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A Coastal Jet in the Chukchi Sea

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ABSTRACT. Data collected in the nearshore region between Point Lay and Icy Cape, Alaska, support the thesis that a well-developed coastal jet is present during the summer. The temporal variability of the current is as predicted by theory. The physical characteristics of the region suggest a strong signal-to-noise ratio for the baroclinic coastal jet. It is probably the dominant mode of summer coastal circulation for the entire Chukchi Sea coast of the Alaskan North Slope.

RÉSUMÉ. La masse de renseignements acquis concernant la region littorale, située entre Point Lay et Icy Cape, Alaska, confirme la thèse d'un courant littoral présent pendant l'èté. L'inconstance du courant était prouve par la théorie. Les caractéristiques physiques de la region suggérent un rapport signal sur bruit, élevé pour ce courant littoral "baroclinique." C'est probablement le point fondamental de la circulation littorale estivale pour toute la côte de la mer de Chukchi concernant le "North Slope" d'Alaska.
Traduit par Alain de Vendigies, Aquitaine Company of Canada Ltd.

INTRODUCTION

Early oceanographic work in the Arctic Ocean has been generally confined to deep water (e.g., Coachman, 1963). With the recent interest in oil development along the Alaskan coast, though, nearshore oceanography has become important. Coastal hazards, as well as the fate of pollutants in the marine environment, must be known. Using data collected near Point Lay, Alaska, in the summers of 1972 and 1975, we have identified the baroclinic coastal jet as a major summer circulation mode along the Alaskan Chukchi Sea coast.

We will first describe the large-scale physical setting in which our data were collected and briefly present a review of the principles of the coastal jet. We will then present our field data and compare it with theoretical predictions of the structure of a coastal jet. Finally, we will discuss other data available from the coastal waters of the Alaskan North Slope and the probable range of occurrence of the coastal jet in Alaskan arctic waters.

OFFSHORE ENVIRONMENT (POINT LAY REGION)

The coast between Cape Lisburne and Icy Cape (Fig. 1) forms a broad embayment of the Chukchi Sea. To the south, between Cape Lisburne and Cape Sabine, the coast is mountainous; farther north it consists of barrier islands, which are backed by a narrow, shallow lagoon and then low tundra. Numerous small rivers and streams run into the lagoon, including the Utukok,

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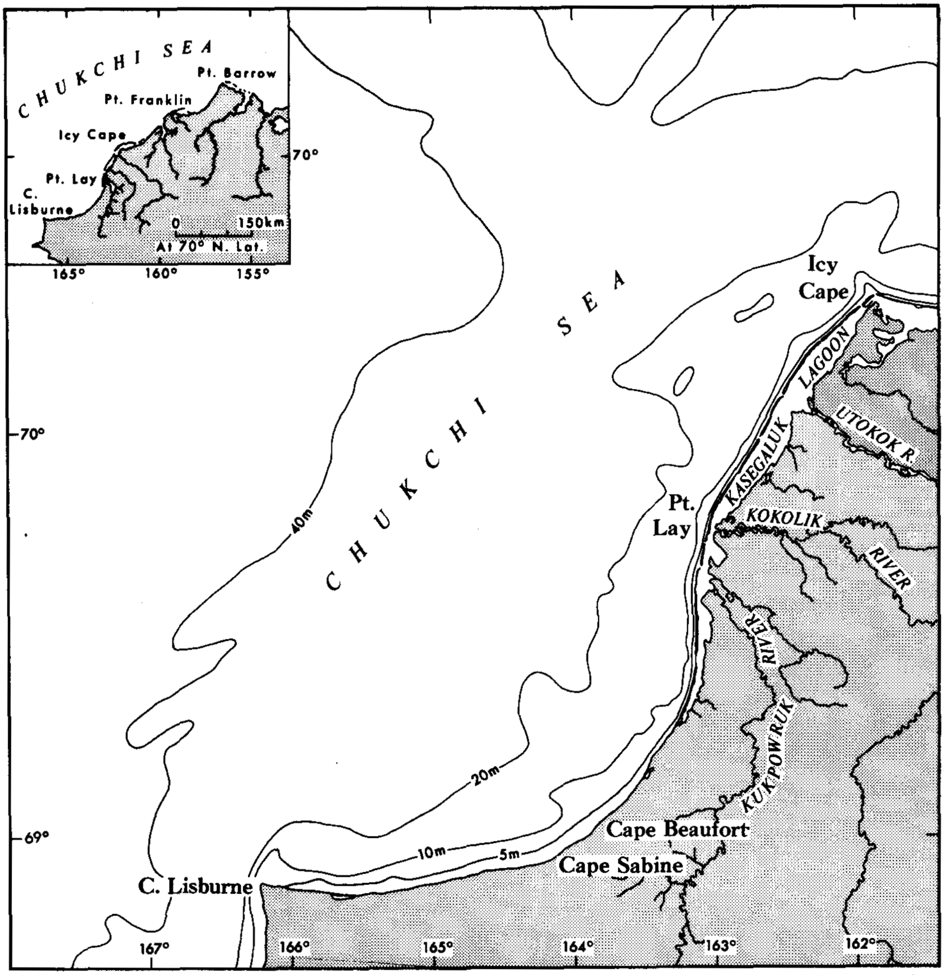

