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SUDDEN STRATOSPHERIC WARMING: THE ROLE OF SOLAR WIND AND OZONE

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Polar vortex is the key phenomenon of the functioning of our atmosphere with solar activity. After a very hot year 2023, very disturbed by a powerful solar activity with a sudden significant **stratospheric sudden warming** (SSW 27/02) at the vortex N (see SCE 2023 ; Vinós, 2024). As early as fall 2023, a new one is announced for early January 2024 according to the media with a second likely surge in late January (NOAA). This first SSW (2/01/24) was considered responsible for the change in the weather pattern with cold waves in January on the United States and Europe. According to forecasts of 01/15/2024, winds induced in the stratosphere by a weakened Arctic vortex, "will just reach the threshold of a sudden stratospheric warming which is expected on January 16, 2024". This happened only one month later, on 13-16 February 2024 (see part II Observations). Another similar event occurred on 2/03/14 and lasted only 2 days, like that of 5/07/2023. Many researchers are questioning the meteorological evolution of this year, following the SSW of January, considered as one of the consequences of the anthropogenic warming of the troposphere. The media do not hesitate to send alarming messages concerning particularly El Nino "exceptional" this spring in relation to anthropogenic warming.

We demonstrate that these phenomena are related to the perturbations induced on the polar vortex in the stratosphere, in direct relation to the quality of the insolation, the power of solar winds and the mode of destruction of stratospheric ozone. This suggests that whatever the strength of the vortex, it is its spatial configuration associated with powerful solar winds that bring either an SSW (weak vortex) or a hole in the ozone layer (strong vortex), partly boosted by natural or anthropogenic halogens. The strato-mesophere (turbosphere) is the key to our weather in connection with solar activity.

PART I: THE CONTEXT OF SUDDEN STRATOSPHERIC WARMING

1. A TURBULENT AND THERMALLY HIGHLY DISSYMETRIC PLANET.

The surface of our planet receives its direct energy mainly by the solar irradiance or insolation, which is maximum in the intertropical zone, the zone most perpendicular to the solar radiation. A significant energy proportion comes from solar winds, resulting from eruptions on the surface of the sun, the corona. On the other hand, the terrestrial hemispheres are not similar as energy receptors while 70% of the Earth's surface is occupied by the ocean, a specificity of our planet. The southern hemisphere (HS) is 64% dominated by the oceans while the continents dominate in the northern hemisphere (HN). Atmospheric thermal reactivity to insolation is powerful and rapid over continental masses, such as the Sahara, or Antarctica due to a high albedo. On the other hand, the ocean mass is partially transparent to visible light and especially to the UV which penetrates it up to 500 m of depth, at the intertropical latitudes, allowing a major and cumulative thermal storage in the surface/ subsurface of the ocean, direct IR re-emission and vaporized water (the first and most abundant GHG). On the other hand, the troposphere constitutes about 80% of the mass of the Earth's atmosphere and this mass, as well as the composition of the air, makes the troposphere quite opaque to the thermal IR emitted by the planet's surface ((SCE, 2020).

A second dissymmetry is generated by the obliquity of the axis of rotation of the earth and the alternation of continuous days and nights at the poles. This leads to the formation of a strong winter counterclockwise cyclonic vortex in the stratosphere at the N pole, over the Arctic. Its analogue hourly appears in the southern winter over Antarctica. In fact, these polar stratospheric vortices are restricted to the hemispheric winter. For the northern hemisphere, (HN) they are formed during the passage from the earth to the perihelion, thus the closest to the Sun (January 3-4, 2024: 147.1 106 km), with a stratospheric Arctic strongly cooled by IR radiation (polar night). For the SH, the vortex is formed at the aphelion much farther from the sun (152.1 106 kms). The source of vortex rotation is the tidal resonance (lunar + solar) and this resonance is favored by the Coriolis force. But a strong solar gust can disturb it with an SSW (SCE 2023), a very frequent but poorly understood phenomenon in the Arctic zone.

2. ROLE OF TERRESTRIAL ATMOSPHERIC TURBULENCE (OUTSIDE THE VORTEX)

Our troposphere and tropopause constitute the "lower atmosphere": this is where turbulence is most effective. The stratosphere and the mesosphere above our troposphere are called the "average atmosphere" or "turbosphere" which extends from 12 2 to 90-100 km above sea level. The turbosphere as well as the terrestrial troposphere has convective activities, at least up to the turbopause (90 -100 km). But winds exist higher, in the thermosphere, which is attested by the morphology of "waves of fast wind" generated by the superposition of winds of different speeds. These undulations or instabilities of Kelvin-Helmholtz, appear in that of noctiluscent clouds between 75 and 85 km of altitude (fig. 1B).

A little higher, the mesopause, at about 80-90 km altitude, separates the mesosphere/ turbosphere from the thermosphere, the second true outer layer of the Earth's atmosphere (Figure 2). The mesopause almost coincides with the turbopause (100 km). Winter turbulence in the medium atmosphere is more intense than in hemispherical summer and increases with latitude (Danilov et al. 1992) and can also disrupt vortex dynamics.

Figure 1. A) Jupiter's swirling clouds (NASA 3D image over 50 kilometres in height and hundreds of kilometres in diameter. Their resemblance to cumulonimbus and tropospheric cirrus clouds is astonishing. B) Noctiluscent clouds disturbed by Kelvin-Helmholtz.ripples generated by high wind (80 km: thermosphere; Iceland. Vedur.is). C & D, northern lights with vorticity (Iceland), sometimes disturbed

Turbopause serves as a transition between the turbulent mixing regime of the turbosphere (medium atmosphere) and, a molecular diffusion regime in the thermosphere, the upper atmosphere (Danikov, 1984; Danilov et al., 1992). At the level of the polar cones, the appearance of these lines of currents and vortices (Figures 2C and D) show that there are between 90 and 110 km of altitude spatial and temporal variations, based on the auroral circles (about 300 km).

These polar auroras are developed when there a collision between these charged particles of the solar wind and the ions occurred in the thermosphere. They are associated with strong solar activity. These auroras are also disturbed by thermospheric winds (instabilities of Kelvin-Helmholtz; Palmroth et al., 2020) and are guided at the edge of vortices by the magnetic field lines that stretch on the side of the Earth opposite the Sun. Most of the turbosphere therefore seems to have some turbulent activity by strata, including in the stratosphere as well in the troposphere and in the case of Jupiter. Turbulent or convective atmospheres have been observed for the Sun, on 7 of the 8 planets of the solar system and on the Titan satellite: the Earth is no exception.

