Jörn Thiede ✓

Polynyas as a Possible Source for Enigmatic Bennett Island Atmospheric Plumes

DIRK DETHLEFF

GEOMAR Research Center for Marine Geosciences, Kiel, Germany

During polar winter open waters are well defined energy source areas, which release significant amounts of oceanic heat and water vapor forming buoyant atmospheric plumes. In this study the coincidence of a large polynya and the presence of high altitude plumes in the vicinity of Bennett Island on February 18, 1983, is discussed. Heat flux data derived from a balance-model reveal that the released energy of approximately 650 W/m^2 from the open water surface during the initial phase of the events by far exceeded the amounts necessary for turbulent upward air movements. The net heat flux as high as $2.4x10^{11}W$ from the entire polynya of 300 to 375 km^2 extent is suggested to be the energy source for the origin of strong local thermal updrafts and subsequent upper tropospheric plume formation. Submarine methane outbursts from sediments or underlying coal beds were mainly suggested as a valid source for such features near Bennett Island. However, all plumes of that remote area documented in the literature were observed during winter or early spring, when temperatures are extremely low and the Polar Ocean is ice covered, whereas the release of natural gases due to thermally weakened permafrost should rather happen during summer.

INTRODUCTION

Atmospheric plumes are warm, moist and buoyant *or* extremely cold and horizontally extended clouds of vapor or even ice crystals [*Matson*, 1986; *Schnell et al.*, 1989; *Sechrist et al.*, 1989]. Some of these features rise from point sources of different diameter and reach altitudes as high as 7-13 kilometers [*Kienle et al.*, 1983; *Clarke et al.*, 1986; *Matson*, 1986]. They have been described since the early 70s as a significant meteorological feature in the high Arctic [*Kienle et al.*, 1983; *St. Amand et al.*, 1985; *Clarke et al.*, 1986; *Matson*, 1986; *Sechrist et al.*, 1989; *Kerr*, 1992]. Frequently occurring at the northern tip of Novaya Zemlya and off the eastern and southeastern coast of Bennett Island (Figure 1, Figures 2 and 2a), those phenomena were explained as volcanic eruptions, methane and gas hydrate releases from shelf sediments or underlying coal beds, as orographic clouds or even as anthropogenic impacts. However, neither seismic records revealing tectonic, eruptive or explosive events in those regions have ever been reported, nor atmospheric concentrations of methane and relevant trace metals or elements were ever elevated during the occurrence of a Bennett Island or any other atmospheric plume [*Kienle et al.*, 1983; *St. Amand et al.*, 1985; *Schnell et al.*, 1992; *Paull and Buelow*, 1993].

According to Hansen and Schnell [quoted after *Kerr*, 1992] and *Schnell et al.* [1992], the scientific mystery of, at least, Bennett Island plume formation was solved as an orographic and meteorological cloud phenomenon. However, concerning Hansen's and Schnell's observations [quoted after *Kerr*, 1992], *Paull and Buelow* [1992] admitted that the distinction between plumes and "normal" clouds is rather uncertain. Nevertheless, apart from the question "plume" or "cloud", at present there is still one link missing: What is the energy source causing plumes or "normal" clouds in the vicinity of Bennett Island?

SHORT NOTES ON TERMINOLOGY

The term "plume" in this scientific context is either used for (i) a large-volume, buoyant, turbulent, and continuing convective upward heat and moisture flux over leads [e. g. *Glendening and Burk*, 1992; *Schnell et al.*, 1989] or (ii) for

The Polar Oceans and Their Role in Shaping the Global Environment
Geophysical Monograph 85

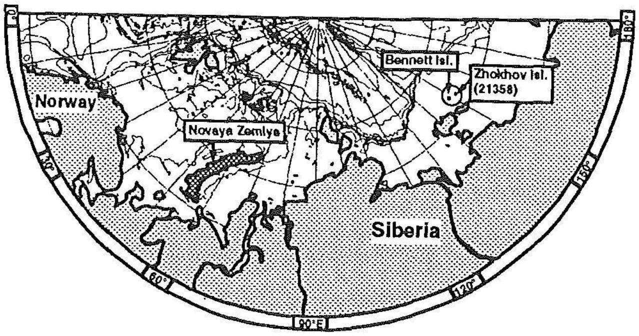


Fig. 1. Map of the eastern Arctic. Bennett and Zhokhov Islands are part of the De Long Islands. Zhokhov weather station is identified by the five digit code of the World Meteorological Organisation (WMO).

long extended ice clouds developing from high-altitude point sources [e. g. *Kienle et al.*, 1983; *Matson*, 1986]. The author assumes that both kinds of phenomena, at least near Bennett Island, are closely connected. Thus, both features are called "atmospheric plumes" and for simplification here will be named "plumes".

COINCIDENCE OF PLUMES AND POLYNYAS

Polynyas or flaw leads in the East Siberian Arctic can be closed or opened within few days or even less, induced by strong changing winds [*Dethleff et al.*, 1993; *Pease*, 1987]. Due to extreme sea/air temperature differences such open water areas in the Arctic ice cover are important sources for oceanic heat loss and release of water vapor [e. g. *Zakharov*, 1966; *Maykut*, 1982; *Pease*, 1987; *Martin and Cavalieri*, 1989; *Smith et al.*, 1990]. As modelled by *Schnell et al.* [1989] an energy flux of approximately 300 W/m^2 over a 10 km wide polynya could warm and moisten the air sufficiently for convective plume formation reaching altitudes of 4 kilometers, and thus, penetrate the Arctic boundary layer inversion.