FIG. 1. Location map.

Kokolik, and Kukpowruk Rivers. The major runoff to the region occurs during the brief spring freshet. In the northern section water depth increases to 15 m within approximately 2 km of shore; the slope is somewhat less to the south. The bathymetry then gently slopes to depths of 40 m approximately 150 km offshore.

The region is generally ice covered from late October or early November until early July, but there is significant year-to-year variability in ice conditions. Of the 2 years during which data were collected, 1972 was a light ice year and 1975 was a very heavy ice year. Ice conditions near the coast, as well as the general circulation, are strongly influenced by local winds. The predominant summer winds are from the east and northeast, with speeds of 5-10 m/s, but the major storm winds blow from the southwest, a direction giving them maximum fetch.

Tides are semi-diurnal and small (O (15 cm)) (Matthews, 1970). Although the tidal period is close to the inertial period, which would tend to give large tidal currents for small tidal ranges (Sverdrup, 1927), the nearshore tidal currents appear to be small (O (1 cm/sec)) (Wiseman *et al.*, 1974; Mountain *et al.*, 1976). Approximately 100 km offshore, a warm current originating in the Bering Straits flows northeastward (Ingham and Rutland, 1972; Fleming and Heggarty, 1966; Paquette and Bourke, 1974; Coachman *et al.*, 1975). Farther north the current approaches the coast and flows through the Barrow Canyon into the Beaufort Sea (Mountain *et al.*, 1976). Temporal variations in the transport of the current appear to be associated with large-scale fluctuations in the atmospheric pressure (Mountain *et al.*, 1976).

Between Cape Lisburne and Icy Cape, there is evidence of an anticyclonic eddy separating the coast and the warm current (Fleming and Heggarty, 1966; Ingham and Rutland, 1972) . Within the warm current and the eddy, the surface and deep currents are strongly influenced by the wind stress and, although the surface and bottom currents are not identical, they generally lie within the same octant and are similar in magnitude, suggesting a strong barotropic component in the flow (Ingham and Rutland, 1972). Since most previous current records have been made from icebreakers, data have been restricted to depths of 20 m or greater. One nearshore data point collected by the (M/V) *Brown Bear* shows a strong northerly alongshore flow immediately off the mouth of the Utukok River (Fleming and Heggarty, 1966).

In the offshore regions of the area a pycnocline occurs between 10 and 15 m (Ingham and Rutland, 1972) as a result of ice melt. Nearer shore, the pycnocline shoals to about 5-10 m depth (Wiseman *et al.* 1974) and, at least early in the open-water season, is more intense owing to fresh water runoff.

THE BAROCLINIC COASTAL JET

Csanady (1972a) has discussed the necessity of a boundary layer circulation at the edge of a real ocean. One such circulation pattern is the coastal jet. This mode of motion is an alongshore flow, with a distinct speed maximum offshore, that is nearly in geostrophic equilibrium. Variations in the offshore pressure gradient are driven by a net flux of mass either into or out of the coastal region. This mass flux may be caused by river runoff, Ekman flow in the offshore waters, or meanders of an offshore current over the outer shelf. Theoretically, both barotropic and baroclinic jets may occur. In natural situations, though, the horizontal length scale for the barotropic motion is so large that the assumptions of a boundary layer flow are violated and the baroclinic jet is the only one of importance. Such motions have been studied both theoretically and observationally in a variety of situations, including large lakes (Csanady, 1972b), semi-enclosed seas (Walin, 1972a, b), and open coastal regions (Allen, 1975). Csanady (1972a, b) focuses attention on the baroclinic nature of the flow, but Allen (1975) points out the importance of interaction between the topography and stratification.