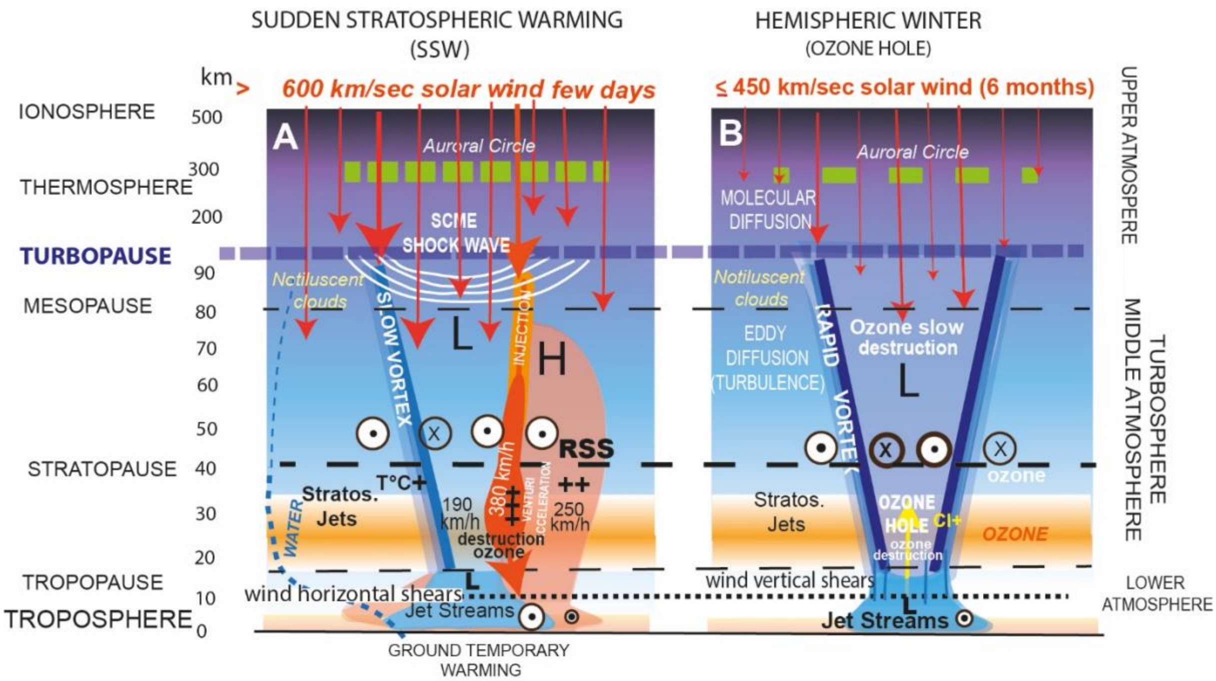

Figure 2: Structure of the Earth's atmosphere and evolution of the polar vortex and ozone in the turbosphere (stratosphere + mesosphere) from images *(NASA). The indicated altitudes are subject to slight variations according to the seasons and the irradiance received. The relationship with troposperic polar jet streams is explained. For the ozone hole vortex (B), the data, including chlorine, are from* Copernicus *(ESA).*

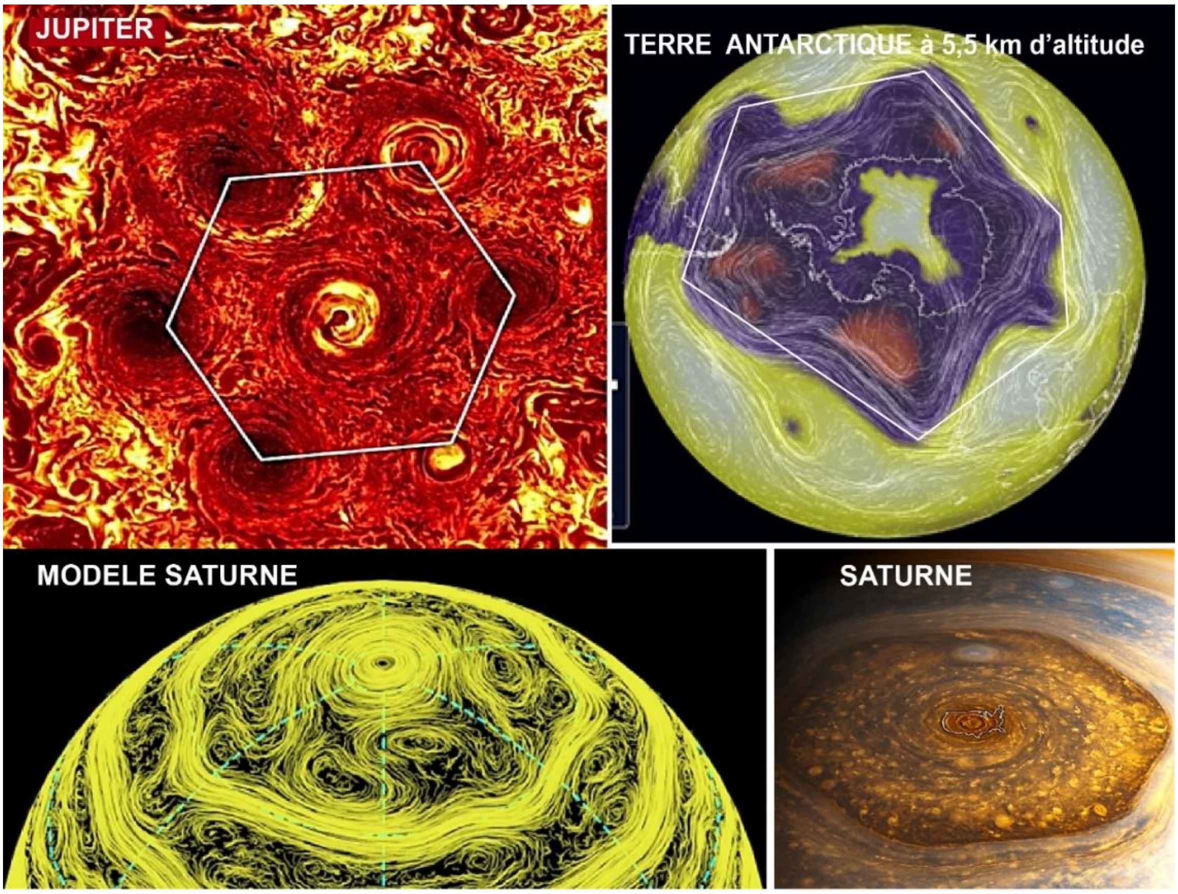

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Figure 3: Hexagon swirls at the pole of Jupiter (Infra-red images, NASA), Hexagon cyclonic vortex (in red) in the troposphere at 5.5 km, above the Antarctic ice sheet (10/05/2023). Turbulent hexagon on the pole of Saturn and its modeling (2014 NASA/JPL-Caltech/Space Science Institute).

3. CONTRIBUTION OF THE SUN TO STRATOSPHERIC VORTEX

Total Solar Irradiance (TSI) is the first source of energy supplied to the Earth's surface. The historical series of sunspots and those of the evolution of the IST are managed by cycles correlated with the evolution of the solar magnetic field and the oscillations of the position of the star in the solar system. The Sun's magnetic field produces inversions every 11 years correlated with the maximum of one sunspot cycle (the Schwabe cycle). They are also controlled by variations in the force of gravity of the different planets in the system. Currently, the maximum activity of cycle 25 is expected in early 2025. The overall irradiance of the sun increases relatively little (0.07%) during a solar cycle at 11 years, but the surface activity of the sun is greatly accentuated by the ejections of solar coronal mass (SCME) in periods of high activity. This may occur independently of the situation in the solar cycle, but the number of solar flares is maximal shortly after the culmination of the cycle. Terrestrial geomagnetic storms are initiated by SCME on the surface of the sun. SCME is accompanied by fast and slow solar winds.

The solar wind is a plasma, composed mainly of electrons and protons. It is continuously ejected from the sun's upper atmosphere in all directions towards interplanetary space, along the solar magnetic field lines. It has two components: a "fast" wind moving at about 500-1000 km/s from the coronal holes at the poles of the sun and a "slow" wind at about 200-450 km/s emitted mainly at the equatorial plane of the Sun and is even more important as the sun is active. But the solar plasma ejected by the EMCS penetrates deep into the atmosphere via the polar cones, following the lines of the Earth's magnetic field (here).

The Earth's magnetic field protects our planet from solar winds and cosmic radiation. The Earth's magnetosphere cannot be penetrated directly by this wind because of its propagation perpendicular to the Earth's magnetic field. The Earth's "insulating" magnetic shield therefore faces the sun and protects the planet from these winds, but not from the direct TSI, given the transparency of the atmosphere with visible radiation, IR, and UV. This magnetic field curves at the poles to form 2 polar cones perpendicular to the surface of the poles and therefore penetrable by the solar winds. It is responsible for injecting magnetized solar particles from the wind into the lower atmosphere. When very strong coronal mass ejections, the brutal and massive intrusion of energetic particles induces significant fluctuations of the Earth's magnetic field and a powerful shock wave responsible for the injection of accelerated solar particles via the cone, to the Earth's surface.