On February 18, 1983, large plumes rose partly at the same time from different sources approximately 10 kilometers east and southeast of Bennett Island (Figure 3, Figure 4). The source regions were about 10 kilometer in diameter and the plumes reached altitudes of probably 7 kilometers [*Kienle et al.*, 1983]. During that day, a large polynya existed east of Bennett Island (Figure 3, Figure 4). It was situated directly below the punctiform plume sources as indicated on NOAA-6 and NOAA-7 satellite images. As will be presented in this study, the formation of plumes near Bennett Island on February 18, 1983 is suggested to be closely connected to the thermal energy and moisture released by the polynya.

MATERIAL AND METHODS

Meteorological and Satellite Data

Basic data were collected in order to balance and quantify the heat flux from ocean to atmosphere and to discuss a possible source and mechanism for the origin of the Bennett Island plumes. Synoptical 6-hour weather data (wind direction and speed, air temperature, humidity, cloudiness) from Zhokhov Island were obtained from the World Meteorological Organization (WMO, Figure 1). The Eastern Arctic pressure charts were adapted from the *European Meteorological Bulletin* [1983]. The satellite images for estimating the polynya extent east of Bennett Island on February 18, 1983, were taken from *Kienle et al.* [1983].

Heat Flux Calculations

The heat flux model used in this work was forced with the 6 hour meteorological data record. The calculations of the ocean-to-atmosphere energy fluxes through the polynya are based on the following heat balance equation:

$$F_{net} = F_S + F_L + R_A - R_L \qquad (1)$$

where F_{net} is the net heat flux, F_S and F_L are the sensible and latent heat flux, respectively, R_L is the outgoing longwave radiation, and R_A is the backscattered longwave radiation from the atmosphere. No incoming shortwave radiation occurs at high latitudes during winter and thus, this term was neglected in the calculations.

Sensible heat flux. The sensible heat flux can be written as:

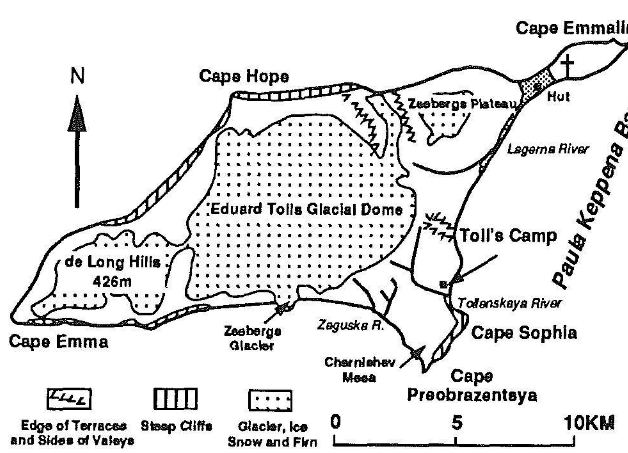


Fig. 2. Bennett Island thematic map, partly adapted from *Vol'nov et al.* [1970] and *Verkulich et al.* [1989].

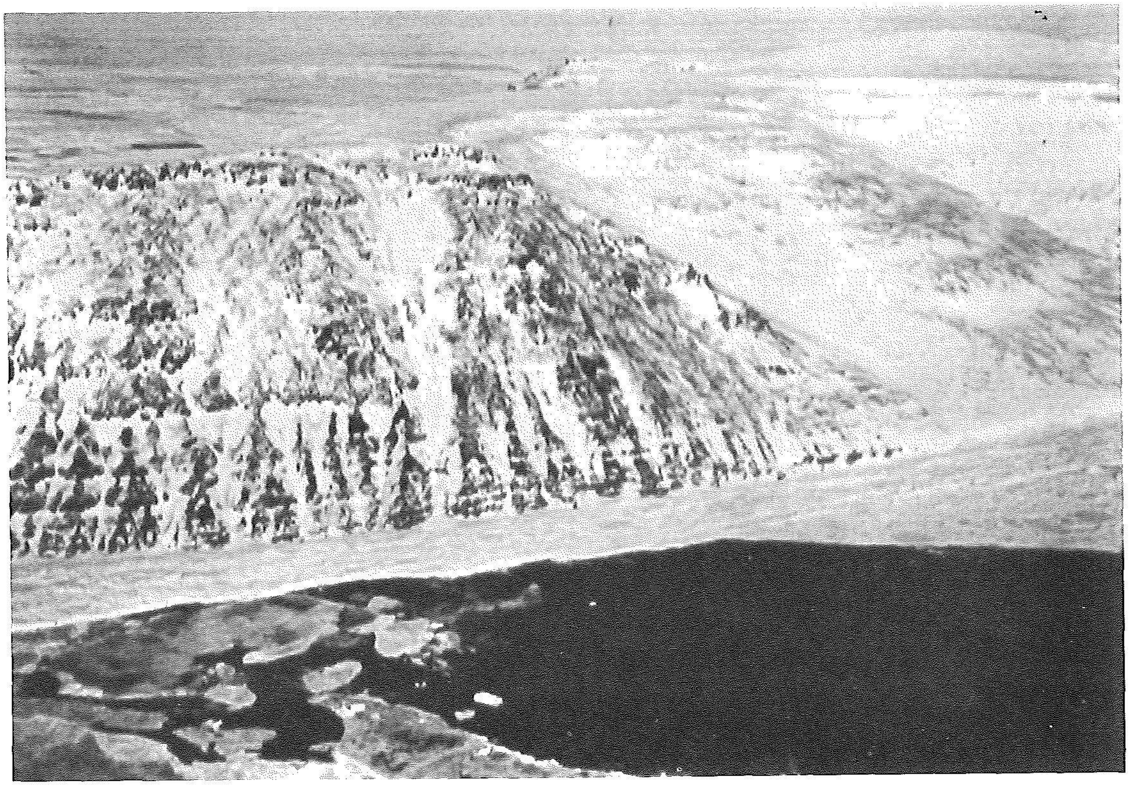


Fig. 2a. The image, taken on April 23, 1992 from helicopter, shows the southwesterly tip of Bennett Island. Direction of view is to the northeast across Eduard Tolls Glacial Dome. Note the snow- and ice-capped, plateau-like surface of the island where no particular high rising peak or lateral extended mountain range is recognizable. Large areas of open water (lower image section) were generated due to a preceding 6 day period of northeasterly winds.