The Arctic Ocean presents a physical environment that is conducive to baroclinic coastal jets. Broad, flat shelves offer a reasonably smooth topography. The low slope topography means that large coastal sea level variations will occur during storms. Ice melt and the spring freshet both release fresh water and produce a highly stratified coastal water mass. The stratification breaks down only slowly during the summer because the pack ice limits fetch and associated wave-induced mixing. The high latitude implies a strong Coriolis force and a short time scale for geostrophic adjustment to transient effects such as the passage of storms. All these features will contribute to a large signal-to-noise ratio for various aspects of the coastal jet circulation patterns.

FIELD DATA

During the open-water season of 1972 a series of STD transects was made along a single line north of the Point Lay inlet. Broader initial surveys showed that the inlet's influence was limited to within about a 0.25-km radius of its mouth. Throughout the season, as the haline stratification broke down, the coastal waters also warmed. Significant variability was superimposed on this long-term trend. Immediately following breakup, a strong nearshore halocline existed. By the end of July, neither river runoff nor ice melt represented a continuing major source of fresh water for the nearshore zone. During periods of southerly or light northeasterly winds, warm, low-salinity waters lay near the coast (Fig. 2a, b). Surface waters were warm and fresh and flowed northward. During strong northeasterly winds, these warm, fresh waters moved offshore with the Ekman drift, and colder, saltier waters upwelled against the coast (Fig. 2c, d). Nearshore surface waters, at this time, flowed southward along the coast.

These motions of the warm, low-salinity nearshore water mass, the alternation of the near-surface current direction, and the simultaneous coastal setup and setdown caused by Ekman divergence in response to the changing winds are precisely the phenomena expected in the presence of a coastal jet.

The coastal Ekman divergence also caused interaction with the waters of Kasegaluk Lagoon and consequent modification of the coastal water mass characteristics.

Coastal sea level varied by 1 m or more in response to the winds (Wiseman *et al.*, 1973). Aperiodic southwest storms or weakening northeasterly winds forced water into the shallow lagoon. Within the lagoon the coastal water mixed with the warm, fresh lagoon waters and was further freshened by the remaining river runoff. Solar heating in the shallow lagoon further warmed these waters. Subsequent northeast winds caused sea level to drop at the coast and the lagoon to drain. The waters from the lagoon moved offshore with the light nearshore surface waters and were subjected to wind and wave-induced mixing with the waters below the pycnocline. As the freshening within the lagoon was slight after the initial spring freshet, the net effect of this cycle was to weaken the pycnocline (halocline).

