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Space and Stratosphere for Extreme Surface Climate

Earth Observation

Recent stratosphere alterations have caused a series of catastrophic environmental and socio-economic events over several northern hemisphere areas. Under these circumstances, the present project idea suggests the development of a combined stratospheric & space service to enhance current satellite measurements and climate models predictability with an unprecedented set of in situ and real-time data. High-Altitude Pseudo-Satellite (HAPS) capabilities are proposed as added value solutions to Earth Observation (EO) space satellite needs. Results from this approach shall support effective policy-making for quicker reactions against such events.

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1. Background

Stratospheric events. Recently observed stratospheric alterations [1,2] have substantially contributed to a wide range of extreme surface climate events. Variations in the pressure, temperature, winds, and composition of vertically propagating planetary-scale waves [3] precede rapid and intense changes in the stratospheric polar vortex [4] sometimes difficult or impossible to predict. Such changes manifest as Sudden Stratospheric Warmings (SSW) [5] when winds rapidly slow and the polar stratosphere warms or conversely as Strong Vortex Events (SVEs) [6] when the polar vortex intensifies and cools. Figure 1 depicts a polar vortex disruption in January 2021 due to a SSW. Since cold air is denser than warm air, geopotential height measurements tend to be lower in colder air masses. Thus, helping to classify the intensity of the event.

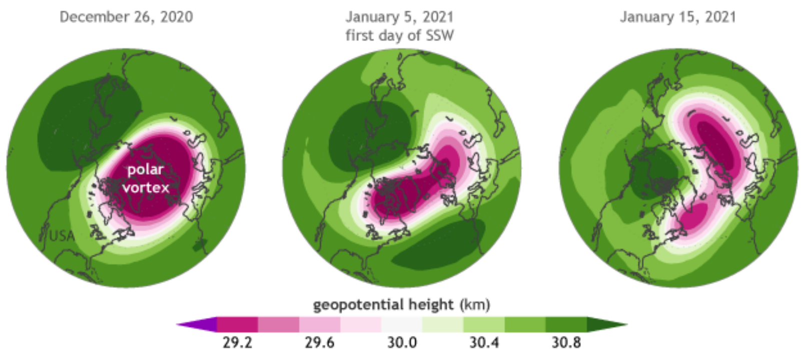

Figure 1. Disruption of the stratospheric polar vortex in early January 2021.Credit: NOAA

It is worth mentioning that SSWs are related to a negative phase of the winter North Atlantic Oscillation (NAO) behaviour while SVEs tend to occur in a positive phase. However, stratospheric alterations also have an influence on the summer NAO [7, 8], another source of major events that can lead to extreme floods, dry periods, or heat stress over northwest Europe. It is, therefore, of key importance to explain and predict variations in the summer climate that could be partially originated at a stratospheric altitude.

In general terms, the stratosphere and its dynamic coupling with the upper troposphere or tropopause [9], which is the atmospheric border that demarcates the troposphere from the stratosphere, are areas of growing interest for the scientific community given the physical processes occurring at that altitude (~20 Km) and its impact on the surface climate. Main reasons behind such interest and in line with the present project idea are:

- Implications on extreme surface climate events due to SSWs and SVEs.
- Effects in the summer NAO behaviour and its link to surface climate.
- Improvements on the sub-seasonal to seasonal weather prediction [10, 11].

As further explained in this section, stratospheric alterations have caused a series of catastrophic environmental and socio-economic impacts over several areas of the northern hemisphere including many European regions among them. Furthermore, climate change may result in a more complex and extreme behaviour of the stratospheric events making their predictability even more challenging given the new physical and chemical alterations introduced in our climate system.

