DOE/ER/61078--T2

FIELD, LABORATORY, AND MODELING STUDIES OF WATER INFILTRATION AND RUNOFF IN SUBFREEZING SNOW ON REGIONAL SCALES TO ESTIMATE FUTURE GREENHOUSE-INDUCED CHANGES IN SEA-LEVEL

Final Report to Department of Energy
Office of Carbon Dioxide Research
Research and Results from Grant No. DE-FGO2-90ER61078

Project Summary from Original Proposal

Our current DOE-supported research program ("Reduce Uncertainty in Future Sea-Level Change Due to Ice Wastage") addressed the question of how the refreezing of meltwater in cold snow affects sea-level changes in a future changing climate. That program approached modeling of water flow in cold snow on scales from the grain scale (millimeters) to the macroscopic scale (10 centimeters), following other porous media approaches and much of the previous work on snow. Modeling at this scale provided insight into the physics of coupled water flow, phase change, and heat conduction which must be the foundation of larger scale modeling efforts. The continuation of that research, proposed here, takes an additional new approach by focussing on processes which can be defined and characterized by measurements on regional scales (kilometers). This new emphasis is intended to be directly applicable to a large-scale analysis from which runoff forecasts (and consequent sea level change) from the entire arctic region can be made.

The research proposed here Greenland addresses the problem of forecasting future sea-level change due to "greenhouse"-induced changes in runoff from polar glaciers and ice caps. The objectives of this work are 1) to observe in ~~the field~~ the processes of infiltration and refreezing which lead to the formation of impermeable firn layers, 2) to reproduce these observed processes in the laboratory to confirm and further quantify our understanding, 3) to develop and calibrate a regional scale numerical model which can simulate these processes, based on measured parameters and driven by boundary conditions determined by climate, and 4) to apply this model to predict the development of impermeable firn (and consequent runoff and discharge to the ocean) in response to predicted future climate change.

Activities During Project Period 8/15/90 to 8/14/93

Our stated objectives at the outset of our 1990-1993 snow hydrology project reflected the pressing unknowns at the end of our previous 1987-1990 project. Most significantly, these objectives included large-scale modeling of runoff which do not require explicit grain-scale information, and using field and laboratory experiments to develop a better understanding of complex heterogeneous flow processes such as piping and layering. Our accomplishments toward these ends are summarized here, broken down by categories of field, laboratory and modeling.

Field Studies

1991 Greenland

A field traverse was conducted between elevations of 1800 and 1600 m on the EGIG line in West Greenland during August 1991. This was a surface traverse conducted by three of us (W. T. Pfeffer, N. H. Humphrey (University of Wyoming), and D B. Bahr) in collaboration with R. J. Braithwaite of the Geological Survey of Greenland (GGU). The function of the traverse was to sample snow stratigraphy along an elevation transect which includes the transition from percolation to wetted facies and the superimposed ice facies. The traverse was also coordinated with a NASA program to obtain airborne SAR imagery on the EGIG line. This imagery contains information in the long wave length P (68 cm), L (24 cm), and C (5.6 cm) bands which reveal kilometer-scale structures which are probably the product of variations in grain and water content structure in the

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top meter of firn. Results from this field project are included in Braithwaite and others (in press), and Pfeffer and others ("Firn structure and airborne SAR... , in preparation). This project also provided data on lateral heterogeneity of firn structure on various length scales to be used as input to stochastic-based models.

1992 Greenland

Field work was concentrated at a single site in West Greenland in 1992, for the purpose of examining the processes of ice piping and layering, using techniques which we developed at Mer de Glace Agassiz during our work in 1988 and 1989. This project included W. T. Pfeffer, and N. H. Humphrey and D. Horning (both University of Wyoming), and was done in collaboration with Ole' Olesen of GGU. The work was staged from GGU's Tasersiaq Research Station. This project gave us a great deal of insight into critical issues concerning the processes of ice pipe formation and interaction with ice layers, and conditions favoring piping and lensing. We also were able to better answer questions which arose in 1991 about the relation of initial firn temperature to the predominance of piping over wetting (this is discussed in Braithwaite and others, in press), and the question raised in Pfeffer and others (1991, Journal of Geophysical Research) of whether or not an impermeable horizon is required to accomplish downslope transport. Results from this work are discussed in Pfeffer and Humphrey ("The determination of timing and location of water movement..., in preparation). This work was submitted to the Journal of Glaciology in May 1994.

Laboratory Studies

Laboratory experiments have been made to test the method of detecting refreezing amounts through temperature measurements, as presented in Pfeffer and others ("The determination of timing and location of water movement... , in preparation). A series of experiments have been made in which snow of known grain size and density is subjected to surface heating at a controlled rate and timing. Temperatures are measured at several depths in the snow and the spatial and temporal temperature gradients are then used to evaluate magnitudes of the pertinent modes of heat transfer. The laboratory environment allows us to duplicate this method, designed for field use, under conditions where the modes of heat transfer, unknown in the field, are under our control. These experiments are still in process with undergraduate support. Data from current experiments are included in the data report supplied to the Oak Ridge Laboratory (attached).

Modeling Studies

The objectives of the modeling studies were: (1) to develop new and improve existing point scale models to simulate the physical processes of meltwater generation, water infiltration and freezing in a layered subfreezing snowpack, (2) to determine the effective parameters which need to be used in the simulation of the above processes in the regional (Greenland Ice Sheet) scale and (3) develop and apply a regional scale model to make predictions on annual meltwater runoff to the ocean from the Greenland Ice Sheet.

