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THE UPPER AIR CIRCULATION OF THE ATLANTIC OCEAN

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THE UPPER AIR CIRCULATION OF THE ATLANTIC OCEAN

By E. W. Barlow, B.Sc.

Introductory.

The object of this Note is to give an account of the upper air observations made over the Atlantic Ocean, to summarise the results and to indicate their bearing on our knowledge of the general atmospheric circulation. The observations concerned are chiefly those made by means of kites and pilot balloons from ships or from islands; reference is, however, also made to miscellaneous observations, such as those of cloud motion and the spread of volcanic dust. The region considered is the temperate and tropical areas of the North and South Altantic Ocean but some mention is made of certain work carried out in Arctic and Antarctic zones. It has also been thought of interest to give an outline of the meteorological aspect of Atlantic flying derived from both theory and practice to date.

The Note is subdivided as follows:—

Part I. Atlantic Upper Air Observations, historical and general.
Part II. Summary of Results.
Part III. The Meteorological aspect of Atlantic Flying.
Appendix I. contains tables and Appendix II. a bibliography of the works consulted. Throughout the text reference is made to the published work containing the detailed observations by means of a number affixed to it in Appendix II.

Part I. Atlantic Upper Air Observations, historical and general.

In the *Historia Ventorum* Bacon mentions the idea of using kites for meteorological purposes. The first actual meteorological flight was made by Dr. Alex. Wilson, of Glasgow, who in 1749 raised thermometers in this manner. As far as is known the first kite observation made over the ocean was during Capt. Parry's second voyage for the discovery of a north-west passage from the Atlantic to the Pacific in 1821–3, when a registering thermometer was raised by a paper kite to a height of 400 ft. without showing any temperature change. During Capt. Back's expedition to the Arctic shores in H.M.S. *Terror* in 1836–7 similar experiments were made, but it was found that there were very few occasions when wind and ice were both favourable. Once when the ship was fast in ice a Six's thermometer raised to

1,200 ft. read 8°F. lower than the temperature on the ice. The temperature of the air over Hudson's Strait was also found by flying a kite from the island of Iglvalik (long. 81° 44′ W., lat. 69° 21′ N.).

There appears, however, to be no record of a flight made from a vessel in motion until A. L. Rotch's initial experiment in Massachusetts Bay, in 1901. The systematic adoption of kites and ballons sondes during the last quarter of the nineteenth century for sounding the upper air over the land surfaces led Dr. A. Woeikof to emphasise, at the Meteorological Congress in Paris in 1900, the importance of similar observations over the ocean and particularly over the equatorial region. At that time nothing was known of the thermal conditions prevailing a mile or more above the equator, except as a result of the few observations made on the Andes and Central African mountains. Woeikof stated that within the Trade Wind belts, north and south of the equator, kites might be employed to determine the height to which the Trades extend and also the strength and direction of the upper winds, concerning which the high clouds that are rarely seen in these latitudes had given what little information was then possessed. Rotch accordingly tested the feasibility of kite-flying from a steam tug during anticyclonic conditions on August 22, 1901, and found that by manœuvring the vessel and taking advantage of the wind a kite carrying a meteorograph could be raised to half a mile. The use of kite flying from a moving vessel being thus established, Rotch left Boston six days later on the ss. *Commonwealth* for Liverpool, taking the kites, which were flown on five days out of eight, anticyclonic conditions prevailing. Flights would have been possible every day had he been able to change the ship's course. An altitude of 610m. was reached and synchronous records were obtained from a meteorograph on deck. The chief feature of the records was the rapid change of temperature with height. The average decrease for four flights was 1·8°F. per 100m., which is the adiabatic lapse-rate for dry air, but in one instance a decrease of 3·2°F. was shown in the first 100m. On August 31, the air was 5·6° warmer at an altitude of 130m. than at sea level. During the highest flight humidity continued to increase with altitude, as it does over land up to the level of cumulus clouds when these are present. It was, however, usually found that a shallow stratum of nearly saturated air existed immediately over the ocean and that above this the air became drier.

[Bibl. 24.]

Early in August of the same year Dr. H. R. Mill had attempted some experiments in kite-flying from the *Discovery* which he accompanied as far as Madeira at the outset of her Antarctic voyage but his experiences were not published.

