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History of Meteorology

Meteorological aspects of Salomon August Andrée's attempt to reach the North Pole by balloon in 1897 based on 20CR data

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Abstract

On 11 July 1897, a Swedish expedition under Salomon August Andrée attempted to reach the North Pole from Spitsbergen by balloon. The flight was terminated after only three days, as the weight of the balloon increased above a critical limit, due to an ice load caused by freezing fog and drizzle. Here the meteorological context of this expedition is discussed, in particular concerning the planning of the flight and in-flight weather conditions. Based on recently released pressure fields for the Arctic region for July 1897, obtained from the twentieth century reanalysis project (20CR), it can be shown that the Andrée expedition would not have reached the North Pole even with a perfect balloon, due to unfavourable wind conditions in the central Arctic after their departure from Spitsbergen.

Keywords: Andrée, balloon, Arctic, North Pole, twentieth century reanalysis

1 Introduction

Today the North Pole can be reached by research aircraft and ice-going vessels more or less without problems, or with more effort by well-equipped land expeditions. Even tourists can travel to the Pole on board Russian ice-breakers. This was not the case 120 years ago. In 1897 nobody had reached the North Pole. Fridtjof Nansen and Hjalmar Johansen had reached the farthest point north in 1895, having travelled to 86° 12′ N after leaving the vessel Fram under captain Otto Sverdrup, which was designed to be frozen in the sea/pack ice, north-east of Franz Josef Land to reach the pole by marching over the pack ice with the help of sledges and kayaks. Expeditions by Albert Markham reached 83° 20′ N in 1876, and by James Lockwood and David Brainard 83° 24′ N in 1882. Many other expeditions at that time failed to reach the North Pole (several of these are described e.g. in Fleming, 2001). What all of these attempts had in common, with the exception of the Fram expedition, is that ships, material, and lives were lost over the long course of each one. These casualties were what motivated the Swedish engineer Salomon August Andrée to propose an expedition to the North Pole by means of balloon transport (Andrée, 1896). His main argument was that a balloon could travel over a distance of about 400 km per day, which would take the usual ship/land expeditions several weeks. Hence he envisaged a trip in a balloon from Spitsbergen to the Pole to be feasible within a week, if the winds were suitable. The balloon would then drift further on towards the northern territory of Canada or to Siberia, depending on the weather situation after having crossed the pole.

Despite many criticisms from the polar scientific community, Andrée managed to obtain funding for a balloon, which was named Eagle, and finally took off on 1345 UTC 11 July 1897, with Knut Fraenkel and Nils Strindberg, from the Danes Island close to Spitsbergen. As this was the first attempt to use air transport for polar expeditions, Andrée's flight was termed "the beginning of polar aviation" by Sollinger (2005). Unfortunately the journey ended on 0730 UTC 14 July 1897, due to technical problems with the balloon, about 480 km north of the starting point. The three men then started a march over the moving pack ice which ended at the White Island north-east of Spitsbergen on 5 October 1897. For reasons which are still debated today, all members of the expedition died sometime in October of that year. After a 33 year wait, the remains of the expedition were found on the island by a Norwegian expedition travelling on board the ship Braatvag on 6 August 1930, and some days later by the crew of the vessel Isbjörn. As the diaries of the three men were found nearly intact, and as some of the photographic films could be developed, even after such a long time, the whole expedition has been reconstructed by a team from the Swedish Society for Anthropology and Geography (Andrée et al., 1930). In later years, many books have been written about this tragic expedition, e.g. Capelotti (1999), Hempleman-Adams and Uhlig (2001), Sollinger (2005), Wilkinson (2012), and Wrakberg (1999a), which cover nearly every aspect of this historic balloon flight in some detail.

The meteorological aspects of the expedition concerning weather prediction, weather conditions during

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the flight, and the general possibility of reaching the North Pole by balloon have received less attention. This is the motivation for this paper, which builds upon some earlier remarks on the weather conditions during ANDRÉE's balloon flight by WALLÉN (1930) and WRAKBERG (1999b), and some more detailed discussions by SOLLINGER (2005). In particular, recently released pressure fields for the Artic region in 1897, produced by the twentieth century reanalysis project 20CR (COMPO et al., 2011), are used to discuss whether the large scale wind conditions in July 1897 were favourable for a balloon flight from Spitsbergen to the North Pole at all.

2 Balloon flight and meteorology

Of all airborne vehicles, the balloon is the most dependent upon the weather, especially the wind. The reason is simple: a balloon has no device for steering like aeroplanes or airships. Once airborne it is floating with the wind, and the flight track is dependent on the wind speed and direction in the air mass surrounding the balloon. The only way to change the direction of flight is to move the balloon up or down to find layers in the atmosphere with the desired wind direction. This can be achieved by trial and error if the vertical variation of wind direction is not known, or by using information from wind forecasts based on numerical weather prediction models before launching and during flight. Special models like FLEXTRA (RIDDLE et al., 2006) or HYSPLIT (STEIN et al., 2015) for forecasting balloon trajectories are available. In fact, both methods are used today for short-distance hot air ballooning and long-distance flights (e.g. trans-Atlantic or global circumnavigation) in gas balloons or combined gas-hot air balloons (so-called Roziere balloons). However, even if all wind information is available to the pilot, it is still not simple to reach a certain destination from a particular launch site by balloon. This is especially true if the balloon flight will take several days, as in the case of long-distance flights (e.g. BAUMANN and STOHL, 1997). It is no surprise, therefore, that the first successful balloon flight to the North Pole was performed by the British adventurer DAVID HEMPLEMAN-ADAMS in the year 2000, more than 100 years after the failure of the Andrée expedition. This flight will be discussed briefly at the end of the paper.

In the year 1897, when ANDRÉE attempted to reach the North Pole by balloon, no weather prediction for the polar regions existed. There were not even detailed information available on the weather in the central Arctic north of 80° N. In order to avoid being completely at the mercy of the as yet unknown wind conditions after the launch, ANDRÉE invented a kind of steering mechanism, which would allow him to manoeuvre the balloon within an angle of about 25° from the wind direction. This system comprised several long ropes which would drag along the surface and which could be released from the balloon if needed. This would lead to a reduction in balloon speed compared with the wind speed, which is essential if one is to steer an airborne vehicle. The steering itself was performed by sails mounted on the balloon, and the balloon was supposed to react like a ship sailing downwind. Details of this special steering system can be found in ANDRÉE et al. (1930) or SOLLINGER (2005). Fig. 1 provides an impression of the balloon configuration.

Figure 1: The balloon shortly after start from Danes Island on 11 July 1897. The guide- and ballast ropes are touching the sea surface. The steering sails can be seen above the basket. Source: Öklund, Tekniska Museet, Stockholm

3 Meteorological information available for the planning of ANDRÉE's balloon flight

The balloon flight in 1897 was to start from the Danes Island, close to the north coast of Spitsbergen at about 80° N. To reach the North Pole, southerly winds were required. For the launch itself local observations were performed, and the expedition set off on 14 July 1897 after a long wait for a suitable wind conditions (see ANDRÉE et al., 1930). For the planning of this expedition however, information about weather and wind conditions for the summer months around Spitsbergen were needed. There were no meteorological stations before 1880 in this area, and it was only during the first International Polar Year (IPY-1), August 1882–August 1883 (Lüdecke, 2004; WOOD and OVERLAND, 2006; TAMMIKSAAR et al., 2010), that meteorological observations were available for the regions up to 80° N, which could be used for flight planning. One of the observation stations,

Table 1: Mean atmospheric conditions at the station Cap Thordsen (Spitsbergen) for the month July 1883 as observed during IPY-1. From Ekholm (1890).

