The Influence of the Hydrologic Cycle on the Extent of Sea Ice with Climatic Implications

Semi-annual Progress Report: August 1991
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The overall objective of this project is to analyze the role of the hydrologic cycle on the distribution of sea ice, and its influence on forcings and fluxes between the marine environment and the atmosphere (Fig. 1). River discharge plays a significant role in degrading the sea ice before any melting occurs elsewhere along the coast. This investigation considers the influence of river discharge on the albedo, thermal balance and distribution of sea ice. Quantitative atmospheric-hydrologic models are being developed to describe these processes in the coastal zone. Input for the models will come from satellite images, hydrologic data and field observations. The resulting analysis will provide a basis for investigating the significance of the hydrologic cycle throughout the Arctic Basin and its influence on the regional climate as a result of possible future climatic scenarios. The area offshore from the Mackenzie River delta was selected as the study area (Fig. 2).

Image Analysis:

Sixteen Digital NOAA Advanced Very High Resolution Radiometer (AVHRR) images and one Landsat Thematic Mapper (TM) image have been acquired of the Mackenzie delta area (Appendix 1). Several years of AVHRR photographic images were reviewed to identify the year with the largest number of low cloud-cover images and individual scenes showing river and sea ice interactions. This search revealed that 1986 was the year with the most favorable cloud conditions and therefore fourteen images recorded between April and September were acquired . Two AVHRR data sets and a Landsat TM data set were also acquired in the spring of 1991 to coincide with field observations.

The satellite data have been processed to provide quantitative measurements and qualitative interpretations. The 1986 data have been subsectioned, geometrically corrected and radiometrically calibrated such that temperature can be read from the thermal images and albedo from

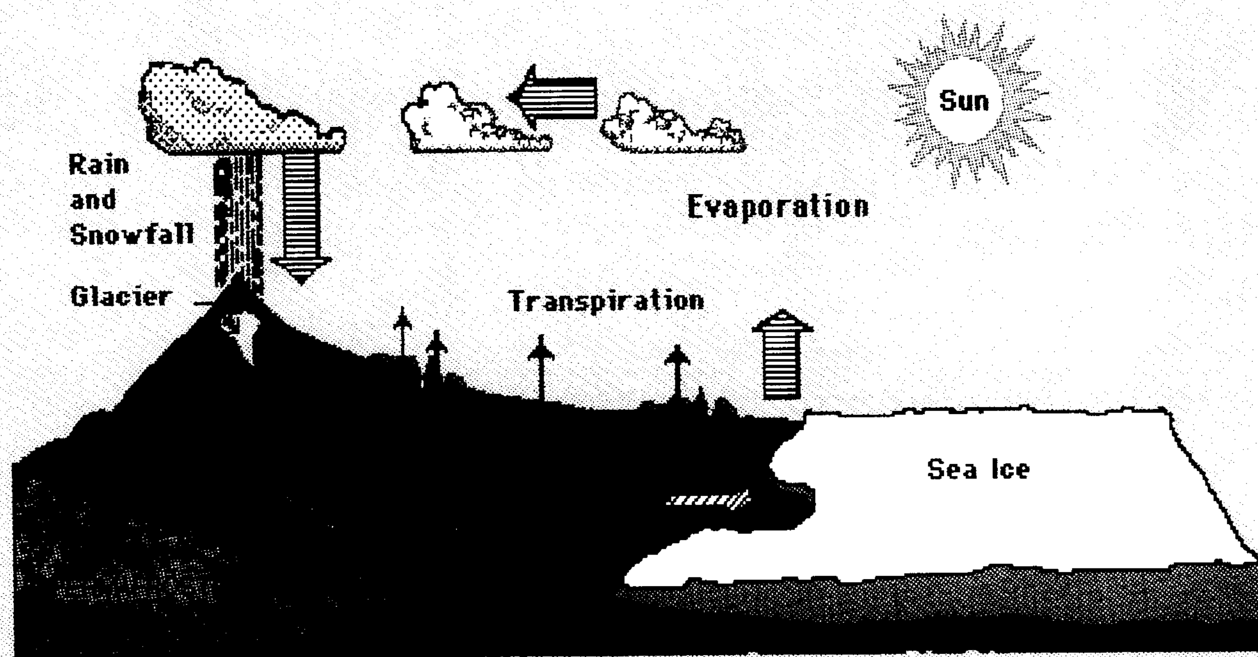
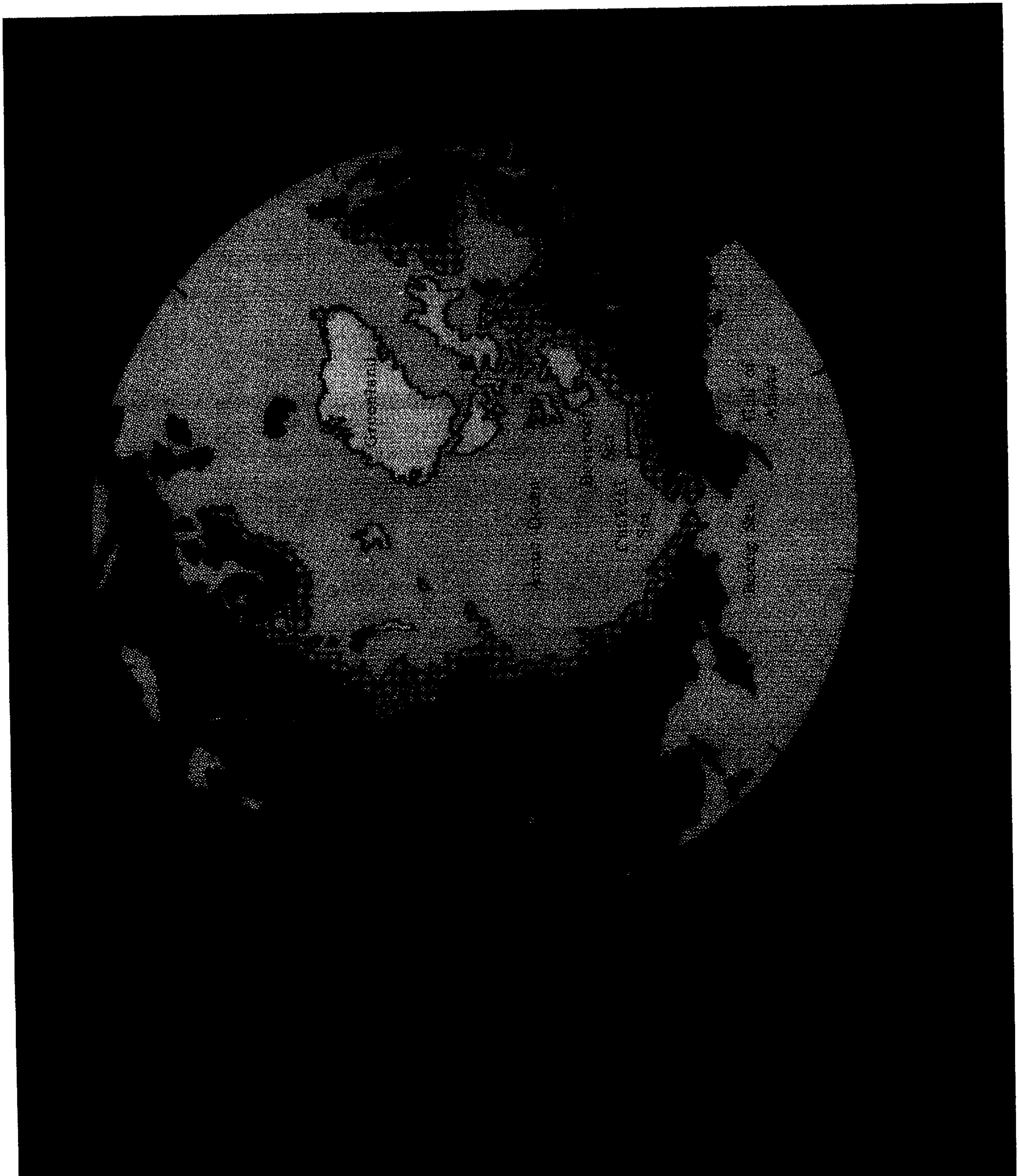