Development of point scale model

The equations governing the basic physical processes were developed from basic principles. The model uses the Stefan condition as an independent governing equation on the exterior moving boundary (snow surface) to calculate the snowpack thinning, the flow of water through a variably saturated layered porous medium, and heat conduction with phase change.

The heat conduction was further separated and treated in two ways: the local heat conduction between every single snow grain and its surrounding water film and the global heat conduction with phase change. In order to handle several moving boundaries within the snow pack, a specific form of enthalpy formulation was used for heat conduction with phase change. The governing equations were solved in a two-dimensional domain, using the finite element method.

Determination of effective parameters
In this part of the study we focused on the formulation of regional equations of water infiltration and heat transfer, definition and evaluation of effective parameters, and evaluation of uncertainties of output variables. Both perturbations and Monte Carlo methods were used for conditions of dry-snow, soaked-snow, and percolation-snow facies zones in the Greenland ice sheet. The point scale model was used in the Monte Carlo simulations. The results showed that the effects of the heterogeneity on the regional phenomena of mass and heat transfer are small and can be neglected, if the scales of spatial variations in snow properties are much less than the scale of the domain to be considered. The regional average values of the parameters can be used as the effective parameters.

Regional scale model
An efficient regional model was developed to simulate runoff processes from the Greenland ice sheet, based on the parameter evaluation. The model was applied using limited field data. The simulation results showed that the total runoff from the Greenland ice sheet is about 123 km^3/yr under the current climatic conditions, which is equivalent to 0.34 mm/yr rise of sea level. Sensitivity analysis showed that the solar radiation, annual air temperature, snow grain size, and slope of ice layers are the most important parameters controlling runoff. If annual air temperature increase by 4.5 degree C for a doubling of concentration of CO_2, the annual runoff production is 150 km^3/yr.

Results of the modeling studies are presented in two papers by P.-H. Tseng and others (in press and in review), and in two papers by Jianhua Zou and others (in preparation).

Publications

1. Modeling of Snow Melting and Uniform Wetting Front Migration in Layered Subfreezing Snowpack. P.-H. Tseng, T. H. Illangasekare, and M. F. Meier. Water Resources Research, Vol. 30, No. 8, Pages 2363-2376. 1994

2. Retention of Greenland runoff by refreezing: implications for projected future sea level change. W. T. Pfeffer, M. F. Meier, and T. H. Illangasekare. Journal of Geophysical Research, Vol. 96, No. C12, Pages 22,117-22,124. 1991

3. Ice, Climate, and Sea Level; Dow We Know What is Happening? M. F. Meier. in NATO ASI Series, Vol I 12. Ice in the Climate System. ed W. Richard Peltier. Berlin, Springer-Verlag. 1993.

4. Modeling of Meltwater Infiltration of Subfreezing Snow. T. H. Illangasekare, R. J. Walter, Jr., M. F. Meier and W. T. Pfeffer. Water Resources Research, Vol. 26, No.5, Pages 1001-1012. 1991

5. Analysis and Modeling of Melt-Water Refreezing in Dry Snow. W. T. Pfeffer, T. H. Illangasekare and M. F. Meier. Journal of Glaciology, Vol. 36, No. 123, Pages 238-246. 1990

Theses

1. A Numerical Model for Fluid Flow and Heat Transfer in Subfreezing Snow. Rodney J. Walter, M.S. Thesis, Dept of Civ., Environ., and Architect. Eng., Univ. of Colo., Boulder, 1988.

2. The finite element method for snow melting and water infiltration in a layered subfreezing snowpack. Peng-Hsiang Tseng. Ph.D. Thesis, Dept of Civ., Environ., and Architect. Eng., Univ. of Colo., Boulder, 1991.

3. A Regional Scale Model for Meltwater Generation, Infiltration, and Runoff from the Greenland Ice Sheet. Jianhua Zou. Ph.D. Thesis, Dept of Civ., Environ., and Architect. Eng., Univ. of Colo., Boulder, 1994.

Papers in Preparation

1. A 2-D Finite Element Method for Water Infiltration in a Subfreezing Snowpack with a Moving Surface Boundary during Melting. (Advances in Water Resources, in review) by P.-H. Tseng, T. H. Illangasekare, and M. F. Meier

2. Modeling of Snowmelting and Evolution of High-Density Layers due to Meltwater Refreezing. (Abstract submitted to EGS XIX General Assembly) by P.-H. Tseng, T. H. Illangasekare, and M. F Meier

3. Stochastic analysis of snow melting and meltwater infiltration, Paper in preparation, by Jianhua Zou, T. H. Illangasekare, M. F. Meier and W. T. Pfeffer.

4. A regional scale study of snow melting, meltwater infiltration and runoff of the Greenland ice sheet, Paper in preparation, by Jianhua Zou, T. H. Illangasekare, M. F. Meier and W. T. Pfeffer.

5. The determination of timing and location of water movement and ice layer formation by snow temperature measurements in subfreezing firn. Paper in preparation, by W. T. Pfeffer and N. F. Humphrey

6. Firn structure and airborne SAR imagery on the western EGIG line, Greenland. Paper in preparation, W. T. Pfeffer, N. F. Humphrey, M. Fahnestock

7. Spatial and temporal temperature structure in high Arctic firn. Paper in preparation, W. T. Pfeffer

8. Variations of near-surface firn density in the lower accumulation area of the Greenland Ice Sheet, Pakitsoq, West Greenland. R. J. Braithwaite, M. Laternser, W. T. Pfeffer. Journal of Glaciology, in press.