Extreme surface climate events. Some of the most remarkable events due to stratospheric alterations recorded over the last two years have been gathered below:

1. ***Northern Europe's massive floods***. In July 2021 heavy rainfall episodes took place in northern and part of western Europe leaving behind devastating floods damage due to the summer NAO [12, 13].
   Thus-far, past NAO circulation patterns have fluctuated as part of changes in the northern hemisphere climate [14, 15] and due to variations in the stratosphere-troposphere dynamic coupling [8]. This is particularly relevant in context of climate change [16] since future variations can be expected to have a stronger impact on the social and environmental wellbeing as seeing in the past [17]. Therefore, the stratosphere-troposphere dynamic coupling and climate change variability, which are directly related to the NAO behaviour, play a major role to accurately predict and understand such events.
   The floods in July 2021 left numerous confirmed fatalities like widespread power outages, forced evacuations or damage to infrastructure and agriculture areas. **More than 200 people were killed** and severe disruptions were specially caused in Belgium and Germany, with a **total cost of 2.55 billion euros in insured losses** [18] and a **minimum of 10 billion euros in damage cost only in Belgium** [19].

2. ***Storm Filomena in Spain***. Storm Filomena left unusual snowfalls and precipitations due to a SSW in January 2021 throughout many areas of Spain. A series of stratospheric events that were traced to late December 2020 caused a polar vortex disruption in January 2021 [20, 21, 22]. Temperatures in the stratosphere rose by 55ºC over the North Pole in a matter of days.
   For instance, only in the municipality Madrid the forest mass damaged showed a loss of approximately its 14% [23], half a million of Madrid's trees. **Total costs of the disaster, including business interruption and property damage, were initially estimated at nearly 1.8 billion euros** [24] **During the event 5 people lost their lives in Spain**.

3. ***Record-breaking rainfalls in the UK.*** While SSWs are related to a negative phase of the NAO, SVEs tend to occur in a positive phase. This was the case for the UK and part of northern Europe in February 2020. A SVE associated with the successive storms Ciara, Dennis, and Jorge left record-breakings in the UK with 209mm of rain which is 237% above the average for February precipitations [25]. Among the three mentioned storms **more than 1.9 billion euros were estimated in insured losses** [26] **and a total of 24 lives were lost**. The socio-economic impact of such event took away homes, cars, bridges, roads and floodplains. Fatal damages measured in billions of euros and people's lives.

These extreme climate events share similar characteristics in terms of stratospheric alterations, northern hemisphere climate variability, and lack of predictability to avoid devastating environmental and socio-economic damage. Under these circumstances, the present project idea aims at developing a combined stratospheric & space service to enhance current satellite measurements and climate models predictability with an unprecedented set of in situ and real-time data. High-

Altitude Pseudo-Satellite (HAPS) capabilities are proposed as added value solutions to Earth Observation (EO) space satellite needs. Results from this approach are expected to support effective policy-making for quicker reactions against the aforementioned events.

In order to address the objectives of this project idea the present paper is organized as follows: i) Section 2 details how HAPS can provide added value to enhance and combine current EO satellite activities with a stratospheric environment. It describes a game-changing proposal regarding past and ongoing atmospheric measurements given the lack of predictability and understanding with respect to extreme surface climate events originating in the stratosphere; ii) Section 3 highlights the project idea implementation with its potential envisioned services, preliminary architecture, and risk analysis based on ECSS-M-ST-80C. The main idea within this section relies on describing how space and stratosphere interact to provide a novel and unified service; iii) Section 4 presents the expected results and traceability of this project's idea objectives to its sustainable development goals as described by "The 2030 Agenda for Sustainable Development" adopted at the United Nations Summit in New York September 2015; iv) Finally, section 5 presents the conclusions of the paper.

2. HAPS to Enhance Predictions from Space. (A Game-Changing Proposal)

Many northern hemisphere climate events depend, in large part, on stratospheric alterations as introduced and described in section 1. While there is no doubt about the stratosphere's role in our climate system [27], many are the uncertainties in climate predictability [28, 29, 30] because of gaps in our understanding of physical processes occurring at that altitude. This highlights the need to enlarge a scientific knowledge in different atmospheric areas with an impact on Earth's surface climate [31] (e.g., stratosphere's composition and chemistry, stratosphere-troposphere dynamic coupling, climate change relationship).