In the latter part of 1901 the Royal Meteorological Society appointed a committee to organise an investigation above English waters and the British Association appointed a co-operating committee at their Glasgow meeting. W. H. Dines undertook to make the observations and chose Crinan, on the west coast of Scotland, as a suitable locality, and one where the conditions with the prevailing westerly winds would be equivalent to those of the Atlantic Ocean. The kite used was a rhomboidal form of the Hargreave kite. The kites were flown from a small steam tug in the sounds of Jura and Scarba and in the open sea south of Mull during the months June to August 1902. In all 71 temperature observations were secured at an average height of 1,250m. and 38 charts from self-recording instruments at an average height of over 1,800m. were obtained. The temperature gradient observed was normal, about 1°F. for every 100m. of altitude. Other facts brought to light were the steady motion of the wind over the sea compared with that over an inland station and the smaller change of velocity and direction with elevation over the sea. A sea breeze was occasionally noted and found not to extend higher than 300–400m., above which height it was generally calm on these occasions. A great uniformity was found to prevail from hour to hour in the sea temperature; changes occurred from time to time but apparently had no daily period. The daily range of temperature was deduced as less than ½°F. [Bibl. 9.]

The method was soon adopted by various meteorologists, notably by Berson and Elias during a voyage to Spitsbergen in 1902 and by Teisserenc de Bort at Hald, in Jutland, in 1903 when a height exceeding 5,900m. was reached by a kite for the first time. At the British Association meeting above referred to, Rotch had proposed the exploration of the upper trade wind region, but on account of questions of expense no further steps were taken until after Assmann had introduced small rubber balloons inflated with hydrogen and rising with approximately constant velocity, the trajectory of which could be determined from one fixed point on shore or shipboard.

In 1904 Prince Albert of Monaco undertook two expeditions in his yacht *Princess Alice*, with the collaboration of Professor Hergesell, to study the conditions over the trade wind region.

Two series of observations were carried out (i) in the triangle Oporto–Teneriffe–Azores during 1904 (ii) on the route Gibraltar to the Sargasso Sea and back to Azores in 1905. The results of the first expedition may be summarised as follows. The mean speed of the NE trade is 7m/s in its lowest strata. There is an adiabatic fall of temperature with height and an increase of relative humidity from 70–80 per cent. up to 95 per cent., and often to 100 per cent., in which case cumulus clouds will be formed at the upper limit of the saturated layer the height of which varies from 100–600m. This cloud is the well-known Trade Cumulus. Above the cloud layer temperature rises suddenly by several degrees and the humidity falls as low as 10–20 per cent. This layer of inversion has a thickness of about 1,000m. and the winds in it are feeble and irregular, but as a rule back with increasing altitude from NE to N towards NW. On two occasions a veer was found, viz., NE–E–SE–S.

Above the inversion the gradient becomes exactly adiabatic and a NW wind reigns in this stratum, which continues up to at least 4,500m., the greatest altitude obtained. Here also relative humidity increases with height, the vapour tension remaining constant, suggesting the existence of downward currents. Only once was SW counter-trade observed in this stratum. As a result of the expedition Prof. Hergesell announced to the French Academy of Sciences that a SW current corresponding with the theoretical counter-trade had not been found, the upper NW wind being on the other hand very persistent. He also stated that the Azores pressure maximum was fed from the north side by the upper NW wind. These conclusions were verified by the 1905 expedition, in which the average speed of the trade was found to be 5–6 m/s and that of the NW wind 10–15 m/s. At the most southerly point of observation an upper wind of SW–SE was once found. [Bibl. 15.]

In April and May, 1904, Cave and Dines made nine pilot balloon ascents at Barbados. A high lapse rate was found for the first 500m. The humidity increased from 60 per cent. at the surface to 80–90 per cent. at heights of 300–600m., often decreasing with greater altitude to 50 per cent. or less. [Bibl. 8.]

During June to August of the same year two vessels of the German Navy, the *Hohenzollern* and the *Sleipner* made a few kite ascents off the coast of Norway. [Bibl. 12.]

In July and August, 1905, Dr. G. C. Simpson made eight kite ascents from the mission trawler *Queen Alexandra* in the North Sea. The chief points brought out by the six good records were the high temperature gradient during the first 300m., and the existence of a layer of very dry air on three occasions, commencing at heights of 450, 900 and 300m. respectively. [Bibl. 30.]

Hergesell's conclusion with regard to the counter-trade seemed to require further investigation. Accordingly, T. De Bort and A. L. Rotch organised three expeditions during the years 1905–7 on the yacht *Otaria*. The observers were Clayton and Maurice, who traversed various parts of the Eastern Atlantic between the temperate zone and the equator. The results obtained by kites and pilot balloons were of great interest and the observations are still considered the most important ones made in this ocean. The first voyage started on July 1st, 1905, and the ship successively visited Madeira, Canaries, Cape Verde Isles, Canaries and Azores. Pilot balloon observations were made from various island stations and kites were sent up from the ship. The second voyage was a short one, made in February 1906, the object of which was to see if ocean flights gave the same superposition of currents as those made at Teneriffe. The existence of the countertrade above the trade in the region of the Canaries in winter was proved. The third voyage was made in the summer of 1906 to Madeira, Cape Verde Isles, Sierra Leone, Ascension, Teneriffe, Azores and over an extensive area of the ocean between the latter islands and long. 45° W. in order to determine the inter-tropical conditions. 24 pilot balloon and 46 kite ascents were carried out, also captive balloons with registering instruments were sent up in calm periods, attaining nearly 5,000m. and reaching the counter-trade. Teisserenc de Bort organised a further expedition which left Havre on July 1st, 1907 for the Azores. Balloons were sent up thence as far as to south-west of Cape Verde Isles; in the latter region, where the trade is extremely regular, the daily circulation was followed fairly continuously during two periods of 13–14 days each. 41 ascents were made; 29 were by ballons sondes and of these 20 gave good records. The isothermal layer was undoubtedly reached several times.