4. THE ARCTIC VORTEX AND SUDDEN STRATOSPHERIC WARMING

Polar vortices or vortex are wind-sheathing cones in the turbosphere derived from the Coriolis force, framing a low-pressure core characterized by a cyclonic rotation. The vortices do not exceed 2,000 km in diameter but descend in winter to the Earth's surface, the Icelandic depression in the HN and the one on East Antarctica in the HN Coriolis, an inertial and centrifugal force, interacts perpendicular to the direction of motion of the rotating planet in the solar system. The speed of rotation of our planet is therefore a critical factor in understanding atmospheric dynamics, vortex dynamics and associated phenomena such as tropospheric jets or stratospheric ozone holes. The core of normal vortices is turbulent in the turbosphere as shown by the evolution of the two polar vortices this spring (Figure 4), including small evolutionary vortices from 200 to 400 km in diameter. This core develops in the Stratosphere (15-30 km alt., 300km/h), surrounded by powerful anticyclonic winds, the sensu-stricto vortex, but it also exists in the Mesosphere, at least up to 65 km altitude (Schranz et al., 2020). This vortex sheath is either counterclockwise in the HN and clockwise in the HS.
A rapid rotation of the sun seems induce an intense magnetic earth field, and therefore a braking of the rotation of the earth by the magnetized solar winds. The increase of the solar wind induces a pressure that slows down the Earth' rotation of the by transferring electrical energy to the annular current of the Earth's magnetosphere. The vortex thus should slow down in periods of strong solar winds (2021-24; 900 km/s in February 2023), the speed of the vortex evolving normally from 300 km/h (standard) to 220-250km/h in periods of high solar activity (SCE, 2023). This is observed for the Arctic polar vortex at 10 hPa (30 km elevation).

Sudden Stratospheric Warming (SSW) occurs within the turbosphere, but especially in the Mesosphere (Schranz et al., 2020) above the thermal maximum of the stratopause (about -3°C; https://wikipedia.org/wiki/stratosphere: temperature). Higher, the temperature of the Thermosphere (Figure 2) at the top of the turbopause increases virtually with altitude and reaches up to 1,000 - 1,500 K, temperatures that can be explained by the absorption of short wavelengths of solar radiation by residual oxygen and nitrogen molecules. The turbulent Mesosphere could therefore also be very sensitive to this solar warming.

Long-term changes in the Turbosphere include (i) modest increases in water vapour [noctilucent clouds, tropical storms, volcanic eruptions such as Krakatao in 1883 or with the eruption of Hunga Tunga in early 2022 (Zhu et al., 2023)] and traces of greenhouse gases, (ii) ozone depletion, and (iii) systematic cooling of this region of the atmosphere from 1980 to 2000 (Pahlavan et al., 2021). This is particularly related to the increase in solar activity, given the presence of water vapor diffused by turbulence, which shows the noctiluscent clouds mainly produced by the very large volcanic eruptions or tropical storms.

5. SSW RELATED TO THE SURFACE ACTIVITY OF THE SUN AND THE SOLAR WIND

- The cyclonic vortex forms each hemispheric winter and is generally stable in the turbosphere but its wind sheath is usually fast (c. 300 km/h). The vortex usually forms in late autumn, around early December due to the polar night. However, the tropospheric polar jet stream remains normally as fast (c.300 km/h) and keeps the air cold in the Arctic Circle (60°lat.N).
- Regularly, in the northern hemisphere, winter polar vortices are subject to an SSW at the end/beginning of the year, so as close to the sun: perihelion.
- For the HS, the earth is further away from the sun (aphelion), which makes it possible to understand why SSW are much rarer in Antarctica. Only 3 events were observed: in 2002, 2009 and 2019.
- In the HN, SSW are therefore most often associated with rapid solar wind peaks exceeding 600 km/s (900 km/s, 27/02/2023b) and average slow winds greater than 400 km/s (SCE, 2023) according to available data (Space Weather & Solen Info).
- The periods of occurrence of SSW often correspond, but not systematically to periods with tidal coefficients higher than 100 thus a very strong lunar and solar attraction. Solar wind peaks of > 850 km/s (fast winds) linked to SCME induce rapid stratospheric warming (SSW) at the northern polar vortex of a few days (SCE, 2023). They modify the configuration of tropospheric temperatures in the Arctic: this region can then undergo a regional warming (Gerrard et al., 2002; SCE, 2019) which can extend to lower latitudes.
- The slower peaks of rapid winds (<600 km/s) lead to the same vortex morphology as the rapids: that of 2/03/24 lasted only 2 days, without SSW, before weakening. It should be noted that in HS the morphologies are identical but without necessarily giving an SSW to the aphelion (Figure 5).

