NUMERICAL SIMULATION OF SNOW TRANSPORT, DEPOSITION, AND REDISTRIBUTION

T. W. Tesche[1]

1.0 INTRODUCTION

Numerical modeling of orographic snow storms has been pursued over the last two decades for a variety of reasons. Obviously, predictions of the spatial distribution of precipitation in mountainous areas is crucial to operational hydrology. Research into snowfall augmentation through cloud seeding has benefitted significantly from numerical modeling. As a result of the enormous increase in scientific computing power over the last ten years, modeling of orographic storms has matured from the early pioneering attempts to simulate the dynamics and microphysics of winter snowfall (e.g., Fraiser, et al., 1973; Young, 1974; Plooster and Fukuta, 1975; Colton, 1976). This research addresses a less traditional problem although the modeling methods and results have broad applicability. We seek to simulate intense winter orographic snow storms with sufficient accuracy to be of use in local storm and avalanche hazard forecasting. To succeed, it is essential that the three-dimensional character of snow transport, deposition, and drifting over mountain terrain is treated in a realistic manner.

Use of wind transport and snow deposition simulation models for avalanche forecasting was first described by Rhea (1975, 1978) and Tesche and Yocke (1977, 1978). The latter workers examined the problem of windfield prediction over two- and three-dimensional mountainous terrain while Rhea emphasized the moisture supply and snowfall formation processes. Results from Rhea's two-dimensional model have been used for many years by the Colorado Avalanche Warning Program (Judson, 1976; Williams, 1980). Recently, Hayes (1986) described a new two-dimensional orographic model developed for the Pacific Northwest which offers significant potential for highway maintenance decision-making and avalanche hazard forecasting. The orographic precipitation models developed to date generally emphasize a restricted set of physical processes, treating others simply or ignoring them altogether. Young (1974), for example, developed a detailed cloud microphysics model, but coupled it with a very simplified wind flow description. Hayes' (1986) model, in contrast, couples a detailed, two-dimensional diagnostic windfield model with a very simple precipitation scheme.

This paper describes the development of the Snow Accumulation and Numerical Transport Algorithms (SANTA) model. The SANTA model consists of a Mountain Windfield Model (MWM), a sophisticated Transport and Diffusion Model (TDM), and a bulk Cloud Microphysics Model (CMM). The model is formulated to treat atmospheric transport, cloud microphysics, snow deposition and resuspension at comparable levels of sophistication. In its general formulation, SANTA is a three-dimensional, time-dependent, multispecies hydrometeorological model. It simulates the time evolution of solid, liquid, and vapor water fields within cold orographic storms over complex mountain topography. It may be applied for both local scale and regional scale analyses.

Also presented in this paper is a summary of model verification exercises, beginning with SANTA's wind and transport/diffusion components. The model is then applied to an orographic snowstorm which occurred in the Sierra Nevada mountains in late March 1982. This storm, intensively monitored by the Sierra Cooperative Pilot Project (SCPP) as part of weather modification research (SCPP, 1982), set seasonal snowfall records in the Sierra and induced a widespread avalanche cycle which claimed several lives.

2.0 MODEL FORMULATION

The SANTA modeling system, as shown in Figure 1, consists of a meteorological model, a transport model, and a cloud microphysics model. Time-dependent, three-

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[1] President, Alpine Geophysics, Inc., Placerville, California, and Principal Scientist, Radian Corporation, Sacramento, California