A game-changing proposal. To a great extent, the lack of understanding and gaps in climate predictability are due to the difficulty to obtaining high quality, long duration and in-situ observations of the stratosphere. In order to reach the stratosphere and cover this gap, several past initiatives and ongoing programs like high altitude balloons [32], un/manned Jets [33] or HAPS have been deployed, as depicted in figure 2. All of them with its limitations and benefits in terms of flight duration, payload, endurance, autonomy or movement constrains, among others.

Figure 2. a) Stratospheric balloon inflatable test from the Canadian Space Agency. b) Northrop Grumman Global Hawk unmanned jet for ATTRAX mission by NASA. c) HAPS from Sceye company taking off in its first flight test.

Nevertheless, compared to other means to reach the stratosphere, HAPS provide a better performance [34] at very low operational costs which makes them perfectly suitable to obtain in-situ and long duration observations of the stratosphere. In addition, they offer excellent capabilities to support satellite services, as depicted in table 1, which is particularly useful since space satellite measurements combined with HAPS could provide an unprecedented set of high quality, in situ and real-time data to enhance the accuracy of climate models and society's response to extreme surface climate events.

Capabilities	Satellites	HAPS
Launching & Landing Capabilities	Red	Green
Manufacturing Costs	Red	Green
Maintenance Costs	Red	Green
Payload Capacity	Green	Red
Movement Constraints	Red	Green
Target Area Coverage	Green	Yellow
Autonomy	Green	Green
Latency	Yellow	Green
Good (green)	Medium (yellow)	Bad (red)

Table 1. HAPS vs Satellite capabilities.

Therefore, taking these capabilities as a reference as well as HAPS performance to carry out a variety of stratospheric measurements and the possibility to combine them with space satellite EO activities, enables a game-changing approach to cover an existing gap in obtaining high-quality, long-duration, and in-situ data of the stratosphere.

3. **Project Idea.** (A Novel Approach to Unify Space & Stratosphere)

HAPS4ESA 2019 workshops [35] clearly highlight the good feasibility level of such systems for a variety of missions and payloads. With this baseline, the present project idea aims at unifying both scenarios (Space & Stratosphere) to provide a synchronized and in real-time service to release the full potential of stratospheric information.

Services & Preliminary Architecture. Current EO/atmospheric activities performed by Sentinel-5P [36] in partnership with NASA's Suomi-NPP spacecraft offer a wide range of possibilities to define a novel collaborative approach with a stratospheric environment. Figure 3 depicts a preliminary architecture for such a collaborative approach and the deployment of the main envisioned services described below:

1. ***Inter-scenarios links.*** The aim of this service is to provide a set of radiocommunication services in both directions between satellite and HAPS, ground stations and HAPS, End users and HAPS, and even between ground stations through HAPS or satellites. This technology is regarded as the main enabler to unifying both scenarios (space & stratosphere).
2. ***Synchronized overpasses***. Such service's main objective depends on the pre-synchronization operations to make coincide Sentinel-5P and/or Suomi-NPP orbital dynamics with the stratospheric position of a HAPS over an area of interest to carry out a set of defined and scheduled measurements. For instance, the inter scenarios links service is a key enabler to verifying and confirming a synchronized overpass service.
3. ***Data acquisition and production***. Via Sentinel collaborative stations and inter scenarios link services, data acquisition and production services are envisioned for HAPS and satellites to ground stations information

transmission. Such information is intended to be tailored for a particular coverage/region of interest or a particular measurement as detailed in section 4. Thus, it shall provide a service to keep up-to-date main stratospheric measurements through correction, projection, calibration, and merging of data received from HAPS and Sentinel-5P or Suomi-NPP spacecraft.

4. ***Calibration and validation activities.*** Through the acquisition and production of data from HAPS and Sentinel-5P or Suomi-NPP spacecraft, a set of calibration and validation activities are expected in order to compare the measurement values of the different sources to identify incorrect data, reconfigure instruments remotely and reschedule mission operations if needed. These activities are considered a necessary and added value service to enhance the quality of the data and measurements taken of the stratosphere.
5. ***End user alerts***. This is considered an additional service to reach End users with instant alert notifications in order to keep them up to date regarding the identified stratospheric alterations that could cause significant damage to their daily life. So far, it is expected to realize such service through HAPS communications or through Sentinel collaborative stations data dissemination.