$$F_s = \rho_{air} c_p C_s V_w (T_{air} - T_{sea}) \quad (2)$$

where ρ_{air} is the air density (1.25 kg/m^3), c_p represents the specific heat of air at constant pressure (1004 J deg^{-1} kg^{-1}), and C_s is the sensible heat transfer coefficient (1.75x10^{-3}) according to *Parkinson and Washington* [1979]. The term V_w represents the wind velocity, and T_{air} is the synoptically recorded air temperature at Zhokov Island WMO-station. The sea surface temperature (T_{sea}) is set to a freezing point of -1.6° C.

Latent heat flux. The flux of latent heat (F_L) is mainly driven by the wind velocity and the difference of the specific humidity between the air at the water surface and the air at 10 m altitude (q_{10} - q_0). This relationship can be expressed as:

$$F_L = \rho_{air} C_L L_v V_w (q_{10} - q_0) \quad (3)$$

where C_L represents a latent heat transfer coefficient 1.75x10^{-3}) and L_v is the latent heat of vaporization .5x10^6 J/kg).

Longwave radiation. The longwave radiative energy loss (R_L) of the polynya may be approximated by the following equation:

$$R_L = \varepsilon_s \sigma T_{sea}^4 \quad (4)$$

where ε_s is the surface emissivity (0.97) and σ represents the Stefan-Boltzmann constant (5.67x10^{-8}Wm^{-2}deg^{-4}).

Atmospheric longwave radiation. The atmospheric long-wave radiation (R_A) is obtained from the following term:

$$R_A = E_{air} \sigma T_{air}^4. \quad (5)$$

E_{air} is parameterized as a function of air temperature and fractional cloud cover (Cl, given in 1 to 8 eighth):

$$E_{air} = 0.99(1 - 0.261(1-0.75Cl^2) \exp(-7.7x10^{-4}(T_{air} - 273)^2)). \quad (6)$$

RESULTS

The meteorological data reveal a 6 day period from February 15 to 20, 1983, predominated by southwesterly,

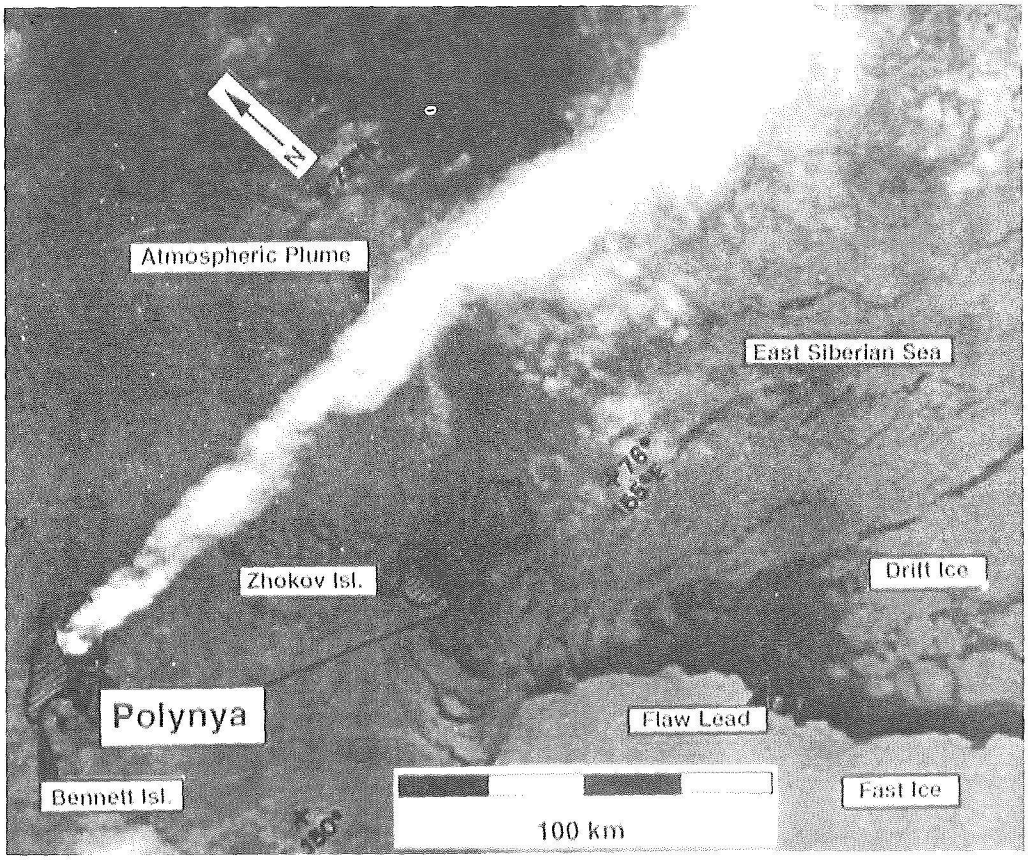
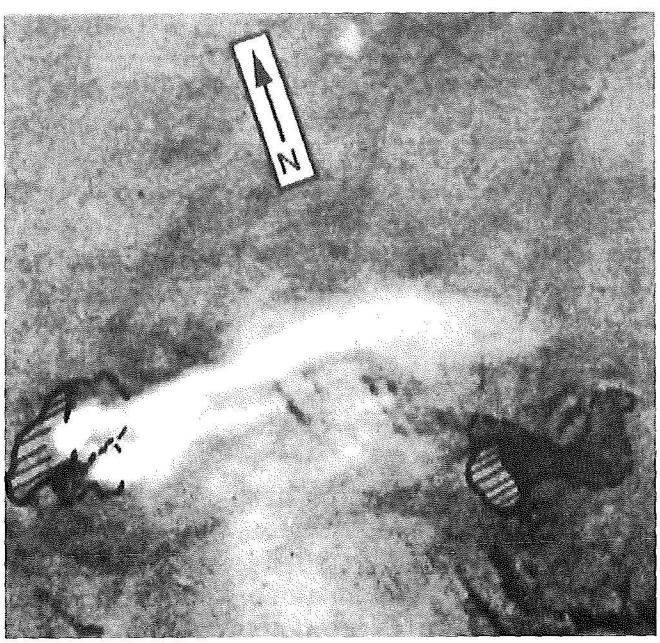