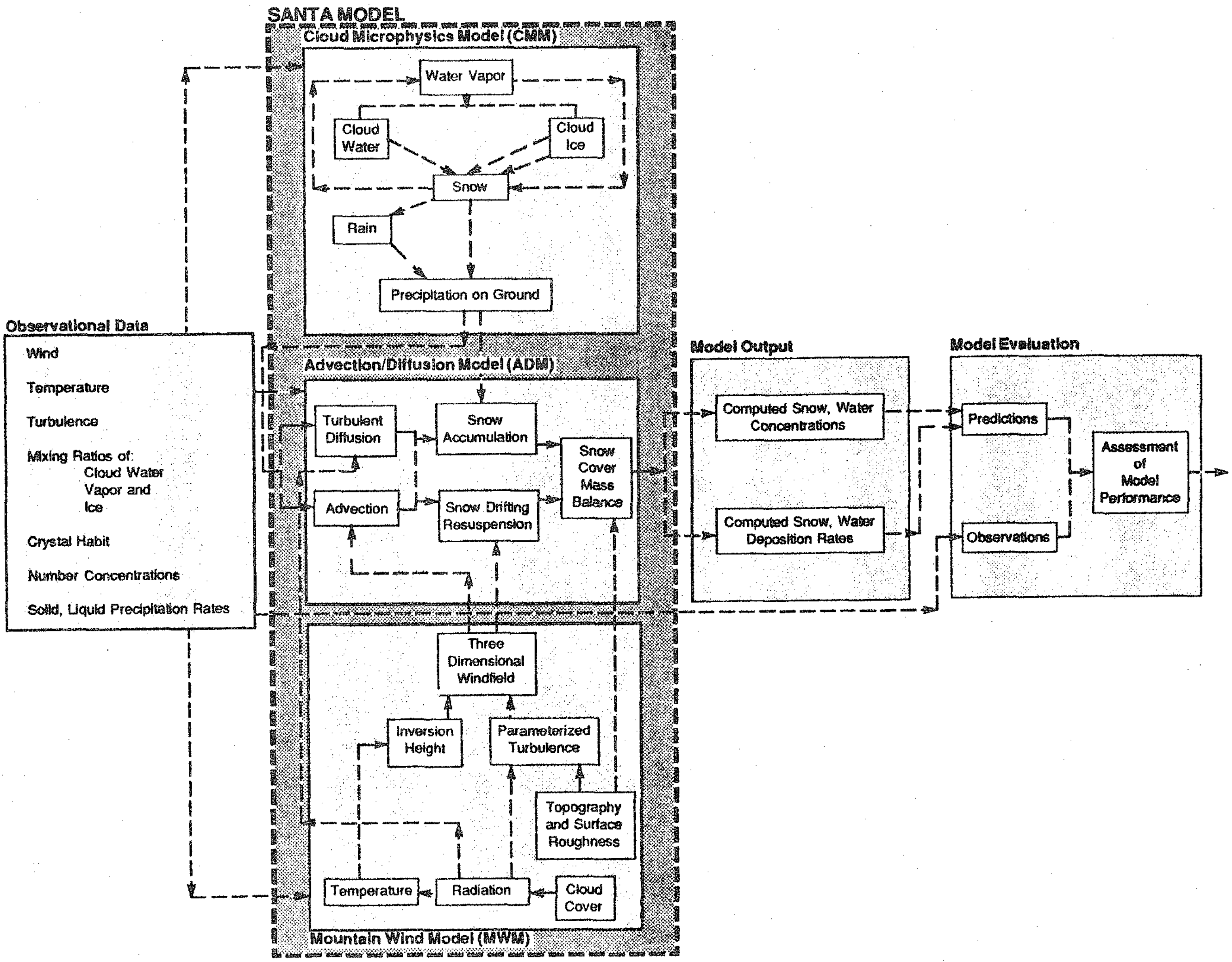

Figure 1. Overview of the Snow Accumulation and Numerical Transport Algorithms (SANTA) Model.

dimensional simulation of transport, dispersion, deposition, and snow resuspension processes are treated by the TDM code. This code is driven by meteorological fields supplied by the Mountain Wind Model. Description of ice phase nucleation and the growth of ice crystals by vapor deposition, and collection of water droplets is treated by the Cloud Microphysics Model. Brief technical descriptions of each component model follow.

The Mountain Wind Model (MWM). Three distinct conceptual approaches are available for modeling windfields in mountainous terrain: objective analysis (e.g. interpolation), diagnostic modeling, and prognostic simulation based on the Navier-Stokes equations for atmospheric flow. Prognostic (or primitive equation) modeling is theoretically preferable, being based on a full description of mass, momentum, and energy conservation relationships. This method is computationally intensive, however. SANTA model wind fields currently are developed from objective and diagnostic modeling methods. The Mountain Wind Model employs a two-step procedure whereby diagnostic algorithms generate an initial three-dimensional flow field which is strongly influenced by topography and boundary layer forcing. The three-dimensional, steady state mass conservation equation is solved numerically subject to boundary layer parameterizations of topographic lifting, channeling, convergence due to friction and thermal effects, mountain-valley wind circulations, and flow separation over ridges. The field is then objectively filtered to remove unrealistic or spurious accelerations and ensure mass conservation. The diagnostic algorithms are reported elsewhere in detail (Tesche and Yocke, 1977, 1978).

The Transport and Dispersion Model (TDM). The most complex component of the SANTA model is the Transport and Dispersion Model (TDM). It is based on a time-dependent, three-dimensional numerical solution of the atmospheric diffusion equation, written for multiple, coupled species. Currently, the TDM treats five water species: cloud ice, snow, cloud water, rain, and water vapor. The mass continuity equation, which expresses the conservation of mass of each water species in a turbulent fluid, may be written as:

$$\frac{\partial q_i}{\partial t} + \frac{\partial (uq_i)}{\partial x} + \frac{\partial (vq_i)}{\partial y} + \frac{\partial (wq_i)}{\partial z} = \frac{\partial}{\partial x}\left(K_H \frac{\partial q_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H \frac{\partial q_i}{\partial y}\right)$$

$$+ \frac{\partial}{\partial z}\left(K_V \frac{\partial q_i}{\partial z}\right) - w_t \frac{\partial q_i}{\partial z} + P_i + E_i + D_i \quad (i = 1,5) \tag{1}$$

where q_i = mixing ratio for species i,
u,v,w = wind velocity components in the x,y,z directions, respectfully,
w_t = settling velocity of species i in a turbulent atmosphere,
K_H, K_V = horizontal and vertical turbulent diffusivities, respectfully,
P_i = production (or destruction) rate of species i, given by the Cloud Microphysics Model,
E_i = erosion rate of species i from the snow surface through wind action,
D_i = surface deposition rate of species i.

In deriving Equation 1, it is assumed that species transport due to turbulence is adequately parameterized through the use of the eddy diffusivity concept and that turbulent fluctuations have a negligible effect on volume-averaged cloud microphysics. Advective transport is governed by the wind velocity field, supplied by the MWM. The Cloud Microphysics Model links the five simultaneous partial differential equations for the various water species.

Surface removal processes are treated in the SANTA model with the deposition velocity concept. The deposition flux of material i at the surface, D_i, is proportional to the ground-level concentration, C_{gi}. The proportionality constant is the effective deposition velocity, V_{di}. Mathematically, the flux can be written as follows:

$$D_i = V_{di} \bullet C_{gi} \tag{2}$$

Accumulation of snow on the ground takes place in three sequential stages: (1) transport to just above the surface by advection and turbulent diffusion; (2) transport to the surface itself by processes that are influenced by the shape of the surface; and (3) incorporation into the ice crystal matrix at the snowpack surface. Thus, the overall removal rate is affected by both atmospheric transport and microphysical processes.

