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Influence of a Beaufort Sea Storm Surge on Channel Levels in the Mackenzie Delta[1]

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ABSTRACT. A storm surge in the Canadian Beaufort Sea during September 1985 resulted in a maximum water level of 1.73 m asl and a maximum surge component of 1.38 m at Tuktoyaktuk. This surge resulted in rises in channel water levels of 1.05 m in the outer delta, 0.66 m in the middle delta, and 0.16 m in the upper delta, with the peak water levels at these stations lagging 4, 17, and 21 hours respectively behind the peak water level in the Beaufort Sea.

This surge clearly illustrates a number of points. First, throughout the Mackenzie Delta increased water levels resulting from surges must be taken into account when calculating channel discharge from a stage-discharge relationship. Second, storm surges play an important role in the flooding of delta lakes. However, further work is required to illustrate the relative importance of flooding by the Mackenzie River versus storm surge related flooding. Third, the surge of September 1985 illustrates the potential effect of rising sea level. Although this surge cannot be used as a direct analogue for future sea level rise because the dynamics of the system are non-linear, it clearly shows that a rise in sea level would have a major impact on the water level regime of delta channels and lakes. Further work should utilize a numerical simulation model to illustrate the effect of rising sea level on water levels in the Mackenzie Delta.

Key words: Mackenzie Delta, storm surge, channel water levels, climate change

RÉSUMÉ. Une onde de tempête dans la partie canadienne de la mer de Beaufort, qui a eu lieu en septembre 1985, a produit un niveau d'eau maximal de 1,73 m ASL et une composante de houle maximale de 1,38 m à Tuktoyaktuk. Cette houle a fait monter le niveau d'eau du chenal de 1,05 m dans la partie extérieure du delta, de 0,66 m dans la partie médiane, et de 0,16 m dans la partie supérieure, le niveau d'eau optimal à ces divers endroits étant respectivement atteint 4, 17 et 21 heures après l'avoir été dans la mer de Beaufort.

Cette houle illustre clairement un certain nombre de points. Premièrement, il faut tenir compte, dans tout le delta du Mackenzie, de l'élévation du niveau d'eau due à la houle lorsqu'on calcule le débit du chenal d'après la relation hauteur-débit. Deuxièmement, les ondes de tempête jouent un rôle important dans l'inondation des lacs deltaïques. D'autres travaux sont cependant nécessaires pour illustrer l'importance relative de l'inondation due au fleuve Mackenzie par rapport à celle due aux ondes de tempête. Troisièmement, la houle de septembre 1985 illustre l'effet potentiel d'une élévation du niveau de la mer. Bien qu'on ne puisse utiliser cette onde comme représentation exacte d'une future élévation du niveau de la mer — car la dynamique du système est non linéaire —, elle montre cependant clairement qu'une élévation aurait d'importantes répercussions sur le régime du niveau d'eau dans les chenaux et lacs deltaïques. Il faudrait poursuivre les travaux en utilisant un modèle de simulation numérique pour illustrer l'effet de l'élévation du niveau de la mer sur le niveau d'eau dans le delta du Mackenzie.

Mots clés: delta du Mackenzie, onde de tempête, niveaux d'eau de chenal, changement climatique

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INTRODUCTION

The Mackenzie Delta is a unique, extremely productive alluvial ecosystem in northern Canada (Mackenzie River Basin Committee, 1981). As in all alluvial ecosystems, the dynamic nature of the system is responsible for its high productivity. In the Mackenzie Delta, highly variable water levels (Marsh and Hey, 1989) play a major role in controlling sedimentation rates, the input of nutrients to delta lakes, and therefore ecosystem productivity. Discharge from the Mackenzie River is of primary importance in controlling flow in the delta channels, but stream flow from other rivers, such as the Peel and Arctic Red rivers, also make significant contributions. During the spring breakup period, the occurrence of ice jams in the main channels of the Mackenzie Delta results in higher water levels than those that occur under open water conditions. In fact, the combination of snowmelt discharge and ice jams results in the highest water levels in the Delta (Marsh and Hey, 1989). Another factor controlling delta water levels, one that is often overlooked, is sea level changes in the Beaufort Sea.