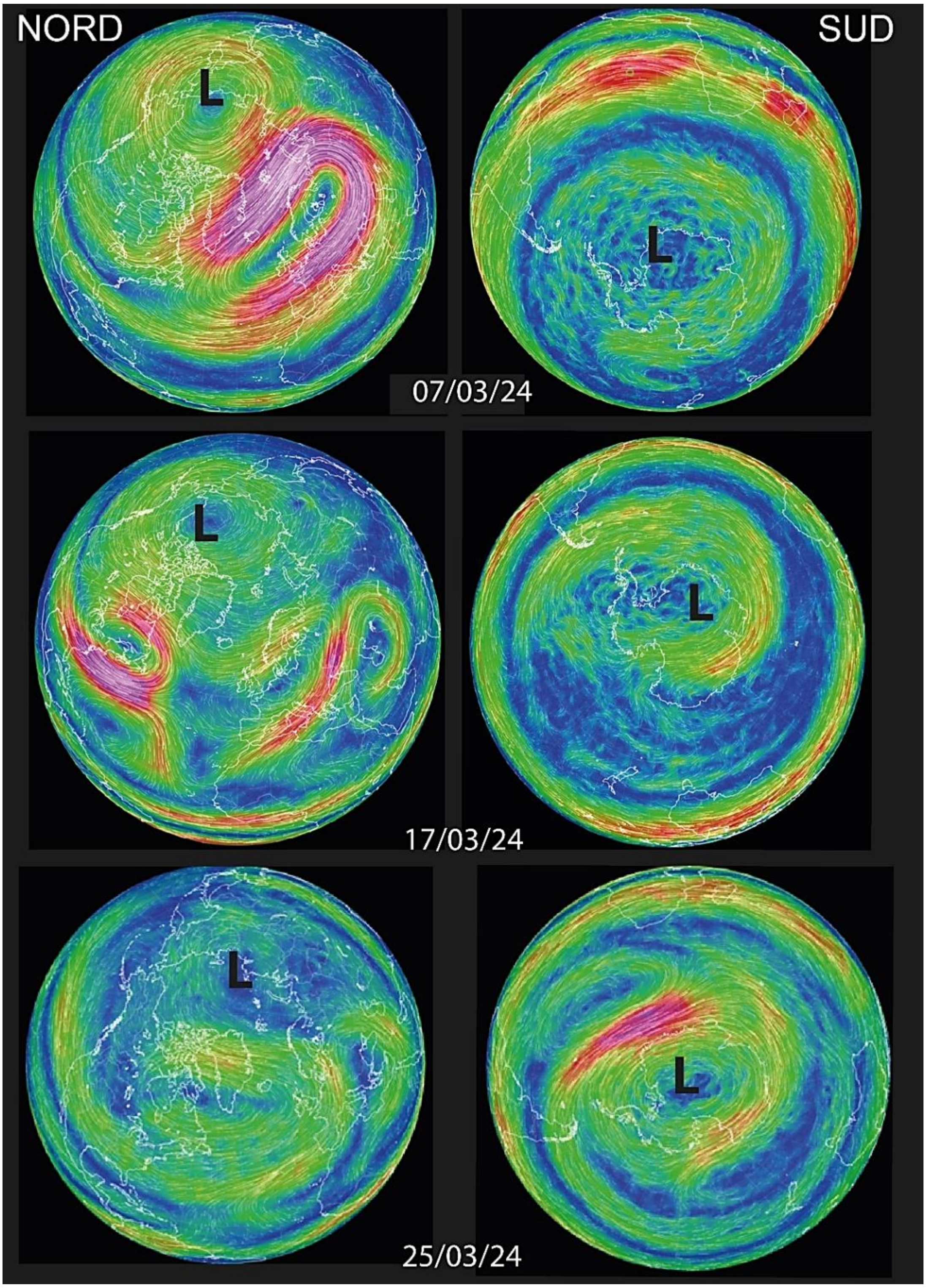

Figure 4: State of the two terrestrial vortices on 07/03/2024, 17/03/2024 and 20/03/24 at 10 HPa. Note that the N vortex begins its disappearance by seriously slowing down (50 km/300km/h) and also the particular aspect of the South Pole with granulation linked to micro-vortices at the tropopause, reminiscent of the surface of Jupiter (here). For Antarctica, the construction of the vortex is centripetal, which also appears for the HN in winter. It should also be noted that the major disturbances of the HN vortex are located above the Atlantic and not the Pacific (Rossby waves, linked to the relief of Greenland and Scandinavia).

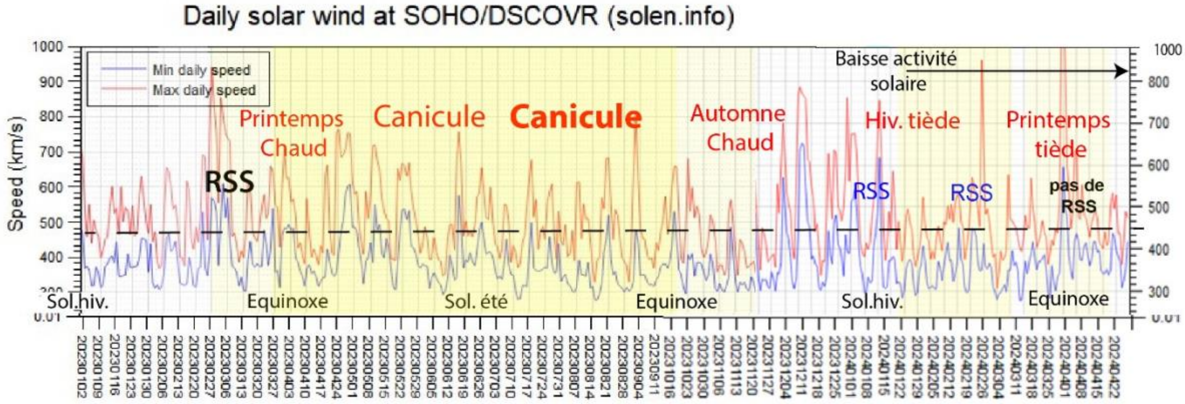

Figure 5: Fast and slow solar winds from January 2023 to late April 2024. for the last ultra-fast peak (1000 km/s), the vortex of last spring 2024 was without any counter-vortex and therefore without SSW (RSS).

- Their frequency also grows especially in relation to the increase since 1950 of the solar irradiance corresponding to a cycle 121 years (11 x 11 years; Vinos 2022) under control of the apsidal precession of the Earth orbit, in coupling each magnetic cycle to "11" years of the sun.
- A priori, in addition to the distance between Earth and the Sun, planetary or gravity waves (Rossby), given the topography of Antarctica, can exert a lesser influence than in the Arctic. These are conventionally considered to be an important movement transfer mechanism between the troposphere and the stratosphere (SSW) (see Figure 7B).
- The base of the vortex is located at the top of the tropopause, about 16-17 km high, but it transmits its kinetic energy to the tropopause/ or very high troposphere. The 2-year analysis of images from the southern hemisphere shows that the winter polar vortex base at 10 hPa (30 km) swirled down to the top of the tropopause (16 km) and takes the winds reaching 72° lat. S, with a hexagonal pattern at least from 30 km in altitude, but its expression is maximum at 5.5 km altitude (10/05/2023; Figure 3). The imagery produced by Schranz et al. (2020) also attests to a sudden change in the velocity of the vortex sheath at this altitude.
- The record SSW of mid-January 2009 in the HN (Lida et al., 2014) would have brought sudden and dynamically coupled latitudinal changes in the tropical tropospheric zonal circulation, but also in the stratosphere. Convective activity of HN has weakened to the detriment of HS.

6. DATA

It is for all these reasons that we carried out a 2-year follow-up of the activity of the fast solar wind, showing that the high peaks appear at the end of December to the end of February, but with a quasi-monthly recurrence for the average peaks, (rotation of the sun: 27 days). High peaks occur in the HN approximately every year in winter, suggesting that it is still the same area of that emits SCME from the surface of the sun. Near the perihelion, the solar influence is more powerful in the HN than in the HS, and the cyclicity for very large events is +/- one year (27/02/23 and 03/01/24). The frequency of SSW decreases after perihelion and subsequent tropospheric warming is no longer enough powerful to influence our climate. Normally, in the HN, the frequency of occurrence of SSW in the Arctic is about 2 years. This phenomenon significantly disrupts our weather via jet streams.

2018-2019 Sudden N and S stratospheric warming

This is one of the best recorded events in the HN but also exceptional in Antarctica, in August-September 2019: this is the second recorded case. Most of the N warming in January 2019 was followed between 30 and 60 km (Schranz et al. 2020), so in the mesosphere and stratosphere N (Figure 6) with 2 successive events, one from 22/11 to 25/12/2018 and the second, significantly more powerful from 12/01/2019 to 03/03/2019 (Figure 6). The 2018-19 RSS affect the atmosphere mostly above the stratosphere and not from the troposphere as incriminated by Cohen et al. (2014), the base of the vortex above the tropopause, remaining very cold and slowed down.