Estimates for V_{di} are based on the concept of a resistance to transport, R_t, and to surface removal, R_{si}. The transport resistance is estimated from theoretical considerations of turbulent transfer in the atmospheric boundary layer, and the surface resistance is obtained from experimental data on the uptake of various materials by different types of surfaces (Killus et al., 1977). In the present calculations, the effective deposition velocity for snow crystals varies between 1 to 3 m/sec.

The mechanics of snow erosion and resuspension in SANTA are analogous to the erosion of cohesive sediments in hydraulic systems. The rate of erosion, E_s, is proportional to the ratio of the surface to critical shear stresses;

$$E_s = M\left(\frac{\tau_o}{\tau_c} - 1\right) \tag{3}$$

where M is an erodability function. The critical shear stress, τ_c, is related to a threshold wind speed below which snow erosion does not occur. For the present, a threshold value of 3.0 m/sec is assumed, following Berg (1986). Note that τ_c is not, in general, equal to τ_o. Normally, $\tau_o < \tau_c$ because once a snow crystal strikes the pack it becomes mechanically bound to the existing snow matrix. To later erode this crystal, greater stress (τ_c) is required to rupture the intergranular bonds than was needed originally to minimally maintain the crystal in suspension (τ_o). To prescribe the rate at which erosion of snow occurs, the erodability function (related to the mechanical properties of the snow) and critical shear stress (related to a characteristic near-surface wind speed and snowpack tensile strength) must be estimated. In the present formulation, M is assumed constant and the surface shear stress distribution, τ_o, is obtained from the MWM boundary layer parameterization. The erosion rate increases with the square of the near surface wind speed.

The Cloud Microphysics Model (CMM). The cloud microphysics formulation in SANTA is based on the bulk parameterization schemes developed by Lin et al., (1983) and Orville and Kopp (1977). Five water species are considered (water vapor, cloud water, cloud ice, rain, and snow). Only the bulk snow microphysics is mentioned here; representation of the other species follows analogously and is described by Lin et al., (1983).

Processes which form snow in cold orographic storms are included in the production term P_i in Equation 1. The snow production rate, P_s, is given by:

$$P_s = \text{(conversion from cloud ice to snow)} + \text{(accretion of cloud ice by snow)} + \text{(accretion of cloud water by snow)} + \text{(deposition/sublimation of snow)} - \text{(melting of snow to form rain)}$$

$$= P_{SAUT} + P_{SACI} + P_{SACW} + P_{SDEP} - P_{SSUB} - P_{SMLT} \qquad (4)$$

It is assumed in this formulation that a Marshall-Palmer exponential size distribution exists for all precipitating fields.

Numerical Methods

Equations 1 and 4 represent a system of five coupled partial differential equations. The equation set is solved numerically using the method of fractional steps. This technique subdivides the original four-dimensional problem in (x,y,z,t) into a series of three two-dimensional problems in (x,t), (y,t), and (z,t), which are solved sequentially. Horizontal advection is solved by an explicit scheme recently proposed by Smolarkiewicz (1983) while the vertical diffusion step is integrated using an implicit Crank-Nicholson algorithm. Further details on the numerical methods and their accuracy are discussed in Tesche (1987). The current version of the SANTA model is exercised on a MicroVAX-II computer operating under VMS. A twenty-four simulation requires 18-20 hours of CPU time for a typical application.

3.0 MODEL COMPONENT VERIFICATION

A comprehensive hydrometeorological data base for verification of the SANTA model is available from the 1981-1982 SCPP field program (SCPP, 1982). This data set enables detailed comparisons between model predictions and observable quantities (e.g. surface wind velocities, snowfall intensities, precipitation intensities). A preliminary SANTA model evaluation is discussed Section 4.0. However, the performance of specific components of the SANTA model is known from past verification studies. These verification results are presented briefly.

Detailed evaluation of the transport and diffusion algorithms in SANTA is reported by Tesche, Haney, and Morris (1987) in a study sponsored by the DOE's Atmospheric Studies in Complex Terrain (ASCOT) program. The model was tested with data collected from a large series of complex terrain tracer diffusion experiments. The TDM was exercised with data from a total of nineteen different tracer experiments. Hourly-averaged model predictions were compared with multi-tracer concentration measurements throughout a sampling grid of over 3 dozen sequential monitors. The model evaluations emphasized conditions of limited vertical mixing and strong cross ridge flow, phenomena common to orographic storms. The overall bias and error in SANTA transport predictions of hourly averaged tracer gas concentrations was +6 percent (slight overprediction) and 24 percent, respectively.

Verification of the wind model algorithms have also been carried out. For example, comparisons with hourly-averaged data from 27 meteorological stations in the South Coast Air Basin of Southern California revealed an overall bias toward underestimation of wind speed by 0.1 m/sec and a slight overall discrepancy (8 degrees) in the prediction of wind direction. Of course, hourly-avereraged individual comparisons showed larger variability. The difference between predicted and observed wind speeds was typically 1.0 m/s ($\sigma = \pm 0.70$ m/s). Most of the discrepancies in wind direction for hourly pairs of prediction

These and other model evaluation results suggest that the transport and wind algorithms perform well in situations where sufficient data are available for input preparation. Of course, the most rigorous test of the SANTA model is whether it is able to reproduce observed precipitation fields (water equivalent and snow) under orographic storm conditions. We turn to this subject next.

