parameter (see Section 7-4 of the Calibration Manual) and then use the ratio of observed wind speed to this average speed to get values for the .UADJ MOD. While the wind function given in Section 7-4 is likely not universal and in many watersheds there is a fair amount of uncertainty in the calibrated value of the UADJ parameter, the most difficult part of this approach would be deriving the actual areal average wind speed at 1 meter over the snow surface for a complex watershed based on measurements of wind speed at point locations which may not even be within the watershed. An alternative approach to determining an appropriate value for the .UADJ MOD is given in the next section.

How to Utilize Energy Budget Computations

1. The application of an energy balance snow model to a large region seems to be a major undertaking requiring a considerable amount of knowledge and expertise. A number of tasks are involved. First, the input data fields must be monitored. There may be a need to interactively adjust some of the input such as the form of the precipitation. If an energy budget model were run at an RFC, the monitoring and adjusting of the input data would most likely be part of the HAS function. Second, there is a need to calibrate the model or at least make some changes to coefficients and parameters so that the model reasonably mimics what actually is occurring. A full calibration would be needed if the model were being used to provide direct input to rainfall-runoff computations. Any level of calibration requires a detailed knowledge of the data analysis and modeling procedures. Third, the model must periodically be updated by assimilating the model results with all available snow observations. From my understanding this involves various interactions with the observed data that requires a certain amount of knowledge and experience. The question becomes can an energy balance snow model be run effectively at each RFC where snow is important or should such a model be run at a central location such as the NOHRSC as is currently the case with SNODAS?

If an energy balance snow model is run at each RFC there are two alternatives as I see it for how the model is utilized. The first would be to actually use the energy balance model as a direct step in the streamflow simulation process just like SNOW-17 is currently used. Computations would be done on a watershed basis within each forecast component segment. In this case the output from the model would directly be passed to a soil moisture accounting model and used to compute runoff. In this situation the model must be properly calibrated using not only snow observations but also streamflow data. The model would be rerun for each watershed every time the RFC forecast system is rerun. Some MODs would likely be needed so that the forecaster could make changes when computed values differ from observed in addition to the assimilation of snow observations to update the total amount of snow. While results would be generated segment by segment, a method of viewing the results over the entire RFC area would be needed to maintain spatial consistency and perform the assimilation step. The model would be used for both short term and extended forecasts. It may be that some kind of scale or modeling transition would need to be made as you go further out into the future when the quality of the energy input becomes very uncertain to keep computational requirements at a reasonable level.
The second alternative for using an energy budget snow model at an RFC would be to run the model outside of the regular forecast system similarly to how SNODAS is currently run at the NOHRSC. In this case the model would likely only be run for the current time and for a

few days into the future. Results from the model would be used to update the states and computations for SNOW-17 as discussed later in this section. A full calibration wouldn=t be required though adjustments would be needed to insure that the model was realistically reproducing nature. Either alternative would require that the staff of each RFC using the model have a very good understanding of the data analysis, modeling, and assimilation procedures involved so that the model could be used effectively across the country. If such a snow model was run at the RFCs, it would be essential that energy budget snow modeling expertise be available at the national level, probably at the Office of Hydrologic Development (OHD), to provide assistance and training to the RFCs.

If a energy balance snow model is run centrally the most logical place is the NOHRSC. The NOHRSC has considerable expertise and experience with all types of snow data analysis and modeling procedures though currently one person has most of the energy balance modeling expertise. It would be imperative in this case that a sufficiently knowledgeable staff is maintained so that the whole energy budget modeling effort wouldn=t be in jeopardy if one or two people left as in the case of the SEUS project. The same can also be said for OHD and the RFCs if the energy budget snow model were run as an integral part of each RFC=s forecast system. If an energy budget snow model is run at the NOHRSC, it would most logically be used to provide updates to the SNOW-17 model at the RFCs as discussed later in this section rather than having the snow cover outflow be used directly to compute runoff. It is critical that the RFCs be able to run their forecast models whenever needed and not be dependant on direct modeling results from an external office.

2. As mentioned above, an energy balance snow model could be run as an integral component of the RFC forecast system to generate both short term and extended forecasts. This would likely create a considerable computational burden for the forecast system if hourly energy computations were performed at a fine grid for all time steps. If this were the case, it would also mean that input data fields for all the variables would need to be provided for each ensemble when probabilistic predictions were being generated. Since the benefits of an energy balance model are highly dependent on having high quality estimates of the needed data, it is likely that as one goes out into the future and the ability to forecast wind and radiation fields rapidly diminish there is no longer a need to utilize the same temporal and spatial scale nor even to continue with energy budget computations. Thus the scale and modeling approach could change after the first few days of the forecast period, as long as the results were consistent.