Relative sea level along the outer edge of the Mackenzie Delta changes on a variety of time scales. Hill *et al.* (1985) and Blasco (1991) suggest that relative sea level rose gradually over the last 10 000 years, with a total rise of approximately 60 m; the rate of rise slowed to less than 0.3 m per century over the last 3000 years. Factors contributing to a rise in relative sea level include global eustatic and steric components, and subsidence related to fore-bulge collapse and sediment loading (Forbes, 1980).

Shorter period changes in sea level result from both gravitational tides and storm surges due to wind effects. Gravitational tides are relatively small in the Beaufort Sea, with diurnal and higher frequency constituents having a maximum range of approximately 0.37 m (Henry and Heaps, 1976). On a day-to-day basis the gravitational tides are often overshadowed by the effects of wind, and during periods of high wind the Beaufort Sea is prone to large storm surges. Although these surges may occur during both ice-covered and open water periods, the largest surges occur during the open water season. Storm surges result from wind stress on the water surface, which causes a strong net displacement of water, leading to either a rise or fall of the water surface (Pugh, 1987), with the surge magnitude often accentuated in shallow water and along shorelines. The main components of a surge include the true surge component, wind-generated waves, and the tidal elevation. For a station that measures only the combined surge and tide components, the true surge component can be determined simply by subtracting the predicted tidal elevation from the measured sea level. Storm surges in the Beaufort Sea have been discussed by Harper *et al.* (1988), Henry (1975, 1984), Henry and Heaps (1976) and Reimnitz and Maurer (1978, 1979). Maximum surge elevation with an approximate 100-year return period in the Tuktoyaktuk region is 2.4 m (Harper *et al.*, 1988).

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Rising sea level has had a dramatic effect on the Mackenzie Delta. It has resulted in both erosion and retreat of the delta shoreline, increased flooding, and therefore aggradation of the delta plain (Lewis, 1991). If rates of sea level rise increase substantially, as suggested by recent work on the effect of climate change on global sea levels (Warrick and Oerlemans, 1990), there would be a dramatic increase in coastal erosion, inundation of the coastal plain, and saltwater intrusion into the channels and lakes of the delta. Unfortunately, for a given rate of sea level rise, there is no information on the resulting rise in water levels throughout the Mackenzie Delta or the resulting effect on sedimentation rates.

Short-term changes in sea level also affect water levels in the Mackenzie Delta. Mackay (1963) and Smith *et al.* (1964) noted the effect of storm surges on water levels in the outer delta, and it is common knowledge that strong offshore winds raise water levels in the middle delta. However, no detailed work has documented the spatial and temporal changes in delta water levels resulting from a surge. Such short-term rises in water levels are important because they may result in the flooding of a large number of lakes and the intrusion of saltwater into channels and lakes of the outer delta (Henoch, 1960), and they may change the stage-discharge relationship, resulting in significant errors in estimating channel discharge.

This study looks at the temporal and spatial variation in the response of Mackenzie Delta water levels to a single storm surge in the Beaufort Sea. The analysis has implications for understanding the flooding of delta lakes, measuring discharge in delta channels, and providing a preliminary estimate of the effect of rising sea level on delta water levels. However, it should be noted that the paper deals with only a single storm surge. As a result, it simply illustrates the importance of sea level changes to the water levels in the Mackenzie Delta. It does not provide general inferences that can be applied to all future events.

STUDY AREA

The Mackenzie Delta is approximately 200 km long and 65 km wide (Fig. 1), with an area of approximately 12 000 km^2. Within the delta there is a large system of interconnected channels (Fig. 1). The water level regime of these channels is dominated by the spring breakup in May and June, when high discharge and the occurrence of ice jams result in the highest water levels of the year. Following spring breakup, water levels decline, with brief periods of higher water levels due to rain storms in the southern portion of the basin and storm surges in the Beaufort Sea. These variations cease with freeze-up in October and November, after which the water level regime experiences relatively small variations until spring breakup.