4.0 SANTA MODEL EVALUATION

The SANTA model was exercised using data collected by the SCPP program for the 26-31 March 1982 storm which deposited record precipitation totals in the central Sierra Nevada mountains of California. Satellite photos for this period reveal an intense extra-tropical cyclone centered off California with a broad band of cloud covering most of the central portion of the state. Between 0600 on 26 March and 0600 on 31 March, a total of 225 cm (89 inches) of snow fell at the Alpine Meadows Ski Area adding to an existing base of 2.3 meters. During this period, wind gusts at the Sierra crest were reported in excess of 180 meters/sec (125 mph). The storm forced closure of highways and ski areas due to high winds and heavy snowfall and initiated a widespread cycle of avalanche activity (Penniman, 1986). On 31 March, a massive slab avalanche destroyed a lift terminal and the ski patrol headquarters at the Alpine Meadows, killing seven people, including Mr. Bernie Kingery, a noted avalanche researcher.

The March 1982 storm was intensively monitored by the SCPP program which included researchers from the National Center for Atmospheric Research (NCAR), the University of Wyoming (Marwitz, 1987a,b), and the University of North Dakota. The detailed surface and airborne measurements of meteorological and microphysical parameters collected during the March 1982 storm provides an unusual rich data base for model evaluation. Hydrometeorological data from the SCPP project, local ski areas, and other mountain weather stations were assembled and used as input for the SANTA model simulations of mesoscale and microscale orographic snowfall for 0000-2400 PST 30 March 1982. Model evaluation results are summarized briefly below. More extensive verification exercises are underway.

4.1 Mesoscale Simulations

The modeling domain for the mesoscale SANTA simulations is a 35 x 40 grid mesh with 2 km horizontal resolution (Figure 2). Eight vertical levels of 250 meter thickness are used. Extensive University of Wyoming (UW) aircraft soundings on the 30th revealed a neutrally stable layer up to the 0°C level (870 mb) with stable conditions aloft. Surface winds were southerly veering to southwesterly at 3,000 meters, slightly above the height of the Sierra crest. Wind speeds increased to approximately 25 meters/sec near the crest. Measured vertical winds were of order 0.2 to 0.4 meters/sec. Figure 3 depicts the surface flow field over the mesoscale domain for 1200-1300 PST, computed by the Mountain Wind Model. Details of the storm thermodynamic and kinetic structure are presented by Marwitz (1987a,b).

Data from the UW aircraft flights were used to initialize the cloud water fields. Representative mixing ratios for cloud ice and cloud water were 4×10^{-4} gm gm^{-1} and 1×10^{-4} gm gm^{-1}, respectively. The concentration of ice particles within cloud upstream of