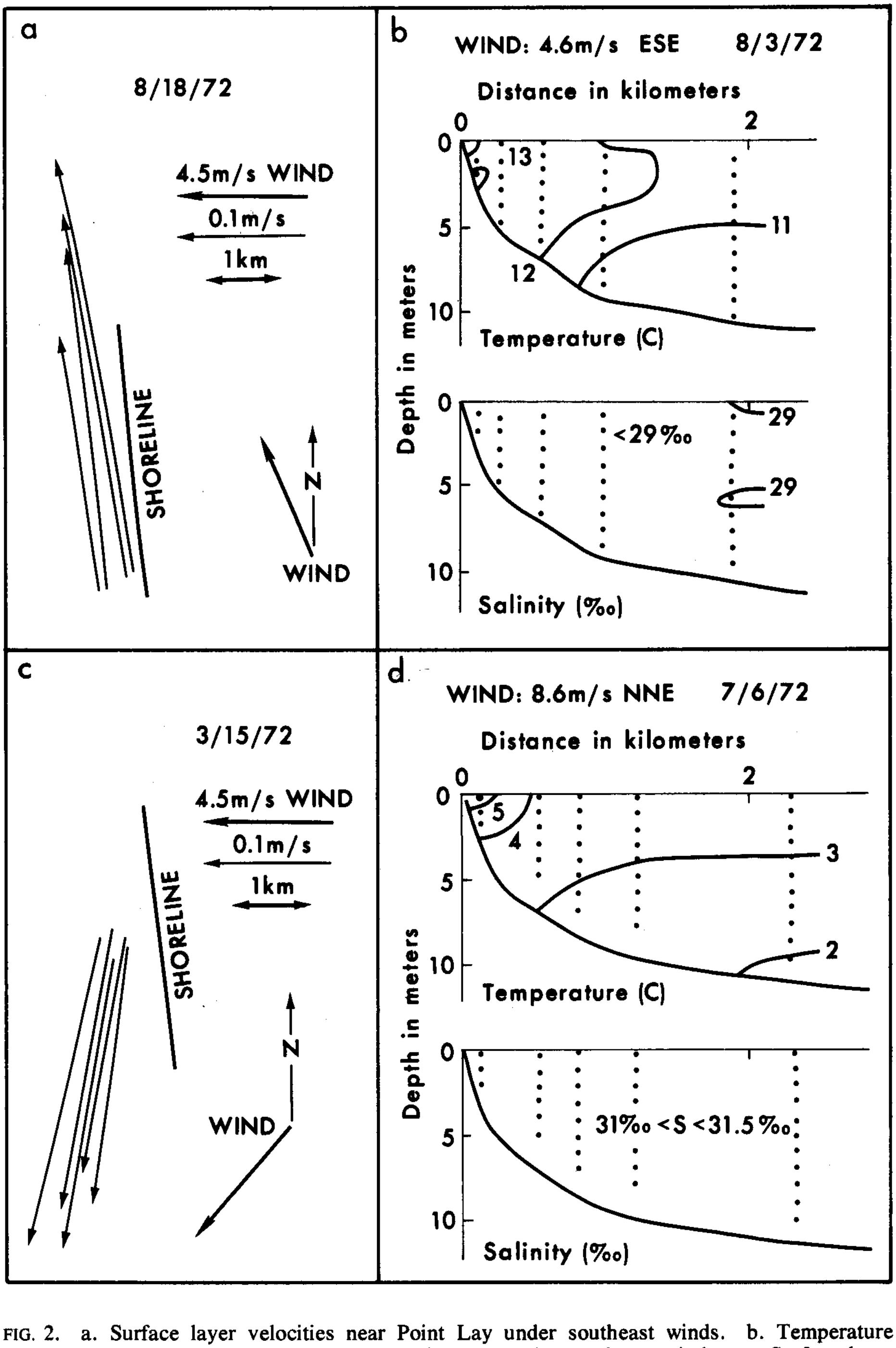

FIG. 2. a. Surface layer velocities near Point Lay under southeast winds. b. Temperature (upper) and salinity (lower) sections near Point Lay under southeast winds. c. Surface layer velocities near Point Lay under northeast winds. d. Temperature (upper) and salinity (lower) sections near Point Lay under northeast winds.

The series of temperature and salinity sections mentioned above were supplemented by current measurements. Short records at mid-depth, in 9.8 m of water, indicated a mean current vector parallel to shore and to the north. The alongshore component attained speeds as high as 70 cm/s and was commonly near 40 cm/s. The records also exhibited rapid shifts from alongshore northerly motion to alongshore southerly motion at time scales that were not related to tidal motion. Unfortunately, lack of an absolute time base on the current records precludes correlation of the current reversals with wind shifts.

To investigate the spatial variability of the flow, 1.7 m^2 biplanes buoyed at 2 m depth were tracked by radar. The observed tracks followed the wind component parallel to shore (Fig. 2) and responded rapidly to changing wind stress. A series of data taken on 18 August 1972 (Wiseman *et al.*, 1973, Fig. 24) indicated that the nearshore currents respond to a wind shift within only a few hours. This time scale is short compared to that necessary for geostrophic readjustment, the scale that is probably appropriate farther offshore, but compares favorably with measurements off the coast of Florida (Murray, 1975).