Parameter	Magnitude
Temperature, mean	4.4 °C
Temperature, minimum	0.4 °C
Temperature, maximum	12.3 °C
Precipitation	6.8 mm
Days with rain	10
Days with snow	0
Days with fog	11
Cloud cover	74 %
Relative humidity	84 %

run by Swedish scientists, was located at Cap Thordsen, about 40 km north of Longyearbyen at Spitsbergen. The expedition was led by the meteorologist Nils Ekholm and Andrée was also a member of the crew. The original observations for Cap Thordsen from August 1882 to August 1883 were published by Ekholm (1890) and are available from the repository ePIC of AWI at http://dx.doi.org/100013/epic28881. Data for Cap Thordsen and other stations of the IPY-1 have been digitized as part of a Wdc-Mare project (Krause et al., 2010) and can be accessed though the Pangea data library at www.pangaea.de. During the planning of the expedition Andrée used these data for choosing the best month for the balloon journey. It transpired that July was the most suitable month in terms of temperature and precipitation. Some data for Cap Thordsen for July 1883, obtained during IPY-1, are given in Table 1.

These data are valid only for July 1883, but are close to the typical values at the station Longyearbyen today. The modern average temperature (5.8 °C) and precipitation (18 mm) are somewhat higher, so July 1883 was quite dry in comparison. One might also mention that, in the area north of Spitsbergen, fog is observed on 20 days in July on average (Przybylak, 2003) as compared to the 11 days observed at Cap Thordsen during July 1883.

The most important information was data relating to the wind situation, as southerly winds were needed to reach the Pole from Spitsbergen by balloon. At Cap Thordsen there were two wind stations, one at 90 m a.s.l. and another one at 269 m a.s.l. The latter station was the most suitable for wind information, as the balloon was supposed to travel at heights between 200 m and 300 m above sea level (this was due to the use of guide ropes for steering the balloon). Data were collected on hourly basis for each day of the month from August 1882 until August 1883.

At 269 m, southerly wind directions, SE–SW (135°–225°) occurred 32 % of the time in July 1883. If we exclude weak winds below 1 ms^{-1}, southerly wind directions occurred in 19 % of all hours. The average wind speed when light winds are excluded was 4.4 ms^{-1}, with maximum winds of 16.2 ms^{-1}. With this wind information Andrée could estimate the time it would take to travel to the North Pole. The distance between Danes Island and the Pole is 1140 km. If the wind speed on the flight is equal to the average wind speed of 4.4 ms^{-1} (16 kph), the shortest flight would take 71 hours (3 days). For higher wind speeds, for example 10 ms^{-1} (36 kph), flight time would be 32 hours. Of course a direct flight in a balloon to the Pole is unlikely, as wind directions are not likely to be exactly southerly, and may vary during the flight. Hence a realistic duration of the planned flight between Spitsbergen and the North Pole could be twice as long as the minimum flight times, i.e. between three and six days, depending on wind speed and wind direction.

These estimates were based only on wind observations at a single station in Spitsbergen. But at this time, no long-term observations of weather and winds in the area between Spitsbergen and the North Pole were available. In order to provide some estimates for this region, Ekholm (1895) analysed data collected from all stations during the month of July 1883 of the IPY-1. From these he outlined a circumpolar surface weather map, where the pressure field for the areas north of 80° N was estimated. This map is shown in Fig. 2. Besides monthly averaged surface isobars, which would allow the estimation of the general wind conditions between Spitsbergen and the Pole, the typical directions of moving cyclones are also indicated. The main features in the pressure distribution which might impact a possible balloon flight from Spitsbergen to the North Pole are the location of a low pressure system over Greenland, and a high pressure region north of Norway. This situation would allow large scale southerly winds in the area north of Spitsbergen, which are necessary for a successful balloon flight towards the North Pole.

This map was the main basis for the arguments of Ekholm (1895), that wind conditions in July were suitable for a flight in a balloon from Spitsbergen to the Pole. It was, of course, an estimation of the unknown surface pressure field in July for the central Arctic region north of Spitsbergen, but there was no better information available at the time. A comparison with a recent reanalysis of the pressure fields during July 1883, obtained from NOAA/ESRL (see Fig. 6), which will be discussed in Section 5, shows that Ekholm's analysis was somewhat optimistic concerning the pressure distribution, and hence the near surface wind field in the area between Spitsbergen and the North Pole. In this context it might be noted that Ekholm was a member of Andrée's balloon crew during the first attempt at reaching the North Pole in August 1896, which was abandoned due to unfavourable winds. For the flight in July 1897, Ekholm withdrew from the crew and was replaced by Nils Strindberg.

4 Trajectory of the balloon

Before the meteorological conditions during the actual flight of the balloon from 11–14 July 1897 are described,

Figure 2: Mean surface pressure for the month July 1883 for the area north of 50° N as based on data obtained during IPY-1. Source: Ekholm (1895).

information of the route taken after the launch is presented. The balloon's trajectory in the horizontal and vertical directions has been reconstructed from notes found in the diaries of the crew, and can be found in Andrée et al. (1930). The horizontal flight path, as displayed in Fig. 3, can be subdivided into three flight legs. During the first 12 hours (leg 1), the balloon was moving toward the north-east, covering a distance of about 400 km, with an average speed of about 38 kph (10.5 ms^{-1}). After the end of leg 1, the balloon remained stationary from 0130 UTC–0300 UTC 12 July due to calm winds. Thereafter, the balloon was driven towards the west with nearly no progress in a northerly direction (leg 2). From 2200 UTC 12 July until 1100 UTC 13 July the balloon remained stationary at its most western position, because the guide ropes were locked on the ground in the pack ice. After getting free, the balloon moved in a north-west direction until the termination of the flight on 0730 UTC 14 July (leg 3). The active parts of the flight legs, when the balloon was moving in the horizontal direction, are also indicated in Fig. 4. The total distance covered was 630 km, the farthest point north was 82° 55′ N after landing, so the North Pole was still 750 km away. The reason for this trajectory can be attributed to the winds, which were quite strong during the first day (about 10 ms^{-1}) but light and variable after this part of the flight. More information on the wind conditions will be provided in the next section.

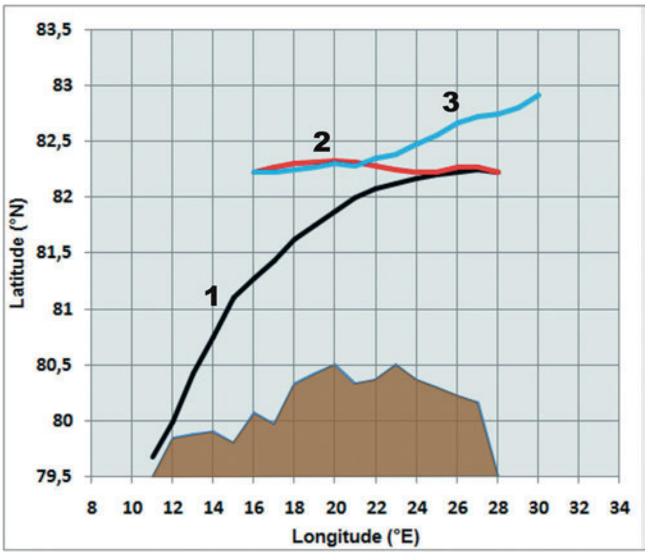


Figure 3: Horizontal trajectory of the balloon. The flight path can be divided into three legs: Leg 1: 1350 UTC 11 July–0130 UTC 12 July. Leg 2: 1500 UTC 12 July–2200 UTC 12 July. Leg 3: 1100 UTC 13 July–0730 UTC 14 July 1897. The outline of Spitsbergen is shown schematically in brown colour. After Andree et al. (1930).