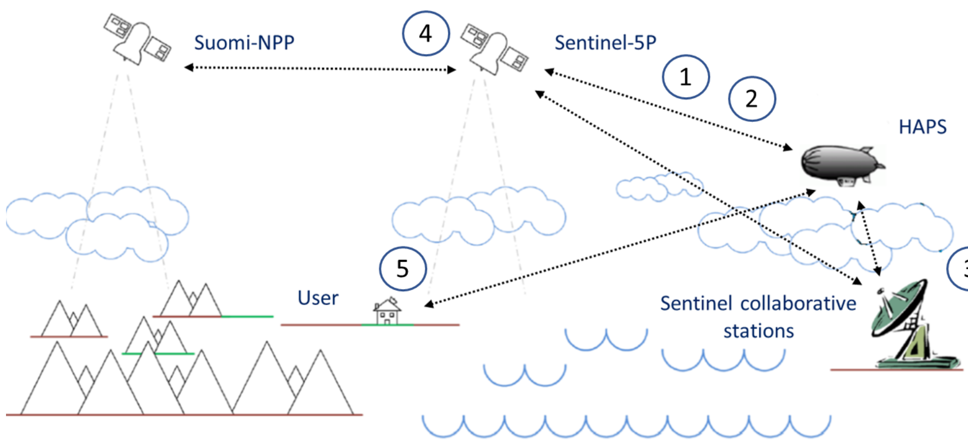

Figure 3. Preliminary architecture and main envisioned services deployment**.**

Risk analysis (*ECSS-M-ST-80C*). A set of high-level risks are identified in this section to avoid, to the extent possible, serious costs, schedule, technical performance, or science-value impacts within the project life cycle and for the effective deployment of the aforementioned services.

Such risks are rated as described in the European Cooperation for Space Standardization documents, in particular, the ECSS-M-ST-80C standard for risk management [37]. Furthermore, an action criterion is defined for those within the 3C-5C-3E-5E quadrant [38], which turns out to be the most likely and severe area for an identified risk, see table 2. It is also worth mentioning that the present high-level risk analysis has identified a high dependency on the first service deployment, “Inter-scenarios links”, with respect to the whole project objectives and the remaining services deployment. Therefore, it becomes a focal point for the successful services’ performance in order to unify space and stratosphere under the same framework/project.

Type of Risk	*Detailed Risk*	*Risk Rate based on ECSS-M-ST-80C Risk Index*	*Justification*	*Action Criterion*
Failure in all inter-scenario links.	-	5A - Low	Although highly severe but low probable, it would mean a complete collapse in all the services deployment given their high dependency.	-
Failure in one inter-scenarios link.	1) *HAPS-to-Satellite link failure and vice versa.*	2C - Low (Temporary) 5C - High (Permanent)	A permanent failure would impact on service number 2 & 4, and it would require from maintenance during mission activities. Temporary failures severity could vary depending on the time span.	i) Redundant technology; ii) State of the art studies to ensure reliable technology, iii) Alternative ways to the keep the mission active (e.g., synchronization through ground station).
-	2) *HAPS-to-Ground station link failure and vice versa.*	3C - Low (Temporary) 5C - High (Permanent)	A permanent failure would impact on service number 3 & 4, and it would require from maintenance during mission activities. Temporary failures severity could vary depending on the time span.	i) Redundant technology, ii) State of the art studies to ensure reliable technology.
-	3) *HAPS-to-End user alerts link failure.*	3C - Low (Temporary) 5C - High (Permanent)	A permanent failure would impact on service number 5. Failures, either temporary or permanent, could entail severe harm to End Users whose reaction against stratospheric alterations depend on this service.	i) Redundant technology; ii) state of the art studies to ensure reliable technology; iii) Alternative ways to the keep the mission active (e.g., Communications from ground station to end users if not constrained by geographical or signal power issues, among others).
Failure in the stratospheric measurements acquired by the designated payload.	-	2E - Medium (Partial data corruption) 4E – Very High (Complete data corruption)	Such risk is highly dependant on the amount of data corrupted. More than 50% data corruption would have a devastating impact on the whole mission, and it would require from maintenance during mission activities. Services 3, 4 & 5 would be highly affected.	i) Exhaustive calibration and validation procedures to compare corrupted data with reliable sources; ii) Redundant technology; iii) State of the art studies to ensure reliable technology.