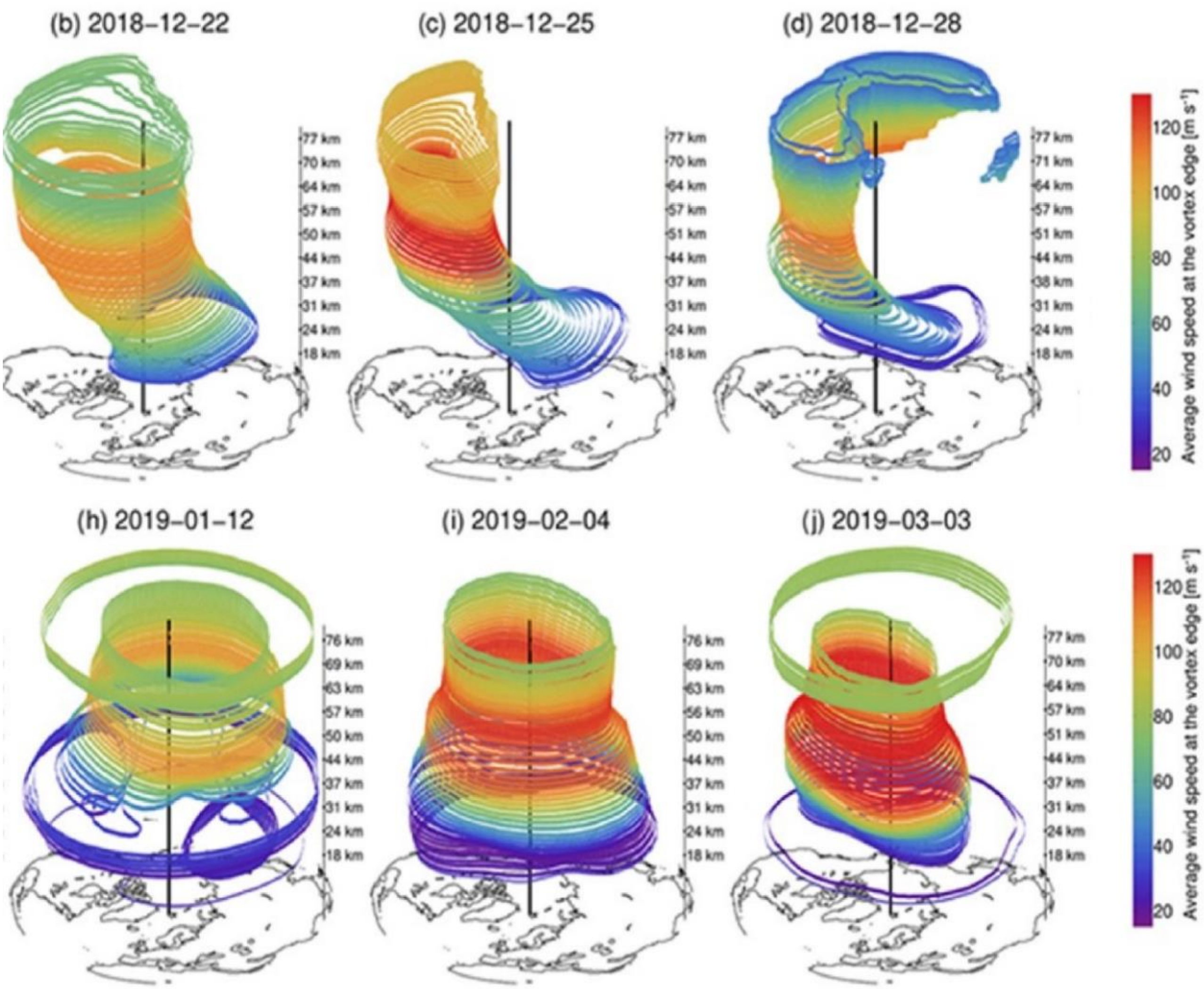

Figure 6: Following several from 12/2018 to 03/19, the speed in red reaches 430 km/h, the speed in dark blue 70 km/h and in green, the mean of the vortex, or 300 km/h (Schranz et al., 2020). Note that for the SSW of 17/02/2023 the speeds reached were 380 km/h and 8/01/2024

360 km/h for the contact zone between the cyclonic vortex and the counter-vortex. In our opinion, it is not the vortex but the anticyclonic countervortex that heats up.

This sudden and powerful double stratospheric warming in the HN was followed by a tropospheric heat wave descending from the pole between 24 and 27 July 2019, particularly in the Arctic climate zone (SCE, 2019), which resulted in an exceptional melting of the ice cap and multiyear pack ice in northern Greenland (NSDIC). It was followed at the end of August 2019 by a powerful, and exceptional Antarctic warming associated with a series of 6 solar wind peaks (Figure 7A), with for the median peak the max 870 km s^{-1}, resulting in significant ice pack retreat after an exceptional winter and glacial melt over Greenland (Lim et al. 2019). This suggests high and persistent solar activity with a solar wind supported by regular coronal ejections, similar to that of 2023, but with an initially less warm Earth ocean.

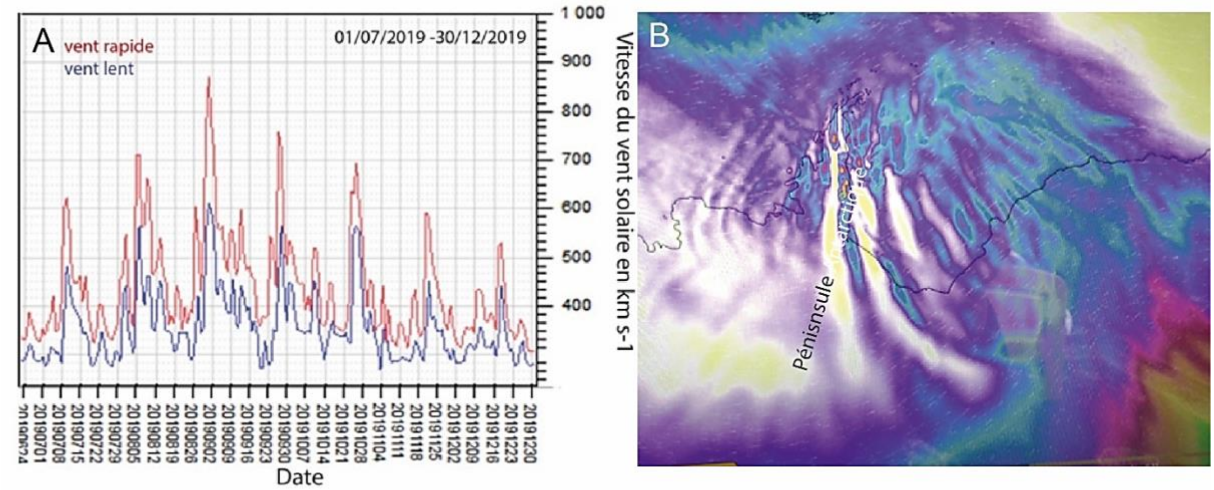

Figure 7: A) recording of fast and slow solar winds during the 2019 Antarctic SSW. Note the regularity of extreme peaks, including for slow winds. Source Solen info, daily solar winds SOHO- DISCOVR.   B) Stratospheric winds 30 km above the Antarctic peninsula highlighting Kelvin-Helmholtz instabilities generated in the upper stratosphere by planetary waves from the relief of the peninsula (Windy, 6/05/2024, winds, 30 km altitude).

PART II. HEATING THE VORTEX:
THE ROLE OF THE SOLAR WIND AND OZONE

1. OFFICIAL HYPOTHESES

Officially, during an SSW, the polar vortex would appear to decompose or split, accompanied by a cooling above warming and a deceleration of its base followed by a warming of the air at polar latitudes. The surface temperatures of the North Atlantic in 2023 have shown historically warm levels since March 2023, that just followed the SSW 2023. This has been observed particularly in tropical and subtropical latitudes, but also further north, towards mid-latitudes.

SSW are events that impact the upper stratosphere atmosphere, and the mesosphere of both polar hemispheres are, according to Baldwin et al., 2021 and Schranz et al. 2020, but under control of upward propagation from the troposphere of planetary waves (Figure 7B) particularly related to relief. The waveguides are inherited from specific configurations of atmospheric winds, or "jet streams", under the tropopause above the irregular surface of the Earth.

In August 2019, planetary activity would have spread upward from the troposphere and "significantly weakened the rotation of the polar vortex over the entire height of the stratosphere" (Schrantz et al., 2020). According to Shen et al. 2020, the 2019 Antarctic event would then be followed by the rise of a record planetary wave. SSW would therefore warm from the man-warmed troposphere (Cohen et al. 2014 & 2020; Albers et al. 2016; Shen et al. 2020, White et al., 2021, Curry, 2024). According to Cohen in 2019, the Siberian anticyclone could even cause a radiative energy transfer from the troposphere to the stratosphere, under undisturbed influence of planetary waves. The winds of vortex N would weaken, disappear, or seem to reverse to flow from east to west. As a result of this sequence, the "cold" air of the cyclonic vortex is supposed to descend rapidly, causing a sudden increase in stratospheric temperature to 50º C in a few days.