The vertical trajectory is shown in Fig. 4. Immediately after launch, the balloon reached heights of about 600 m, far above the planned flight level of 250 m. This

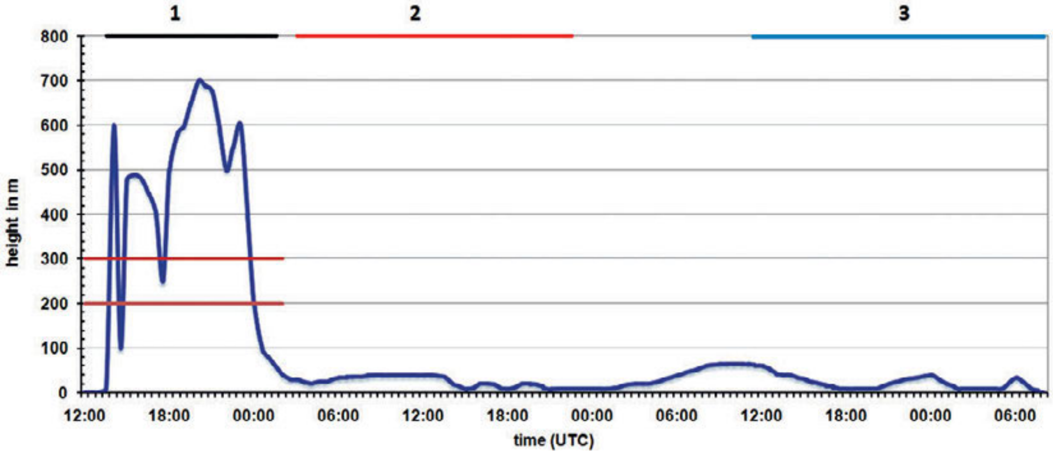


Figure 4: Vertical position (in meters) of the balloon during its flight from 1345 UTC 11 July until 0730 UTC 14 July 1897. The short horizontal lines at 200 m and 300 m indicate the range of the anticipated flight level. The active parts of the three flight legs from Fig. 3 are indicated at the top. After Andrée et al. (1930).

was due to the loss of parts of the guide ropes during launch, which reduced the ballast of the balloon. Thereafter, flight levels were mainly between 250 m and 700 m until the end of the first day. Afterwards the balloon sank down to about 100 m, and remained below this level until the termination of the flight on 14 July. The reason for the sinking was the cooling of the balloon gas in the shadow of a large cumulus cloud. After dropping below the clouds, the balloon was in contact with the ground on several occasions, or was flying close to the ground at heights around 40 m. For the most part, the balloon was never flying at the planned flight level of about 250 m. The reasons for this will be given in some more detail in the next sections, where the influence of weather on the balloon trajectory is discussed.

5 Weather observations during the flight

In the diaries of Andrée and Strindberg (Andrée et al., 1930) information on the weather during the balloon flight can be found. Here a short summary of the different weather elements is provided.

Temperature and moisture: Measurements for dry and moist air temperature were taken regularly. In the first hours, at flight levels around 600 m, T(dry) = 1.0 °C and T(moist) = 0.4 °C, giving a relative humidity $f = 90\,\%$. After descending to below 100 m, temperatures were slightly lower with T(dry) = 0.4, T(moist) = 0.2, $f = 96\,\%$. On the last day of the flight, T(dry)$y = 0.3$ °C, T(moist) = −0.1 °C and $f = 93\,\%$ were reported.

Clouds: Throughout the whole journey, the cloud cover was near 90 %. As the balloon ascended through the clouds after launch and remained above them during the first 10 hours, the cloud top was estimated at 500 m. Concerning cloud base, no information is available, but the balloon crew mention thin clouds in their diaries. Hence the cloud layer might have been Arctic stratus of about 100 m thickness, with cloud base at about 400 m height.

Weather: During the first 10 hours, the balloon was above the cloud. After the balloon descended below 100 m, fog was more or less permanently recorded. Drizzle also occurred over long periods of time. On 13 July, the crew noticed the formation of hoar frost on the basket ropes, which persisted until the end of the trip on 14 July.

Wind: At launch on 1350 UTC 11 July the wind was from the SW at about 9 ms^{-1}. During the first 10.5 hours, the wind direction remained the same, and the wind speed varied between 9 ms^{-1} and 13 ms^{-1}. In the first hours of 12 July, the wind was light and from the SW at 1–2 ms^{-1}. Thereafter, the wind direction was E at 3.3 ms^{-1} until 2200 UTC. After this period, the wind direction changed again to NW at 5.5 ms^{-1} for six hours and then to W at 3.9 ms^{-1} until 2100 UTC 13 July. After this, the wind was 5.3 ms^{-1} from the SW until landing at 0730 UTC 14 July. After landing, the wind direction changed to NW until 15 July with speeds of about 4.8 ms^{-1}.

In summary, the weather conditions from 12–14 July, after the balloon had descended below the clouds, were much more unfavourable than observed in July 1883 during IPY-1. The temperatures were near 0 °C at the end of the balloon flight. Fog was observed nearly all of the time, with only occasionally short periods during which fog break up and sunshine were reported. From 13 July, a combination of fog and drizzle with temperatures near freezing led to the formation of hoar frost on the balloon, which could not be melted away due to lack of sunshine. The wind situation was quite favourable during the first day, just as expected from the IPY-1 observations. During the other three days, winds were quite variable in speed and direction, with very unfavourable north-westerly directions on 14 July, the last day of the flight.

6 Meteorological reasons for the failure of ANDRÉE's balloon expedition

6.1 A short digression on balloon physics

In order to understand the reasons for the failure of ANDRÉE's balloon flight it may be helpful to have some basic information on balloon physics. All balloons function after the well known principle of Archimedes, which states that the vertical acceleration of an air parcel depends on the difference between the density of the environmental atmosphere (denoted by ρ_a) and of the air parcel (denoted by ρ_p). The vertical acceleration (dw/dt) per unit volume due to Archimedes' principle can be written as:

$$\rho_p dw/dt = g(\rho_a - \rho_p). \tag{6.1}$$

The term on the r.h.s. is called buoyancy force in meteorological applications. If the air parcel is less dense (warmer) than the surrounding air it will be accelerated upward, if it is more dense (cooler) than the environment, it will sink down. Basically, this is the principle of thermal convection. Equation (6.1) is also the basis for ballooning. Here, the density of an air parcel ρ_p has to be replaced by the density of the balloon gas ρ_g. The main difference between the application of (6.1) to the atmosphere and to balloons is that the balloon gas is enclosed in an envelope and can not mix with the surrounding air. For ballooning, the volume V of the balloon is an important parameter. Hence we multiply (6.1) by V and introduce the density of the balloon gas ρ_g to obtain:

$$V\rho_g dw/dt = gV(\rho_a - \rho_g). \tag{6.2}$$

In balloon flight, one is not so much interested in the vertical acceleration due to buoyancy force as given by (6.2) but in the weight that a balloon can carry. Hence it is usual in the ballooning literature (e.g. YAJIMA et al., 2009) to divide (6.2) by gravity "g" to obtain a normalized acceleration with units of a mass (kg), which is called lift (L):

$$L_f = V(\rho_a - \rho_g). \tag{6.3}$$

Relation (6.3) is called "free lift" (L_f), which is the maximum mass that a balloon with volume V can lift in the vertical direction. For example, under standard conditions (pressure = 1013 hPa and temperature = 0 °C), the density of air is $\rho_a = 1.29\,\mathrm{kgm^{-3}}$. If we take hydrogen as the balloon gas, we have $\rho_g = 0.09\,\mathrm{kgm^{-3}}$. Hence the free lift per unit volume of hydrogen is $L_f = 1.2\,\mathrm{kg}$ under standard conditions. This positive lift is counteracted by the mass of the balloon itself, excluding the mass of the gas ($m_g = V\rho_g$), which can be named m_b. This includes the balloon envelope, ropes, basket, equipment, and passengers. The difference between free lift L_f and balloon mass m_b is called "total lift" (L_t):

$$L_t = L_f - m_b = V(\rho_a - \rho_g) - m_b. \tag{6.4}$$

In order for a balloon to ascend, the total lift has to be positive. Consider a typical radiosonde used for vertical measurements of meteorological data: the balloon volume is about $1\,\mathrm{m^3}$, hence the free lift is 1.2 kg. Therefore, the mass of the balloon envelope and the radiosonde must be less than 1.2 kg in order to obtain positive lift. ANDRÉE's balloon had a volume of $V = 4800\,\mathrm{m^3}$, hence its free lift was 5760 kg under standard conditions. The weight of the balloon including envelope, ropes, basket etc. was about 3000 kg, the ballast was 1300 kg (see SOLLINGER, 2005 for details). The weight of equipment and passengers therefore had to stay below 1460 kg in order to get airborne.