The results attained by these expeditions are given in greater detail below. The region covered was from lat. 35° N.–8° S. and from the European coasts to long. 45° W. and the wind régime was found sufficiently regular to enable the entire circulation over the Atlantic between these latitudes to be deduced. The NE trade stratum does not exceed 1,000m. in height. Above this is a zone where the wind has a northerly component and ordinarily blows from NW, as found by Hergesell. The NW winds cease at about 12° of latitude north of the point of convergence of the trades, which in summer is at 8° N. (south of Cape Verde Isles). Above this zone is a region where the wind has a southerly component; this constitutes the counter-trade, which considered in its entirety is composed of air currents coming from SE in its most southerly latitudes and successively from S, SW and finally W in the latitude of the Azores. There are of course daily irregularities; the trade was occasionally observed to extend up to 7–8km., and on July 8, 1906, the wind near Teneriffe retained a N–NNE direction up to 11,050m. Sometimes also the counter-trade is not found at any height, but such occurrences are transitory or local effects, limited to portions of high pressure areas. As the equator is approached, the altitude of the counter-trade decreases so that while in the neighbourhood of the Canaries it blows above 3,000m., it is found at Cape Verde Isles at about 1800m. Its height is however very variable.

Winds with an easterly component predominate in the equatorial regions to the highest altitudes attained. South of lat. 5° S. upper winds with a northerly component, the counter-trades of the southern hemisphere, are experienced, blowing sometimes from NE and sometimes from NW. Hergesell's conclusion that the Azores high pressure area was fed from the north by the upper NW wind is confirmed by these results. The existence of the counter-trade is fully proved.

The vertical temperature and humidity distributions revealed are approximately the same as those found by Hergesell. The temperature decrease up to 1,000m. is most rapid near the northern and southern limits of the trade (average 0·78°C. per 100m.) and least rapid in its central regions where conditions up to that height are nearly isothermal. The trade is damp and usually carries Cu or St–Cu cloud in its upper portion. The

NW intermediate zone is very dry and at its lower limit adjacent to the trade calms or light winds with a marked temperature inversion are found. The counter-trade is less dry than the NW stratum but is still relatively dry. The adiabatic rate of temperature decrease was found to prevail at night as well as in the daytime. [Bibl. 6 & 7.]

During the summer of 1906 Prof. Hergesell made use of ballons sondes over the Arctic Ocean near Spitsbergen and concluded that the isothermal stratum was reached there as low as 7,000m. [Bibl. 13.]

An expedition on board S.M.S. *Planet* was carried out in 1906–7 by Hergesell and Köppen in the Atlantic and Indian Oceans. The former observations confirmed those of the "Otaria" expedition. [Bibl. 12.]

By instruction of the Deutsche Seewarte officers of some of the Hamburg—S. America liners made pilot balloon ascents in 1906–8 to determine the upper wind direction south of the equator. In all, 65 ascents were made and the series was continued in the Atlantic and Pacific Oceans by H. Meyer on the company's training ship *Norddeutsche Lloyd*. The results obtained in both southern oceans were analogous to those found for the northern ocean by the *Otaria*. An ascent made on Jan. 5, 1910 in lat. 2° 6′ S. long. 29° 36′ W. shows an upper NE wind corresponding with the upper SE wind of Cape Verde Isles. Ascents between lats. 15° S. and 31° S. demonstrate the NW counter-trade. On one occasion the SE trade extended in the Pacific up to 8500m. [Bibl. 20 & 22.]

On Nov. 6–8, 1907 pilot balloon ascents were made at Barbados showing the prevalence of ENE wind up to 1650m. [Bibl. 2.]

Cave also made similar ascents at Barbados from Dec. 6th–11th, 1909, indicating an increase of speed of the trade with height up to a certain point, usually about 500m.

In December of the same year Hergesell made flights from the S.M.S. *Victoria Louise* in the neighbourhood of the Antilles. His observations showed that the trade blows from E to about 7000m. with a relatively strong velocity (9 m/s) up to 3000m. but feeble and variable above this. Higher than 7000m. the counter-trade was found blowing from W, backing gradually above 10000m. to SW with the mean speed of 2 m/s. [Bibl. 14.]

