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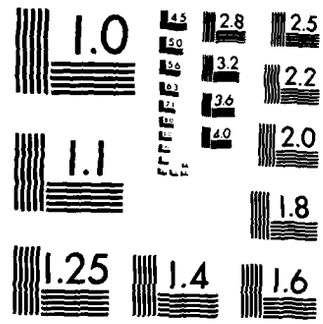

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The primary objective of this research was the development of a basic scientific understanding of frazil and anchor ice including their formation, growth, characteristics, and evolution in form and dynamics and their role in the development of the initial ice cover on a river. Interpretation of these data were directed toward developing an understanding of the physics of freeze-up as it involves frazil and anchor ice.

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Cover figure. Frazil ice floes in the Yukon River generated by the compaction, extrusion flow and drag cut-off mechanism. These extremely large floes exceed 1 km in horizontal dimensions. Cut-off appears to be partially controlled by river geometry. These floes play an important role in the initiation of ice jams during freeze-up on the river.

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FINAL REPORT

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   i) Osterkamp, T. E. and J. P. Gosink, Frazil ice formation and ice cover development in interior Alaska streams, Cold Regions Science and Technology, 8, pp. 43-56, 1983.

   ii) Osterkamp, T. E., R. E. Gilfilian, J. P. Gosink and C. S. Benson, Water temperature measurements in turbulent streams during periods of frazil-ice formation, Annals of Glaciology, 4, pp. 209-215, 1983.

   iii) Gosink, J. P. and T. E. Osterkamp, Measurements and analyses of velocity of velocity profiles and frazil ice crystal rise velocities during periods of frazil ice formation, Annals of Glaciology, 4, pp. 79-84, 1983.

   iv) Gosink, J. P., Exact solutions for the temperature distribution in a river downstream from a dam or reservoir, submitted to Water Resources Research, 1984.

   v) Osterkamp, T. E. and J. P. Gosink, Ice cover development on interior Alaska streams, Report No. UAGR-293, Geophysical Institute, University of Alaska, Fairbanks, Alaska, 1983.

   vi) Osterkamp, T. E. and J. P. Gosink, Selected aspects of frazil ice formation and ice cover development in turbulent streams, Paper presented at the Workshop on the Hydraulics of Ice-Covered Rivers, Edmonton, Alberta, Canada, June 1-2, 1982.

   vii) Osterkamp, R. E. Gilfilian, J. P. Gosink and C. S. Benson, Water temperature measurements in turbulent streams during periods of frazil ice formation, Paper presented at the Second Symposium on Applied Glaciology, Hanover, NH, August 23-27, 1982.

   viii) Gosink, J. P. and T. E. Osterkamp, Measurements and analyses of velocity profiles and frazil ice crystal rise velocities during periods of frazil ice formation on rivers, Paper presented at the Second Symposium on Applied Glaciology, Hanover, NH, August 23-27, 1982.

ix) Gosink, J. P., T. E. Osterkamp, and P. A. Hoffman, Modeling of ice covered lakes, Poster session presented at Frontiers in Hydrology Specialty Conference of ASCE, M.I.T., Cambridge, Massachusetts, August 1983.

8. Scientific personnel supported by this project and degrees awarded during this reporting period:

Scientific personnel:

T. E. Osterkamp
J. P. Gosink

Graduate student:

Philip Hoffman (graduate student in Arctic Engineering, Master's degree program; work commitments have delayed completion of his degree)

Final Report

An Investigation of Frazil and Anchor Ice: Formation, Properties, Evolution and Dynamics

Considerable effort has been expended in the investigation of annual ice covers. However, most of this work has been directed toward understanding the nature of the ice cover after it has been fixed in place and prior to its disintegration. The most dynamic periods of time for annual ice covers are during their periods of formation and decay with the growth period being relatively quiet. These periods of formation and decay are also the most difficult to study, with the difficulties largely associated with extreme environmental conditions and the dynamic nature of the processes involved. The primary objective of this research was the development of a basic scientific understanding of frazil and anchor ice including their formation (nucleation or sources), growth, characteristics, and evolution in form and dynamics and their role in the development of the initial ice cover on a river. Interpretation of these data were directed toward developing an understanding of the physics of freeze-up as it involves frazil and anchor ice. This information will be useful to engineers seeking solutions to frazil and anchor ice problems.