Figure 1. Conceptual model of the water cycle in the Arctic.

ORIGINAL PAGE
COLOR PHOTOGRAPH


Greenland

optical images. Land has been masked on these data and a digital coastline is being merged with the images.

The river and sea ice interactions have been analyzed using digital number (DN) level slicing techniques and the formation of color composites. Color was assigned to temperature and albedo ranges to form the level slices. These slices were applied to the visible band (band 1), near infrared band (band 2) and thermal infrared band (band 4) data. A standardized temperature range and color assignment was developed for the thermal data but not for the optical bands due to the magnitude of their data range. Custom slices were also developed for each of the three bands per scene of data that were analyzed. Color composites were formed using bands 1, 2 and 4 for qualitative assessment of cloud cover, sea ice and over ice flooding conditions.

Results from the analyses reveal differences in the temperature and albedo of ice, stream-ice overflows and on the sea surface. These differences vary both as a function of geography on individual images and seasonally as the summer progresses. These differences first become distinct on the 25 May image which shows that multi-year ice is approximately 5° C colder than shorefast ice in the vicinity of the delta. Shorefast ice away from the delta is approximately 2 degrees colder than ice near the delta. At the same time warmer river water has flowed over the sea ice offshore from the delta stream channels. The cold temperature of these overflows indicates that they are frozen at the surface at the time the image was recorded. The albedo of multi-year ice is lower than that of shorefast ice but the overflows have considerably lower albedo than sea ice.

By 4 June the overflows have grown considerably as seen on the color composite satellite image (Fig. 3) compared to the 25 May image and a large lead can be seen offshore. On the visible band image the albedo of the overflows is very low compared to the surrounding ice. The shorefast ice in the vicinity of the delta also has a lower albedo than much of the multi-year ice (Fig. 4). The thermal band shows that the ice has warmed considerably with multi-year ice at - 5° C, shorefast ice at -1° C and river overflows at 0° C (Fig. 5).

Overflows continue to grow and near shore ice completely thaws resulting in open water extending from shore to the multi-year ice edge in

Figure 3. AVHRR satellite image of the Mackenzie River delta, 4 June 1986. Black tongues of river water (lower center) can be seen overflowing shorefast ice adjacent to the delta and immediately offshore from major stream channels. An elongated body of open water (polynya) separates the shorefast ice from the multi-year ice. The image is a color composite of visible (band 1), near-infrared (band 2) and thermal infrared (band 4) data.