In 1910 G. Jonas was sent in S.M.S. *Freya* to complete the work in this region. Pilot balloon ascents were made at Port of Spain and over the open ocean near Trinidad. Hergesell's results were fully verified. Up to 4000m. the ESE wind was constant and fairly strong; between 4000 and 8000m. it was feeble and variable. Higher still the wind was either NW or SW.

Between May and September, 1911, the S.M.S. *Möwe* on an oceanographical and meteorological expedition made nine kite ascents with observations of wind direction and speed, temperature and humidity between lat 39° N. and 20°S.

[Bibl. 24.]

In 1913, following the *Titanic* disaster, a special investigation of ice conditions and meteorology was undertaken by the Board of Trade. G. I. Taylor was the observer on board ss. *Scotia*, which carried kites and balloons. The chief meteorological work was the investigation of temperatures and humidities during the formation and dissipation of fog in the Newfoundland region. The most remarkable features of the kite ascents were the large negative temperature gradients found, evidently the result of the cooling of the lower layers of the atmosphere when it passes from warmer to cooler regions of the sea. Fogs were found to be divisible into two classes :—(i) Light fogs with a small negative temperature gradient; (ii) Heavy fogs with a large negative gradient. Fog production in the cases investigated was found to depend on the cooling of moist air, not by molecular conductivity, but by " eddy conductivity." The fog is really produced by the mixing of layers of air of different temperatures and humidities. [Bibl. 27.]

During the months April–July, 1915, the U.S. cutter *Seneca* made a series of 27 flights with Marvin box kites to the south and south-east of Newfoundland to study the conditions over the meeting of the warm and cold ocean currents. The average height attained was 1054m. Temperature distribution with height was found to be governed by local conditions. Four types of lapse-rate were deduced: (i) Above the Labrador current, temperature increases up to 400m. and then falls. (ii) Above the Great Bank and coastal waters the increase ceases at 300m. (iii) Over the Gulf Stream there is a continuous decrease with altitude. (iv) Above mixed waters there is a variable lapse-rate.

[Bibl. 28.]

In the Spring of 1919, when much attention was being given to the possibilities of Atlantic flight, the Air Ministry organised an investigation of upper air Atlantic conditions with kites of a new type. Permission was given to use the ss. *Montcalm* for this purpose on her voyage from London to St. John N.B. and back. Lieut. G. Harris, R.A.F., was the observer in charge; he was also the designer of the kites which were believed to be capable of flying in stronger winds and reaching greater altitudes than the patterns previously used. As regards the former point the kites were successfully flown in winds up to 75 mi/hr at an altitude of 700m., but their altitude capabilities could not be tested owing to the limitations of winch and crew. Much interesting information was secured as to the condition of the atmosphere up to the height stated, also with regard to the prevalence of fog and " bumps " and the formation of Fr–St and Fr–Cu cloud. Dines's results as to the very small variation in direction between the surface and upper winds in the region of prevailing westerlies was confirmed. In three ascents the lapse-rate was found to be adiabatic as far as the kite went; on two occasions a lapse-rate somewhat less was found and in one case an excessive temperature fall was indicated in both the ascent and descent, no explanation of which has been suggested. As a rule in clear weather, eddy motion, as shown by the lapse-rate, persisted to at least 550m. Unfortunately no flights could be made over the junction of the Gulf Stream and Labrador currents owing to fog stopping the ship on both voyages. East of long. 35° W. the sea and air temperatures nowhere differed by more than 4°F., although the wind blew from all directions. The conclusion is that sea temperatures are more evenly distributed in this region than in the western part of the ocean. The most rapid change was 2° F. in a distance of 10 sea miles. These results demonstrated the smallness of the diurnal variation of sea temperature, if it exist. For this reason surface winds do not die down at night as they do in inland regions. Similarly "bumpiness" over the ocean is independent of the time of day. The atmosphere over the whole Atlantic east of long. 35° W. is remarkably free from temperature "bumps" both by day and night. Westward of this meridian the variations of sea temperature are great and abrupt owing to the meeting of warm and cold currents. The western boundary of the Gulf Stream is well-defined and very sudden temperature changes were found, on one occasion 18°F. in a distance of 10 sea miles. Other abrupt changes were recorded, corresponding either with distributory currents or with masses of water detached from the main current by storm winds. Consequently the air temperature follows the sea temperature much less closely, the difference sometimes exceeding 10°F., the former being usually in excess. This condition is associated with the formation of fog, which is very prevalent in the western ocean at this season.