One method of analyzing frazil ice and anchor ice dynamics involves the use of photography. This method allows both quantitative and qualitative measurements to be made, besides providing insight into the basic physical mechanisms. A number of observations of frazil ice formation in turbulent streams in interior Alaska have been documented with photographs. These include photographs of cooling conditions, frazil discs, anchor ice, edge ice, flocs, pans, snow slush and floes. Photographs of the observed hydrological conditions that lead to the production of large frazil ice floes and frazil ice jams were also compiled.

These observations suggest that convective heat transfer and surface roughness may increase heat loss in a turbulent stream relative to a calm water surface. Photographs have been obtained that show two of the potential frazil ice nucleation mechanisms proposed by Osterkamp (1975), ejection of small water droplets into the cold air above the stream and mechanical fragmentation of frazil ice crystals in the stream. Underwater photographs of in situ frazil ice crystals show that their diameters range from 0.1 to 1 mm with concentrations ranging from 10^4 to 10^6 or 10^7 discs per m^3 of water. The discs become scalloped when they reach 3-5 mm in diameter.

Three growth mechanisms for anchor ice have been identified: free growth, growth by accumulation on objects in the flow and growth by a layering process. Anchor ice attaches to bottom sediments which can subsequently become buoyant thus transporting the sediments downstream. Frazil discs evolve into frazil flocs and then into frazil pans or slush depending on the water turbulence. The frazil pans, consisting of platy and granular grains a few mm in cross-section, can exceed 2 m in diameter and 1 m in thickness on the Tanana River and may exceed 10 m in diameter on the Yukon River.

Three mechanisms for edge ice growth have been identified: free growth, growth by conductive heat transfer through the ice and growth by accumulation.

Large frazil ice floes are produced by at least five mechanisms: (1) contact, penetration and bonding, (2) compaction and drag cut-off, (3) compaction and convergent flow with cut-off provided by impact of incoming pans, (4) extrusive flow with drag cut-off, and (5) agglomeration with cut-off controlled primarily by river curvature.

Frazil ice jams can be initiated by jamming of frazil flocs, frazil pans an/or large frazil floes. The jams usually occur in stream sections where the flow velocity is low, where the stream is constricted by edge ice growth

and/or where radius of the curvature is small. Frazil ice jams formed during the extrusive flow of pans or floes through narrow stream reaches are the most common. The resulting ice cover consists of frazil ice and sheet ice with wide variations in thickness.

Frazil ice concentrations can significantly affect river velocity and discharge by altering the effective viscosity of the river. The frazil ice is will-mixed initially at low concentrations and in turbulent river reaches, and stratifies into a two-layer water and ice flow in more quiescent reaches. By means of a time-scale analysis, we have determined a criterion for distinguishing between well-mixed and stratified flow. A buoyant time scale, T_B, represents the time required for a frazil crystal to rise buoyantly from the river bottom to the water surface, and a diffusive time scale, T_D, represents the time required for a frazil crystal to be transported by turbulence through the depth. The ratio of the time scales, T_B/T_D, defines the nature of the layering process; in particular if $T_B/T_D < 1$, then buoyant forces will lift a frazil crystal much faster than turbulent diffusion can redistribute it and the flow will be layered. Conversely, if $T_B/T_D > 1$, turbulent mixing will proceed faster than buoyant lifting and the flow will be well mixed. For frazil particles of diameter 2 mm or more, this ratio corresponds to "rule of thumb" velocity criteria developed in Norway and Canada to distinguish layered frazil ice-water flow from well-mixed flow.

The development of this theory depends in large part upon the determination of the buoyant time scale, which in turn depends upon the rise velocity of frazil ice crystals. A simple force-balance model was developed for the rise velocity for a frazil crystal. Field observations during frazil ice formation in Goldstram Creek and in the Chatanika River north of Fairbanks were made, including a series of measurements of frazil ice crystal rise

velocities. Typical frazil particle size was about 2 mm with a rise velocity of about 10.0 mm sec^{-1}.

A knowledge of the water temperature in turbulent streams during periods of frazil ice formation can be used to increase our understanding of heat losses, supercooling, frazil ice nucleation, frazil ice growth and other processes and parameters associated with frazil ice formation. However, very few in situ measurements of water temperature during periods of frazil ice production have been reported. This situation is surprising in view of the fact that frazil ice appears to be the dominant ice form occurring in turbulent streams in Alaska as well as in other northern regions.