Figure 4. AVHRR visible band 1 satellite image of the Mackenzie River delta, 4 June 1986. The data have been level sliced to show the differences in albedo with purple as low and yellow as high. Overflows have considerably lower albedo than ice and land, and hence absorb incoming solar radiation and thus hasten the thawing of sea ice. As the extent of the overflows increase the thermal fluxes increase as recorded on sequential satellite images. Satellite albedo values will be used as input to the model and to calculate radiation flux.

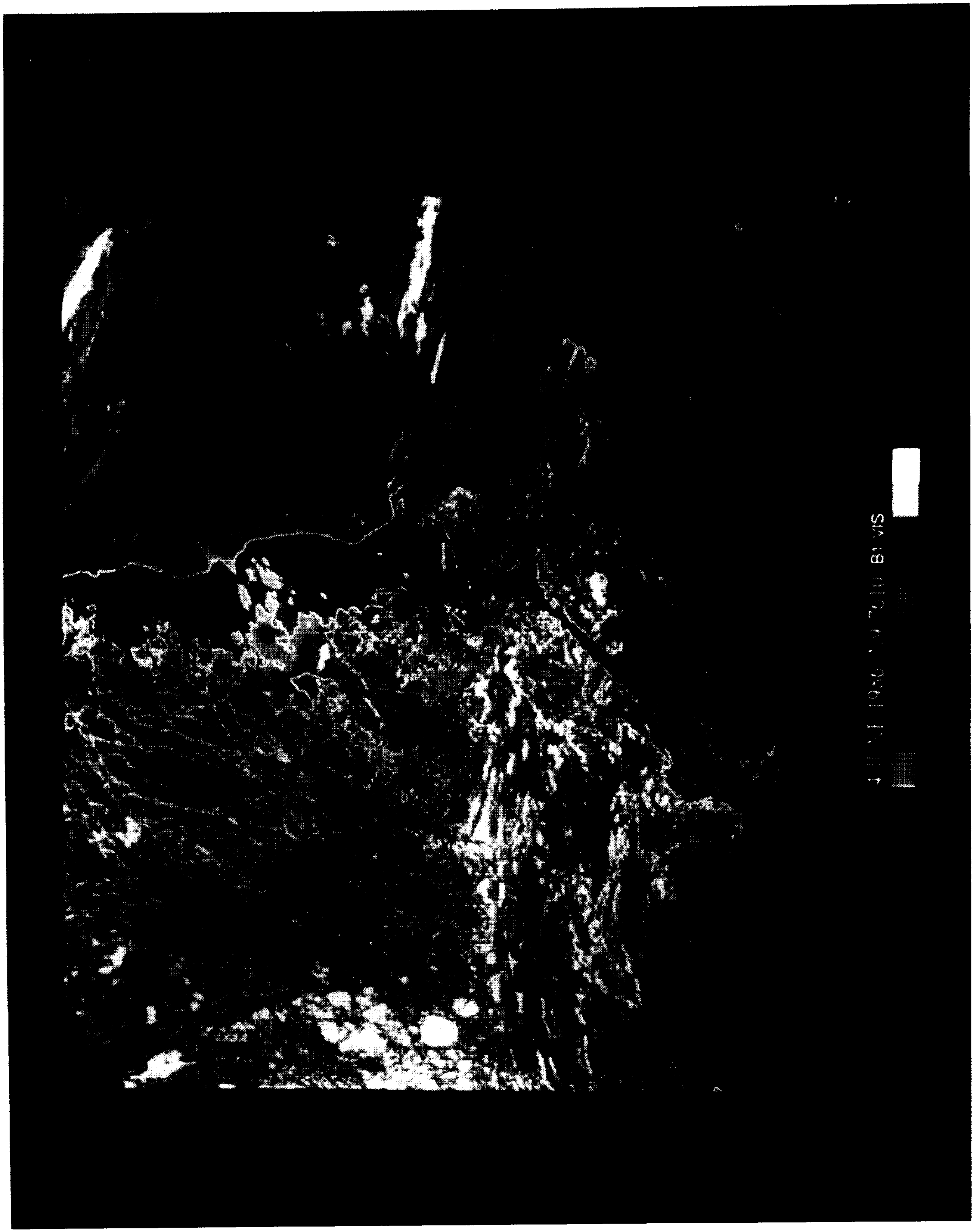


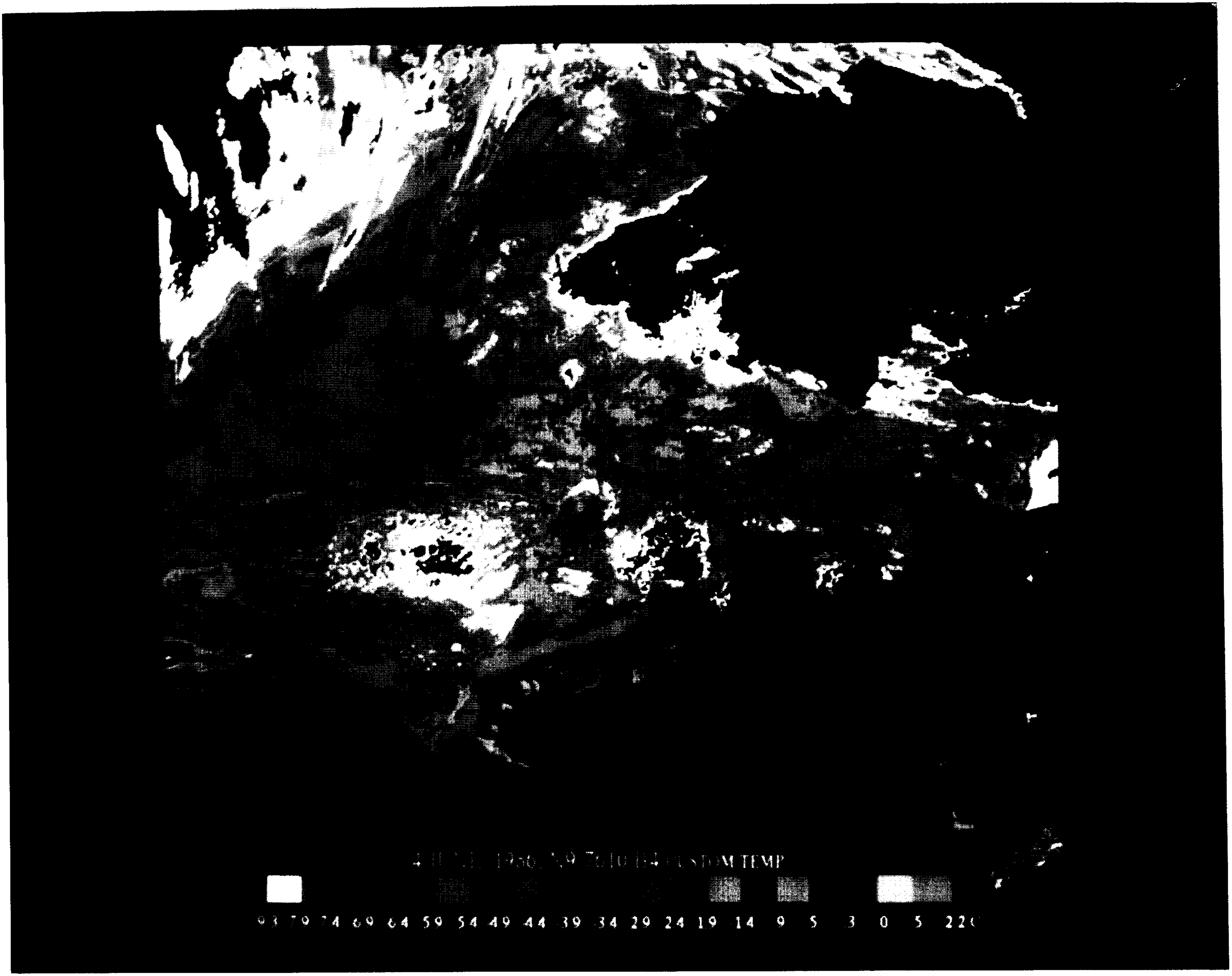
Figure 5. AVHRR thermal infrared (band 4) satellite image of the Mackenzie River delta, 4 June 1986. The data have been level sliced to show the differences in temperature with red as warm and blue as cold. Some surface temperatures are as follows;

overflows 0 to 0.5 °C (yellow),

ice offshore from the river delta 0 to -0.9 ° C (red, orange and gold),

multi-year ice < - 2 4 ° C (blue tones).

The warmer temperatures of water and ice in the vicinity of the delta are due to warm water discharged by the river. Warm water discharged by the river contributes energy which thaws the ice as recorded by time sequential satellite images. Surface temperatures and their aerial extent will be used as input to the model and to calculate heat flux.


TEMP
93 79 74 69 64 59 54 49 44 39 34 29 24 19 14 9 5 3 0 5 22

July. By 3 July much of the overflows are probably open water on their nearshore side with presumably no subsurface sea ice. The 3 July image shows that temperatures of overflows and open water are approximately 10 ° C and ice temperatures are between 0 and - 5 ° C. The 16 August image shows that shorefast