In every case the records showed a fairly continuous diminution of relative humidity in the air between 150m. and 750m. throughout the whole period of the ascent. This result could hardly be due to lag as in several cases the hair hygrometer was kept aloft from 2 to 5 hours. All ascents were made in fair or fine weather between 11h. and 18h. (ship's time) and presumably this decreasing humidity is characteristic of this time of day in such weather.

Reference must now be made to cloud and volcanic observations. Abercromby seems to have been the first to observe the motions of the upper clouds over the doldrums. In the course of voyages through the Atlantic and Pacific Oceans, he found that there was a single easterly current and that the poleward motion of the air near the equator was very small. [Bibl. 1.]

This was confirmed by the propagation of dust ejected by the great eruption of Krakatoa, near the equator, in August 1883. Fine dust was projected to a very great height and as observed by sunset glows made the entire circle of the equatorial regions in 12 days, which implies a velocity of 34·5 m/s. This phenomenon constituted the first actual proof that the easterly current flows round the whole earth. The dust, on the contrary, spread extremely slowly in a meridional direction and did not arrive at Buenos Aires and Valparaiso until the beginning of October, or at the North Cape and in Greenland until the end of November.

In an old work on meteorology* it is stated that on February 25, 1835, ashes emitted by the volcano Cosiguina, in Guatemala, fell a short time afterwards over Kingston, Jamaica. This gives a WSW direction for the upper wind which is in exact accordance with the modern observations of the counter-trade in this region.

It has also for a long time been a matter of general remark that the ashes from the volcanoes of the Antilles fall to eastward of the source of origin.

On March 29 and 30, 1875, a very heavy rain of ashes fell in various parts of Scandinavia from the volcano Askja, in Iceland, the height of which is about 1000m. This indicated a north-westerly current of 23·8 m/s over the ocean, diminishing to 14·1 m/s in its passage. On this occasion the ashes were carried by lower and intermediate currents, but, as in the case of Krakatoa, the volcano Katmai, in the Aleutian Isles, threw dust, on June 6–8, 1912, to the extreme limits of the atmosphere. The products were carried eastward, by the temperate westerly current, successively to N. America, the Atlantic Ocean, Europe, Siberia and Japan, and as far south as Southern Algeria.

In the work already cited Kæmtz states that the navigator Paludan had noticed that little clouds often float in a contrary direction to the trade wind.

The chief observations of upper cloud over the Atlantic are those of Toynbee in 1870, some unpublished ones of Chaves made at Horta, Azores and the West Indian series, edited by Bigelow. The latter series of observations was made by eleven members of the U.S. Weather Bureau in 1899–1903, at various West Indian stations. They demonstrated the fact that the counter-trade to the height of Ci-St or Ci-Cu clouds (7–8km.) blows from W or WSW, in exact opposition to the direction of the trade, which comes from E or ENE. Between these currents a layer with variable winds exists, at the height of the intermediate clouds which varies somewhat with the season.

[Bibl. 4.]

With regard to mountain observations a detailed account of wind and cloud observations made on the summit of the Peak of Teneriffe (3707m.) by von Humboldt, Piazzi Smyth, Marget, Abercromby and others is given by J. Hann in *Meteorologische Zeitschrift*, Vol. xxiii, pp. 559–561. Clayton also made observations from the peaks of Teneriffe and Fogo during the *Otaria* expeditions. The observations may be summarised by saying

* Kæmtz. *Complete Course of Meteorology.* (London, 1845.)

that at the summit of the Peak the SW to W counter-trade mainly occurs, but the NE trade is sometimes felt. Forty out of seventy-six observations in winter showed the counter-trade.

Part II. Summary of the Results.

Around the thermal equator flows a great air current from E to W, giving light easterly winds at the surface (" Equatorial Calms," or " Variables ") but a very strong and constant speed in the higher strata of the atmosphere (average speed 34 m/s). In both temperate zones the currents are opposed to this, giving the prevailing westerly winds at all heights. The lower part of this westerly current, and sometimes the whole of it up to the level of the stratosphere, is affected by the passage of areas of high and low pressure, the line of which, carried round the globe, forms according to Bjerknes the polar front or line of division between cold air from the pole and warm air from the equator. The actual wind in the lower layers of the westerly current may therefore blow from any direction, but the greater the altitude the more constant is the westerly wind.