Except for radiosonde observations in the atmosphere, where a balloon is supposed to ascend permanently, balloons generally travel in the horizontal direction at a certain flight level, like airships or aeroplanes. In level flight, the total lift equals zero, hence the desired flight level can be calculated from (6.4) by $V\rho_a = V\rho_g + m_b$, when the vertical profile of air density $\rho_a(z)$ is known. From its equilibrium level, a gas balloon can be moved up by reducing the balloon mass m_b by releasing ballast. In order to move down, the volume V has to be reduced by releasing gas from the balloon.

The lift of a balloon can be influenced by the atmosphere in several ways: first by changing the density of the surrounding air (ρ_a), which can lead to increase or decrease of free lift L_f (6.3). Second, by increasing the mass of the balloon m_b by adding weight due to the deposition of rain, snow, or ice on the balloon's surface, which will always lead to a decrease in total lift L_t (6.4) and hence to sinking. A more subtle influence is related to the cooling of the balloon gas during night time or in the shadow of clouds due to outgoing long wave radiation, which leads to a reduction of the balloon volume V, and hence a reduction in free lift. This is counteracted during day time as the balloon is heated by solar radiation (in clear sky conditions). Due to these effects, balloons travelling for several days undergo a vertical variation in height, even without losing gas or ballast, which is well known in the scientific ballooning community (e.g. YAJIMA et al., 2009).

With respect to ANDRÉE's balloon flight, it transpired that this cooling effect, in combination with the mass increase of the balloon due to icing, was responsible for loss of lift and the final termination of the flight. Evidence for this statement will be provided in the following section.

6.2 Meteorological reasons for terminating the balloon flight

The early end of ANDRÉE's flight was due to technical problems with the balloon, which led to a drastic reduction in lift. The first reduction was caused by the unexpected rise up to 600 m (see Fig. 4), when some of the guide ropes were detached from the balloon during the launch procedure, which was an estimated loss of ballast of about 200 kg. As the balloon was balanced for a flight level of 250 m, the pressure in the balloon increased when the balloon rose up to 600 m. As a result, an estimated 300 m^3 of gas was released from the valve (Sollinger, 2005), compensating for the loss of the guide ropes. The balloon stayed at this height for 10 hours before it entered the shadow of a large cumulus cloud. This led to shading from the sun, a cooling of the balloon gas, and hence a reduction in the volume of the balloon. As a consequence the balloon sank down to 100 m (see Fig. 4) and, as gas was lost during the early ascent, the lift was now less than calculated for level flight at about 250 m. Hence in the following hours, the balloon had to fly below the clouds and the sun could not heat up the balloon gas again. As the air was saturated with water vapour in the lower levels, and because the expedition encountered some drizzle, the balloon get soaked with water and gained weight, leading to a further reduction of lift. The air temperatures were around or below 0 °C during the last two days of the flight which could have lead to the freezing of fog and drizzle onto the surface of the balloon. Indeed the balloon crew noted icing on the ropes of the basket on the last day of the flight (Andrée et al., 1930). Given the meteorological conditions during the flight after the balloon was forced to fly near the surface, it seems very likely that the balloon was covered with ice on 13 and 14 July, which increased the weight and hence decreased the lift below some minimum value.

A rough estimate of the possible weight gained by icing may be made. The balloon's volume was about 4800 m^3, hence its surface was about 1380 m^2. If an ice layer of 1 mm thickness is assumed, this translates to 1.38 m^3 of ice, which converts into a 1380 kg increase in load if the density of water is assumed. The extra weight is less if icing in the form of hoar frost is considered. This is of the same order of magnitude of lift lost from the balloon between start and landing as attributed to an ice load of about 1000 kg, as estimated by Amundson and Malmer (1930) and Sollinger (2005).

In summary, unfavourable weather conditions after the first day of flight hindered the balloon in recovering from its lift reduction due to loss of hydrogen after the launch procedure. Once the balloon was forced to travel below the clouds within areas of fog and drizzle, low temperatures around 0 °C led to an accumulation of ice on the balloon's surface. As dense clouds prevented the sun from melting the ice and warming up the gas, the balloon did not have sufficient lift to rise up to higher flight levels again. Therefore Andrée decided to terminate the flight by releasing gas from the balloon.

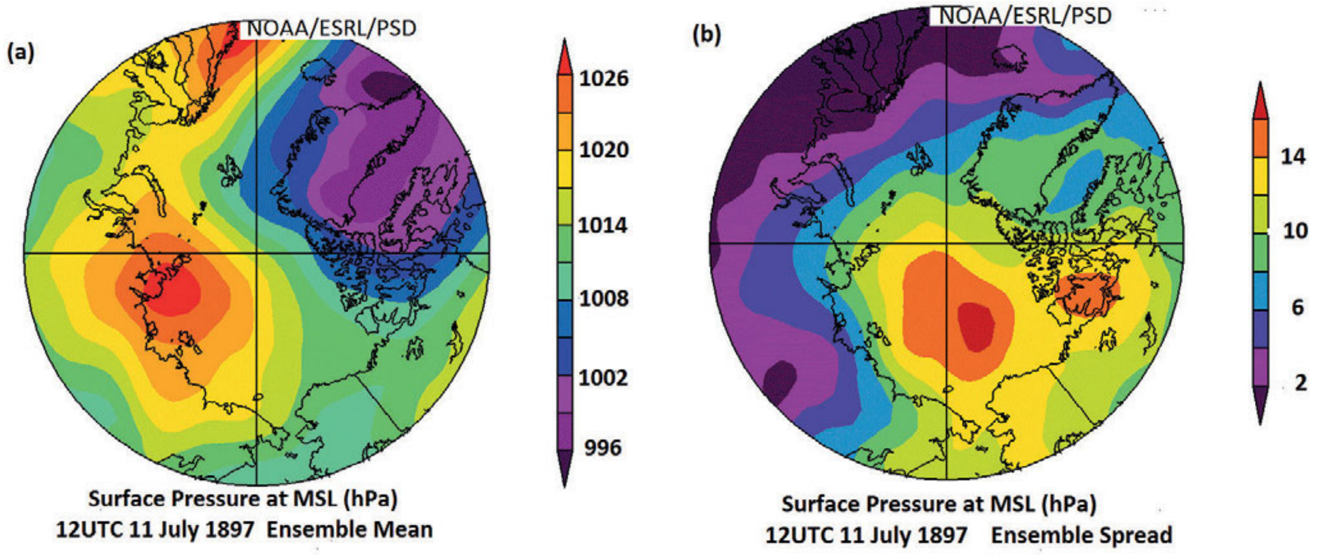
7 Andrée's balloon flight in the light of atmospheric reanalysis data for July 1897

7.1 Reanalysis

In the some of the literature on Andrée's balloon expedition, the following questions have been put forward: What would have happened if the balloon had stayed intact from the beginning, and could preserve its flight level of about 200 m–300 m (below the clouds and above the fog) as planned? Would Andrée have reached the North Pole? And if not, could he have terminated the voyage on land, e.g. near Cape Flora at Franz-Josef-Land, where he had arranged a depot with food and equipment? These hypothetical questions have not been answered so far, as no weather data for the area north of Spitsbergen were available for the days after 11 July 1897. This situation has changed recently with the twentieth century reanalysis project (20CR), where the global state of the atmosphere has been reconstructed for the years 1851–2012 (Compo et al., 2011). This reanalysis has been performed only from surface observations (Compo et al., 2006), as upper air observations were not available before the beginning of the twentieth century (Stickler et al., 2010).