ice has melted, turbid water is being discharged by the Mackenzie River and multi-year ice is well offshore (Fig. 6). The thermal band image from 16 August shows a plume of warm Mackenzie water extending approximately 400 km northwest of the delta with sea surface temperatures (SST) ranging from 14 ° C near the delta to 6 ° C (Fig 7). Although only images from each of two dates are shown, twelve other scenes have been processed to about this level.

The series of images show that in the spring sea ice is warmer near the delta than elsewhere along the coast as well as offshore. Two processes appear to be responsible for the warming and hence hastened thawing; discharge of warm river water via the delta channels and absorption of solar energy by the low albedo overflows. The images also show a significant amount of heat (warm water) is being added to the Beaufort Sea by discharge from the Mackenzie River during the mid-summer. Quantitative albedo and temperature measurements from these images will be used to model atmospheric radiation fluxes and will be a component of the river-ice interaction numerical models.

Modeling:

Previous models for this project have focused on determining the flow regime beneath the ice cover throughout the Mackenzie Bay. Work proceeded towards this through the development of complex, two and three dimensional finite-difference models based on the Navier-Stokes equations. While in principle this posed no exceptional difficulty, attention has shifted to predicting the surface flooding of the ice to initiate thawing. This change in focus has occurred as the nature of the problem became clearer based on the available data as well as certain limitations to highly complex flow models.