3. As an alternative to running an energy-and-mass-balance snow model as an integral part of an RFC forecast system, the model could be run externally and the results used to update an index snow model like SNOW-17. This is the basic idea behind the SNODAS effort at the NOHRSC. SNODAS was developed in response to recommendations from the report on the 1996 snowmelt flood in the northeastern U.S. [Office of Hydrology(1998)]. That report indicated a method was needed to utilize all available snow observations to determine a best estimate of the amount of snow available for melt. In the eastern and central portions of the U.S. there are few regular measurements of water equivalent and the quality of many of these

are questionable. Especially during large snow years there are additional water equivalent measurements at points and over flight lines, but even these lack the necessary spatial coverage in most areas to produce good areal estimates. However, there are a large number of depth observations that are routinely collected. The idea behind SNODAS was to run a distributed energy-and-mass-balance snow model utilizing the latest science to simulate the states of the snow cover including depth, density, water equivalent, liquid water content, and temperature. It would then be possible to assimilate both depth and water equivalent observations with the model results to produce an improved estimate of the total amount of snow and its spatial distribution. Thus, the initial primary focus of SNODAS was to provide improved estimates of mean areal water equivalent to the RFCs for each of their watersheds in order to update the values being generated by SNOW-17.

Besides water equivalent, a stable, properly adjusted energy-and-mass-balance snow model with quality input should be able to be used to update various other states, plus internal computations of an index model like SNOW-17. In order to derive an objective procedure, in most cases, there must be several years of stable, overlapping results from both models since there is no way to guarantee a one-to-one correspondence between the estimates from both models. The SNOW-17 values that could be updated with information obtained from an energy budget model like SNODAS, possible updating techniques, and factors to consider are discussed below.

a. Water Equivalent - As indicated, SNODAS was developed to provide improved estimates of water equivalent for RFCs in the eastern and north central regions of the U.S.. SNOW-17 was updated at some RFCs this past winter using SNODAS estimates. The SNODAS values merely replaced the SNOW-17 estimates. To avoid a possible bias and insure that the updating is near optimal, several years of overlapping data from both models are needed to develop an objective procedure. Western RFCs adjust SNOW-17 water equivalent estimates with updating procedures that utilize snow course data. One problem with these procedures is that the relationship between the model and the snow courses can vary throughout the snow season. The equations that are used for updating are typically fairly stable when the snow cover is accumulating, but break down during the melt season since the point to area relationship is constantly changing during the ablation period. Since SNODAS is modeling the entire accumulation and melt process, it is likely that there would be a consistent relationship throughout the entire snow season between SNOW-17 and SNODAS water equivalent estimates, thus offering the possibility of an improvement over current updating procedures.

b. Melt Rates - One of the major problems when using SNOW-17 operationally is the lack of a method of determining exactly when and by how much to adjust melt rates. It is known that a temperature index model cannot accurately calculate the amount of melt during certain meteorological situations. By knowing current conditions a forecaster can guess at whether a melt adjustment is required, but has no real idea of the magnitude of the correction. An energy budget snow model that has been adjusted to produce a realistic representation of the ablation period should be able to provide reasonable values for the .MFC and .UADJ MODs. The non-rain melt factors (divide the surface melt computed by the energy budget by the air temperature minus the base temperature) and wind functions (solve the SNOW-17 rain-on-snow melt equation for the wind function with the melt set to the value computed by the energy budget model) that would be needed to generate the melt produced by the energy balance equations could be calculated for a multiple year period for the areas being modeled with SNOW-17 (generally either watersheds or elevation zones). These quantities could then be compared to the calibrated values used by SNOW-17 to derive an objective procedure for adjusting the temperature index melt estimates. Since there are uncertainties even in the energy budget melt estimates, derived adjustments would likely only be used when the value clearly indicates abnormal conditions. Melt adjustments could be determined for the observed data periods and also out into the future using forecast values of the energy budget input variables. Adjustments in the future could vary from one ensemble to another when making probabilistic predictions to reflect the uncertainty of the forecasted value of the input variables. Besides adjusting melt rates during abnormal conditions, such a procedure might modify diurnal variations in melt when air temperature doesn=t produce the correct pattern. When using such a procedure operationally, interactive capabilities may be warranted to insure spatial consistency in the adjustments and to allow for forecaster input.