The 1972 data strongly suggested a well-developed coastal jet, and in 1975 we had intended to investigate the offshore structure of the coastal current system between Point Lay and Icy Cape. Unfortunately, this was a very bad

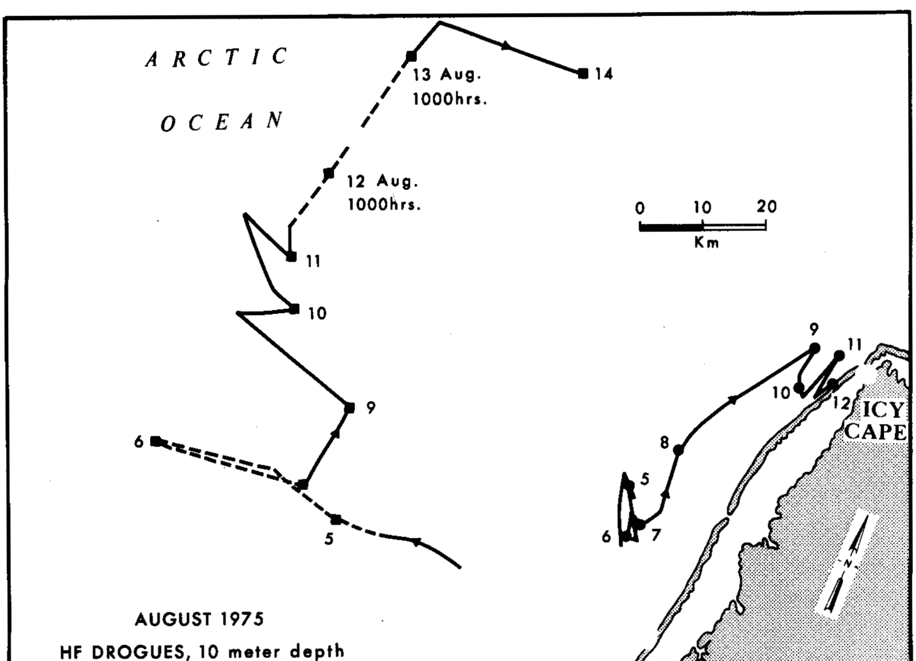

FIG. 3. Drogue trajectories from August 1975 in the Chukchi Sea. Dots and squares represent fixes at 1000 hours on the indicated day. Broken lines indicate questionable fixes, but all 1000-hour fixes were good. (From Wiseman *et al.*, 1974)

ice year. The sea train bound for Prudhoe Bay was stopped at Icy Cape for several weeks, and the research boat that was to be used for offshore measurements was never able to get to the field site. We were, though, still able to obtain two sets of data which further demonstrate that a well-developed coastal jet existed between Point Lay and Icy Cape.

Biplanes buoyed at 10 m depth were tracked for a number of days. This was accomplished over distances in excess of 50 km using a high-frequency direction-finding system (Murray *et al.*, 1975; Wiseman *et al.*, 1977). The two drogues tracked for the longest period of time are shown in Figure 3. The drogue nearest shore was apparently in a baroclinic coastal jet, while that farther from shore was carried by the larger scale circulation associated with the proposed eddy lying between Cape Beaufort and Icy Cape. The motion of the nearshore drogue implies that it was moving with water above the pycnocline. When the winds blew from the south, the drogue moved alongshore to the north, presumably in response to an onshore Ekman flux. When the winds blew from the north, the drogue moved to the south with a slight offshore motion (Fig. 3).

If one plots the winds measured at the same time as the drogue data were collected, a threshold wind direction may be associated with reversal of the flow regime. Theoretically, the alongshore component of surface (lower) layer