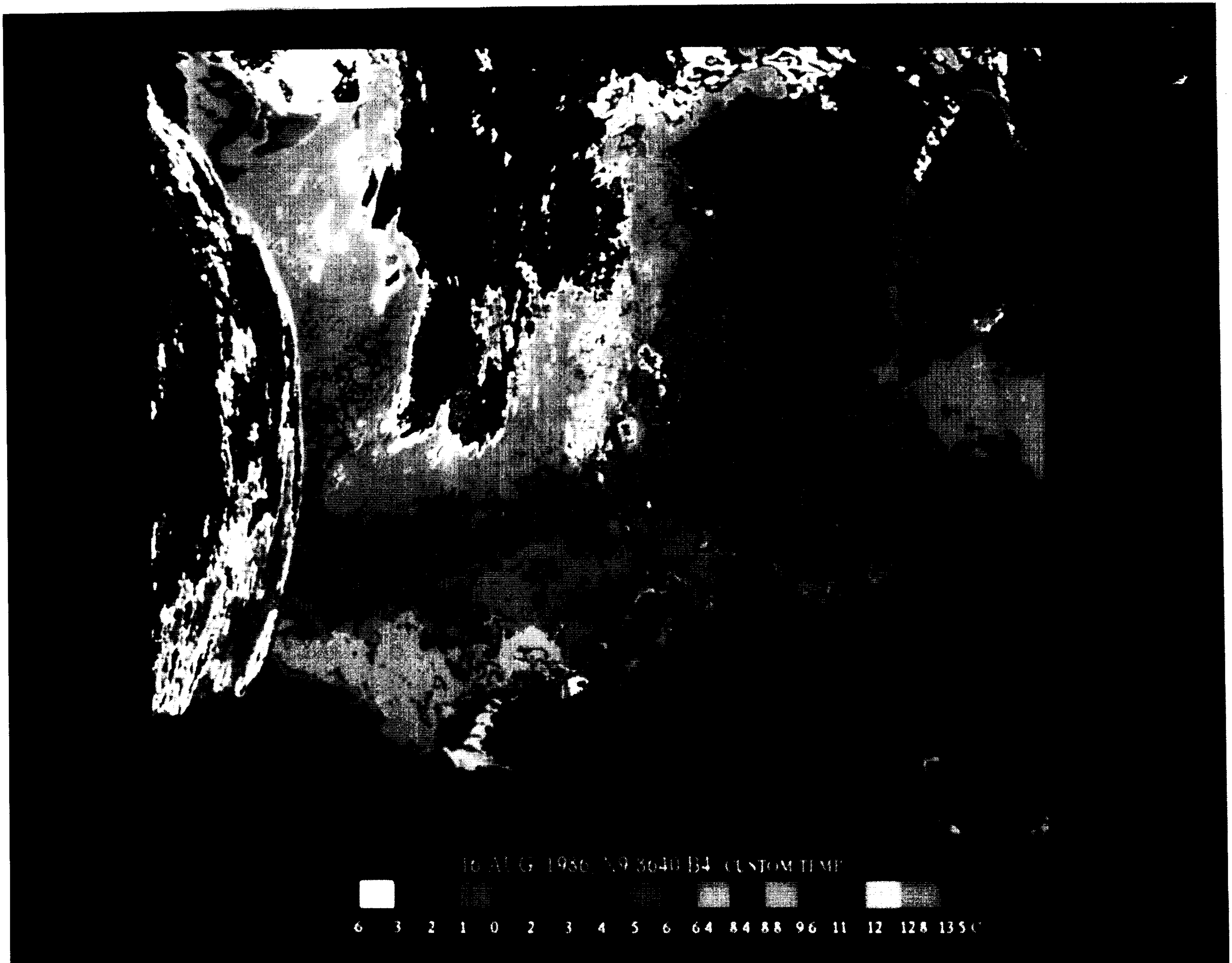
By the time the Mackenzie River abruptly increases its discharge in late May, the fast ice along the delta region is frozen to the bottom except for a few small chanels. Consequently the flood plume is forced onto the surface of the ice. This flooding supplies sensible heat and decreases the

Figure 6. AVHRR satellite image of the Mackenzie River delta, 16 August 1986. Shorefast ice has completely melted and the ice edge is now 200 km offshore as seen on this image. Turbid water (red tones bottom center) is discharged by the Mackenzie River. The image is a color composite of visible (band 1), near-infrared (band 2) and thermal infrared (band 4) data.

Figure 7. AVHRR thermal infrared (band 4) satellite image of the Mackenzie River delta, 16 August 1986. The data have been level sliced to show differences in temperature. Some surface temperatures are as follows;

water adjacent to the delta at 12 to 13.5 ° C (yellow and green),
water adjacent to the ice edge at 0 to 2 ° C (dark blue) and
multi-year ice at 0 to -1 ° C (med. blue).

As to be expected, water near the delta is warm and water near the ice edge is cold but two components of the Mackenzie River discharge are present; a warmer westward one and a cooler eastward one. The ice edge has receded the greatest in the west, downstream from the warmer component thus forming a notch in the ice edge. In the notch, open water and floes can be seen (center left, partially hidden beneath a cloud). The higher temperatures of the Mackenzie water are apparently responsible for the enhanced melting that occurred in the notch. Surface temperatures and their aerial extent will be used as input to the model and to calculate heat flux testing this hypothesis.


6 3 2 1 0 2 3 4 5 6 64 84 88 96 11 12 128 135 C

albedo to initiate thawing of the ice cover. Eventually the ice edge recedes offshore revealing an area of open water, further increasing the solar absorption. The modeling problem is then expressed as a longitudinal decay of the ice cover, at least in the initial stages. Eventually the flow underneath the ice should become important and thawing will occur at the top and bottom. Emphasis for now is being placed on parameterizing the various phenomena appropriate to various stages of the spring season beginning with the overflow situation .