The surface pressure data have been provided by the International Pressure Surface Pressure data base (ISPD) version 3.2.9, (see https://www.esrl.noaa.gov./psd/data/ISPD/v3.0/). Sea surface temperature (SST) and sea ice concentration have been obtained from the Hadley Centre Sea Ice and SST dataset (HadISST). The reanalysis is based on the 2008 experimental version of the NCEP Global Forecast System (GFS) and 56 ensembles have been simulated for each dataset. The data have been provided on a 2° × 2° horizontal grid with 24 pressure levels in the vertical, and with six-hourly resolution for each day. More technical details on twentieth century reanalysis (20CR) can be found in Compo et al. (2011). During their investigation it turned out, that the version 20CRv2 contained some mismatch with respect to the sea ice data, which was corrected in the follow-up version 20CRv2c used in the study presented here. The 20CR data have been applied to the Arctic climate on Greenland ice sheet surface mass balance for the years 1870–2010 by Hanna et al. (2011) and to Iceland's great frost winter of 1917/1918 by Moore and Babji (2017). With respect to synoptic scale events this data set has been used by Brönnimann et al. (2012) to reconstruct historical storms in the northern latitudes since 1871, and by Stickler et al. (2015) for comparison with upper air observations in the Atlantic for the years 1925–1927.

As the reanalysis was performed for the year 1897 one might ask, if there were enough surface pressure data available for the Arctic region. The numbers and locations of stations used in the ISPD can be obtained from https://www.esrl.noaa.gov/psd/data/ISPD/v3.0/. For the year 1897 294 stations are listed in total, where only three stations are located north of 65° N. These are at the east coast of Greenland, the north coast of Iceland and at Murmansk. Hence in the central Arctic north of 70° N there are no pressure information for input in the 20CR, but this is also true for much larger areas of the Northern Atlantic and the Northern Pacific. Hence one might expect, that results of the reanalysis show more scatter in the Arctic than at other regions. As example



Surface Pressure at MSL (hPa)
12UTC 11 July 1897 Ensemble Mean

Surface Pressure at MSL (hPa)
12UTC 11 July 1897 Ensemble Spread

Figure 5: Surface pressure at mean sea level for 12 UTC 11 July 1897 as obtained from the twentieth century reanalysis project (20CRv2c). (a): Ensemble mean, (b): Ensemble spread. Source: NOAA/ESRL/PSD.

the surface pressure field for 1200 UTC 11 July 1897, the day of the start of ANDRÉE's balloon flight, is shown for the ensemble mean in Fig. 5a. The ensemble spread for the same date is provided in Fig. 5b. The latter shows indeed, that the maximum ensemble spread is located in the Arctic, but in the area north of Canada and Alaska. This might be due to the fact, that there were no pressure observations in Canada and Alaska at all north of 50° N for 1897. In the area between Spitsbergen and the North Pole, which is investigated in this study, the ensemble spread is much less, which might be due to available pressure observations in Europe north of 50° N. Hence there is some confidence in the results of 20CRv2c with respect to the Andree expedition in July 1897. But in general, the 20CRv2c data set should be also useful for other studies in the Arctic, as the reanalysis is based on ensemble runs with a weather prediction model, delivering physically consistent pressure and wind fields over the northern hemisphere. Hence with the 20CRv2c reanalysis data it may be possible to shed some light on the questions put forward at the beginning of this section, especially regarding whether ANDRÉE would have reached the North Pole at all, even with a perfect balloon. The data have not been analysed by the author, but the graphics shown in the next sections have been provided by NOAA/OAR/ESRL PSD from their web site at http://www.esrl.noaa.gov/psd/.

7.2 Reanalysis for July 1883 within the polar year 1882–1883

Firstly, the reanalysis for the month July 1883 is compared to the analysis of EKHOLM (1895) for this month, which was the basis of the meteorological planning for the balloon voyage to the North Pole (see Section 3, Fig. 2). Fig. 6 shows the mean pressure at sea level for July 1883, as obtained from the twentieth century reanalysis (Version 20CRv2c). The principle features of Ekholm's map can also be found in the reanalysis, i.e. a low pressure system (1012 hPa) over Greenland and a high pressure system (1015 hPa) north of Norway between Iceland and Spitsbergen. However, in the reanalysis, Spitsbergen is not situated between these systems, but is located on the eastern flank of the high pressure area, with surface winds towards the south. The area north of Spitsbergen is characterised by low pressure, but very weak pressure gradients. Hence the reanalysis data show that, on average, the surface pressure field, and hence near surface winds, were not favourable for a balloon flight from Spitsbergen to the North Pole in July 1883. Close inspection of the daily surface pressure maps for this month show that, on a few days, pressure fields quite similar to Ekholm's proposal occurred in the Artic region. On average, however, the pressure distribution as shown in Fig. 6 was found in the reanalysis.

This suggests that the limited observations in polar regions, and the lack of full understanding of large scale atmospheric dynamics in the years of Ekholm's analysis, led to a too-optimistic view (concerning a possible balloon flight to the North Pole) of the average pressure distribution in July north of 80° N.

7.3 Reanalysis for the 11–18 July 1897

Now we turn to the days of the balloon flight, 11–14 July 1897 and some days afterwards.

Again, we use surface pressure maps from 20CRv2c as provided by NOAA for estimating the wind directions between Spitsbergen and the North Pole, as the balloon flight was below 100 m throughout most of the time. These maps are available for 00, 06, 12, and 18 UTC

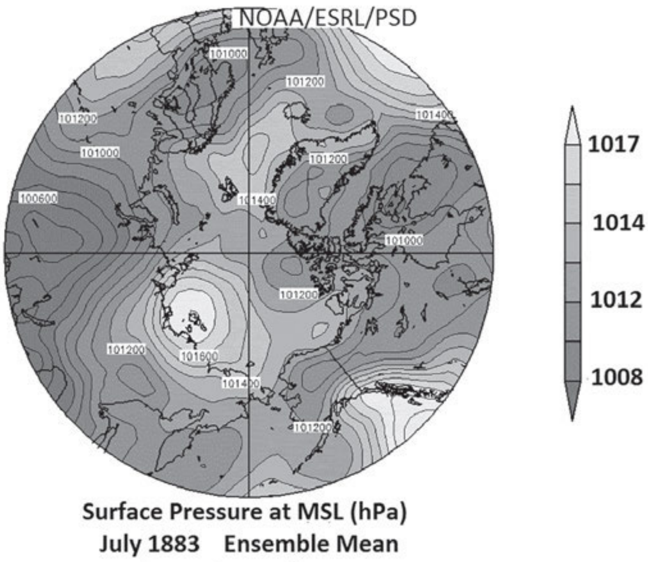


Figure 6: Mean surface pressure in the Northern Hemisphere north of 50° N for the month July 1883 as obtained from the twentieth century reanalysis project (20CRv2c). Source: NOAA/ESRL/PSD.