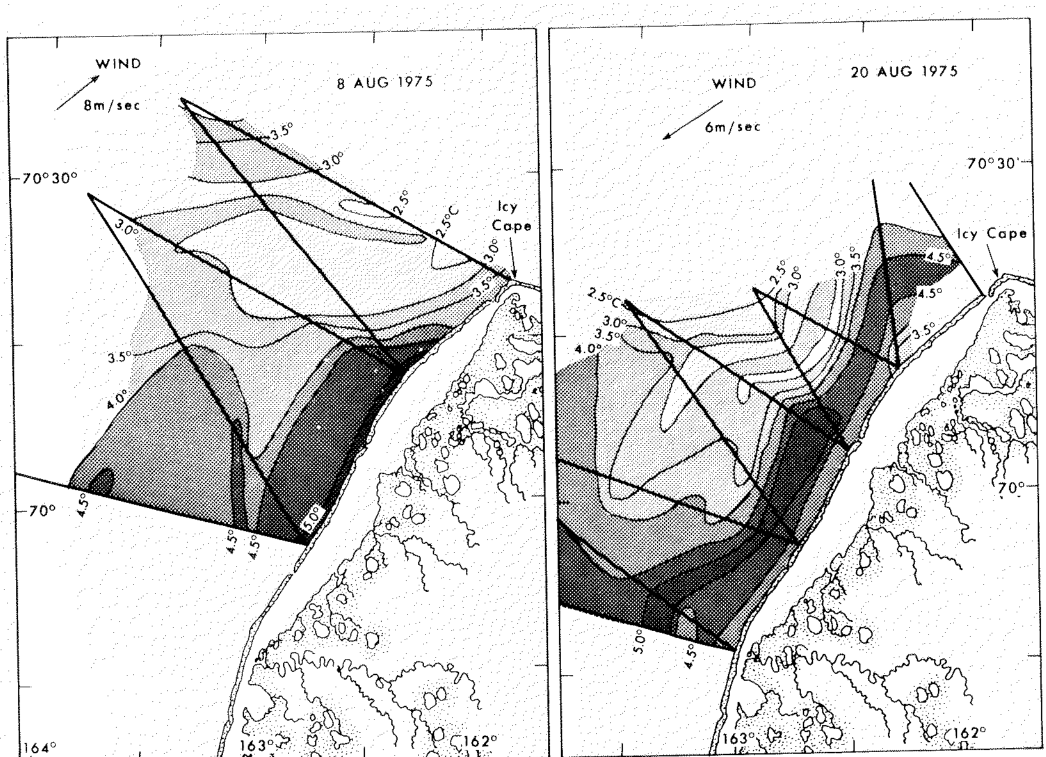

Fig. 4a. Radiation sea surface temperature under southwest winds.
Fig. 4b. Radiation sea surface temperature under northeast winds.

flow within the coastal jet should be in the same (opposite) direction as the alongshore component of the wind stress, if the wind drives the current. In our data, the current does not change direction until the wind direction crosses a line approximately 25° off of perpendicular to the coast. Thus some process other than a wind-driven baroclinic jet may also be active in the coastal zone, possibly a mean flow driven by a north-south pressure gradient.

Because of the bad ice in 1975, the research boat we had intended to use for making hydrographic sections never reached the field site. We did obtain some information on temperature distribution from two PRT-5 radiation thermometer overflights of the area (Fig. 4). One occurred during northeasterly winds and one during southwesterly winds. During the southwesterly winds, warm surface waters were piled up against the coast, while during the northeasterly winds the warm waters were displaced slightly offshore and cooler waters upwelled against the coast. Again, this is what one might expect in the case of a coastal jet driven by Ekman divergence at the coast. Furthermore, the e-folding offshore length scale, computed assuming a density difference between the upper and lower layers of four sigma-t units and layer depths of 10 m each, is 3.2 km (Csanady, 1971). This is of the same order of magnitude as the offshore length scale for the warm current measured during the PRT-5 flights.

DISCUSSION

There have been a few other sets of coastal current data collected along the Alaskan North Slope. Some data of our own show that farther north, in the vicinity of Point Franklin, a coastal boundary layer flow exists, but the presence of the Alaskan Coastal Current very near shore may interfere with the full development of a coastal jet (Thibodeaux, in preparation). In the Beaufort Sea, shore-parallel currents near the coast respond strongly to shifts in wind stress (Wiseman *et al.*, 1974). The few data available concerning stratification concurrent with these latter current data also have a structure similar to that found at Point Lay, but less intense. Extensive STD data collected by Barnes *et al.* (1977) near Oliktok Point show a structure expected in a coastal jet under the observed winds.

Data from the North Slope of Alaska thus demonstrate that the baroclinic coastal jet is a principal mode of circumlation during the summer season. Because of the fortuitous combination of strong winds, shallow bathymetry, large Coriolis parameter, and strong strtification, this jet is probably the dominant condition during the summer months. Certainly, as development of North Slope resources progresses, the presence of such a circulation mode must be taken into account in operational planning

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