An important feature of the delta is the large number of lakes, which cover approximately 25% of its surface area. The hydrologic regime of these lakes is dominated by flooding from the Mackenzie River (Marsh and Hey, 1989), with the lowest elevation lakes remaining connected to the delta channels throughout the summer, while the highest elevation lakes are not flooded during the summer and are flooded less than annually during spring breakup. The remainder of the lakes, accounting for 55% of all lakes in the middle delta study area of Marsh and Hey (1989), are flooded annually in the spring and may also flood in the summer. It is these lakes that are most prone to increased flooding due to both short- and long-term changes in sea level.

DATA SOURCES

Tide records from the Canadian Hydrographic Service show that a storm surge occurred at Tuktoyaktuk between 15 and 18 September 1985. The event, which had a maximum water level of 1.73 m asl, was chosen for study because of the unusually good availability of wind, tide, and channel level data during the surge event. Wind speed and direction were available from Atmospheric Environment Service (AES) at Tuktoyaktuk and observed water levels for the Beaufort Sea at Tuktoyaktuk from the Canadian Hydrographic Service (CHS). The CHS also provides predictions of Beaufort water levels without the effect of storm surges. The storm surge component can then be estimated by subtracting the predicted from the observed water levels. In addition, Water Survey of Canada (WSC) had ten operational water level stations within the delta and a discharge station measuring water input to the delta. Data from the following WSC stations were used in the analysis: Middle Channel below Langley Island (10MC010), Reindeer Channel at Ellice Island (10MC011), East Channel above Kittigazuit Bay (10LC013), Marcus Channel below Middle Channel (10MC009), Middle Channel below Raymond Channel (10MC008), Aklavik Channel above Schooner Channel (10MC005), Peel Channel above Aklavik (10MC003), Middle Channel at Tununuk Point (10LC002), Kalinek Channel above Oniak Channel (10LC006), Mackenzie River below Point Separation (10LC011), and Mackenzie River at Arctic Red River (10LC014) (see Fig. 1 for station locations). In order to determine the rise in channel water level due to the storm surge alone, the standard method of base flow separation (Gray, 1970) was applied to estimate the channel water level without the surge. The surge component was then determined by subtracting the predicted channel water level without the surge from the observed channel level.

All of the WSC water level data are referenced to mean sea level. This was done using an inertial survey (McElhanney, 1983). Since this survey data had a confidence level of only ± 0.5 m, the resulting water level values may have a similar error, explaining why some of the WSC station water levels in the outer delta have values below -0.5 m asl.

STORM SURGE

Storm Surge of 15-18 September 1985

During the period 11-14 September (Julian day 254-257) 1985 the predicted and observed tide levels at Tuktoyaktuk were similar (Fig. 2d). Subsequently, however, the observed and predicted began to diverge in response to a change in wind speed. On 14 September (Julian day 257), the wind direction changed from southeast to northwest (Fig. 2a), and the wind speed began to increase, reaching a value of approximately 40 km/h early on 15 September (Julian day 258) (Fig. 2b). By early on 16 September (Julian day 259), wind speed had decreased to 10 km/h, followed by a rapid increase to nearly 45 km/h later in the day, reaching a peak of 56 km/h on 17 September (Julian day 260). After that, the wind speed declined gradually.

Observed water levels at Tuktoyaktuk mirrored these changes in wind speed and direction (Fig. 2d), with observed and predicted levels diverging dramatically on 15 September (Julian day 258). The highest observed water level and surge component, 1.73 m asl (Fig. 2d) and 1.38 m (Fig. 2e)