Fig. 3. NOAA-6 satellite image of the Bennett Island area at 06:16 UT on February 18, 1983 [adapted from *Kienle et al.*, 1983].



westerly and northwesterly winds with mean speeds of approximately 10 m/s and temporarily high net heat fluxes from the open water near Bennett Island (Table 1, Figure 6). The air temperatures range between -23° and -33° C (Figure 5). Strong westerly winds namely between February 16, 18.00 UT and February 17, 18.00 UT formed a large polynya east of Bennett Island as evident in Figures 3 and 4. According to the mean temperature (-27° C) and wind speed (10 m/s) during that 24-30 hrs period a maximum and stable polynya width of roughly 15 km can be estimated considering the studies of *Pease* [1987, see Figure 5., p. 7051]. As calculated by the same author, a 30 hrs offshore-

Fig. 4. NOAA-7 satellite image of the initial phase of plume development at 00:47 UT on February 18, 1983, reproduced from *Kienle et al.* [1983]. Note several source areas for the plumes. Overlapping of one of the circular plume sources and the shape of the island is assumably caused by the position of NOAA-satellites and subsequently, the angle of view.

TABLE 1. Basic meteorological data from Zhokhov Station and energy fluxes over the polynya as calculated from equation (1) to (6) in the Bennett Island area during February 15 to 20, 1983.

Date	Time (UT)	Air Temperature (°C)	Wind Speed (ms^{-1})	Wind Direction (°)	Heat Flux (Wm^{-2}) Sensible	Latent	Longwave	Backscatter	Total
15	0.00	-33.0	6	220	-292	-38	298	163	-466
	6.00	-31.4	7	210	-324	-44	298	171	-495
	12.00	-28.3	12	190	-497	-73	298	185	-683
	18.00	-24.4	12	210	-424	-70	298	195	-598
16	0.00	-25.9	13	200	-490	-78	298	192	-675
	6.00	-26.5	10	220	-386	-60	298	172	-572
	12.00	-24.8	12	200	-432	-71	298	200	-601
	18.00	-23.3	14	280	-471	-81	298	177	-673
17	0.00	-26.5	10	280	-386	-60	298	172	-572
	6.00	-28.6	8	300	-335	-49	298	169	-513
	12.00	-28.6	8	300	-335	-49	298	169	-513
	18.00	-28.0	10	250	-409	-61	298	173	-596
18	0.00	-24.0	13	210	-452	-76	298	178	-648
	6.00	-23.9	12	230	-415	-70	298	191	-592
	12.00	-23.1	11	230	-367	-63	298	205	-523
	18.00	-25.5	9	240	-334	-54	298	198	-487
19	0.00	-24.5	11	240	-391	-65	298	201	-553
	6.00	-24.1	1	270	-35	-6	298	202	-137
	12.00	-25.6	8	240	-298	-48	298	198	-446
	18.00	-25.7	8	240	-299	-48	298	198	-447
20	0.00	-24.4	12	240	-424	-70	298	201	-592
	6.00	-25.2	11	250	-403	-65	298	199	-567
	12.00	-24.7	9	250	-322	-53	298	195	-479
	18.00	-24.7	9	250	-322	-53	298	195	-479

wind period was necessary to open such a large area of ice free water. Both values, the polynya width and the opening time, derived from the paper mentioned above, are in convincing agreement with (i) the observed lateral extent of the polynya east of Bennett Island on February 18, 1983 (Figure 3, Figure 4) and (ii) the duration of the preceding period of westerly winds between February 16, 18.00 UT and February 17, 18.00 UT (Table 1, Figure 5). The longitudinal size of the open water area can be estimated to as much as 20-25 km (Figure 3). Consequently, a total polynya area of roughly 300-375 km^2 occurring during the plume events can be evaluated.