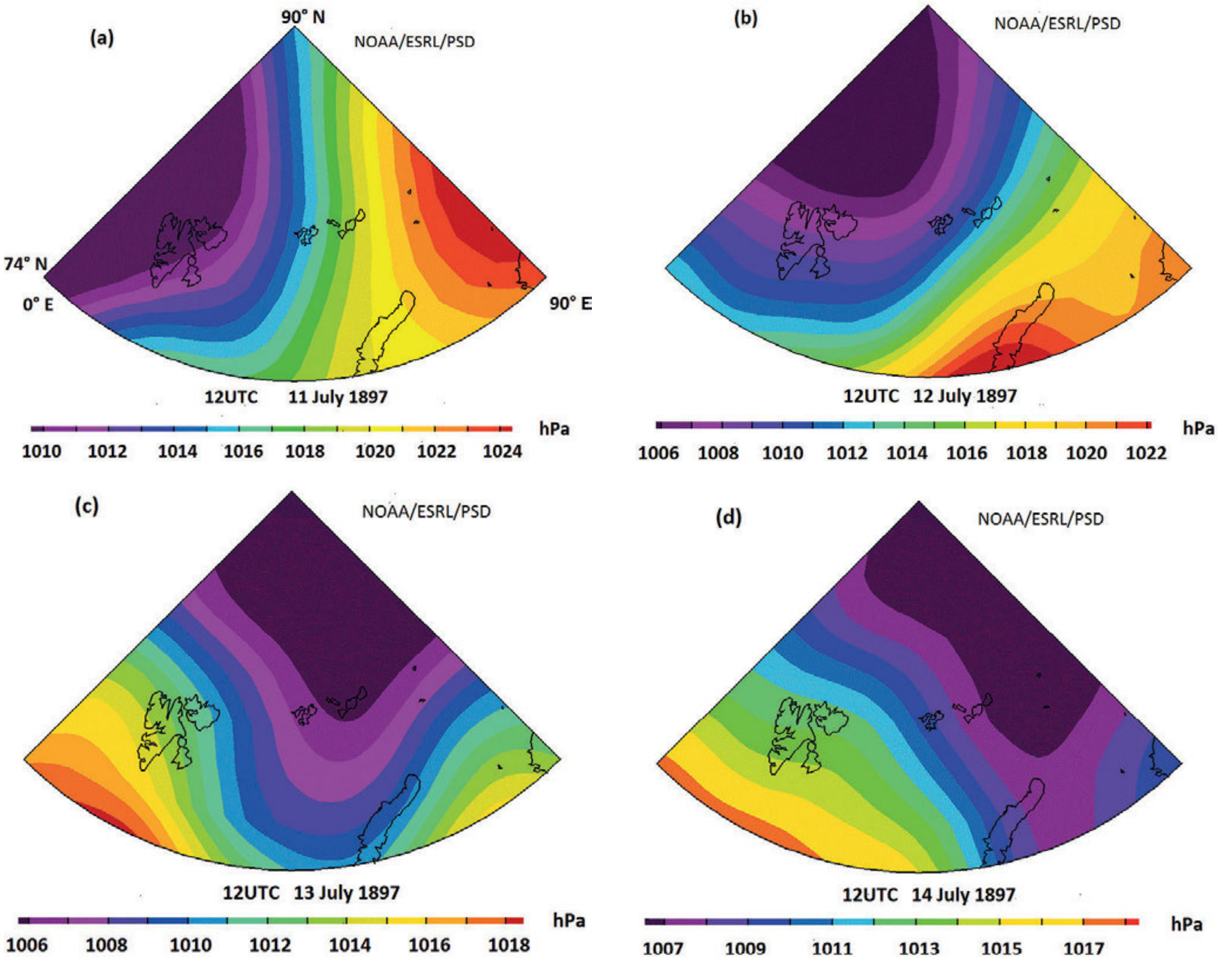


Figure 7: Surface pressure at mean sea level as obtained from the twentieth century reanalysis project (20CRv2c) for the area between: longitude 0°–90° E, latitude 74°–90° N. Spitsbergen is located at the lower left of the maps. Pressure fields are shown for 1200 UTC for following days of the balloon flight: (a) 11 July, (b) 12 July, (c) 13 July, (d) 14 July 1897. Source: NOAA/ESRL/PSD.

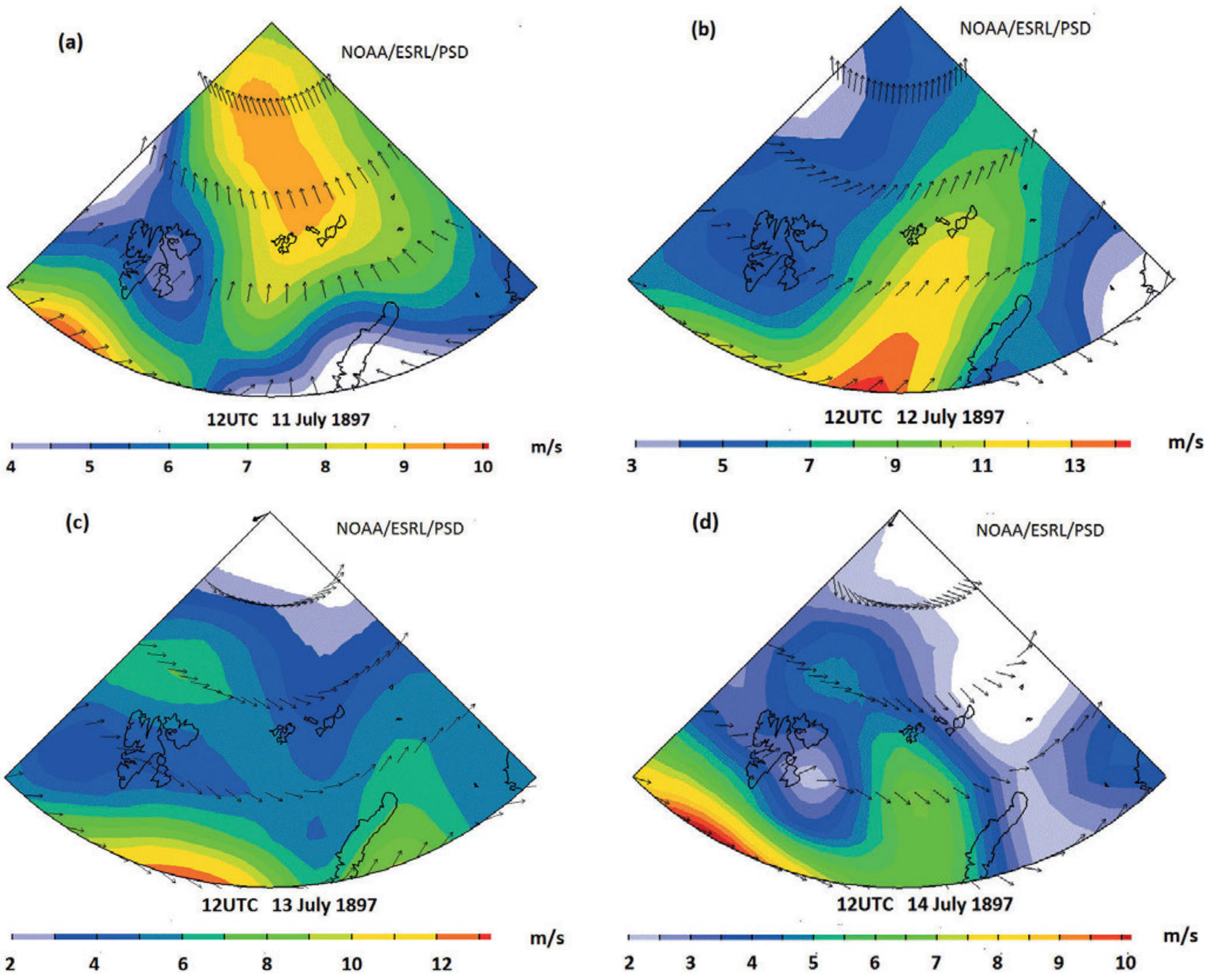


Figure 8: Same as Fig. 7, but for the wind velocity at 1000 hPa. Arrows: wind direction. Colours: wind speed in ms^{-1}. Source: NOAA/ESRL/PSD.

for each day. Here, only the situation on 12 UTC for the days 11–19 July 1897 are shown. In Fig. 7, surface pressure for the days of the balloon flight, 11–14 July 1897, are shown. A low pressure system was located north-west of Spitsbergen on 11 July, which brought favourable southerly winds. The centre of the system moved towards the north-east until 14 July, leading to a turning of the wind direction from southerly to westerly. The accompanying wind field is determined at the 1000 hPa level, which is about 60 m a.s.l. and hence approximately in the flight level from 12–14 July, and is shown in Fig. 8. Wind speed and wind direction correspond to the flight report and the balloon trajectory (Fig. 3), except for 12 July, where the balloon drifted to the west. These easterly winds, which lasted from 0130 UTC to 2230 UTC on 12 July (see Section 5), have not been captured in the reanalysis available for the hours 00, 06, 12, and 18 UTC of 12 July 1897. Considering this westward motion of the balloon on 12 July, it could be supposed that a small scale depression north of Spitsbergen (not caught by the reanalysis) was moving towards the south, bringing the balloon into easterly winds on its northern side. This aspect will be discussed in Section 7.4.