c. Areal Snow Cover - Objective procedures could currently be derived using overlapping periods of satellite based areal cover estimates and model generated values to update SNOW-17. In the future, areal cover estimates from SNODAS that have been verified to be realistic based on comparisons or updates with satellite based values could be used to derive an objective procedure to update the areal extent of snow cover in SNOW-17. In either case, the updating procedure would have to account for the fact that the areal cover needed by the model is not typically the same as what would be observed in nature. This is due to the fact that the relationship between the melt rate over the snow covered portion of the area being modeled and the melt rate when the entire area is snow covered is implicitly incorporated into the SNOW-17 areal depletion curve.

d. Heat Deficit - The heat deficit in SNOW-17 is defined as the amount of energy that must be supplied to the snow cover in order to return it to the combined thermal and liquid water state as when the heat deficit was last equal to zero. The accumulation of a heat deficit doesn=t differentiate between liquid water that may be refrozen within the snow and the lowering of the snow temperature. The SNOW-17 heat deficit only indicates the amount of energy that must be supplied to return the snow cover to its original combined temperature and liquid water state. As an example, a snow cover could have been isothermal at 0EC with 5 mm of liquid water in storage when the heat deficit began to accumulate. When the heat deficit returned to zero, the temperature and liquid water content could be back to their original values or there could still be parts of the snow profile where the temperature was below freezing, but the overall amount of liquid water in storage is now greater than the original 5 mm. It is not possible to compute the heat deficit directly based on the temperature and liquid water profile of the snow cover, either measured or modeled, at a given point in time. This is because the temperature and liquid water states when a heat deficit began to accumulate in SNOW-17 are unknown. An energy budget model, like SNODAS, could be modified to calculate the heat deficit so that an objective updating procedure could be developed for use with SNOW-17.

e. Since SNOW-17 can now calculate snow depth as well as water equivalent an objective procedure could be developed to update the snow depth based on SNODAS estimates.

How to Utilize Distributed Modeling

1. It is quite clear that an energy budget snow model should be run in a distributed mode; certainly for any watershed with varied terrain and forest cover. It doesn=t make a lot of sense to use a physically based model and then apply it in a lumped manner unless possibly conditions are very uniform across the drainage. If an energy budget model were applied in a lumped manner (would require some kind of depletion curve to account for the areal snow coverage) there might be some improvement in the computation of melt during events with very abnormal meteorological conditions, but the combination of the dampening of the spatial variations and uncertainty in the values of the input variables would cause the results during most days to be no better and more likely worse than could be obtained with a temperature index model.

2. The SNOW-17 model could be applied in a distributed manner though some research would be required to determine whether the spatial variability of the input variables can be adequately defined, how to derive or calibrate the parameters, how to update the model operationally, and when it is advantageous to apply the model in a distributed mode. Some thoughts on these questions follow.

a. In order to really benefit by a distributed application of any model it is essential to have good estimates of the spatial distribution of the primary input variables. For SNOW-17 air temperature and precipitation are the two driving variables. Air temperature primarily is a function of elevation though temperature can also vary with aspect, forest cover, and other factors. Though seasonally varying average lapse rates can be readily estimated, there are deviations in the relationship between temperature and elevation depending on meteorological conditions. An approach similar to that currently used by SNODAS involving the downscaling of NWP model estimates could be used for a distributed application of SNOW-17 though it seems like at least all available surface observations ought to be assimilated to produce the final gridded fields.

Good spatial estimates of precipitation in regions with significant snowfall and especially in mountainous terrain would likely require further procedure development and testing. Reasonable estimates of spatial variations in rainfall can frequently be obtained in flat terrain by combining radar information with gage measurements and other observations. In mountainous terrain and especially when snow is occurring, the accuracy of radar based estimates deteriorates. In regions with significant relief, precipitation could be allocated spatially for distributed applications of the snow model based on long term isohyetal patterns. However, a more dynamic approach, perhaps including the use of a orographic precipitation model, would be a big improvement not only for distributed applications of the snow model but even when the model is used in a lumped mode with multiple elevation zones For both temperature and precipitation it is essential that however the spatial estimates are derived for operational use that they are unbiased compared to the data used to calibrate the model.