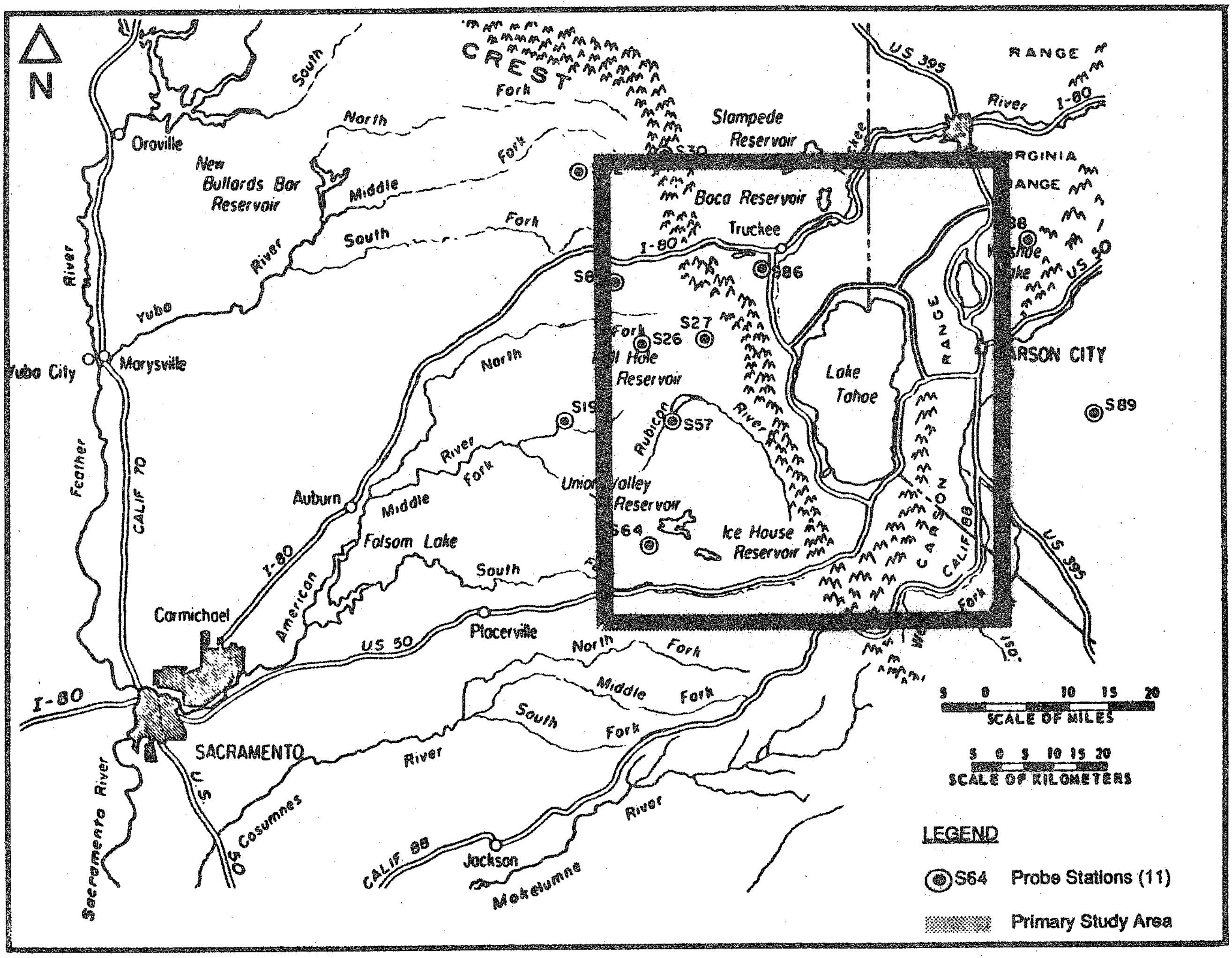

Figure 2. 1981-1982 SCPP Meteorological Network and the SANTA Modeling Region. (Adapted from SCPP, 1982.)

the Sierra barrier was estimated at $30\ \ell^{-1}$. These values are consistent with earlier studies of Lamb et al. (1976) and Heggli et al. (1983).

More than three dozen SCPP precipitation stations were in operation during the storm, 26 of which are contained within the mesoscale modeling grid shown in Figure 2. These stations and five other mountain weather stations are listed in Table 1 together with measured daily water equivalent precipitation totals. The SCPP precipitation data, reported as 15 minute averages, were averaged over one hour to be consistent with model output predictions.

Also included in Table 1 are the SANTA model predictions of maximum hourly and daily total precipitation (in mm of water) and total daily snowfall (in cm) at six sites. The agreement between predicted and observed total precipitation is quite close. The average observed and predicted daily precipitation rates throughout the 31 station network were 38.8 mm and 36.6 mm, respectively. This represents a six percent error in daily

TABLE 1. SANTA MODEL PERFORMANCE IN SIMULATING MAXIMUM 1-HOUR AND DAILY TOTAL PRECIPITATION AND SNOWFALL FOR THE 30 MARCH 1982 STORM

			Maximum One Hour Average Precipitation (mm, Water Equivalent)			Daily Total Precipitation (mm, Water Equivalent)			Daily Total Snowfall (cm)		
Monitoring Station	AGI Identifier	SCPP Site No.	Observed Maximum	Predicted Maximum	Percentage Difference	Observed Total	Predicted Total	Percentage Difference	Observed Total	Predicted Total	Percentage Difference
Goose Meadow	GOOS	S86	1	1.5	50	--	34.5	-100			
Cisco Grove	CISC	S09	9	--	--	92	--	--			
Plavada	PVDA	S10	7	1.3	-82	63	30.0	-52			
Sierra Snow Lab	CSSL	S11	4	1.6	-61	51	37.4	-27			
Soda Springs Exit	I-80	S14	3	1.5	-49	22	36.2	65			
Castle Valley	CAST	S21	2	1.6	-22	17	36.8	117			
Hobart Mills	HOBR	S29	2	1.5	-27	21	34.4	64			
Fordyce Lake	FORD	S31	3	1.5	-51	34	34.8	2			
Boca Res.	BOCA	S33	1	1.5	45	14	32.9	135			
French Meadows Res.	FRCH	S49	6	1.4	-76	80	28.8	-64			
Pyramid	PMID	S76	6	1.8	-71	29	41.4	43			
Echo Summit	ECHO	S77	4	1.5	-62	22	36.3	65			
Donner Grade	DONN	S84	2	1.8	-12	24	41.9	74			
Sagehen Creek	SAGE	SN1	2	1.9	-7	20	42.8	114			
Thunder Cliff	THUN	SN2	2	1.9	-5	--	41.6	--			
Brockway Summit	BROK	SN4	3	2.2	-27	39	49.3	26			
Squaw Valley	SQAW	SNL	3	1.5	-51	69	33.4	-52	61	33.4	19
Lost Corner Mt.	LOST	SM1	2	1.5	-24	8	36.7	358			
Upper Van Vleck	UVAN	SM2	4	2.0	-50	51	47.6	-7			
Morattini	MORA	SM3	2	2.2	9	39	51.7	32			
Lower Van Vleck	LVAN	SM5	4	1.9	-52	60	45.7	-24			
Wrights Lake	WRIT	SM6	1	1.6	63	24	38.9	62			
Loon Lake	LOON	SM7	2	1.8	-13	36	41.5	15			
Schlein R.S.	SCHL	SM8	3	2.0	-33	40	47.7	19			
Big Hill	BIGH	SM9	1	2.3	134	12	53.3	344			
Jaybird Springs	JAYB	SMB	3	1.2	-60	26	5.5	-79			
Tahoe City	CITY	--	4	1.6	-61	34	36.9	8	33	36.8	12
Alpine Meadows	ALPN	--	4	1.3	-67	60	31.3	-48	53	31.2	-41
Donner State Park	DSP	--	--	2.3	--	31	54.0	74	43	54.0	26
Sugar Bowl	SUGR	--	--	--	--	71	40.6	-43	71	40.6	-43
Twin Bridges	TWIN	--	--	--	--	--	--	--	64	32.5	-49
Average			3.1 mm	1.7 mm		36.6 mm	38.8 mm		54.2 cm	38.1 cm	
Std. Dev.			1.9 mm	0.3 mm		21.5 mm	9.2 mm		14.2 cm	8.5 cm	

precipitation total. The model underestimated the average daily snowfall across the six reporting sites (54.2 cm) by 30 percent. The overall bias and error in hourly average water equivalent precipitation rates (paired in time and space) at 30 stations are +10.8% and 52.5%, respectively. In Figure 4, the total predicted precipitation for 30 March 1982 is presented; bold numerals directly above the stations names indicate the observed precipitation totals for the day.