The question asked at the beginning of Section 7.1, i.e. what would have happened after 14 July, if the balloon had not been kept down due to icing but had continued journey, will now be considered. Surface pressure maps from 15–18 July 1897 are presented in Fig. 9, and show that the low pressure core close to the North Pole continued to move to the east, hence the wind direction changed approximately to north-west on 15 July, and to north-north-west the following days. This is in agreement with the last observation found in the diaries for 15 July, where a wind speed of $4.8\,\mathrm{ms}^{-1}$ and a wind direction NW was reported. Inspection of the surface pressure maps for 19–22 July, not presented here, reveals that the situation did not change too much in the area between the North Pole and Spitsbergen and no favourable pressure distribution with southerly winds reappeared. This trend can be also found in the maps of the 950 hPa level.

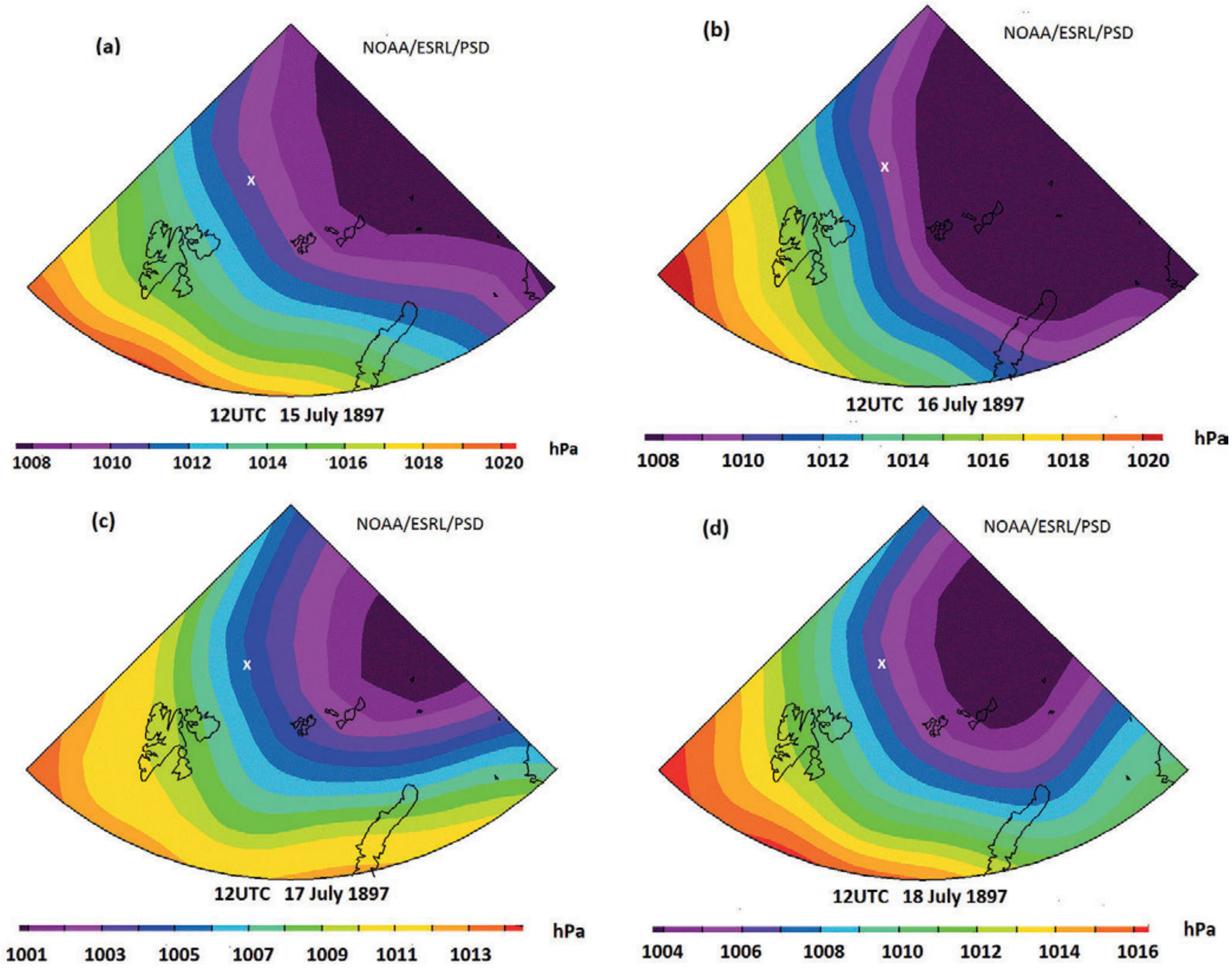


Figure 9: Same as Fig. 7, but for the days after landing. The landing position is indicated by (**x**). (a) 15 July, (b) 16 July, (c) 17 July, (d) 18 July 1897. Source: NOAA/ESRL/PSD.

Even with the balloon working perfectly as desired by ANDRÉE and his crew, the expedition would not have reached the North Pole due to the wind conditions in the period 11–22 July 1897, as reconstructed by the twentieth century reanalysis project. An outcome that was possible is that after 14 July (the day of termination of the flight), the balloon could have moved towards Franz-Josef-Land with the north-westerly winds prevailing in this area and perhaps a landing close to Cape Flora would have been possible.

7.4 Reanalysis data as compared to the balloon track

In Section 7.3 results from the twentieth century reanalysis (20CRv2c) have been used to discuss the question, if ANDRÉE's balloon expedition would have reached the North Pole at all concerning the synoptic conditions during the days 11–18 July 1897. One could also reverse this problem and ask, whether the reanalysis data are supported by the balloon trajectory. Most important for the balloon trajectory was the wind direction during these days. By comparing the flight path displayed in Fig. 3 with the surface pressure maps shown in Fig. 7 it can be seen, that leg 1 from 1345 UTC 11 July until 0130 UTC 12 July is approximately in agreement with the orientation of the isobars (Fig. 7a). This is also found for leg 3 from 1100 UTC 13 July until 0730 14 July (Fig. 7c). For day 15 July, after landing, the observed wind direction from NW also is in reasonable agreement with the surface pressure field shown in Fig. 9a.

The main mismatch between the reanalysis pressure maps and the balloon trajectory is for leg 2 from 0300 UTC 12 July until 2200 UTC 12 July (see Fig. 3), when the balloon drifted to the west with easterly winds. But the pressure maps for this time period (only 12 UTC 12 July is displayed in Fig. 7b) show the centre of the low pressure system located near the North Pole with south-westerly and westerly winds in the area north of Spitsbergen all the time.

Following short interpretation of the balloon trajectory for 12 July 1897 has been provided by Wallén (1930): a weak, shallow depression was located west of Spitsbergen on the evening of 11 July and moved towards the north-east. The balloon was captured in the centre of this system by the beginning of 12 July and was located at its northern side during 0300 UTC until 22 UTC 12 July in weak easterly winds (average balloon speed was about 3 ms^{-1}). After this time, the small depression disappeared and the pressure distribution was dominated by a low pressure system north of Spitsbergen.