b. A distributed application of the SNOW-17 model could be attempted by using the parameters from a lumped calibration for every grid cell. This would probably only be realistic where the spatial variability during rainfall events is the major reason for running models in a distributed manner. This would most likely be for a region that is non-mountainous with little variation in forest cover or one where snowmelt runoff is generally insignificant. In mountainous regions where there is a substantial amount of runoff from snow, it seems like if there is any advantage in running the SNOW-17 model in a distributed mode it is to try to simulate the variation in the accumulation and ablation pattern over the area. The parameters for a distributed application of the SNOW-17 model could be obtained by running the model in a distributed mode for a sufficiently long historical period and adjusting parameter values in some logical manner or the parameters from a lumped calibration could possibly be modified, maybe involving a few years of distributed input, to reflect their spatial variation. It would likely be quite difficult to obtain the historical data that would be required by new procedures for generating spatial temperature and precipitation patterns to provide an adequately long historical record for calibrating the model by running it in a distributed mode. This calibration approach is likely more feasible after a sufficiently long, stable, historical record has been obtained by archiving gridded input estimates. In the short term, at least, it seems that trying to utilize the results from a lumped calibration is the most realistic alternative.

One possible approach for deriving the spatial variation in SNOW-17 energy exchange rate parameters (MFMAX, MFMIN, UADJ, and maybe NMF) is to utilize an energy budget model like SNODAS. SNODAS could be run and melt factors computed using a year or two of archived data. The ratio of the average parameter estimate for each grid cell to the average for the area being modeled (either a watershed or elevation zone) could be calculated and used to assign values for these parameters for a distributed application of SNOW-17. Even if the average areal parameter estimates calculated from the energy budget were different than those for the SNOW-17 calibration, the ratio of the estimates for each grid cell to the area average should provide a reasonable approach of accounting for spatial variations in these energy exchange rate parameters due to elevation, slope, aspect, and forest cover. The pattern for distributing some of the minor SNOW-17 model parameters could be based on guidelines for how these parameters vary with climatic and physiographic factors given in the Calibration Manual. The spatial and temporal scale of the application shouldn=t have a significant effect, as it does in the case of the Sacramento Model, since SNOW-17 is basically a linear model. The biggest potential problem for deriving distributed SNOW-17 parameter values based on a lumped calibration revolves around the depletion curve. For a distributed application of the model each grid cell should either be snow covered or bare. The areal snow cover pattern and overall extent of the snow cover for the area is then computed based on which grid cells are snow covered at any given time. The areal cover in a distributed application would be based on the assumed spatial distribution of temperature, precipitation, and the model parameters, especially those controlling melt rates, in an explicit manner. In a lumped application of SNOW-17 all the factors that control the typical accumulation and melt patterns over the area being modeled are included in the area depletion algorithm. This includes spatial variations caused by typical temperature, precipitation, and melt rate patterns, as well as implicit variability due to such things as how the ratio of the actual melt rate over the snow covered area to the total area melt rate varies as the snow cover is depleted and how snow is redistributed by wind after it reaches the ground. A distributed application of SNOW-17 wouldn=t directly account for all these factors and thus, would likely produce biased results as compared to the lumped application. Some adjustment to the distributed parameters derived from a lumped calibration would likely be necessary. A few years of distributed input would probably be needed to make these modifications

c. A distributed application of the SNOW-17 model could be updated operationally based on information derived from an energy-and-mass-balance model in a similar manner to that described previously in this section for a lumped application of SNOW-17 under item 3 of AHow to Utilize Energy Budget Computations.@ Updates would be applied grid cell by grid cell rather than a lumped basis.

d. There is undoubtedly a benefit to be gained by running rainfall-runoff and channel system models in a distributed manner for watersheds where it has been shown that rainfall variability has a significant effect on hydrograph response. Whether it is essential from a modeling perspective and whether improved results can be obtained by running the snow model in a distributed mode for such watersheds needs to be verified. It might be possible to run the snow model in a lumped manner, as long as convective events with spatially varying rainfall patterns are unlikely during periods when snow exists. Many watersheds that fall into this category are in the central and northern Great Plains region of the U.S.. In these cases there should not be much spatial variability in air temperature and model parameters. In order to benefit by applying the snow model in a distributed manner in this region one would have to deal with problems in obtaining good spatial estimates of precipitation during snow events and the redistribution of the snow cover by wind (frequently in this region much of the snow ends up in drifts, ditches, hedgerows, etc.).