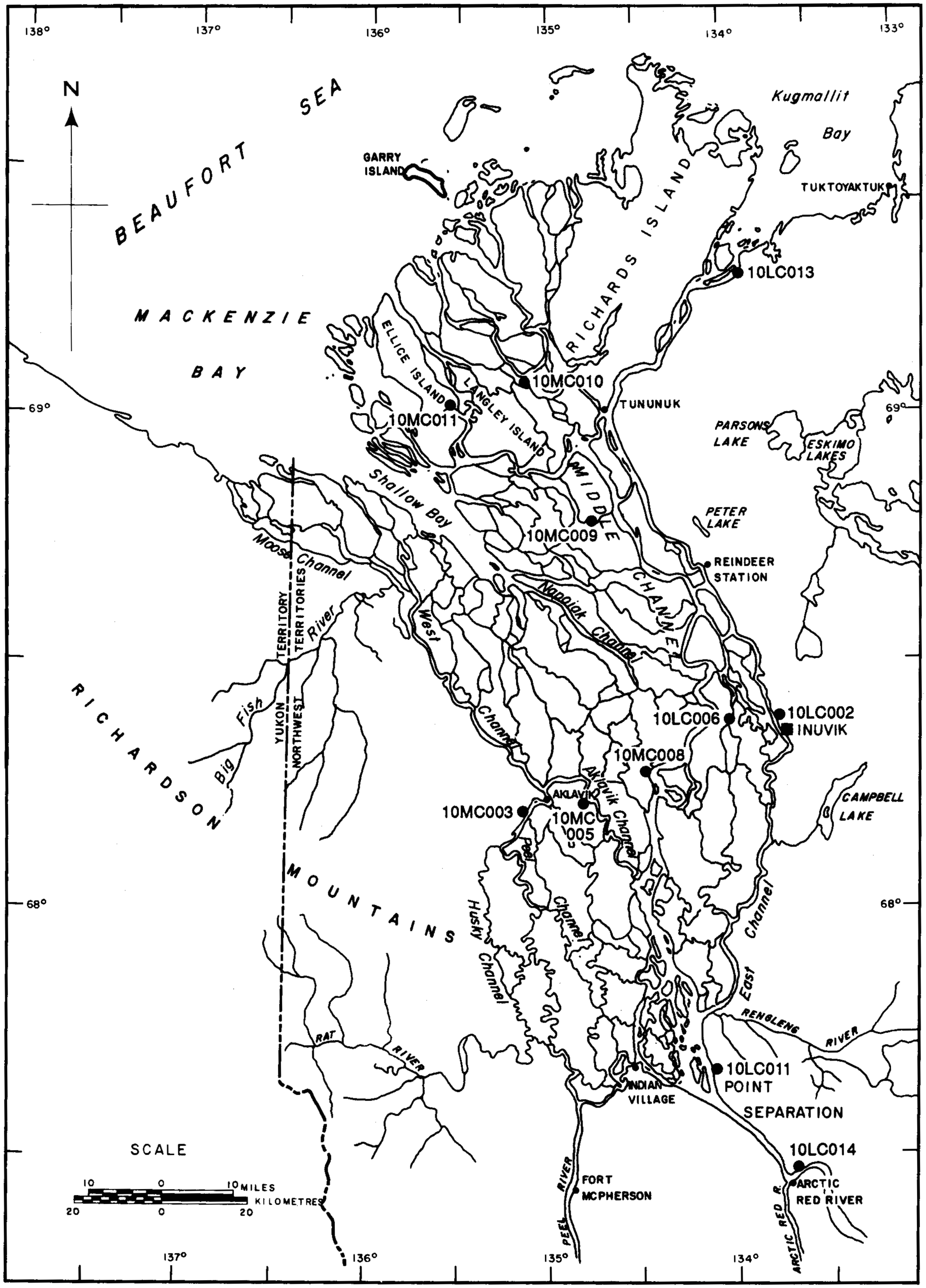

FIG. 1. The Mackenzie Delta, showing locations of Water Survey of Canada water level stations. The Canadian Hydrographic Service tide gauge and the Atmospheric Environment Service weather station are located at Tuktoyaktuk.