The failure of the reanalysis 20CRv2c to capture this small scale pressure system might be mainly due to the coarse horizontal resolution of 2° × 2° but also due to the fact, that there were no surface observations in the central Arctic for July 1897 as discussed in Section 7.1. In addition, the low pressure system north of Spitsbergen was not very strong with central pressure of 1004 hPa and winds about 4 ms^{-1} in the area of the balloon position. For much stronger cyclones, small scale events might be caught better by the 20CR as was shown for the Tay Bridge storm in Scotland on 29 January 1879 by Brönnimann et al. (2012), who used the former version 20CRv2 for their reanalysis of historical strong wind events in Europe.

8 The first successful balloon flight to the North Pole

From the analysis of the weather situation during Andrée's flight in the previous section, it becomes clear that Andrée would not have started his expedition if he had information about the weather situation three to five days ahead, a situation that would only become possible after the introduction of numerical weather prediction in the 1950's. With modern products of weather prediction models, it is quite standard to calculate the trajectories of balloons with trajectory forecast models like FLEXTRA (Riddle et al., 2006) or HYSPLIT (Stein et al., 2015) some days ahead for preliminary planning of the route, and to update these regularly during the flight. One well-known example is the weather routing for the first successful flight in a balloon around the world performed by Bertrand Piccard and Brian Jones in 1999 (Piccard and Jones, 1999). Within nearly 20 days (1–21 March 1999) they covered a distance of about 45750 km. The weather information during that flight, especially the advice concerning the height variation for reaching an optimal flight route, was delivered by the Belgian meteorologist Luc Truellemans. He was also the weather router for the first successful flight to the North Pole in a balloon by the British adventurer David Hempleman-Adams in May 2000 (Hempleman-Adams and Uhlig, 2001).

Hempleman-Adams, who had already reached the North Pole during a surface expedition (Hempleman-Adams and Uhlig, 1998), wanted to realize the original plan of Andrée. Hence he also started from Spitsbergen (from the site at Longyearbyen) and used an open basket (instead of a pressurized cabin like Piccard and Jones) as a gondola. This restricted the maximum height of the balloon flight to 6000 m for reasons of possible oxygen shortage. He used a state-of-the-art balloon, i.e. a Rozier-type, which is a combination of a gas balloon and a hot air balloon. These balloons can be directed in the vertical quite exactly, hence the steering by finding the desired wind direction by moving the balloon up or down can be realized quite easily. Hempleman-Adams started on 1800 UTC 28 May 2000 and reached the North Pole after 92 hours days on 1400 UTC 1 June 2000. During this flight, the trajectory of the balloon was continually adjusted by the ground crew based on weather prediction models. The height variation during the flight was between 900 m and 3900 m, meaning that Hempleman-Adams avoided the low level clouds which, amongst other factors, led to the failure of Andrée's expedition. In fact, Hempleman-Adams did not reach the North Pole at exactly 90° N, but was short by 20 km due to unfavourable winds moving the balloon south. However, this is still the closest approach to the North Pole by a long range balloon flight. Originally it was planned that the balloon would get into the rear of a cyclone and travel towards northern Canada after reaching the Pole. But the cyclone moved faster than originally thought and the winds drove the balloon back to Spitsbergen, where he landed on 0600 UTC 3 June. The return journey to Spitsbergen took only 40 hours due to strong winds, and the landing place was determined by weather routing. The full description of the flight with detailed information about the wind forecast as obtained from numerical weather prediction models can be found in Hempleman-Adams and Uhlig (2001).

Considering the wealth of weather information for trajectory predictions available to make Hempleman-Adams' balloon flight a success it becomes clear, in retrospect, that Andrée would not have reached the North Pole even with a modern Rozier-balloon, as he had no information on weather and wind for the hours ahead of his ongoing flight. Hence it is no surprise, that after Hempleman-Adams only one more successful long distance balloon flight in the Arctic has been undertaken. The French adventurer and scientist Jean-Luis Etienne started from Spitsbergen on 5 April 2010, and reached an area close to the North Pole at 88° 12′ N on 7 April (Etienne, 2010). After this, a strong cyclonic storm moved his balloon towards Siberia, where he landed on 10 April. Within only 5 days he covered a distance of 3160 km. For this balloon journey, weather routing using NOAA's trajectory model HYSPLIT was carried out by a ground staff, including Luc Truellemans, and this was essential for performing this trans-Arctic flight.

9 Summary and conclusions

Despite its failure, Andrée's North Pole expedition in July 1897 is among the most discussed in the literature, because it was the first attempt to reach the Pole by air.

The reason for terminating the balloon flight after only three days, still 750 km away from its destination, was a combination of technical problems with the balloon during the beginning phase of the flight, and adverse weather conditions after the first day of the journey. As a consequence of the loss of lift, the balloon sank down to 100 m later on in the flight, and stayed below the clouds until the landing. During these days, fog and drizzle occurred more or less permanently, which soaked the balloon envelope with water. Temperatures around freezing led to formation of ice on the balloon which resulted in an additional mass on the balloon of about 1000 kg. As full cloud cover remained, the sun could not melt away the ice and warm up the hydrogen in order for the balloon to gain enough lift to return to higher flight levels.

Despite the unfortunate circumstances which led to the failure of the balloon expedition, the question remained whether a balloon flight to the North Pole would have been feasible at all in the year 1897. In response to this question the meteorological reasoning for the flight planning has been discussed, which was based on observations at Spitsbergen during the First International Polar Year (August 1882–August 1883). From these and other observations in the northern hemisphere, a surface pressure map for the Artic regions north of 70° was constructed by Ekholm (1895), which showed that southerly winds would prevail in July, making a balloon expedition to the North Pole feasible. In order to evaluated Ekholm's proposal for pressure systems around the Arctic in July 1883, recently released data from the twentieth century reanalysis, version 20CRv2c, available from NOAA/ESRL/PSD, was used. These data show some of the large scale features of Ekholm's analysis, but pressure distribution and hence near surface winds in the area between Spitsbergen and the North Pole do not show favourable southerly winds on average for July 1883.

The question of whether Andrée would have reached the North Pole if the balloon had no technical problems and could still stay aloft after 14 July was then discussed. To answer this question, the reanalysis of surface pressure and wind fields for every 6 hours on 11–18 July 1897 were used. It was shown that only the first day had very favourable south-westerly winds, bringing the balloon to about 400 km north of Spitsbergen. On 13 July, the wind shifted to more westerly directions, and during 15–18 July it shifted to the north-west. In the following four days the weather situation did not change to favourable southerly winds. As a consequence, even with an intact balloon and favourable weather conditions (temperatures above freezing, no fog or rain), the large scale pressure distribution during 11–22 July 1897 would not have permitted a balloon flight from Spitsbergen to the North Pole. This was not known at the time, as no information on the atmosphere north of 80° N was available, and weather forecasting was still in its infancy.

Finally, in order to show that Andrée's attempt to reach the North Pole by balloon was not feasible at this time due to lack of modern weather prediction methods, the first successful balloon flight from Spitsbergen to the Pole by Hempleman-Adams was discussed. This flight took place in the year 2000, more than 100 years after the Andrée expedition, and was possible only through the use of continual weather routing by a ground staff, which relied on numerical weather prediction models. Interestingly, this was not only the first successful flight to the North Pole by balloon, but also the first attempt after the failure of the Andrée expedition in 1897. It became clear after Andrée's failure that the North Pole cannot easily be reached by air with a balloon, but that dirigible aircraft like airships or aeroplanes have to be used instead. However, some early attempts by the American Walter Wellman to reach the Pole with an airship in the years 1905–1909 also failed (see Capelotti, 1999). It was not until 1926, that the airship Norge under the lead of Roald Amundsen and Umberto Nobile reached the North Pole after starting from Spitsbergen, and continued its flight over the Arctic towards Alaska. During the flight of about 71 hours, the airship covered a distance of 3880 km (see e.g. Nobile, 1961). These airship flights and other attempts to reach the North Pole by air are described in some detail by Bleibler et al. (2009).

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