Field measurements of water temperatures in turbulent streams in interior Alaska were made during periods of frazil ice production. The measured equilibrium temperature of the water, $T_c \approx -0.005°C$, agrees with the value calculated from the electrical conductivity of the water. Average cooling rates during the summer-to-fall stream cooling period are on the order of several tenths of a degree per day with average surface heat losses of -5 to -18 W/m^2. Just prior to a frazil event the water cooling rates were -1 to -3 mK/min with corresponding surface heat losses of -47 to -140 W/m^2. Supercooling at the water surface of a stream prior to and during periods of frazil ice production does not exceed 0.2°C as shown by measurements of air-water temperature profiles and by radiometer measurements. Water supercooling at the time of frazil ice nucleation was < 10 mK. These measurements show that frazil ice nuclei in streams must be other ice particles, cold organic materials, cold soil particles or a combination of these that may be introduced into the stream by mass exchange processes at the air-water interface.

The maximum observed supercooling was $\Delta T_m \approx 40$ mK. Two measured values or the residual supercooling were 3 to 9 mK. These observed values of upercooling suggest that most of the frazil ice production during a night of upercooling occurs in a relatively short time span near the time of maximum upercooling, t_m, unless the period of residual supercooling is very long.

Additional field measurements have been made of both anchor ice and edge ce formation and growth. Analyses of these data are continuing. Finally, xperiments and ideas for analyzing freeze-up and break-up processes involving he application of newly acquired instrumentation were devised. The nstrumentation includes a remote sensing package which will allow extensive ata sets to be acquired, such as ice floe frequency, size and velocity, river ater and ice flow temperature, air temperature and surface heat exchange, and iver curvature and geometry. This information could be used in analyses of ce floe generation mechanisms, ice jam dynamics, and river thermal regime uring break-up. Additional instrumentation includes a cold room outfitted as hydraulics laboratory for turbulence-frazil ice experiments, and a computer ystem for data acquisition and analysis. In short the instrumentation opens p new potentials for river ice research, both in the field and in the aboratory.

FRAZIL ICE FORMATION AND ICE COVER DEVELOPMENT IN INTERIOR ALASKA STREAMS

T. E. Osterkamp and J. P. Gosink

Cold Regions Science and Technology, 8(1983)43-56

ABSTRACT

A number of photographs are presented which illustrate selected aspects of frazil ice formation in turbulent streams in Interior Alaska. These include the various forms of frazil ice found in turbulent streams and the processes involved in the development of an ice cover on the streams. All of the photographs depict frazil ice under field conditions. They include photographs of cooling conditions, frazil discs (both in situ and removed from the stream), anchor ice, edge ice, frazil flocs, frazil pans, snow slush, and frazil floes. Photographs of hydrological conditions that lead to the production of large frazil ice floes and of different types of frazil ice jams are also included. These photographs provide visual documentation of the key role that frazil ice plays in ice cover development on turbulent streams in Interior Alaska.

WATER TEMPERATURE MEASUREMENTS IN TURBULENT STREAMS DURING PERIODS OF FRAZIL-ICE FORMATION

BY

T. E. Osterkamp
R. E. Gilfillian
J. P. Gosink and C. S. Benson

Annals of Glaciology 4 1983

BSTRACT

Field measurements of water temperatures in two turbulent streams in nterior Alaska have been made during periods of frazil-ice production. he measured equilibrium temperature of the water, $T_e \approx -0.005°C$ agrees ith the value calculated from the electrical conductivity of the water. verage cooling rates of the sreams during the summer-to-fall stream ooling period were on the order of several tenths of a degree per day ith average surface heat losses of -5 to -18 W m^{-2}. Just prior to a razil-ice event, the water cooling rates were -1 to -3 mK min^{-1} with surface eat losses of -47 to -140 W m^{-2}. Supercooling at the water surface of a tream prior to and during frazil-ice production does not exceed 0.2°C as hown by measurements of air-water temperature profiles and by radiometer easurements. Water supercooling at the time of frazil-ice nucleation as < 10 mK. These measurements show that frazil-ice nuclei in streams ust be other ice particles, cold organic materials, cold soil particles r a combination of these, that may be introduced into the stream by mass xchange processes at the air-water interface.