2. THE OBSERVATIONS

The troposphere and tropopause rotate in the same direction as the vortex (Figure 8). Planetary waves occur in direct relation to the rotation of the planet. Mörner, (2010 and - al., 2020), proposed a significant slowdown in the rotation of the planet under the impact of solar winds and not planetary waves.
The SSW process is installed in about ten days on either side of the vortex rotation maxima (Schranz et al., 2020). Maxima can be multiple or unstable as is the vortex speed (Schranz et al., 2020). Therefore, given the synchronicity of SSW with extreme solar wind events and their rapid recurrence according to the 11-year cycle (SCE, 2023), the process is to be sought in solar activity and not that of man (Figures part I- 2 & 5).

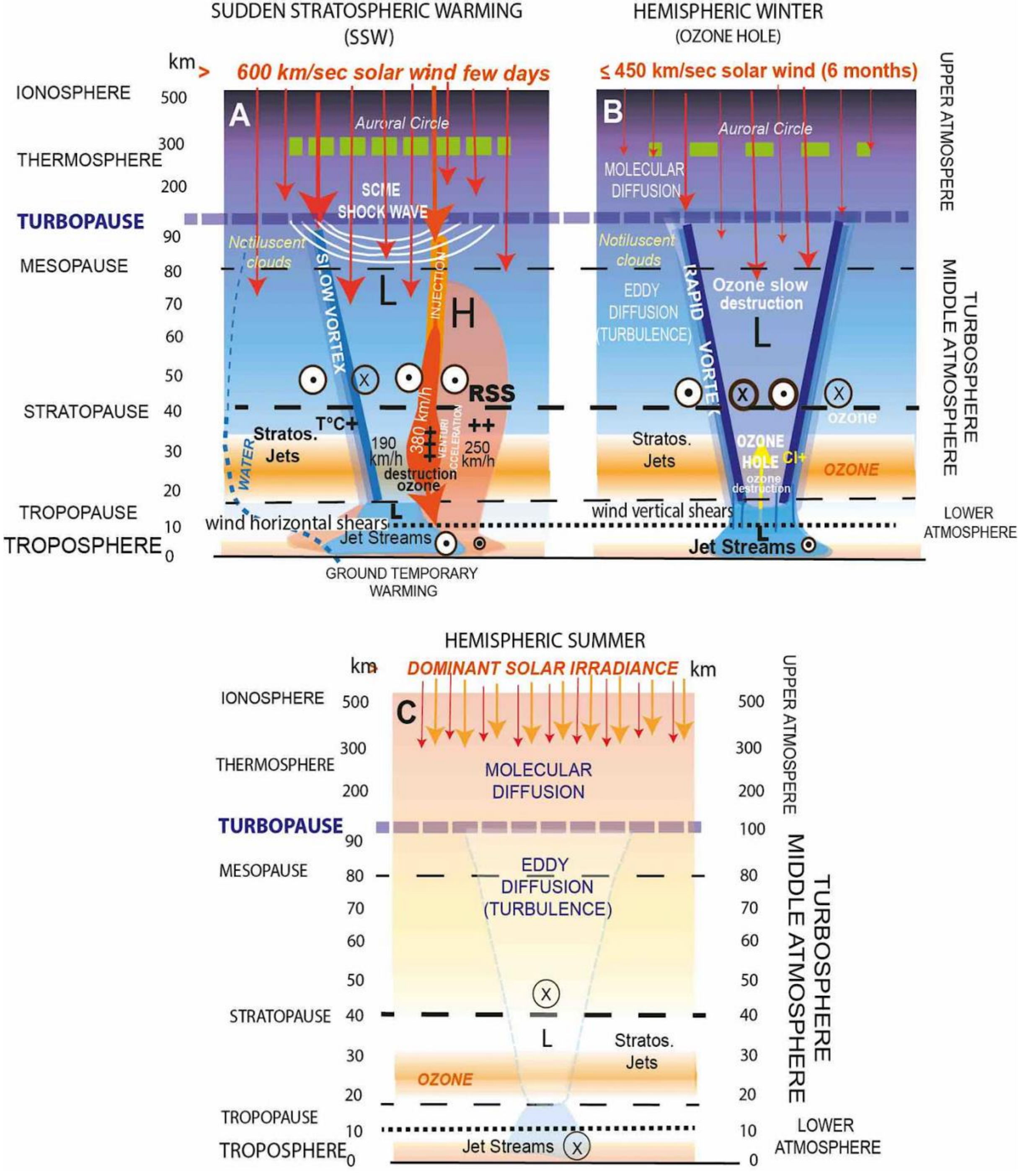

Figure 8: (A) structure of the Earth's atmosphere and evolution of the polar vortex and ozone in the turbosphere (stratosphere + mesosphere) according to the images (NASA). The indicated altitudes are subject to slight variations according to the seasons and the irradiance received. The relationship with tropospheric polar stream jets is explained. For the vortex with ozone hole (B), the data, including chlorine, are from Copernicus (ESA). Copy of figure 2.

We have noticed that similar morphologies of the cyclonic vortex at 10 hPa are related to the shoulder or the reaction neoformation of a counter-vortex of anticyclonic nature in the outer zone of the vortex wind sheath (see here) and not a vortex division, whether in Antarctica or the Arctic. There may be several anticyclones migrating in the vicinity via stratospheric jets. During the winter RSS of the last 3 years, these morphologies are identical to the 2 poles but are not specific to winter periods (Figure 8). They can form an SSW only in the hemispheric winter.

The slow solar wind speed is normally about 300 km s-1. It varies little depending on the solar cycle but follows solar activity, all as for fast winds (Figure part I-5). On the other hand, the rapid solar wind from the SCME varies between 450 and 1000 km s^{-1} (23/03/24). We observed that during the Arctic winter, the occurrence of strong fast winds could give rise to an SSW, if the morphology associated with the stratosphere (30 km) is that of a vortex attached to a counter-vortex (Figure 8).

From Earth's orbit, the protons of the fast solar wind should then be about 10^4 times warmer parallel to the magnetic field along the field lines of the polar horn. This would easily explain the coincidence observed between the rapid solar wind peak and the SSW (SCE, 2023). (Figure 5). This wind is very hot (10,000° K) and its speed is >600 km s^{-1} (Mach 10), so that the transport of solar matter from corona to earth takes about 4 days and its arrival in the Earth's magnetic field is preceded by a shock wave that can inject) vortex. This shock wave is essentially a converter of kinetic energy from the fast solar wind into thermal energy (heating). The particles therefore tend to bounce on the magnetic sheath of the cone and thus accumulate there, while preserving its temperature, while accelerating by Venturi the surface velocity of the sheath of the counter-vortex (Boldyrev et al., 2020), consistent with the observations, but not the ideas of Schranz et al. 2020.

3. MORPHOLOGICAL EVOLUTION OF THE VORTEX IN TIME AND THE VENTURI EFFECT

The Arctic winter cyclone vortex is generally stable in the stratosphere and mesosphere, and fast (c.300 km/h). The vortex usually forms in late November at the beginning of December. During the formation of the south vortex, the polar turbulent zone S is gradually digested by one or two anti-hourly deviations of the zonal jet via the formation of anticyclonic zones (10 hPa), and the jet accelerates progressively while rising in latitude to feed the vortex, but the jet also serves as a rail for the migration of derived anticyclones.

Monitoring of polar vortex N morphology, rotation rates and temperatures measurements at 10 hPa was undertaken (winter 2023-24). It began to form early (11/2023). The counter-vortex (an anticyclone) has independently formed at lower latitude since early December. The counter-vortex was then raised with a zonal wind emanating from the western tropical stratospheric jet from ~50° N to the pole and then joined the already weakened vortex (265 km/h then 160 km/h). At the end of December 2023, the wind speed accelerated very strongly in the transition zone between the two vortexes with peaks at 380 km/h (8/ 01/2024) while the speed of the weakened vortex L remains around 200 km/h with a temperature around -63°C: no major warming of vortex L and a modest counter-vortex H (-21.8°C and 150 km h-1). On the other hand, the juxtaposition from December of these two rotating systems has also induced between them a compressed wind flow that heats up rather quickly, where the compression by Venturi effect is maximum, either upstream or downstream of the compressed zone (downstream in early January and upstream in mid-February). This resulted in early January 2024 in a modest warming of the vortex, a little more marked of the counter-vortex and very important of the contact zone.