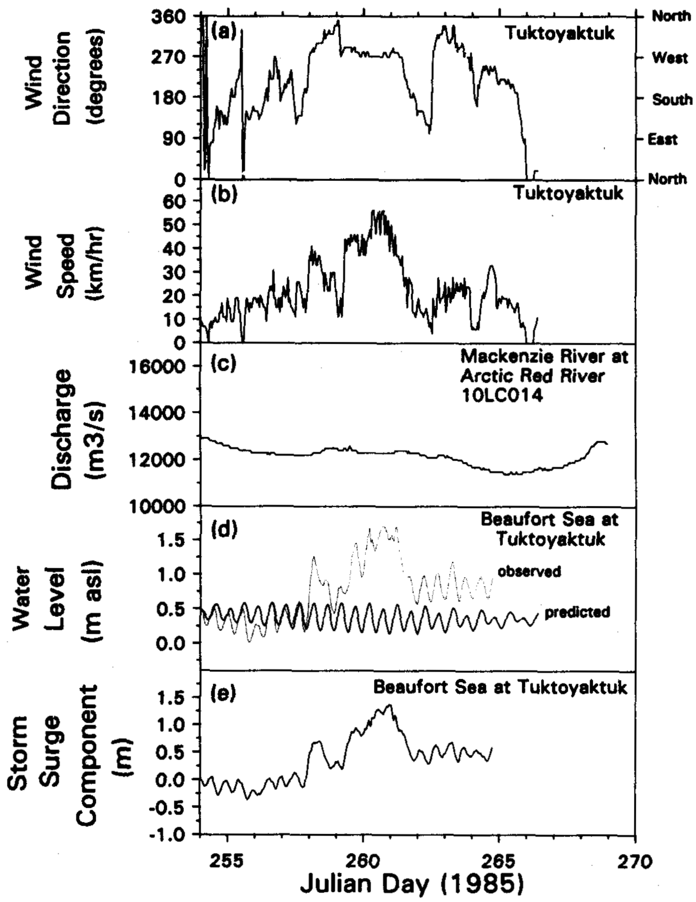

FIG. 2. Changes in: (a) wind direction, (b) wind speed, (d) observed (gravitational plus storm surge components) and predicted water level (gravitational component only) in the Beaufort Sea at Tuktoyaktuk, and (e) the calculated storm surge component (m), determined from the observed minus predicted water levels. Also shown is the discharge of the Mackenzie River at Arctic Red River (c).

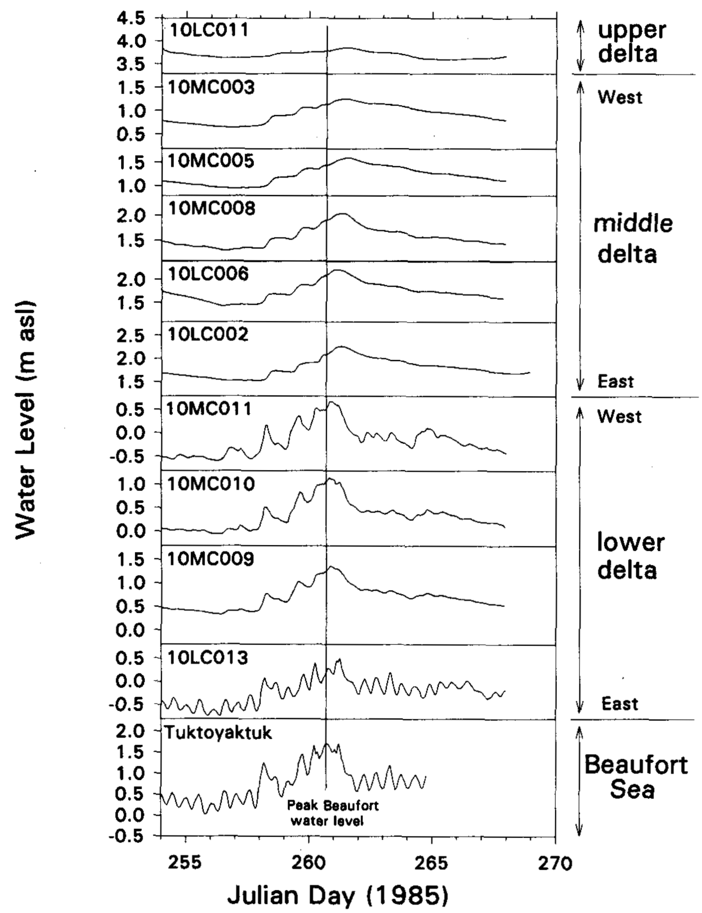

FIG. 3. Changes in water level at 10 stations in the Mackenzie Delta, and water level in the Beaufort Sea at Tuktoyaktuk.

respectively, occurred on 17 September (Julian day 260). However, the peak surge component occurred 6 h later than the peak water level.