Table 2. High-level risk analysis.

4. Project Impact

Expected results. Of special interest are the stratospheric measurements that encompass a direct relation with climate change pollutants gasses directly entering from the tropopause layer (e.g., water vapor, ozone, aerosols, CO2) at an altitude where HAPS operate (~20 Km). Such pollutants have an influence on the stratosphere's chemistry as well as on its dynamic interaction with the upper troposphere. Consequently, an impact is observed on SSWs, SVEs, and NAO behaviour. As described below, this project idea aims at capturing in-situ and from space measurements of some of the main greenhouse gases with a direct impact on the stratosphere and earth's surface climate.

i) ***Stratospheric/Tropospheric water vapor*** anomalies using a HAPS, Sentinel-5P [39] and Suomi-NPP [40] to study its distribution prior and during a polar vortex [41] as well as an existing relationship with the summer NAO and floods over Europe [42]; ii) ***Ozone*** depletion, recovery, chemistry and dynamics to track its impact on SSWs, SVEs and vice versa [43] as well as its effect on the summer NAO [44]. Sentinel-5P and Suomi-NPP [40] are expected to provide a great insight thanks to TROPOMI experiment and MODIS sensors respectively; iii) ***Stratospheric*** CO_2 variations where HAPS and Suomi-NPP combined can be enlightening to better understand SSWs and SVEs [45]; and iv) ***Volcanic aerosols*** impact in the polar vortex strength [46, 47] using HAPS and Sentinel-5P [48].

Sustainable development goals. With these measurements it is expected to enlighten stratosphere's prediction on extreme surface climate and avoid its environmental impact. Furthermore, it shall support evidence for effective government policy-making to enable quicker reaction times and avoid, to the extent possible, heavy socio-economic impacts and enhance society's response. Such applications are traced to 5 different sustainable development goals defined by the United Nations, as depicted in table 3, and with different grades of traceability impact (Low, Medium, High).

Project applications	4 QUALITY EDUCATION	9 INNOVATION AND INFRASTRUCTURE	11 SUSTAINABLE CITIES AND COMMUNITIES	13 PROTECT THE PLANET	15 LIFE ON LAND
Better understanding of the stratospheric physical processes	•			⬤	⬤
Avoid environmental impact				⬤	⬤
Society's response		●	⬤	●	●
Climate models accuracy		●	●	⬤	⬤
Government policy-making			⬤	⬤	⬤

Table 3. Sustainable development goals traceability.

5. Conclusion

Stratospheric alterations have caused devastating environmental and socio-economic damage over several European regions leaving behind more than 200 deaths and more than 16 billion euros in insurance and accidental costs only in the last 2 years. Sudden Stratospheric Warmings, Strong Vortex Events and the North Atlantic Oscillation behaviour have resulted in extreme surface climate events with an unequalled detrimental impact. Lack of understanding with respect to the physical processes occurring at a stratospheric altitude, where these events originate, and the absence of in-situ stratospheric observations makes it difficult or even impossible to accurately predict their impact on the surface. Furthermore, climate change implies more challenging predictability due to the new physical and chemical alterations introduced in our climate system.

Consequently, the present project idea highlights the importance of combining space and stratospheric in-situ measurements under the same project framework to provide a unified and enhanced service with respect to climate models predictability. In particular, Sentinel-5P, NASA's Suomi-NPP spacecraft and stratospheric HAPS are suggested, in a preliminary architecture idea, to gather stratospheric and tropospheric data. Expected results shall help to sustainably support effective government policy-making for quicker reactions against the aforementioned events through an unprecedented set of in-situ and real-time data.

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