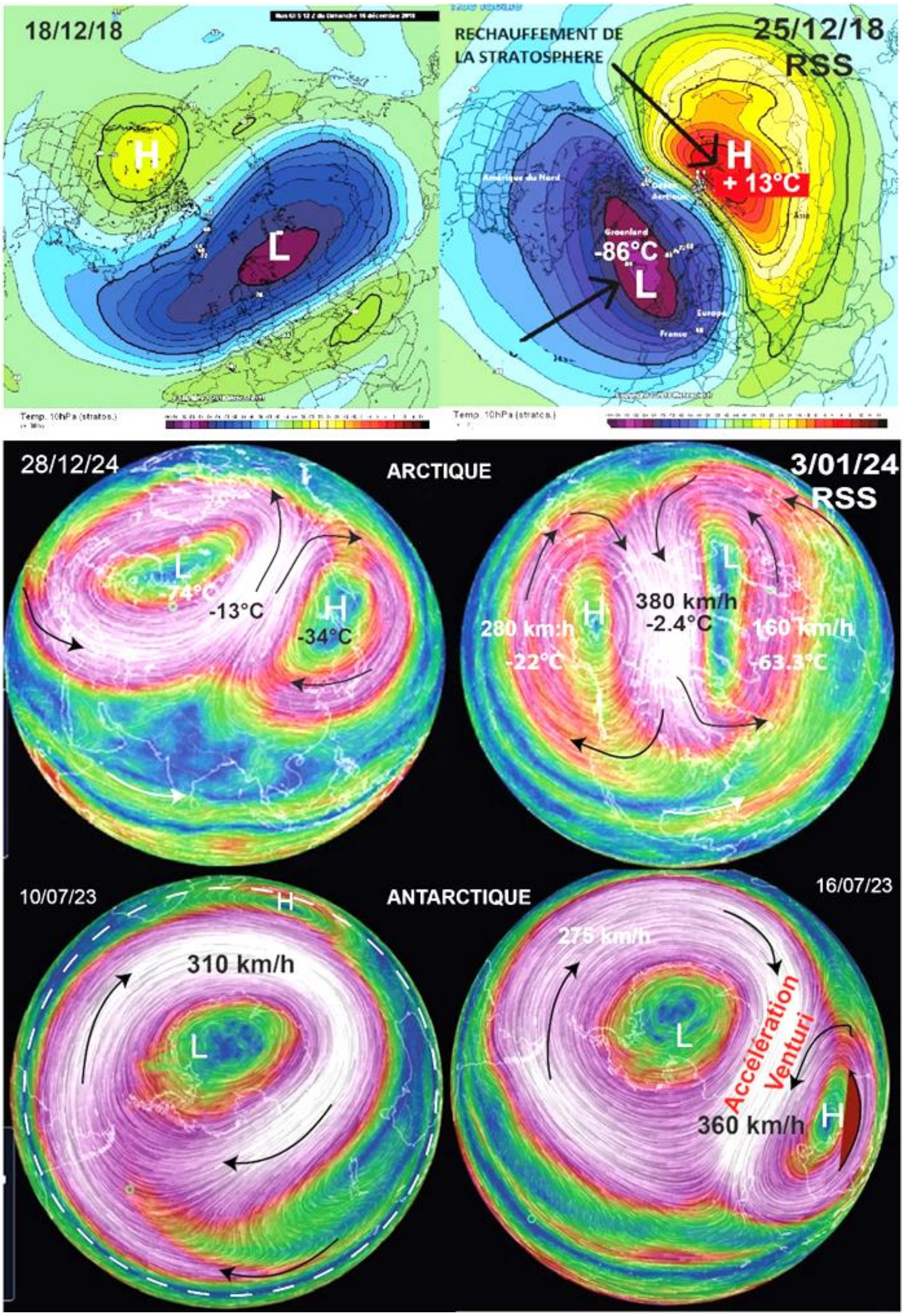

Figure 9: Evolution of the SSW (RSS) the 25/12/18, Météo France). Note the appearance of the high (H) which will warm (Météo France). In fact, the H rises in latitude with the zonal wind to come to stick to the sheath of the vortex (L). The Arctic (3/01/24) and Antarctic vortex organizations are comparable. This organization is particularly associated with the solstices

of each hemisphere. The white dotted line highlights the stratospheric equator (in dark blue). The warming zone is not induced in the vortex but the adjacent high, the counter-vortex. This warming is partially due to a Venturi effect between the 2 vortex ducts. Note that the intensity of the slow solar wind returned to a normal level after the RSS, on 01/8/2024.

Maximum heating is achieved in the transition zone between the 2 vortex L and H (+ 13°C on 28/12/2018; - 6.3°C on 29/12/23; -2.4°C on 3/01/24; -17°C on 6/01/24; Figures 3A and 8). hourly.After this period, the zonal anti-hourly stratospheric wind that feeds the vortex L at 10 hPa, then drifts in early February into a counter-vortex-spread that will transform on 10/02 at 40°N into a zonal stratospheric jet On 13/02/24, the same juxtaposed vortex system was reformed with -15°C and 350 km s^{-1}on the contact zone, and finally passed to -12.5°C and 306 km/h on the same zone on 15/02/24 and -26°C for the anti-vortex. Then the vortex broke apart and disappeared in favour of the tropical stratospheric jet N. In the Arctic, all RSS events in 2019, 2023 and early 2024 are associated with one or more successive peaks of fast solar winds: 900 km s-1 on 27/02/23, 750 km/ s-1 on 01/01/2024, one at 850 km s-1 on 12/02/24 and one at 1,000 km s-1 on 23/03/24, but without vortex coupling morphology. The temperatures reached during RSS in the contact zone between the two vortices reached +13°C at the end of 2018 and -2.5°C on 3/01/24 and -25°C on 19/01/24 (Figures 5 and 9). Wind speeds in the contact area reached 380 km/h on 03/01/24.

4. THE ROLE OF OZONE

Ozone is created during the day, in the stratosphere, when solar UV, very energetic, dissociate oxygen molecules (O2) and form this gas (O3). **This ozone synthesis reaction is endothermic.** At 30 km altitude, in hemispherical summer (Figure part I-2C), solar radiation is normally still energetic enough to **break down ozone, an exothermic reaction**.

The destruction of the ozone layer is probably the main cause of stratospheric warming. Indeed, the ozone layer thickens between the stratopause and the tropopause between 16 and 50 km with a peak of summer concentration at 23-25 km altitude. This layer is thicker in winter and early spring bringing a maximum concentration between 20 and 30 km, 16 km above the tropopause. It is curiously where the vortex winds are the fastest according to the observations of Schranz (et al, 2020) and especially at the vortex/counter-vortex contact (Figures 3A and 9).

Ozone can degrade naturally in winter in the stratosphere under the exclusive impact of solar winds due to the absence of direct solar radiation, especially with the addition of destructive molecules such as chlorine and CFCs. (https://www.canada.ca/en/environment-climate-change/services/pollution-atmospherique/enjeux/couche-ozone/appauvrient-consequences/a-propos.html)

But during the polar night, this exothermic reaction is linked to the solar winds, especially fast and most probably contribute, as we saw above, to the warming of the SSWs. This would explain the sudden appearance of SSW between 25 and 50 km (up to 65 km for speed measurements of Schranz et al. 2020) and its synchronicity with fast wind peaks (SCE, 2023). Increased ozone concentration after SSR is observed below 20 km.