Figure 2c shows that during the period 11-19 September (Julian day 254-262), the discharge of the Mackenzie River into the Mackenzie Delta rose only gradually. This suggests that any dramatic rise in water levels within the Mackenzie Delta must be due to the storm surge, not to an increase in discharge. It is interesting to note that the slight rise in discharge of the Mackenzie River occurred at the same time as the storm surge. It is possible that this reported increase in discharge was in fact due to the Beaufort storm surge, not to an actual increase in channel discharge.

Variations in Delta Water Levels during the Storm Surge

Water levels at the WSC stations in the lower delta responded dramatically (Fig. 3) to the storm surge, with the rise varying from 0.87 to 1.15 m (Table 1). These changes in channel water levels were slightly lower in magnitude than the storm surge measured at Tuktoyaktuk. However, the shape of the hydrographs was similar in all cases, with rapid rises in stage occurring nearly simultaneously at all sites. The water level rise was not uniform across the lower delta, but decreased slightly from west to east (Fig. 4). This may be expected since the winds responsible for the surge were northwesterly. Stations such as 10MC011, therefore, faced directly into the surge, while 10LC013, located near the head of Kugmallit Bay, with a northeasterly exposure, was somewhat protected. This is in agreement with the results of model experiments of Henry and Heaps (1976), who found that maximum water elevations during the September 1972 surge were considerably higher in Shallow Bay than in Kugmallit Bay. The peak water levels at the channel sites in the lower delta generally lagged behind those at Tuktoyaktuk by 4-5 h (Fig. 4). At the water level station closest to the tide gauge at Tuktoyaktuk (10LC013), however, the lag between peak levels was nearly 14 h. However, the water level records at both Tuktoyaktuk and 10LC013 contain three peaks (Fig. 3). At Tuktoyaktuk, these peaks are all of similar elevation, with the middle peak having a slightly higher level. At 10LC013, however, the middle peak is considerably lower than the other two peaks. Assuming that these three peaks correspond at both stations, the actual lag between the middle peaks is approximately 3 h, not 14. Such variations in peak heights is probably due to the complex, non-linear processes controlling water levels.

Water levels at the WSC stations across the middle delta also responded to the storm surge (Fig. 3), with peak increases of between 0.47 and 0.66 m (Table 1). In this case, however, water levels tended to be higher in the east rather than the west (Fig. 4).

TABLE 1. Peak water levels at 10 sites in the Mackenzie Delta and at the Beaufort Sea at Tuktoyaktuk[1]

Station	Water level			Time of peak	Lag (h)	Distance from (km)	
	Measured (m asl)	Predicted (m asl)	Surge (m)	(Julian Day)		Beaufort coast	Western edge of delta
Tuktoyaktuk	1.73	0.51	1.22	260.71[1]	0.00	0	—
	1.52	0.14	1.38	260.96[2]	0.00	0	—
*10MC011	.69	−0.46	1.15	260.92	5.04	25	41
*10MC010	1.16	0.11	1.05	260.88	4.08	33	60
*10LC013	.51	−0.49	1.00	261.29[3]	13.92	2	114
				260.83[4]	2.88		
*10MC009	1.37	0.50	0.87	260.92	5.04	70	—
■10MC008	2.04	1.38	0.66	261.42	17.04	140	45
■10MC003	1.27	0.80	0.47	261.50	18.96	53	15
■10MC005	1.61	1.13	0.48	261.63	22.08	55	29
■10LC002	2.28	1.63	0.65	261.33	14.88	127	72
■10LC006	2.22	1.68	0.54	261.21	12.00	123	—
□10LC011	3.86	3.70	0.16	261.58	20.88	213	—

[1]Stations denoted by * are located in the lower delta, by ■ in the middle delta and by □ in the upper delta. Note that the peak surge component at Tuktoyaktuk[2] occurred later than the peak water level at that site[1]. For site 10LC013, lag times are given for both the peak levels[3] and between the peak level at Tuktoyaktuk and the corresponding peak at 10LC013[4].