In mountainous regions with large amounts of snow there are some potential advantages to running the snow model in a distributed manner. The possible benefits occur primarily at the beginning and end of the snowmelt season. Benefits could also occur during rain-on-snow events. Early in the melt season the snow can be melting in some parts of a watershed while not in other parts (primarily due to elevation and aspect differences). Later in the melt season when significant bare ground exists, a lumped application can provide enough melt water to keep the soil saturated, whereas in reality the soil in those areas that have been free of snow for some time may be quite dry. A distributed application has the potential to improve simulations when rain occurs on an area partially covered by snow. The use of elevation zones allows lumped applications to partly simulate these situations, but a distributed version of the model could likely provide further improvements. During rain-on-snow events a distributed application has the potential to better reproduce the watershed response by knowing more about where the rain is occurring. The biggest question with running the snow model in a distributed manner in mountainous regions is whether all the factors that are included in the areal depletion curve can be adequately incorporated into the distributed version. Overall, for most of the mountainous regions of the U.S., while there is the potential to improve snowmelt runoff simulations by applying SNOW-17 in a distributed manner, it is my guess that substantial improvements are unlikely.

3. One item that needs to be taken into account when considering whether to run hydrologic models in a distributed mode for river forecasting is the requirement for and the impact on extended probabilistic predictions. In some regions there is little memory in the current state of the hydrologic system or the impact of current conditions are only relevant for a fairly short period into the future. In these cases the ensemble of potential future scenarios can likely be generated in a distributed manner from meteorological predictions and limited historical data in order to produce short term probabilistic flood forecasts. Also the computational requirements are probably manageable. However, in most regions where runoff from snow is significant the current state of the snow cover has a major impact on the streamflow that can result for a considerable period into the future. In these regions ESP products, in many cases extending months into the future, are very important to the RFC=s clients. Possible streamflow ensembles are produced by utilizing historical estimates of the model input variables with possible modifications based on meteorological predictions. Many potential input scenarios are needed to adequately define the probability distribution of the future streamflow. With a lumped model, the historical traces that were generated in conjunction with the calibration process are used for ESP runs. In the case of a distributed application, it is unlikely that gridded historical data estimates could be reasonably generated for a sufficiently long period due to data availability and resource limitations. This would certainly be the case for an energy budget snow model, however, for a distributed application of SNOW-17 it would depend on whether gridded data fields could be derived from historical lumped MAP and MAT time series or whether new methods involving additional data are being used to produce gridded precipitation and temperature values. It will take many years to accumulate a sufficiently long record for ESP applications by archiving real time gridded data fields. Also, in order to use such archived records for ESP runs the underlying input and the algorithms used to produce the gridded fields must be consistent over time. There appears to be two options in this case. One is to somehow statistically generate the gridded ensembles of the input variables and the other is to switch from a distributed to a lumped mode when making extended ESP runs. The switch could occur for the entire length of the ESP run or could occur a few days into the future when the skill level in producing gridded forecasts greatly deteriorates. In the case of the Sacramento Model this would require that parameter values be altered when the switch occurs to reflect changes in

the temporal and spatial scale of the application. In the case of SNOW-17 it would require utilizing the areal depletion curve to account for the effects partial snow cover. Either the rules for changing parameter values or two sets of parameters would need to be available in order to switch from a distributed to a lumped mode when making an extended ESP runs.

Conclusions

My personal recommendations for future efforts in snow modeling for the NWS Hydrology Program, based on the preceding discussion, are as follows.

1. <u>An energy-and-mass-balance snow model based on the best available science should be utilized</u>. Such a model will increase the understanding of the current state of the snow cover and the changes that will occur based on meteorological forecasts. It will readily allow for the assimilation of all available snow observations to be used to update model states. The model should not only be run for observed data periods, but also for as long into the future as warranted based on the skill level of forecasting the variables needed for energy budget computations. In order for such a model to provide maximum benefits high quality, unbiased estimates of the input data must be available. This likely means that improvements be made to some of the data fields, especially precipitation, that are currently used by SNODAS. The model parameters and coefficients, including those used to downscale meteorological data and account for vegetation effects, need to be adjusted so that the model realistically simulates snow accumulation and ablation over its entire area of application. Even a limited calibration should involve not only snow observations, but also some streamflow data.

2. <u>The energy-and-mass-balance snow model should be developed, applied, and maintained at a central location rather than being an integral part of the RFC forecast system</u>. The expertise needed to properly apply such a model and the resources, both human and computational, required to run the model, monitor the input data, and assimilate observations is more than can be realistically expected at each RFC where snow computations are important. Also the benefits that can be obtained by utilizing an energy budget model can fully be attained by running the model at a central site. The most logical place for the model is the NOHRSC. It is critical that the NOHRSC be provided with the resources, again both human and computational, to perform this function. This effort cannot be dependent on one or two people. Sufficient human resources are needed so that if key people leave the NOHRSC the modeling effort will continue to be properly supported.