4.2 Microscale Simulations

Microscale SANTA simulations were also performed, using a 35 x 40 grid with 400 meter resolution. Centered over the Alpine Meadows/Squaw Valley Ski areas, the purpose of this local scale simulation was to assess the reasonableness of model snowfall predictions in the vicinity of major, dangerous avalanche paths. Initial and boundary conditions were obtained from the mesoscale simulation. Figures 5 and 6 give the predicted 1200-1300 PST surface wind field and the daily total snowfall distribution within the microscale domain. While the general snowfall totals across the two ski areas compares favorably with the measured values (53 cm at Alpine; 61 cm at Squaw Valley), there is less spatial variability in the snow deposition field than is expected based on field experience. Further investigation into the reasonableness of the snow drifting and wind transport algorithms is warranted, especially for exposed windward and steep lee zone accumulation areas.

5.0 AVALANCHE HAZARD FORECASTING

As much as 90 percent of all avalanche activity occurs during or within 24 hours after a storm (Tesche and Yocke, 1977). Of the several factors known to contribute to the

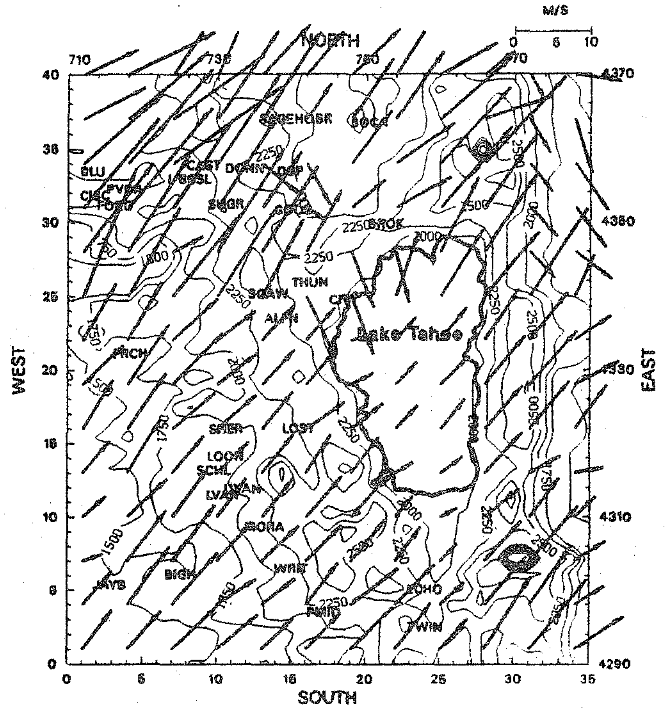

Figure 3. Surface Flow Field From the Mountain Wind Model for 1200-1300 PST on 30 March 1982--Mesoscale Domain. (Elevation contours in meters.)

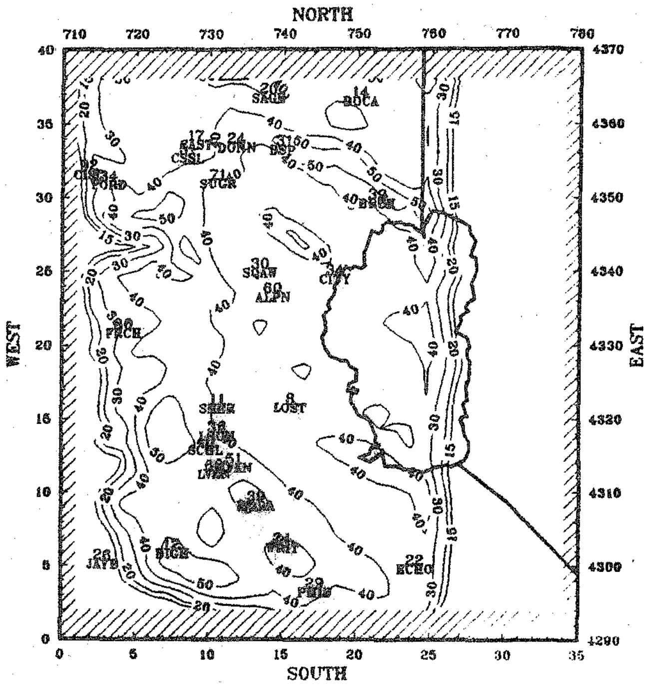

Figure 4. Computed Daily Precipitation (mm Water Equivalent) During the Period 0000-2400 PST on 30 March 1982--Mesoscale Domain.

formation of these direct-action avalanches, the one that often dominates is the rate of snow loading in the starting zone. The snow loading rate is a function of many meteorological parameters, among which crystal habit, snowfall intensity, wind transport, and snow deposition, and temperature are important. If mountain weather simulations can be tailored to the needs of avalanche forecasting, the forecaster may have an additional tool to augment the experience, judgment, and local real-time field observations used in evaluating avalanche hazards.

Suppose that the SANTA model is exercised for a limited number of recurring storm types for a region or even a specific ski area complex. Each simulated storm would produce a "catalog" of snowfall deposition maps (e.g., isohyetal maps) similar to Figures 4 and 6. These maps could be stored in an easily retrievable computer data base. The snowfall deposition maps could be analyzed quickly using a desktop personal computer to identify slopes which might be reaching a potentially dangerous slab formation stage. If the avalanche starting zone is very large, snow deposition maps might be helpful in suggesting locations for the placement of explosives. More generally, these maps might be useful in preparing regional avalanche hazard warnings issued to the public. The feasibility of this approach for the Sierra Nevada is currently under investigation.