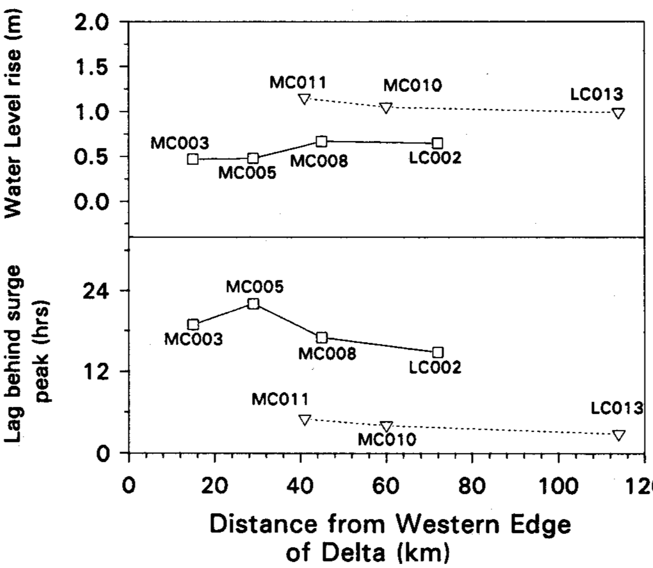

FIG. 4. Changes in water level rise and lag time across the lower (dotted line) and middle (solid line) delta.

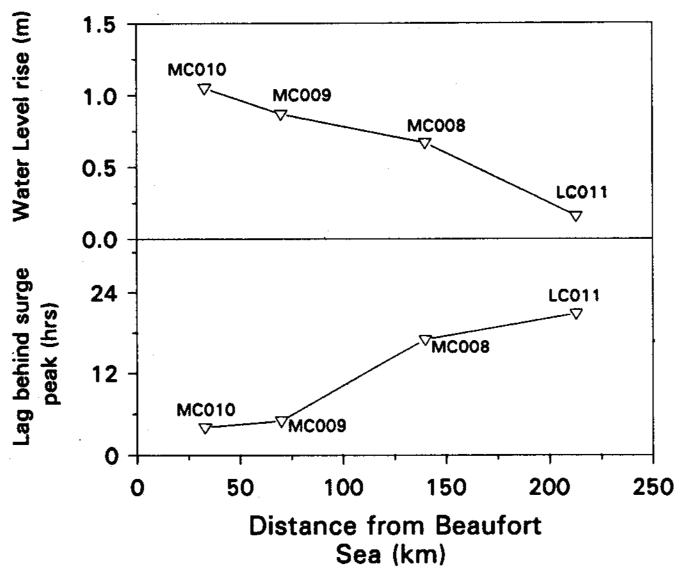

FIG. 5. Changes in water level rise and lag time along a transect from the Beaufort Sea to the Upper Mackenzie Delta.

Again, the shapes of the channel hydrographs were similar to those occurring at Tuktoyaktuk, but were more rounded, with no sharp peaks (Fig. 3). In all cases, the channel water levels rose in three gradual steps, each occurring at approximately the same times as the more dramatic rises and falls that occurred at Tuktoyaktuk and the outer delta WSC stations. Lag times were significantly longer than in the lower delta, varying between approximately 12 and 22 h, with the lag time being shorter in the eastern delta, where the water level rise was highest (Fig. 4).

The water level at the single WSC station in the upper delta also showed an increase due to the storm surge (Fig. 3). However, due to the distance from the sea, the rise was only 0.16 m and was delayed for over 20 h (Table 1).

Figure 5 clearly shows that the water level rise gradually decreased with distance from the Beaufort Sea, and likewise the lag time gradually increased. Since the water level peaks occurred earlier in the lower delta than in the upper delta, the rise in water levels within the delta must have been due to the storm surge, not changes in Mackenzie River discharge.