Besides shifting the emphasis to the overflow and its related albedo change, it is becoming apparent that a simplified approach is necessary to reasonably simulate the river influence. The delta region is complicated by numerous distributaries spreading the discharge over a very large area. Hence, there is no one appropriate distributary to model, instead some measure of the average coverage is more realistic. There is also a lack of a detailed and specific data set to support any complex models. Although the recent field work produced some useful data and yielded excellent insight into the problem, it was not planned to provide such an extensive data set.

A model is currently being developed to describe the dynamics of the overflow plume as it is released and spreads over the ice cover. A set of differential equations which conserve the depth-averaged mass (or volume) flux and longitudinal momentum flux have been derived. The geometry of the overflow is shown below with x representing the longitudinal offshore distance and z is the (positive upward) vertical dimension. $U(x)$ and $H(x)$

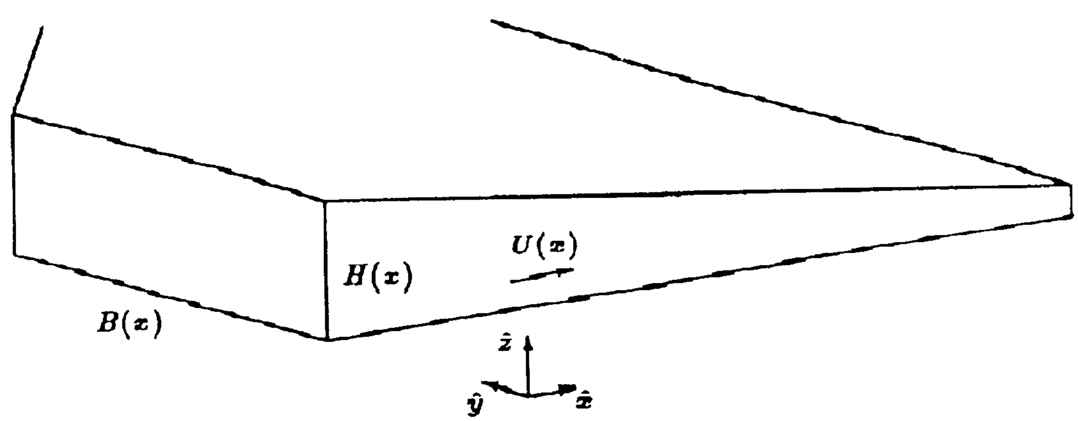


Figure 8. Geometry of river water overflowing sea ice.

are the depth-averaged local velocity and height respectively, while $B(x)$ is the lateral dimension of the plume. The steady state conservation of mass or volume flux is:

$$\frac{d}{dx}(U\,B\,H) = -\,W\,B$$

The left side of this equation represents the mass flux through a surface of width B and height H. The right side is a mass "sink" due to cracks or holes in the ice with W(> 0) the "loss" velocity.

With the plume assumed to be hydrostatic and neglecting the Coriolis force, the steady state momentum flux equation is:

$$\frac{d}{dx}(U^2\,B\,H) = -\frac{d}{dx}\left(g\,\frac{H^2}{2}\,B\right) - B\left(\frac{t_o}{\rho}\right) - S_1\,U\,W\,B$$

Here, g is gravity, t_o is the shear stress at the ice surface, ρ is the density of the water and S_1 if a form factor and should be of order 10°. The left side represents the momentum flux while the right side is respectively, the pressure force due to the hydraulic head, the shear force at the ice/plume interface and the loss of momentum through a mass sink.

To close these equations, a functional form for the lateral spread, $B(x)$, must be specified. There are several choices here, one is to assume a linear spreading rate, $B(x) = B_0 + \frac{dB}{dx}x$. B_0 represents an average initial plume width over the delta. The spreading rate, $\frac{dB}{dx}$, can be based on observations or setting $\frac{dB}{dx} = 1$ places the above equations in a radial coordinate system to provide a natural geometrical spreading. The spreading rate could also be specified using published data on buoyant plumes. Observations of these generally show a lateral spreading rate proportional to the dynamic ratio $\frac{\sqrt{gH}}{U}$. Preliminary model runs with this scheme show a hyperbolic form for the the plume as a result of an accelerating lateral spread. To provide a spreading rate appropriate to the Mackenzie River overflow, enhancement of satellite images should provide some realistic parameterization for $B(x)$.

The shear stress, τ_o must also be parameterized since no reliable data on the vertical flow structure is available for the plume. As a first assumption, a quadratic form drag law such as $\tau_o = \rho C_d U^2$ can be used with C_d a drag coefficient on the order of 10^{-3}. This should be a reasonable assumption unless the depth of the flow becomes comparable to the boundary layer where the stress should then be a function of the depth $H(x)$ as well as U(x).

Observations of the plume in late May show a coverage extending to about 10 km offshore with depths at this distance around 10^{-1} m. No information is known about the velocity but successive satellite images should provide rates for the advancement of the plume front. This of course is not in the steady state, however the plume advancement is sufficiently slow that an areal coverage for various stages of discharge can be predicted. Reasonable values for the initial velocity and depth are to be based on the discharge, using either measured values or time averages for the Mackenzie River. Currently, this system of equations is being run for different paramèterizations and initial values. Results generally show smooth functional forms for $U(x)$ and $H(x)$ at least out to 10-15 km. However, the absolute values do not yet agree with observations. The equations are also very sensitive and become unstable for various combinations of parameters. Refinement of the choice of parameters should lead toward a reasonable model of the plume dynamics. In the next stage of our investigation this will become the basis for a thermodynamic model as a boundary condition for the vertical heat transfer to the ice cover.