In the intermediate or tropical regions are found the trade winds, NE in the northern hemisphere and SE in the southern hemisphere. Above the NE trade, passing from lower to higher latitudes, the wind blows successively from SE, S, SW and finally W in the latitude of the Azores. This is the counter-trade and its gradual veer, which passes without interruption from the east equatorial current to the west temperate one, is due to the deflective action of the earth's rotation. Between the trade and the counter-trade* in relatively high latitudes, is found an intermediate layer of NW wind, which might also in a sense, be called a trade, as it has a component of direction towards the equator. These NW winds, or the more southerly parts of the temperate westerlies, feed the northern side of the Atlantic pressure maximum, while the counter-trade feeds the equatorial side of the maximum. Conditions in the South Atlantic are exactly analagous, the trade being SE and the counter-trade deflected to the left, becoming in turn NE, N, NW and W. From the corresponding pressure maxima in each hemisphere, the Azores and South Atlantic maxima, the trades flow towards the equator merging at their region of convergence into the general easterly current. The vertical height of the trade does not exceed 1000m.; the altitude of the lower limit of the counter-trade is 3000m. at the Canaries, and diminishes to 1800m. at Cape Verde Islands. Its vertical height is much greater than that of the trade; it has been found to extend to 12500m. on one occasion.

For the north polar regions there are very few observations; they, however, show that the wind is frequently E at the surface

* Some writers use the words "anti-trade" and "counter-trade" as synonymous, while others apply the former term to the temperate westerlies.

above lat. 60°–70° N., but in general NW–SW winds blow in the higher strata. This probably is explained by the frequent passage of barometric depressions which are not closed on the polar sides.

With regard to the south polar regions Dr. Simpson has shown that over the snow-covered surface, whether at sea level or at that of the plateau, radiation is so strong that the air is abnormally cooled, especially immediately above the surface. This cooled air is heavier than the surrounding air and therefore pressure increases from the exterior to the interior of the Antarctic area. In other words the pressure distribution is anticyclonic and air motion is in general outward. Above each anticyclone a cyclone forms on account of the relatively rapid vertical pressure change caused by the cold dense air. These cyclones convey air from the region of prevailing westerlies to the polar region and supply the air which passes outwards at the surface.

[Bibl. 29.]

No high current flows direct from the equator to the poles as originally suggested by Halley, nor does a low current pass the whole way in the reverse direction. In Ferrel's and Thomson's theories the NE trade wind should continue, at least in great part, as an upper SW wind to the environs of the north pole. This is not the case, but there is a slow interchange of air along the meridians caused by cyclonic and anticyclonic disturbances which constantly occur in the temperate zones. Each of these transports air on the one side from south to north and on the other from north to south. Also as air has an upward movement in cyclones and a downward one in anticyclones the masses of air at different latitudes become gradually mixed.

In Table I the speed and frequency of the upper winds of various directions in lat. 5°–15° N., long. 30°–40° W. during May to September has been derived from 27 observations made by the *Otaria* expedition. Table II gives similar information for lat. 5° N—5° S, from nine observations.

The barometric maxima, and accordingly the trades and counter trades, have a seasonal shift in latitude, moving a few degrees northward as the Sun's declination increases up to 23½° N and a little southward as the Sun passes south of the equator. Thus in summer in the northern hemisphere the SE trade crosses the equator; the NE trades never blow on the south side of the equator. The seasonal shift is shown by the region of division between the trades which varies from 3° N. to 12° N. The northern limit of the trade in the eastern part of the North Atlantic in summer is 30° N. and the wind begins to be felt just north of the Canaries. In winter it is not found till a little south of these islands.

The various Atlantic observations have also assisted in establishing the following facts. The mean velocity of the wind increases in general regularly with height up to the level of the stratosphere, which on the average is found at about 11000m.;

it decreases from thence up to the greatest heights attained. In the region of upper east winds around the equator, where the stratosphere is found only at rarely accessible heights, the wind velocity increases as far as the observations go.

The *Otaria* temperature gradient results may be summarised as follows. There is a rapid temperature decrease between the sea surface and a height of several hundred metres, the lapse-rate being practically the dry adiabatic. The height of this layer is variable; above it is a layer several hundred metres thick, commencing at from 400m. to 1500m. above sea level, where temperature begins to rise with increasing altitude. Between lats. 40° and 20° this inversion is found at successively lower levels; it is determined by eddy motion and its uniformity is due to the trade being the cause of the eddies. Table III gives the mean gradient from May to August for lat. 0°–35° N. In view of Dines's, Simpson's and Harris's results in more northerly latitudes and also Hergesell's Spitsbergen observations, where lapse-rates as high as those of tropical regions were found, it may be considered that a dry adiabatic lapse of temperature is a reasonable assumption in any latitude, apart from special cases like some of those encountered by the *Seneca*.

Part III. The Meteorological Aspects of Atlantic Flying.

The chief characteristic of the temperate regions of the North Atlantic is its liability to sudden changes of weather and to the rapid springing up of gales and storms. Many of these originate over the ocean itself, but some pass into the Western Atlantic from the American Continent. The frequency of gales and storms is considerable, but varies at any one time in different regions. The summer months are the most favourable for flying, but even then occasional gales occur. During the winter half of the year, October to March, the average number of days of gale varies from about 30 in the easterly portion, say 500 miles west of Ireland, to about 60 in the western mid-Atlantic. Nearer Ireland or to the American coasts and also in eastern mid-Atlantic the average lies between these figures. The maximum frequency is experienced in the western mid-Atlantic between January and March, when 40 days of gale are recorded.