The ozone hole

Some functioning similarities probably exist between the slow winter vortex and the fast winter vortex. The Antarctic is hourly and usually very fast with a hole in the ozone layer, centred on early October but that disappears in December. The 2023 ozone hole was guided at the level of the wind sheath, eroding the upper ozone sheath and induces extremely cold temperatures (below -80°C) from July 2022 did not attack the high layer.

For fast vortex, the ozone destruction reaction must also exist under the impact of solar winds, but at a lower intensity and without the addition of the vortex/counter-vortex factor. The wind sheath at the vortex nevertheless produces a complementary vorticity in the form of small lateral anticyclones at the end of winter.

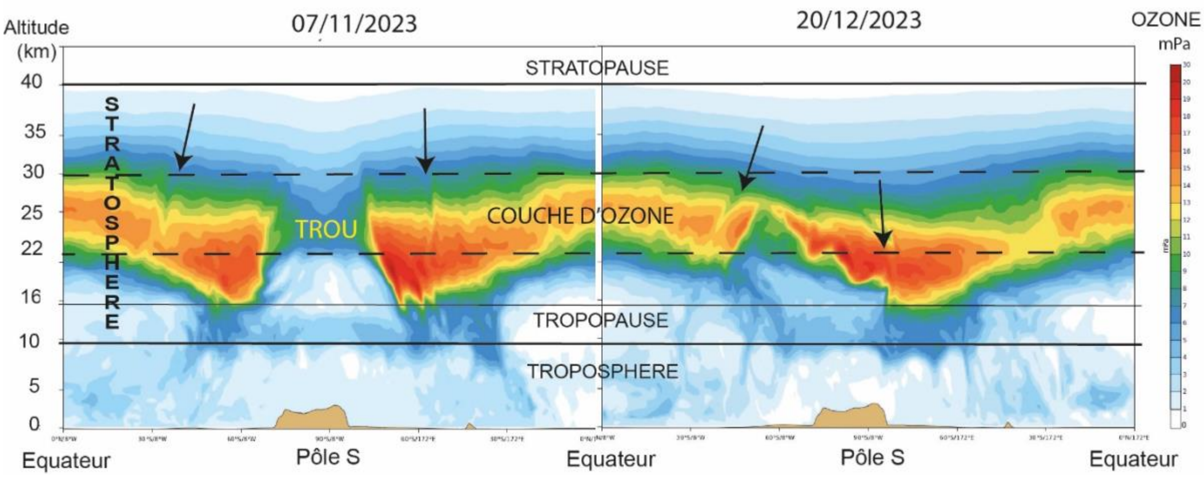

Figure10. Comparison of the ozone content between the South Antarctic hole at the solstice and its final degradation from sea level to the stratosphere. In the animation, Antarctica is in the middle (90°S) and the equator is at both ends (8°W and 172°E). In the spring of the southern hemisphere, ozone depletion is clearly visible in the stratosphere.

The 2023 Antarctic ozone hole was exceptionally large, it formed by opening up and at its base. This process was promoted at the base by halogen inputs, including destructive chlorine as during the injection of the volcanic plume of Hunga Tunga 15/01/22 (Zhu et al., 2023). The maximum opening was reached on 15/09/23. The same can be said for the hole size of 1991 (Pinatubo) and 2010 (Mérapi). Given the frequency of mega-eruptions, the maximum extent of the hole being formed is probably more related to volcanism than to CFCs alone.

The morphology of the Antarctic hole (Figure 8) suggests a mechanical downward suction from the upper stratosphere and a dissociation of ozone under the effect of the rapid solar wind. This is probably the main and logical mechanism of ozone hole formation (Figure 8), which during the polar night is progressive and culminates in September/October (HS; Figures 2 & 9). This is shown by ESA's images of the concentration of this gas in the ozone layer (Copernicus, Figure 10).

It is important to note the existence of large racking shears (arrows, Figure 9), related to the rotation of the vortex that affect the morphology of the ozone layer at the hole from the onset of attenuation activity which also leads to an injection of the tropopause air at its base. A secondary concentration of ozone, intensely sheared above the vortex wind sheath, is also evident at the tropopause. Given the delay between the eruption of Hunga-Tunga and its chlorine injection (15/01/22) and the formation of the exceptional hole of 2023, it would rather be the extraordinary solar activity of 2023 with frequent fast winds that would control the destruction of ozone.

5. IMPLICATIONS

The HS and HN vortex all have the same overall winter behaviour between 65 and 30 km altitude. The differences are essentially their proximity to the sun and polar night in the hemispheric winter (see Part. I), explaining the prevalence of SSW in the Arctic. If the sunstroke (stratospheric vortex) or solar wind are too weak, the SSW process does not start. But a very fast solar wind does not produce SSW if the configuration of the polar winds does not present a vortex and an adjacent counter-vortex or if its speed is too high. The SSW is formed on slow vortex, when a vortex/counter-vortex couple has formed and a rapid solar wind peak penetrates the polar cone, accentuating by Venturi effect in the stratosphere an accelerated warming in the contact zone between the two vortexes. Around 30 km altitude, the decomposition of ozone under the effect of rapid solar wind accentuates the sudden warming.

6. FROM VORTICES TO JET STREAMS

Polar vortices transfer their kinetic energy to the adjacent stratosphere, forming secondary vortices that can evolve into counter-vortices in hemispheric winter. The anticyclonic counter-vortex also transmits this energy from the base of its wind sheath to the Tropopause inducing the underlying polar tropospheric stream streams and widening under 17km (Schranz et al. 2020) to reach the Arctic Circle see more: This is related to the sudden increase in water vapour content and therefore density at the tropopause. when the vortex speed is slowed, this transmission brings a cooling of the lower stratosphere and the tropopause and induced by friction powerful ripples in counter-vortex of the tropospheric jets in contact with the denser troposphere. This is visible by the animation of the Antarctic vortex (Copernicus)

These last counter-vortex constrain in the troposphere polar descents of cold and heavy anticyclonic air within the troposphere, packed by the polar jet stream These are the future polar mobile Anticyclones (AMP) (Leroux, 1993; SCE, 2023). This in turn induces injections of tropical air of a low-pressure nature towards the poles, heatwaves, and therefore, control our weather. The velocity of tropospheric jets is dampened near the Earth’s surface, modulated by the Earth’s planetary waves from the roughness of the continental topography, but not from that of the ocean.

On the other hand, the tropospheric polar jet stream is normally as fast as its stratospheric equivalent under the tropopause. It maintains colder air in the Arctic Circle, creating more temperate conditions for the lower troposphere over most of the United States or Europe (excluding vortex). The heat accumulated in the centre of the counter-vortex warmed by an SSW then migrates to the tropopause, from mid-October to December, injecting via the base of a slowed vortex its residual heat, but can also be the consequences of the shock effect of the solar wind, in the polar zone responsible for the generation and ripple of the polar tropospheric jetstream. The temporal length of warming is likely the offset effect of the associated slow solar wind, which is penetrated directly into the counter-vortex 3 days later but was also temporarily stored for >1 month in the Van Halen radioactive belts.

GENERAL CONCLUSIONS

Episodes of sudden stratospheric warming (SSW) are responsible for transient vortex warming slowed down during periods of high sunstroke, when a jet of rapid solar wind rushes into the polar cones, following an SCME, and a counter-anticyclonic vortex joined the Arctic or Antarctic vortex. A contribution of ozone destruction seems clear. There is no valid evidence of the impact of gravity waves in this process. These warmings that last 2 to 4 months can be responsible for heatwaves or major episodes with true climate impact. According to 10Be records, these SCME ejections are responsible for major tropospheric warming causing deglaciation episodes at 14,300 ka BP and 12,400 ka BP (Van Geel and Ziegler, 2013; Bard et al. 2023), which suggests that these RSS phenomena are associated with particularly high solar activity, at least at the beginning of interglacial.

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