The maximum observed supercooling was $\Delta T_m \approx 40$ mK. Two measured for the residual supercooling were 3 and 9 mK. Frazil growth rates alculaced from the observed values of supercooling show that, unless the eriod of residual supercooling is very long, most of the frazil-ice roduction during one night of supercooling occurred in the transient hermal period from the time of nucleation to the time that the water ecame residually supercooled.

MEASUREMENTS AND ANALYSES OF VELOCITY PROFILES AND FRAZIL ICE-CRYSTAL RISE VELOCITIES DURING PERIODS OF FRAZIL-ICE FORMATION IN RIVERS

by

J. P. Gosink and T. E. Osterkamp

Annals of Glaciology 4 1983

ABSTRACT

The vertical concentration distribution of frazil-ice crystals in a stream during the formation and growth of frazil ice was discussed in a preliminary way by Gosink and Osterkamp (1981). This paper extends and completes the analysis of buoyant rise velocities of frazil-ice crystals and applies the results to an interpretation of measured velocity profiles in rivers during frazil-ice events. Additional experimental data are also presented. Two time scales are defined: the buoyant time scale T_B, which represents the time required for a frazil crystal to rise, buoyantly, from the river bottom to the water surface, and the diffusive time scale T_D, which represents the time required for a frazil crystal to be transported by turbulence through the depth. It is shown that the ratio of the time scales T_B/T_D defines the nature of the layering processes; in particular, if $T_B/T_D < 1$, then buoyant forces will lift a frazil crystal faster than turbulent diffusion can redistribute it and the flow will be layered. Conversely, if $T_B/T_D > 1$, turbulent mixing will proceed faster than buoyant lifting and the flow will be well-mixed. This ratio, for frazil particles of diameter 2 mm or more, corresponds to rule-of-thumb velocity criteria developed in Norway and Canada to distinguish layered frazil-ice/water flow from well-mixed flow.

The development of this theory depends in large part upon the determination of T_B, which depends upon the rise velocity of frazil-ice crystals. A force balance model was developed for the rise velocity of a frazil crystal. Field observations during frazil-ice formation in Goldstream Creek and in the Chatanika River north of Fairbanks are reported, including a series of measurements of the rise velocities of frazil-ice crystals. Typical particle size of frazil ice was about 2 mm with a rise velocity of about 10.0 mm s^{-1}. The agreement of measured rise velocities with the theoretical model is good considering uncertainties in the drag coefficient and in the determination of frazil crystal sizes under field conditions.

Velocity profiles in the Chatanika River and in Goldstream Creek during frazil formation suggest that the time-scale ratio may serve as a transition criterion between layered frazil-ice/water and well-mixed flow. This ratio was calculated with the rise velocity for frazil-ice crystals arbitrarily chosen to be 0.01 m s^{-1}.

EXACT SOLUTIONS FOR THE TEMPERATURE DISTRIBUTION IN A RIVER DOWNSTREAM FROM A DAM OR RESERVOIR

by

J. Gobink

Submitted to Water Resources Research

ABSTRACT

The construction of a dam or reservoir affects the thermal regime in the river downstream from the dam. The water released will be warmer in winter and colder in summer than under pre-construction conditions. Prediction of the river temperatures is of importance to fisheries and farming in the region. In winter, this knowledge is necessary for the determination of the open water length, and the location of the ice front.

The heat released from the dam is advected downstream, and dispersed in the flowing water which is subjected to heat transfer at the water surface. Heat transfer across the air-water interface varies because of diurnal, episodic and seasonal fluctuations in air temperature and radiation. Analytical solutions of the governing equations describing the transient convective and diffusive transport of thermal energy in a river subject to arbitrary combinations of periodic surface heat exchange are presented in this paper. These analytic solutions can be used to calculate temporal and spatial variations in river temperature for a wide variety of time-varying atmospheric conditions. These may also be used to test the reliability of numerical models of river temperature.