Fog is at a maximum during the summer months, when it may occur on 10–20 per cent. of the days in the month over the eastern and central parts of the ocean. The Newfoundland Banks are notoriously foggy and in summer dense fogs may last for several days at a time. At no time in the year does fog occur here on less than 30–35 per cent. of days and at midsummer this increases to 50–55 per cent. over a comparatively large area. The fact that fogs in the eastern Atlantic are less dense and less frequent,but when they occur more widespread than in the western ocean is probably associated with the interlacing of currents of warm and cold water in the eastern Atlantic.

The same conditions which cause sea-fog with wind from one quarter will create "bumpiness" with wind from the opposite quarter. When a S or SE wind blows off the warm Gulf Stream on to colder water a temperature inversion is created in the surface layers of air and the chilled air becomes foggy. If this air returns to the Gulf Stream after a short journey over the colder water, the fog will merely clear, the temperature inversion above the fog acting as a barrier to convection. But when a N or NW wind, whose temperature conditions up to great altitudes have been determined during a long sweep over cold water, from the Arctic, encounters the Gulf Stream, temperature "bumps" extending to enormous heights will result from the great increase of surface temperature. It appears, therefore, that in the western Atlantic where the cold and warm currents interpenetrate rather than mingle, great and sudden bumps should be looked for if fog is absent. This was verified by the experience of the airship R. 34 which encountered "bumps" of great severity with a cloudless sky and little wind over the Gulf of Maine.

In general, therefore, flying conditions will be better in the eastern Atlantic than in the western Atlantic. The air over the Gulf Stream itself is, however, particularly free from "bumps."

As regards the route from western Europe to North America, the summer is undoubtedly the best time. As the prevailing upper winds are westerly in all months, the west-east route will theoretically have an advantage over the east-west one. In practice, however, particularly if the journeys be made at moderate heights, a suitable course may be steered so as to take advantage of the existing cyclonic or anticyclonic winds. The outward voyage of R.34 in July, 1919, afforded proof that flight at a moderate altitude may be made right over the top of a secondary or other shallow depression. Table IV gives the time in hours required for the flight from Newfoundland to Ireland under best, ordinary and worst conditions, for engines capable of different speeds, based on the "Synchronous Weather Charts of the N. Atlantic Ocean, 1882–3." Rotch and Palmer in their "Charts for Aeronauts & Aviators" give a sectional diagram of the best route for both east and west journeys for an airship with an average speed of 25 mi/hr, capable of remaining four days in the air. A variation of this route, via the Azores, involves longer distance but a greater chance of fair weather.

For the route from western Europe to South America, advantage may be taken of the NE trade wind until the region of 5° N is reached. Flight should be made as low as possible in order to have the maximum speed of the trade. For the rest of the route, say to Pernambuco, a height of 2–4 km. would give the best results, viz. a maximum of NE winds and the avoidance of the SE trade between lat. 0° & 8° S. The choice of season for this route is not of much consequence, but probably March and April are the best months. For the return journey the least unfavourable winds would be found by flying low in the first part of the course and high in the latter part.

APPENDIX I.

TABLE I.—WIND SPEEDS AND FREQUENCIES, LAT. 5°–15° N, WEST OF 30° W.

Derived from 27 observations (May to September) by Teisserenc de Bort and Rotch.*

(F=frequency in %, V=velocity in m/s.)

Direction	Surface		0·5–1 km.		1–1·5 km.		1·5–2 km.		2–3 km.		3–4 km.		4–5 km.	
	F	V	F	V	F	V	F	V	F	V	F	V	F	V
N	15	6	17	5	10	4	8	3	4	5	0	—	0	—
NE	52	8	42	7	35	5	32	7	37	9	44	10	21	11
E	18	3	32	5	24	5	36	8	39	11	44	16	47	14
SE	0	—	2	9	0	—	4	3	4	6	0	—	13	5
S	11	3	2	3	14	3	8	3	0	—	8	5	11	5
SW	4	3	5	3	7	4	4	4	7	2	2	10	8	7
W	0	—	0	—	7	3	4	2	7	3	2	5	0	—
NW	0	—	0	—	3	3	4	3	2	3	0	—	0	—
Calm	0	—	0	—	0	—	0	—	0	—	0	—	0	—
Mean Velocity (all Directions)		6		6		4		6		9		12		11

Direction	5–6 km.		6–7 km.		7–8 km.		8–9 km.		9–10 km.		Above 10 km.	
	F	V	F	V	F	V	F	V	F	V	F	V
N	0	—	3	2	0	—	3	10	14	9	6	10
NE	22	12	18	11	17	8	20	6	9	10	9	13
E	60	9	58	10	63	9	54	8	32	9	43	12
SE	10	9	10	9	3	5	14	8	36	9	31	9
S	0	—	0	—	0	—	3	13	0	—	2	4
SW	5	4	0	—	6	6	6	6	9	5	1	5
W	0	—	0	—	0	—	0	—	0	—	3	3
NW	3	10	8	5	8	5	0	—	0	—	5	6
Calm	0	—	3	—	3	—	0	—	0	—	0	—
Mean Velocity (all Directions)		9		9		8		8		9		10

* *See* Appendix II.