The results of the energy balance calculations are presented in Figure 6. The data reveal a net heat flux of 648 W/m^2 continuing from the water surface at 00.00 UT on February 18, solely 47 minutes before the initial phase of plume formation was noticed (Figure 4). An amount of 592 W/m^2 was released at 06.00 UT on the same day while the main plume was emanating from the open water area east of Bennett Island (Figure 3). Due to Bennett Island local meteorological and oceanographic conditions on February 18, 1983, an oceanic energy loss of approximately 1.8-2.4x10^{11} W can be evaluated for the entire polynya during the plume events.

According to the high pressure gradient in about 5 kilometers altitude (≈ 500 hPa level, Figure 7) and above, westerly winds reached velocities comparable to jet streams (> 200 km/h). These storms promoted the far eastward extension of the plumes discussed in this study. According to weather charts from the *European Meteorological Bulletin* [1983] the cloud cover at Zhokov Island was mapped as Cirrocumulus clouds, normally occurring at altitudes as high as 6 to 12 kilometers.

Main errors in the evaluation of the net heat flux from the polynya are based on the reliability of the balance calculations and on the open water estimate. Due to lower heat transfer coefficients used in the equations in respect to other authors [e. g. *Lindsay*, 1976], the sensible and latent energy flux in this study can be wrong by 30 %. Slight differences (lower values) of 5-10 % occur in the calculation of the longwave atmospheric radiation in respect to the term applied by *Parkinson and Washington* [1979]. Under consideration of the heat flux errors and a slightly variable open water extent the estimate of the net energy released

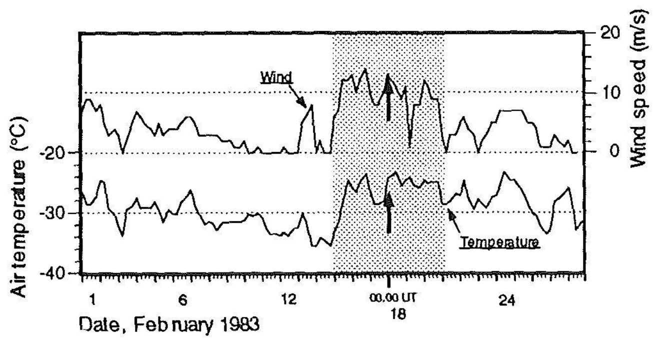


Fig. 5. Run of 6 hours wind speed and air temperature record during February 1983. Bold arrows mark the phase of plume occurrence. The six-day period of strong westerly winds is indicated by a stippled area.

from the entire polynya have an uncertainty of about 30-35 %. The values presented in this work are presumably to low, however, are probably not wrong by more than 50 %.

PHYSICAL CONDITIONS OF PLUME FORMATION

The phenomenon of plume origin on February 18, 1983 east of Bennett Island is suggested to be in causal connection with the significant ocean-to-atmosphere net energy flux from the local polynya. The feature is here proposed to be explained considering basic principles of atmospheric convection and thermal elevation of heated air masses (Figure 8). Due to friction by the surrounding colder atmosphere and additional lateral entrainment, the accelerated body of warm and moist air is slowed down at its margins, promoting the formation of a cylindrical thermal updraft (in short: thermal) of about 10 km in diameter.

The updraft enforces cold air masses from above and the surroundings to descend and substitute for the air at the base of the convective column. Sweeping over the open water area towards the center of thermal rise and withdrawing heat energy from the sea surface, the descended and formerly cold air now becomes part of the circulation. Due to very low surrounding temperatures at the condensation level and above, large volumes of small frozen water droplets are formed which generate ice clouds or plumes as observed on satellite images (Figure 3, Figure 4). According to the thermal energy released during the event, the condensation level of the warm updraft over the polynya is suggested to reach a height of approximately 1-3 km. Caused by its energy excess in respect to surrounding cold atmosphere, the rising warm air penetrated the Arctic boundary layer inversion. Thus, it can be assumed that, in analogy to convective clouds in cold air outbreaks over polar waters, the plume may have reached tropopause height, which was

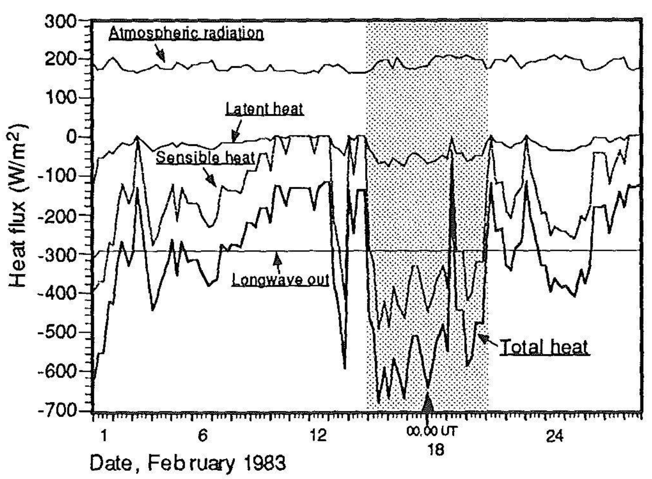


Fig. 6. Heat flux balance over open water near Bennett Island during February 1983. The arrow indicates the beginning of the plume event. The stippled area points out the six-day period of high net heat fluxes.