Field Work:

Field work was initially scheduled for the latter part of May, 1991 but due to an atypical spring thaw the timing was accelerated to early May. The field crew consisted of an oceanographer, physicist/modeler, remote sensing geologist and a remote sensing application specialist/pilot. The operation was based out of the Polar Continental Shelf Project (PCSP) camp at Tuktoyaktuk, Northwest Territory Canada. At the camp room and board helicopter, technical and other miscellaneous logistical support was provided. PCSP supports multiple projects simultaneously.

The original plan for the field program consisted of sampling along two transects normal to the coastline from shore to the edge of shorefast ice, approximately 75 km offshore and a transect parallel to the coast along the ice edge. This operation was to be conducted during the early stages of spring breakup. A similar but more extensive program was being pursued by the Institute of Ocean Research in Sidney, British Columbia. The Canadian program was focused more on oceanography prior to spring breakup. Fortunately, the early thaw resulted in overlap of field operations. Thus, we will be able to use the Canadian data which more than satisfied our initial requirements and permitted us to pursue secondary targets.

The secondary targets were river/ice interactions adjacent to the coast, more specifically the overflows. The operation had two components; aerial surveys and sampling. Aerial surveys consisted of flights over the delta in a fixed wing aircraft and the acquisition of oblique photography and vertical video. The resulting observations were used to locate the sites for ground sampling and for validation of satellite images. Variations in sea ice albedo and morphology were observed and mapped. AVHRR and Landsat MSS and TM data were recorded and acquired during the field operation period.

Ground sampling consisted of measurements of water and ice temperature, water salinity and water depth. A transportable CTD (Conductivity-Temperature-Depth) was the primary instrument used to collect the data. A helicopter was used to transport personnel and equipment to areas selected from the aerial survey data. Holes were drilled into the ice and instruments were lowered into the water.

River discharge data is being acquired from the Water Survey of Canada, Yellowknife NWT. A complete data set was acquired for 1986 on a compact disk to compare with the AVHRR images of that year. Data for 1991 are being acquired on floppy discs each month. These data will be compared to the extent and size of overflows. River water temperature and turbidity will be compared to sea ice and overflow temperatures and albedo.

Presentations

Preliminary results of the analysis of satellite images and modeling have been presented at the following conferences:

International Conference on the Role of the Polar Regions in Global Change, University of Alaska Fairbanks, 11 - 15 June, 1990.

Arctic Science Conference "Circumpolar Perspective", Anchorage Alaska, 8 - 10 October, 1990.

Future Plans

For the fourth coming project period we will be working on the following items:

1. Image Analysis -
   - Finish merging coastline and the image data,
   - Finish generating level slices and color composites,
   - Film remaining images,
   - Plot field sampling sites on the 1991 images,
   - Investigate possible applications of ERS-1 SAR images to river and ice interactions.
2. Modeling -
   - Continue to refine model,
   - Incorporate satellite measurements with the model,
   - Explore climatic warming scenarios and their consequences by inputing hypothetical temperature and albedo values.
3. Field data
   - Analyze field data,
   - Acquire additional field measurements from Institute of Ocean Sciences,
   - Use field observations as constraints in model refinements.
4. Documentation
   - Publish results,
   - Present results at conferences,
   - Generate final report.

APPENDIX

List of low cloud-cover AVHRR Images for 1986

DATE	ORBIT	SAT	BANDS	COMMENTS	10 Bit Data
MAY, 1986					
5/13/86	7300	N-9	1	Delta cloudy, open outside fast ice	
5/14/86	7314	N-9	1	Delta cloudy, open outside fast ice	
5/22/86	7427	N-9	1	Delta cloudy, open outside fast ice	
5/24/86	7455	N-9	1	Delta cloudy, open outside fast ice	
5/25/86	7469	N-9	1	tiny dark spots along delta (bare land?)	XXX
5/27/86	7497	N-9	1	delta visible through haze	
5/28/86	7512	N-9	1		
5/29/86	*7526	N-9	1,4	delta visible -- good image	
5/30/86	*7534	N-9	4	delta recognizable, IR detail	
5/30/86	*7540	N-9	1, 4	good detail B1 - no detail B4	
5/31/86	*7548	N-9	4	slight details visible - good image	
5/31/86	7554	N-9	1		
				cannot recognize delta in B4-IR, everything	
				gray line until May 30 - 1300 GMT	
				* flooding starts	
JUNE, 1986					
6/1/86	7568	N-9	1	no IR detail	
6/2/86	7582	N-9	1	B1 good	
6/3/86	7596	N-9	1, 4	B4 - bay visible but no open water	
6/4/86	7610	N-9	1	delta snowfree with fact ice and lead beyond	XXX
6/5/86	7624	N-9	1		
6/6/86	*7639	N-9	1	some haze - good image	
6/8/86	*7667	N-9	1	good image	
6/9/86	*7681	N-9	1, 4	coastline vaguely visible but not open water -B4	
6/11/86	7709	N-9	1	good image	XXX
6/12/86	7723	N-9	1		
6/13/86	7737	N-9			
6/14/86	**7751	N-9		good image	XXX
6/15/86	7765	N-9			
6/19/86	7822	N-9		melting of shorefast ice at delta became extensive	
6/22/86	7864	N-9		melt pools extensive at delta	
6/28/86	7949	N-9			
6/29/86	7963	N-9			