TABLE II.—WIND SPEEDS AND FREQUENCIES, LAT. 5° S–5° N, WEST OF 20° W.

Derived from 9 observations (May to September) by Teisserenc de Bort and Rotch.*

(F=frequency in %, V=velocity in m/s.)

Direction	Surface		0.5–1km.		1–1·5km.		1·5–2km.		2–3 km.		3–4 km.		4–5 km.	
	F	V	F	V	F	V	F	V	F	V	F	V	F	V
N	0	—	0	—	0	—	0	—	0	—	0	—	0	—
NE	0	—	0	—	0	—	0	—	25	5	13	8	14	5
E	0	—	0	—	7	1	29	2	33	5	87	9	86	8
SE	22	3	37	5	53	4	14	3	25	5	0	—	0	—
S	45	5	53	5	33	4	29	5	17	4	0	—	0	—
SW	0	—	5	4	7	4	14	4	0	—	0	—	0	—
W	0	—	0	—	0	—	0	—	0	—	0	—	0	—
NW	33	4	5	4	0	—	14	4	0	—	0	—	0	—
Calm	0	—	0	—	0	—	0	—	0	—	0	—	0	—
Mean Velocity (all Directions)		5		5		4		3		5		9		8

Direction	5–6 km.		6–7 km.		7–8 km.		8–9 km.		9–10 km.		Above 10 km.	
	F	V	F	V	F	V	F	V	F	V	F	V
N	0	—	0	—	0	—	0	—	0	—	0	—
NE	25	4	38	7	0	—	0	—	0	—	20	9
E	58	6	25	6	67	9	100	9	100	11	63	9
SE	17	6	37	6	33	5	0	—	0	—	17	8
S	0	—	0	—	0	—	0	—	0	—	0	—
SW	0	—	0	—	0	—	0	—	0	—	0	—
W	0	—	0	—	0	—	0	—	0	—	0	—
NW	0	—	0	—	0	—	0	—	0	—	0	—
Calm	0	—	0	—	0	—	0	—	0	—	0	—
Mean Velocity (all Directions)		6		6		8		9		11		9

* *See* Appendix II.

TABLE III.—MEAN TEMPERATURE GRADIENT (MAY TO AUGUST).

(From Rotch and de Bort: "Étude de l'Atmosphère Marine par sondage aériens Atlantique. *Travaux Scient. de l'Observatoire de Trappes.* 1909. p. 56).

N. Latitude	0–500 m.	500–1000 m.	1000–1500 m.	1500–2000 m.
	° C.	° C.	° C.	° C.
35	0·96	0·52	0·18	—
30	0·78	—0·14	0·32	0·14
25	0·68	—0·16	0·36	0·00
20	0·60	—0·14	0·20	0·64
15	0·68	—0·26	0·50	0·26
10	0·72	0·56	0·06	0·26
5	0·68	0·72	0·40	0·12
0	0·78	0·64	0·56	0·14

TABLE IV.—TIMES IN HOURS REQUIRED FOR FLIGHT BETWEEN NEWFOUNDLAND AND IRELAND UNDER BEST (B), ORDINARY (O), AND WORST (W) CONDITIONS FOR ENGINES CAPABLE OF VARIOUS AIR SPEEDS.

(*a*) From West to East

Air Speed	80 mi/hr			100 mi/hr			120 mi/hr		
	B	O	W	B	O	W	B	O	W
April	16	26	33	14½	21	23	15½	16½	17
May	20½	35	41	16	23	28	12½	14	21
June	23	32	61	14½	20	24	12	16	21

(*b*) From East to West

April	27	45	impossible	21	36	47½	18	18½	22½
May	20½	44	impossible	16½	30	impossible	14	24½	68½
June	26	36	64½	20	29	34½	16½	22	25½

"Impossible" implies that head winds would be encountered exceeding the air speed of the machine, *e.g.*, on the most unfavourable day for crossing from east to west in May, winds of 120 mi/hr from west occur. A machine of air speed 100 mi/hr could obviously make no headway against such a wind, even though it occurs only on 300 miles of the route.

APPENDIX II

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