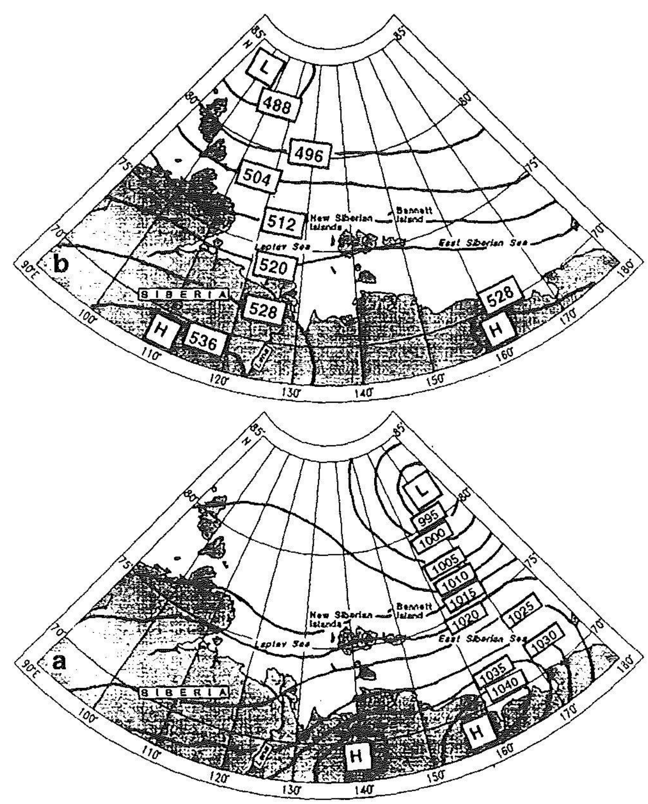


Fig. 7. Atmospheric pressure charts (a: surface, and b: ≈ 5 km altitude) of the east Siberian Arctic at 00:00 UT on February 18, 1983.

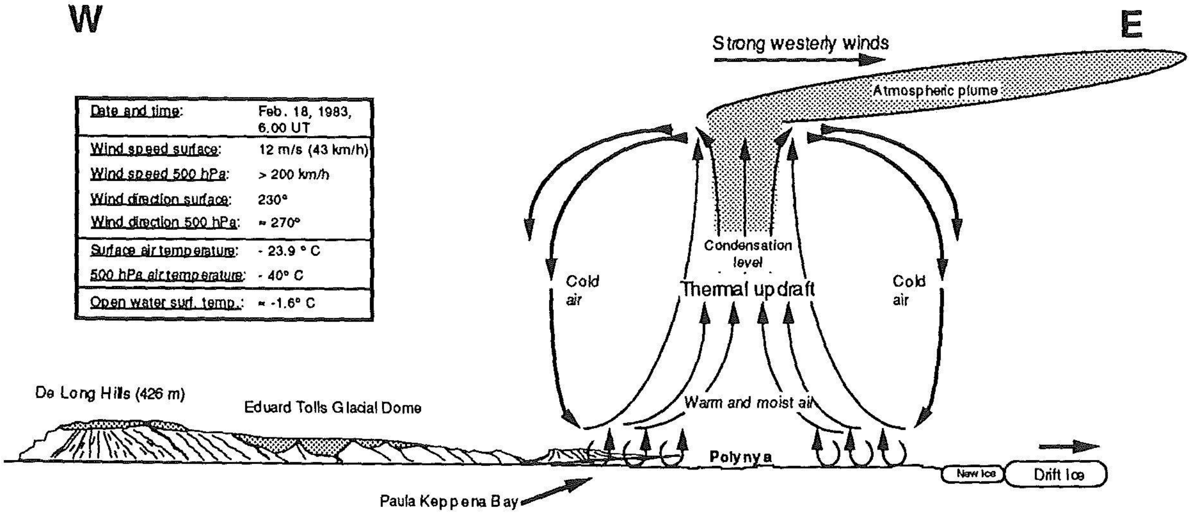


Fig. 8. Sketch of primary convection, thermal air mass circulation and replacement, and plume formation east of Bennett Island. The island profile is reworked from *Makeyev et al.* [1992]. Dotted areas represent snow, firn and glaciers. Note that the figure is not in scale.

at 8.5 km altitude on February 18, 1983 [*Kienle et al.*, 1983].

The appearance of two individual plumes over separated open water areas east of Bennett Island at 00:47 UT on February 18 implies the occurrence of distinct thermals during the initial phase of plume formation (Figure 4). Figure 9 shows, how several columns of rising air circulating in the same direction (a), will merge due to rotational expansion and, consequently, marginal collison and friction-induced turbulence (b). Finally, one single thermal updraft is formed typically tending to lie approximately in the center above the heating area (c).

DISCUSSION

As argued above, westerly winds are necessary for polynya opening and plume formation east of Bennett Island on February 18, 1983. According to long term observations [*Gorshkov*, 1983], however, prevailing winds in that area are from easterly and southerly directions with velocities as high as 16 m/s during the winter period (October to May), whereas westerly winds are infrequent. The relatively rare appearance of plumes east of Bennett Island in general may thus probably be due to a significant lack of strong westerly winds in the area of interest.

A faint low level plume was noticed at 18.04 UT on February 17, 1983 [*Kienle et al.*, 1983]. As shown in Figure 6 and Table 1, the net heat flux from the polynya was about 600 W/m^2 during that time and thus, sufficient energy was released for initiating strong upward movement of buoyant moist air. However, the frame conditions such as polynya width and wind direction were not favorable to maintain or even progress that feature and hence, the plume faded. Subsequently, the formation of plumes over open water east of Bennett Island, at least on the occasion of February 18, 1983, is suggested to depend on the succession and temporary coincidence of some special conditions: (i) the air temperature is significantly lower than -20° C and the mean wind velocity amounts to roughly or even exceeds 10 m/s during the event and before; (ii) a preceding period of strong westerly winds form large *stable-sized* areas of open water east and southeast of Bennett Island within typical synoptical time scales, which depend on air temperature and wind speed; (iii) the polynya opening period (ii) is succeeded by prevailing strong southeasterly winds which are not reduced by the shape of the island and thus, directly sweep over the open water enhancing significant heat loss from the ocean to atmosphere; (iv) extremely cold atmospheric temperatures and jet streams occur in the upper troposphere to promote the conversion of the convected moisture to long extended plume clouds consisting of supercooled small water droplets.