3. <u>The energy-and-mass-balance snow model should be used to provide objective updates to the states and internal computations of the index snow model run at the RFCs rather than providing direct input to RFC runoff models</u>. The most critical updates are for the total amount of snow, primarily water equivalent, and adjustments to the melt rates when abnormal meteorological conditions exist. Adjustments to the melt rates of the RFC model, plus estimates of the uncertainty of these updates, should be provided for both the observed and future data periods. All of the updating procedures should recognize that there is likely not a one-to-one correspondence between the results from each model. The development of

these objective updating procedures should be a joint effort between NOHRSC and OHD with the NOHRSC having the primary expertise on the energy-and-mass-balance model and OHD on the RFC snow model. The RFCs should be frequently consulted and informed regarding how the procedures might operate and the impacts on RFC operations.

4. OHD should conduct research on applying the SNOW-17 model in an distributed manner. This research should determine how such an application could be utilized to provide the full range of forecasts, from short term deterministic to long term probabilistic, required at the RFCs. The effort should include methods of providing gridded input, calibration techniques, updating procedures, and how to generate extended probabilistic predictions. Recommendations for how and when to use the model in a distributed mode should be developed. It is likely that there are still many cases in regions with significant snowmelt runoff where a properly applied lumped version of the snow model (includes use of elevation zones in mountainous areas) will provide results that are at least as good as a distributed application.

5. There should be considerably more effort devoted to making sure that the data used operationally for the SNOW-17 model are unbiased as compared to that used for calibration. A number of problems that the RFCs are experiencing when using the model in real time are likely not due to model deficiencies, but are the result of using bias data. The RFCs need to follow appropriate procedures to make sure that mean areal data estimates from their historical and operational networks produce the same long term averages. OHD needs to correct the problem caused by having different temperature data and algorithms used to compute historical MAT values than are used to generate MAT estimates with OFS.

6. Changes should not be made to the existing RFC index snow model, SNOW-17, unless they are clearly needed and will improve model performance when tested over a wide range of climatic conditions. The recent addition of depth computations is an example of a worthwhile enhancement. The focus in the future should be on how to best update the SNOW-17 model based on energy-and-mass-balance model information and how to utilize SNOW-17 in a distributed manner. Considerable time and resources could be expended trying to add additional variables, such as dew point and wind, to the index computations or utilizing a dynamic wind function. These resources would be better spent on developing objective procedures for updating SNOW-17 based on energy budget model computations.

7. Continued training should be provided to the RFCs on all aspects of snow modeling. There is a need to improve the ability of RFC personnel to properly calibrate and apply the SNOW-17 model. There is also a need for RFC personnel to understand the basics of the energy-and-mass-balance model and especially how information obtained from that model can be used to improve RFC operations.

References

Anderson, Eric A (1973) National Weather Service River Forecast System - Snow Accumulation and Ablation Model, *NOAA Technical Memorandum NWS HYDRO-17,* U.S. Dept. of Commerce, National Weather Service, Silver Spring, MD, 217 pp.

Anderson, Eric A (1976) A Point Energy and Mass Balance Model of a Snow Cover, *NOAA Technical Report NWS 19,* Dept. of Commerce, National Weather Service, Silver Spring, 150 pp.

Anderson, Eric (2002) Calibration of Conceptual Hydrologic Models for Use in River Forecasting (available online at www.nws.noaa.gov/oh/hrl/calb/calibration1102/main.htm).

Carroll, Tom, Don Cline, Greg Fall, Anders Nilsson, Long Li, and Andy Rost (2001) NOHRSC Operations and the Simulation of Snow Cover Properties for the Coterminous U.S., *Proceedings of the 69th Annual Western Snow Conference,* Sun Valley, ID, pp 1-10.

Day, Gerald N. (1990) A Methodology for Updating a Conceptual Snow Model With Snow Measurements, *NOAA Technical Report NWS 43,* Dept. of Commerce, National Weather Service, Silver Spring, MD, 133 pp.

Jordan, Rachel (1991) A One-Dimensional Temperature Model for a Snow Cover - Technical Documentation for SNTHERM.89, *Special Report 91-16,* U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 49 pp.

Office of Hydrology (1998), Northeast Floods of January 1996, *NOAA Natural Disaster Survey Report,* Office of Hydrology, National Weather Service, Silver Spring, MD, 99 pp.