Ice Cover Development on Interior Alaska Streams

by

T. E. Osterkamp and J. P. Gosink

Report No. UAGR-293
Geophysical Institute
University of Alaska

ABSTRACT

A number of photographs are presented which illustrate selected aspects of frazil ice formation in turbulent Interior Alaska streams. These include the various forms of frazil ice found in turbulent streams and the processes involved in the development of an ice cover on the streams. All of the photographs depict frazil ice under field conditions. They include photographs of cooling conditions, frazil discs (both in-situ and removed from the stream), anchor ice, edge ice, frazil flocs, frazil pans, snow slush, and frazil floes. Photographs of hydrological conditions that lead to the production of large frazil ice floes and of different types of frazil ice jams are also included. These photographs provide visual documentation of the key role that frazil ice plays in ice cover development on turbulent streams in Interior Alaska.

Selected Aspects of Frazil Ice Formation and Ice Cover Development in Turbulent Streams

by

T. E. Osterkamp and J. P. Gosink

Paper presented at the
Workshop on Hydraulics of Ice-Covered Rivers
Edmonton, Canada, June 1-2, 1982

ABSTRACT

Several field investigations of frazil ice formation in Alaskan streams during the period of freeze-up are used to review selected aspects of processes and events associated with frazil ice formation and ice cover development in turbulent streams. They include modification of the water cooling process by fog and a turbulent air-water interface, presence of airborne ice crystals, frazil multiplication by secondary nucleation, morphology and nature of frazil discs, frazil disc rise velocities, anchor ice formation, sediment transport by anchor ice, frazil flocs, frazil pans and slush, snow slush balls, frazil ice floes and the initiation of the ice cover by frazil ice jams. A large number of photographs of frazil ice, in various stages of its development, have been obtained during the course of these studies and will be used to illustrate the above processes.

MODELING OF ICE-COVERED LAKES

J. P. Gosink, T. E. Osterkamp, P. A. Hoffman
Geophysical Institute, University of Alaska

Abstract

The capability to predict water quality and thermal regime in northern lakes is essential for rational resource development in arctic and sub-arctic regions. Anthropogenic activities, whether in permafrost terrain or related to glacier-fed streams, present unique problems requiring the modeling of lake dynamics and thermodynamics throughout the year. For example, the temperature of the water released from a hydroelectric facility is necessary for fisheries management in both summer and winter and for prediction of the length of open water and the position of the ice front in winter.

The development of a lake model with the capability of simulating both summer and winter conditions presents specific problems requiring special consideration. Some of these include:

- the modeling of the gradual decoupling of wind forcing to lake dynamics as the ice coverage increases.
- significant changes in ice and snow thermal properties, including albedo, thermal conductivity, and light extinction coefficients.
- appropriate empirical models of surface heat transfer under Arctic conditions, for example, the low wind, unstable atmospheric convection over a cooling lake as depicted in Figure 6.

We have used the DYRESM model of Imberger et al. (1978) for temperate lakes as a basis for the development of an ice-covered lake model. This extension, referred to as DYRSMICE, has the capability of predicting ice cover formation, growth and decay, as well as the temperature regime under the ice. The model contains six adjustable constants for energy parameterization and diffusion and a drag coefficient for each inflowing river; these are held constant throughout the simulation period. Measurements of daily meteorological

conditions, river inflow, and reservoir discharge are the only other input to the model.

Heat flux through the ice and snow covers is calculated by matching the snow and ice surface temperatures determined from the surface heat flux to the analytic solutions for conduction and radiation through the snow and ice layers. A portion of this energy flux, from the short-wave radiation, is stored in the snow, ice and upper water layers.

Presently an empirical formulation has been devised to simulate the gradual decoupling of wind stress from lake dynamics. Future research is necessary to improve this parametization.

DYRSMICE follows the organization and logic of DYRESM with respect to mixing dynamics. A form of the turbulent kinetic energy is solved which includes parametizations of the potential and kinetic energy exchange associated with convective overturn, wind stress, shear production and billowing.

DYRSMICE was tested with meteorological data plus inflow and discharge data available from Eklutna Reservoir in southwestern Alaska. Temperature profiles computed through summer and winter in Figures 7 through 14 are compared with measured temperature profiles. During the 1982-1983 observation period, thermocline deepening was relatively shallow, generally less than 10 m, and surface water temperatures did not exceed 15°C. The calculated temperature profiles reliably track the development and diminution of the thermocline. The intense mixing of late September-October is also well simulated by the model, as well as the subsequent ice cover growth.

The usefulness of the model for discharge temperature prediction, for biological studies and for water quality evaluation is readily apparent. Research addressing some of the more difficult problems associated with ice formation and growth is continuing.

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