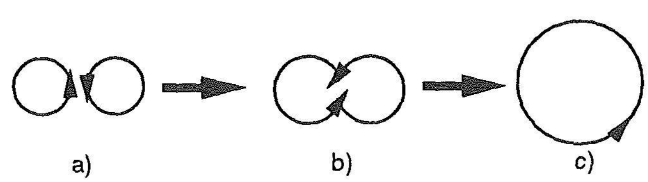


Fig. 9. The sketch shows a horizontal section of plume development.

The *perpendicular* and *undisturbed* thermal updraft over the heating polynya and the near surface peripheric inflow, once induced, is suggested to supply itself by the mechanism of thermal air mass circulation and replacement as presented in Figure 8. The jet streams at 5 kilometer altitude additionally may support the vertical circulation processes by drawing air masses upward inside the thermal comparable to a strong breeze sucking smoke from a chimney. Temporary oceano-graphic energy sources such as upwelling of relatively warm water masses or local currents could intensify the oceanic heat loss from the polynya and thus, may support con-trolling the mechanism of plume formation. Zhokov Island, located roughly 100 miles southeast of Bennett (Figure 3), faces a large east coastal polynya on February 18, 1983 as well, however, no plumes were detected in the vicinity. It can be speculated that Zhokov Island is characterized by local oceanographic conditions which do not promote the formation of visible plumes. The collapse of thermals, and thus, sudden fading of the Bennett Island plumes could be caused by the wrong frame conditions as mentioned above or by a reduced energy release from the water surface due to a cover of newly formed frazil and slush ice.

According to *Verkulich et al.* [1989] the maximum topographic height of Bennett Island is 426 m. This reference is in a good agreement with estimations of approximately 400 m height for Bennett Island, performed during GEOMAR expedition in April 1992 from about 700 m flight altitude (helicopter). Hence, cloud formation at an altitude of around 3000-4000 m (or even more) on the lee side of an "only" 400 m high island due to enforced orographic air movements, as proposed by Schnell [quoted after *Kerr*, 1992], seems to be not *that* likely. However, this unconvincing solution of the plume enigma is presumably attributed to the wrong assumption, that the Island has a height of 1000 m.

The strong surface wind blowing from southwesterly directions (210° and 230°, respectively, see Table 1) during the plume events on February 18, 1983 evidently could not sweep over mountain or glacier peaks on the island kicking up clouds off the eastern or even southeastern coast of Bennett. Orographic clouds, if kicked up at the lee side of the island during that day at all, must have developed *north* of Bennett in accordance to the surface wind directions.

Considering the *circular* base of the plume origin over open water at relatively high altitudes, a release of natural gases from *linear* faults on Bennett Island itself, as postulated by different authors, seems to be most unlikely. A simply forceless "bubbling" release of methane or gas hydrates from narrow, *extended* cracks in the submarine permafrost can be dismissed as a valid source for *punctiform* plumes, as well. Additionally, no fuel burn can generate such amounts of energy which were necessary for Bennett Island plume formation on February 18, 1983. A burning town, as presented by *Priestley* [1959] in a drastic model, would provide "solely" energy amounts of roughly 2.5×10^{10} W for smoke plume formation reaching altitudes of about 2,400 m.

CONCLUSIONS

1) On February 18, 1983, extended atmospheric plumes emanated from punctiform sources directly above a large polynya east of Bennett Island.

2) Polynyas are important sources of thermal energy during polar winter. Approximately $1.8\text{-}2.4 \times 10^{11}$ W were released from the open water area near Bennett Island during that day. The heat flux likely promoted a strong turbulent upward air movement (thermal) and was by far sufficient for high altitude plume formation.

3) The initial development, maintainance and subsequent progress of such thermals depend on the succession and temporary coincidence of distinct frame conditions, which were fulfilled on February 18, 1983: (i) low temperatures and high wind speeds during the event and before, (ii) preceding westerly wind for opening the polynya, (iii) southwesterly winds sweeping directly over the polynya during the event, and (iv) extremely cold temperatures and the occurrence of jet streams in the upper troposhere.

4) The *perpendicular* and *undisturbed* updraft of warm and moist air is suggested to supply itself by the mechanism of thermal air mass circulation and replacement.

5) Additionally, the plume formation may be supported by the chimney-effect attributed to jet-streams from westerly directions. These strong winds also control the far eastward extension of the plume at the 500 hPa level.

6) Faint development or break-down of thermals and thus, sudden fading of the plumes, could be due to unfavorable local meteorological and ice conditions: (i) lack of open water, (ii) reduced release of oceanic heat due to calming winds or due to a cover of newly produced frazil and slush ice, and (iii) changing wind direction.

7) A simply forceless bubbling release of methane or gas hydrates from shelf sediments, as well as volcanic activities or anthropogenic impacts (fuel burns) can be assumably excluded as a valid source for high altitude plume formation in the vicinity of Bennett Island.