6.0 SUMMARY AND CONCLUSIONS

An orographic precipitation model of the distribution of heavy snowfall over mountain terrain must adequately describe several complex physical processes, including the microphysics of snow crystal formation and precipitation, and the mechanics of turbulent suspension and diffusion, snow deposition, and snow erosion. Preliminary performance evaluation results indicate that the SANTA model adequately predicts orographic snowfall dynamics in mountainous regions, given a sufficient data base. Whether computer-based

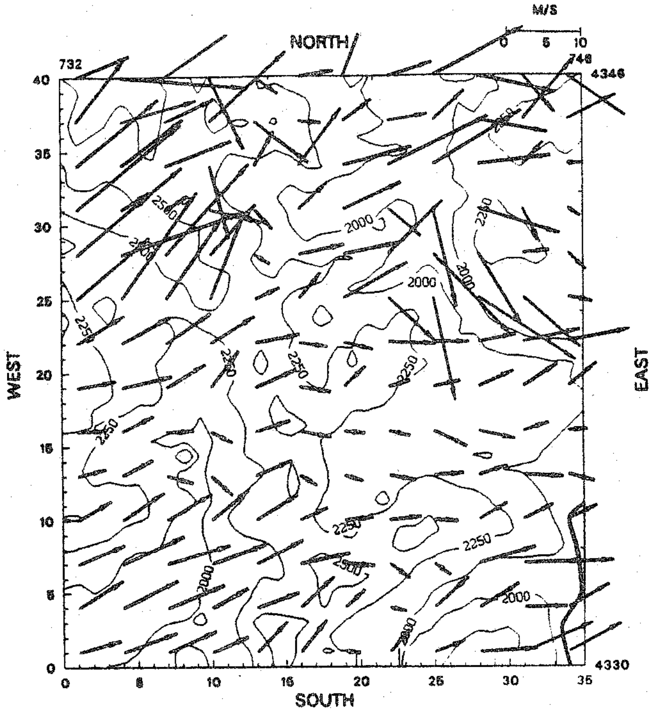

Figure 5. Surface Flow Field From the Mountain Wind Model for 1200-1300 PST on 30 March 1982--Microscale Domain. (Elevation contours in meters.)

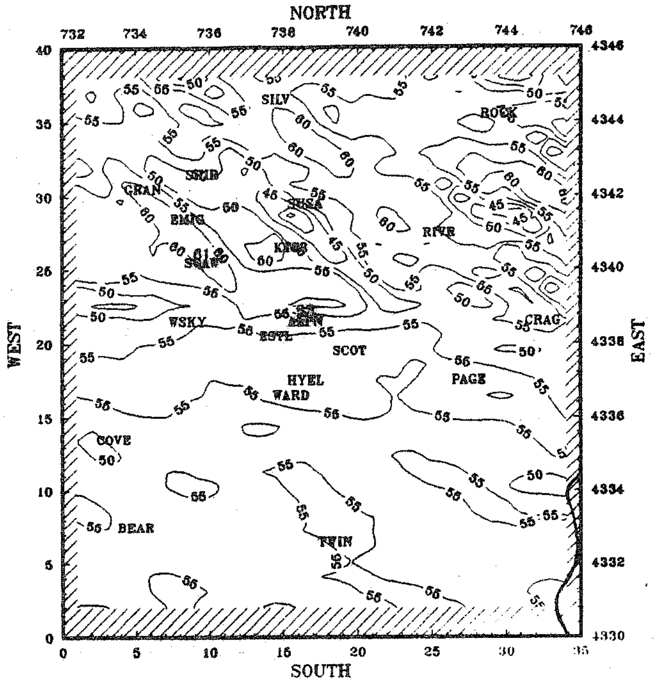

Figure 6. Computed Snow Fall (cm) During the Period 0000-2400 PST on 30 March 1982--Microscale Domain.

predictive models for mountain winds and snow transport can be refined and usefully applied to avalanche hazard forecasting remains an open question. Even though several specific suggestions can be made for further research and model development, this should not preclude moving ahead with attempts at practical applications of the model to avalanche hazard forecasting in the Sierra Nevada.

We reach the following conclusions:

- An Eulerian grid-based three-dimensional hydrometeorological model has been developed to simulate regional orographic snowstorms. The SANTA model consists of a Mountain Wind Model; a bulk Cloud Microphysics Model treating water vapor, liquid water, ice crystals, rain, and snow; a sophisticated, grid-based Advection-Diffusion Model; and a subgrid-scale treatment of snow deposition and erosion.

- Major SANTA Model components have been evaluated individually with tracer diffusion experiments and routine meteorological data sets. The entire modeling system has undergone preliminary evaluation with detailed surface and aircraft measurements made during the 1981-82 SCPP field program in the California Sierra Nevada.

- Comparison of hourly and daily average snow accumulation and water equivalent precipitation predictions for the 30 March 1982 Sierra storm shows that the model predictions of total daily precipitation match observations closely.

- Model predictions of total daily precipitation averaged over 28 monitoring sites match observations to within 6 percent. The accuracy in simulating daily snowfall accumulation at six mountain weather stations is -30 percent. Overall accuracy in reproducing the hourly precipitation rates throughout the SCPP network on 30 March 1982 was 52.5 percent. Small bias (10.8 percent) in model predictions was found.