DISCUSSION

The above-noted changes in channel water levels in response to a brief Beaufort Sea storm surge are significant for a number of reasons. From a purely operational point of view, these data illustrate the need to consider surges when calculating channel discharge from a stage-discharge relationship anywhere in the Mackenzie Delta. If a rise in water level caused by a storm surge was not accounted for, the standard method for determining discharge would result in the overestimation of discharge throughout a surge event. A method to take into account the effect of increased backwater on the stage-discharge relationship should be used during storm surges. In fact, it is possible that the slight rise in discharge in the Mackenzie River at Arctic Red River between 15 and 19 September (Julian day 259-263) (Fig. 2c) was an artifact of the calculation procedure.

The rise in water levels due to the 15-18 September surge would have resulted in the flooding of additional lakes in the delta. Marsh and Hey (1989, 1991) presented data on the sill elevation of lakes at three sites in the delta. Only their study site near Inuvik (Fig. 1) is sufficiently close to a WSC station (10LC002) to determine the effect of the storm surge on lake flooding. With a water level at station 10LC002 of approximately 1.5 m asl prior to the surge, only about 12% of a total of 132 lakes in the Marsh and Hey (1989) study area would have been connected to the main channels. As the channel water level rose in response to the surge, Mackenzie River water would have flooded into lakes with sequentially higher sill elevations. At the peak (2.28 m asl), an additional 17% of lakes would have been flooded by the Mackenzie River. Although similar estimates cannot be made for the study sites of Marsh and Hey (1989) in the lower and upper delta, their data clearly show that the additional lake flooding due to the surge would have been much higher in the lower delta and, as expected, much lower in the upper delta compared to the study site in the middle delta.

Current estimates suggest that sea level rise due to predicted changes in climate will probably be ≤ 1 m during the next century, with estimates of between 1.1 and 0.2 m (Warrick and Oerlemans, 1990). More importantly though, the rate of rise will be about 3-6 times faster than that which occurred over the last 100 years. In addition, climate change may also result in more open water in the Beaufort Sea, and therefore larger surges imposed on the rise in mean sea level. Given such an increase in sea level rise, what would be the expected change in channel levels in the Mackenzie Delta? The water level data from the surge of September 1985 clearly show that a rise in sea level of 1.2 m would have a dramatic effect on channel water levels throughout the delta, with a rise of 1.2 m in the outer delta and 0.15 m in the upper delta. The actual effect on channel water levels will be dependent on the real rise in sea level due to climate change in the coming decades.

There are a number of limitations, however, in applying the storm surge data directly to estimate the effect of long-term sea level rise. First, the surge of September 1985 occurred during a period of relatively low channel water levels. As a result, the surge had the maximum possible effect on delta water levels. If a surge of similar magnitude occurred at a time of higher delta water levels, its effect would have been smaller. Second, the surge event occurred practically instantaneously, whereas a rise in sea level due to climate change will occur gradually over a period of many decades.

Given these limitations, the storm surge cannot be used as a direct analogue for future sea level rise due to climate change. However, it does provide an indication of the effect of sea level rise on channel water levels during periods of low water levels. During periods of high water level, such as during the spring breakup, the effect of higher sea levels would be minimal. The effect of sea level rise on channel water levels over a range of conditions could be estimated by using a model of channel levels such as described by Sydor *et al.* (1989). However, such a model is not yet fully developed for the complicated channel network of the Mackenzie Delta. Such a model would allow for the fact that the dynamics of the system are non-linear and dependent on other system parameters like slope, discharge, and antecedent water levels. This type of a simulation model may provide better prediction of the effect of surges and sea level rise of different magnitudes and under a variety of conditions.

The major difficulty in predicting the effect of sea level rise on the delta is in predicting the resulting change in sedimentation within the delta channels and lakes due to changes in channel water slope. As sea level rises, it results in a decrease in channel slope, therefore slowing channel velocities and resulting in increased sedimentation. For example, as sea level has risen over the last few thousand years, sedimentation has resulted in a gradual increase in elevation of the delta. During this period, it is possible that the delta has remained in a state of dynamic equilibrium. Whether or not this will remain true if sea level rises 3-6 times faster over the next 100 years is not known. Considerable work is required to answer this question of deltaic sedimentation in response to sea level rise before a more definitive answer can be given.

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