Acknowledgments. This study was financially supported by research funds appropriated by the "Bundesministerium für Forschung und Technologie" of the Federal Republic of Germany to the GEOMAR Forschungszentrum in Kiel, Germany. Furtheron, I am indebted to thank Prof. Dr. Lutz Hasse, Dr. Erk Reimnitz, Dr. Dirk Nürnberg, Dr. Robert Spielhagen, Niels Noergaard-Pedersen and Ortrud Runze for reviewing this paper and giving new ideas. Special thanks are given to Eckhard Kleine and Peter Löwe from the "Bundesamt für Seeschiffahrt und Hydrographie" at Hamburg, for performing the heat flux calculations. This paper is dedicated to my dear friend and colleague Erk Reimnitz.

REFERENCES

Clarke, J. W., P. St. Amand, and M. Matson, Possible Cause of Plumes from Bennett Island, Soviet Far Arctic, *AAPG Bull.*, *70*, 574, 1986.

Dethleff, D., D. Nürnberg, E. Reimnitz, M. Saarso, and Y. P. Savchenko, The Laptev Sea - Its significance for Arctic sea-ice formation and transpolar flux of sediments, *Rep. Polar Res.*, *120*, 44 pp, 1993.

European Meteorological Bulletin, *Amtsblatt des Deutschen Wetterdienstes*, Februar 1983, Deutscher Wetterdienst, Zentralamt Offenbach, Germany, 1983.

Glendening, J. W., and S. D. Burk, Turbulent Transport from an Arctic Lead: A Large-Eddy Simulation, *Boundary Layer Meteorology*, 59, 315-339, 1992.

Gorshkov, S. G., *World Ocean Atlas*, 3, Arctic Ocean, 80-103, 1983.

Kerr, R. A., U. S. - Russian Team Solves Arctic Mystery, *Science*, *257*, 35, 1992.

Kienle, J., J. G. Roederer, and G. E. Shaw, Volcanic Event in Soviet Arctic? *EOS Trans. AGU*, *64, 20*, 376-378, 1983.

Lindsay, R. W., Wind and temperature profiles taken during Arctic Lead Experiment, *M. S. thesis*, 89 pp, Dep. of Atm. Sc., Univ. of Wash., Seattle, 1976.

Makeyev, V., V. Pitul'ko, and A. Kasparov, Ostrova De-Longa: An analysis of palaeoenvironmental data, *Polar Record*, *28*, *167*, 301-306, 1992.

Martin, S., and D. J. Cavalieri, Contributions of the Siberian Shelf Polynyas to the Arctic Ocean Intermediate and Deep Water, *J. Geophys. Res.*, *94*, 12,725-12,738, 1989.

Matson, M., Large Plume Events in the Soviet Arctic, *EOS Trans. AGU*, *67*, 1372-1373, 1986.

Maykut, G. A., Large-scale heat exchange and ice production in the Central Arctic, *J. Geophys. Res.*, *87*, 7971-7984, 1982.

Parkinson, C. L., and W. M. Washington, A large-scale numerical model of sea ice, *J. Geophys. Res.*, *84, C1*, 311-337, 1979.

Paull, C. K., and W. J. Buelow, Arctic Mystery: Plumes or Clouds, *Science*, *258*, 725, 1992.

Paull, C. K., and W. J. Buelow, Enigmatic Arctic Cloud Plumes, *Science*, *259*, 164, 1993.

Pease, C. H., The Size of Wind-Driven Coastal Polynyas, *J. Geophys. Res.*, *92*, 7049-7059, 1987.

Priestley, C. H. B., *Turbulent Transfer in the Lower Atmosphere*, The University of Chicago Press, 130 pp, Chicago, Illinois, U.S.A, 1959.

Schnell, R. C., R. G. Barry, M. W. Miles, E. L. Andreas, L. F. Radke, C. A. M. Brock, M. P. McCormick, and J. L. Moore, Lidar detection of leads in Arctic sea ice, *Nature*, *339*, 530-532, 1989.

Schnell, R. C., A. D. A. Hansen, E. Dlugokencky, T. J. Conway, A. V. Polissar, and G. S. Golitsyn, Airborne Investigation of the Bennett Island Plume, in *Abstracts for the Fifth Symposium on Arctic Air Chemistry, September 8-10*, Copenhagen, 1992.

Sechrist, F. S., R. W. Fett, and D. C. Perryman, *Forecasters Handbook for the Arctic,* Naval Environmental Prediction Research Facility, Technical Report TR 89-12, Monterey, CA, 1989.

Smith, S. D., R. D. Muench, and C. H. Pease, Polynyas and leads: An overview of physical processes and environment, *J. Geophys. Res.*, *95*, 9461-9479, 1990.

St. Amand, P., P. J. Clarke, and M. Matson, Curious plumes from Bennett Island, in *Proceedings of the Arctic Oceanography Conference and Workshop, June 11-14, 1985*, Naval Ocean Research and Development Activity (NORDA), Bay St. Louis, 1985.

Verkulich, S. R., A. G. Krusanov, and M. A. Anisimov, Recent State and Changes in the Glaciation of Bennett Island During the Last 40 Years (in Russian), *Arctic and Antarctic Research Institute*, St. Petersburg, Russia, 1989.

Vol'nov, D. A., D. S. Sorokov, and O. A. Ivanov, *Geologicheskaya karta Novosibirskikh Ostrovov* (Geological map of the New Siberian Islands), Moscow, Ministry of Geology, 1970.

Zakharov, V. F., The role of flaw leads off the edge of fast ice in the hydrological and ice regime of the Laptev Sea, *Academy of Sciences of the USSR - Oceanology*, *6*, 815-821, 1966.

Dirk Dethleff, GEOMAR Research Center for Marine Geosciences, Wischhofstraße 1-3, D-24148 Kiel, Germany.