JULY, 1986					
7/3/86	*8019	N-9	1	shorefast ice is outside delta (gone?)	XXX
7/5/86	*8047	N-9		melt tongues cut into shorefast ice	XXX
7/6/86	*8061	N-9			
7/7/86	8076	N-9		melt tongues cut into ice obvious - ice is offshore	
7/8/86	8090	N-9			
7/9/86	8104	N-9			
7/12/86	8146	N-9			XXX
7/13/86	8160	N-9		some clouds	
7/14/86	8175	N-9		partly cloudy	
7/15/86	**8188	N-9			
7/17/86	8217	N-9			
7/19/86	8245	N-9		cloudy	
7/21/86	8273	N-9	1		
7/22/86	8287	N-9			
7/23/86	***8302	N-9		water at delta completely open	
7/24/86	8316	N-9			
				*melt tongues cut into shorefast ice	
				**on the 15th the distinct tongues have melted	
				laterally -- now a large indentation is evident	
				***end of melt sequence	
AUGUST, 1986					
8/1/86	8428	N-9	1	delta mainly cloudy	
8/2/86	8442	N-9		delta mainly cloudy	
8/3/86	8456	N-9		delta mainly cloudy	
8/4/86	8470	N-9		partly cloudy - ice is offshore	
8/5/86	8485	N-9		partly cloudy - ice is offshore	
8/7/86	8513	N-9		partly cloudy - ice is offshore	
8/8/86	8527	N-9		partly cloudy - ice is offshore	XXX
8/11/86	8569	N-9	1, 4	partly cloudy - ice is offshore - IR shows land	
8/12/86	8583	N-9		partly cloudy - ice is offshore	
8/14/86	8612	N-9	1, 4	partly cloudy - ice is offshore	
8/15/86	8626	N-9	1, 4	partly cloudy - ice is offshore	
8/16/86	*8634	N-9	4	good image - land colder than water, almost clear	
8/16/86	*8640	N-9	1	cloud-free, ice is offshore	XXX

8/18/86	8668	N-9	1	delta cloudy	
8/19/86	8682	N-9	1, 4		
8/24/86	8747	N-9	4	McKenzie River warmer than the land	
8/25/86	8762	N-9		McKenzie River warmer than the land	
8/26/86	8781	N-9	1, 4		XXX
8/27/86	8795	N-9	1, 4	delta cloudy	
8/28/86	8809	N-9	1, 4	delta cloudy	
8/30/86	8832	N-9	4		
8/31/86	8846	N-9	4	river visible	
8/31/86	8851	N-9	1, 4		
8/31/86	8852	N-9	1, 4		
				* night thermal	
SEPTEMBER, 1986					
9/1/86	8866	N-9	1, 4		
9/2/86	8874	N-9	4	river clear - delta partly sunny	
9/2/86	8880	N-9	1, 4	river clear - delta partly sunny -land warm, can't see river	
9/3/86	8894	N-9	1, 4		
9/4/86	8908	N-9	1, 4	delta clear	
9/5/86	8922	N-9		delta clear	
9/6/86	8936	N-9	4	delta clear	XXX
9/7/86	8950	N-9	1, 4	delta clear	
9/8/86	8959	N-9	4	delta clear - can almost guess ice edge	
9/8/86	8964	N-9	1	delta clear	XXX
9/10/86	8993	N-9	1	delta clear	
9/11/86	9007	N-9	1	delta clear	
9/14/86	9049	N-9	1, 4	delta clear - night pass also clear	XXX
9/19/86	9120	N-9	1, 4	partly cloudy	
9/20/86	9134	N-9	1, 4	partly cloudy	
9/22/86	9157	N-9	4	mostly sunny	
9/25/86	9205	N-9	1, 4	mostly sunny	
9/26/86	9213	N-9	4	mostly sunny	
9/27/86	9227	N-9	4	partly sunny	
9/30/86	9275	N-9	1, 4	partly sunny	
9/30/86	9275	N-9	1, 4	partly sunny	

10/1/86	9283	N-9	4	river dark - land light	
10/3/86	9312	N-9	4		
10/3/86	229	N-10			
10/6/86	9359	N-9			XXX
10/7/86	285	N-10			
10/9/86	9396	N-9			
10/15/86	399	N-10		aloudy along coast with open water	
10/17/86	428	N-10		good image	
10/19/86	448	N-10			
10/21/86	485	N-10		sea ice almost shorefast, river arms in delta open (?)	
10/22/86	490	N-10			
10/24/86	528	N-10		river frozen (?)	
10/26/86	9642	N-9		river still open?	
10/27/86	9650	N-9			
10/27/86	9655	N-9			
10/27/86	9656	N-9		freezeup begins?	
10/28/86	9664	N-9		delta looks frozen	
10/31/86	9712	N-9		delta looks frozen with overflow	
1991 AVHRR and Landsat Data					
5/4/91	24037	N-10		Mackenzie Delta area clear.	XXX
5/13/91	13563	N-11		Mackenzie Delta area clear but some haze in Banks Is. area.	XXX
5/13/91				Landsat TM Scene Number 5266620032	XXX
				*rivers definately open	
				** wind influence opens McKenzie lead	