- The SANTA Model has potential as a tool in regional and local avalanche hazard forecasting. The use of a series of mesoscale and local scale snowfall forecasts coupled with synoptic forecast data, local observations and multiple regression formulas can provide useful quantitative information to develop local forecasts of direct-action avalanches.

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REFERENCES

Berg, N. H. 1986. "A Deterministic Model for Snowdrift Accumulation." Proceedings of the International Snow Science Workshop, Lake Tahoe, California, 22-25 October.

Colton, D. E. 1976. "Numerical Simulations of the Orographically Induced Precipitation Distribution for Use in Hydrologic Analysis." Journal of Applied Meteorology, Vol. 15, No. 12, pp. 1241-1251.

Fraser, A. B., R. C. Easter, and P. V. Hobbs. 1973. "A Theoretical Study of the Flow of Air and Fallout of Solid Precipitation Over Mountainous Terrain: Part I. Airflow Model." Journal of the Atmospheric Sciences, Vol. 30, pp. 801-812.

Hayes, P. S. 1986. "A Simple Orographic Precipitation Model for the Pacific Northwest." Proceedings of the International Snow Science Workshop. Lake Tahoe, California, 22-25 October.

Heggli, M. F., L. Vardiman, and A. Huggins, 1983. "Supercooled Liquid Water and Ice Crystal Distributions Within Sierra Nevada Winter Storms," Journal of Climate and Applied Meteorology, Vol. 22, No. 11, pp. 1875-1886.

Judson, A. 1976. "Colorado's Avalanche Warning Program." Weatherwise, Vol. 29, No. 6, pp. 268-277.

Killus, J. P., et al. 1977. "Continued Research in Mesoscale Air Pollution Simulation Modeling: Volume V: Refinements in Numerical Analysis, Transport, Chemistry, and Pollutant Removal." Report to the U.S. Environmental Protection Agency, Research Triangle Park, NC, by Systems Applications, Inc., San Rafael, CA (EPA No. 68-022216).

Lamb, D., et al., 1976. "Measurements of Liquid Water Content in Winter Cloud Systems Over the Sierra Nevada," Journal of Applied Meteorology, Vol. 15, pp. 763-775.

Lin, Y. L., R. D. Farley, and H. D. Orville. 1983. "Bulk Parameterization of the Snow Field in a Cloud Model." Journal of Climate and Applied Meteorology. Vol. 22, pp. 1065-1092.

Marwitz, J. D. 1987. "Deep Orographic Storms Over the Sierra Nevada. Part I: Thermodynamic and Kinematic Structure." Journal of the Atmospheric Sciences. Vol. 44, No. 1, pp. 159-173.

Marwitz, J. D. 1987. "Deep Orographic Storms Over the Sierra Nevada. Part II: The Precipitation Processes." Journal of the Atmospheric Sciences, Vol. 44, No. 1, pp. 174-185.

Orville, H. D., and F. J. Kopp. 1977. "Numerical Simulation of the History of a Hailstorm." Journal of the Atmospheric Sciences, Vol. 34, pp. 1596-1618.

Penniman, D. 1986. "The Alpine Meadows Avalanche Trial: Conflicting Viewpoints of the Expert Witnesses." Proceedings of the International Snow Science Workshop, Lake Tahoe, California, 22-25 October.

Plooster, M. N., and N. Fukuta. 1975. "A Numerical Model of Precipitation From Seeded and Unseeded Cold Orographic Clouds." Journal of Applied Meteorology, Vol. 14, pp. 859-867.

Rhea, J. O. 1975. "A Simple Orographic Precipitation Model for Hydrological and Climatological Use." Conference on Analysis of Precipitation for Hydrological Modeling, American Geophysical Union, Davis, CA.

Rhea, J. O. 1978. "Orographic Precipitation Model for Hydrometeorological Use." Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado.

SCPP, 1982. "Project Skywater Data Inventory, 1981-1982 SCPP Season." Sierra Cooperative Project, U.S. Bureau of Reclamation, Denver, CO.

Smolarkiewicz, P. K. 1983. "A Simple Positive-Definite Advection Scheme with Small Implicit Diffusion." Monthly Weather Review, Vol. III, pp. 479-486.

Tesche, T. W. 1987. "Comparison of Two Numerical Schemes for Integrating the Atmospheric Diffusion Equation: Evaluation With Atmospheric Data." International Journal of Mathematical Modeling. Vol. 9, No. 7, pp. 507-519.

Tesche, T. W., J. L. Haney, and R. E. Morris. 1987. "Performance Evaluation of Four Grid-Based Dispersion Models in Complex Terrain." Atmospheric Environment. Vol. 21, No. 1, pp. 233-256.

Tesche, T. W., and M. A. Yocke. 1978. "Numerical Modeling of Wind Fields Over Mountainous Regions in California." Proceedings Conference on Sierra Nevada Meteorology, American Meteorological Society, South Lake Tahoe, California, 19-21 June.

Tesche, T. W., and M. A. Yocke. 1977. "Application of Mountain Wind Models to Snow Avalanche Forecasting." Proceedings of the Avalanche Workshop, National Research Council of Canada, Banff, Alberta, Canada, 1-4 November.

Williams, K. 1980. "Weather and Avalanche Forecasting: Where Do We Stand?" Proceedings of the Avalanche Workshop, National Research Council of Canada, Vancouver, BC, 3-5 November.

Young, C. Y. 1974. "A Numerical Simulation of Wintertime, Orographic Precipitation: Part II. Description of Model Microphysics and Numerical Techniques." Journal of the Atmospheric Sciences, Vol. 31, pp. 1735-1748.