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SUBJECT: **Atmospheric Wind Profiles (3Dwinds):**
Assessment of Observing Systems Capabilities Alternatives and Value to NOAA

Executive Summary:

- 3D atmospheric wind profile measurement has a positive impact on NWP.
- There are two approaches currently - Active/direct (Wind LIDAR); Passive/indirect (From frequent tracers of water vapor or). Both have pros and cons.
- Recommend NOAA include 3Dwinds as part of the capabilities to pursue in SounderSat.
- Recommend NOAA pursue partnerships (with NASA) and pathfinder efforts to mature Active wind measurement technology before considering an operational 3D winds operational mission.

Scope:

The scope of this memo is to provide NESDIS with SAT's coordinated performance- and science-based recommendations regarding how to best address the challenge of atmospheric winds profile measurement gap in our future space constellation. These recommendations are formulated by a set of core-SAT members (all Feds) based on SME expertises, on fact-findings and previous projects results, from within and outside of NOAA, and with participation from NESDIS data users, in this particular case: NWS.

Background:

There is currently a gap in measuring atmospheric vertical wind profiles (which we will subsequently call 3Dwinds) from space. This gap is recognized in the NWP community and more broadly in WMO (WIGOS2040 vision). 3Dwinds was also mentioned in a previous NOAA commissioned study (NSOSA) as the suggested focus area with the most significant potential to provide value to NOAA's next-gen space architecture. Atmospheric winds are currently observed by tracking the movement of clouds and/or water vapor features from geostationary and/or polar-orbiting IR imagers (derived atmospheric motion vectors, AMVs). These AMVs are assimilated operationally in major NWP centers. However AMVs are known to have large vertical placement uncertainties and do not represent the vertical distribution of the wind. To address this gap, technologies have emerged recently to derive wind profiles globally (an extension of the AMV). These include observing wind profiles from space-based active Doppler wind lidar, such as the European Space Agency Aeolus; and from traditional infrared (and potentially microwave) sounders which can resolve water vapor profiles vertically from hyperspectral measurements, and subsequently, water vapor-tracked winds throughout the profile. The European community has led the effort in deploying the first Wind lidar (Aeolus) in space and NOAA has been testing these direct measurements of wind profiles with promising results. University of Wisconsin on the other hand has been funded by both NASA and NOAA to demonstrate the feasibility of deriving and testing 3Dwinds from infrared and microwave sounders. These were assessed in terms of quality (measured against independent sources such as ERA-5 and rawinsondes). The moisture-sounding based approach of measuring atmospheric wind profile obviously depends on the approach to derive moisture itself (from microwave sounders or from infrared sensors: either imagers or sounders).

Findings:

A number of facts and results were collected during the SAT general meeting:

- A reminder that we currently have Atmospheric Motion Vector (AMV) estimates of the winds, generally generated from IR imagers on geostationary orbit (GEO) and/or low-Earth-orbit (LEO). These are well established products and are widely used in NWP. These indirect measurements of the atmospheric winds are however limited by the fact that they are a single-layer type of measurement (not a profile) and suffer from uncertainty on the height assignment.

- In 2018 after a decade of delays, the Europeans launched Aeolus, a Doppler wind lidar that measures wind profiles on a global scale. It uses a single line of sight which results in a horizontal line-of-sight component of the wind. Accuracy obtained (around 4 m/s) is lower than the one expected (of 1 m/s) due to lower than expected transmitter power. Biases were found in the Aeolus data that need varying levels of corrections. The cost of Aeolus was approximately $481M.

- Different technologies (for example, wind lidars) lead to different quality of wind measurements and with different characteristics. NOAA would be more interested in troposphere wind measurement, as opposed to measurements that are limited to boundary layer, although this would still be of value for weather forecasting.

- The Europeans have a tentative plan to have a follow-on Doppler wind lidar satellite based on the current Aeolus mission with the launch planned for the late 2020s or early 2030s. EUMETSAT expressed interest (to the U.S. Aeolus contribution PI: Mike Hardesty) in undertaking this mission jointly with NOAA

- Early OSSEs were performed to evaluate the impact of temperature, wind, and moisture data on NWP and the relative importance of upper and lower level wind data. These experiments showed wind data to be more effective than atmospheric mass data in correcting analysis errors and indicated significant potential for space-based wind profile data to improve weather prediction. Experiments also showed that wind profile data from 500hPa and higher provided the most impact on NWP. The Optical Autocovariance Wind Lidar OAWL concept has shown to have a greater impact than a coherent system concept. Note that OSSEs were done with 3DVAR, not 4DVAR, but results would not likely be different. Wind profiles would still show meaningful impact. The coverage was found to be crucial. Tests were done for different swaths. When this is reduced to a single line of sight, the impact is reduced dramatically. Tests were done for different noise levels, but these were found to have little impact

- More recently, OSEs have been performed to integrate lidar winds into NOAA FV3GFS to assess the impacts on global and hurricane models. These show positive impacts to using wind lidar data in both the northern and southern hemispheres, but observations must be at the right time and location, which is difficult with a single line-of-sight system (and a single sensor).

- NOAA results are in line with independent assessments from ECMWF, DWD, and other European NWP centers (documented in the ESA recent report on Aeolus), where they demonstrated that the use of Aeolus data has provided positive (and statistically significant) impact on the global forecast skills. This is not a significant improvement in a sense of providing a large positive impact. It is a relatively modest positive impact, but usually positive impacts from new sensors take multiple years to be realized in NWP models.

- 4DVAR technique is good at capturing wind information directly from radiance assimilation (through motion of traceable parameters: moisture, cloud, etc). This is primarily the reason why 3D vertical wind profiles are retrievable from infrared (and microwave) sounders with varying accuracies.

- Aeolus winds were compared to hyperspectal 3D winds from AIRS. There are several differences in spatial coverage, temporal sampling, and wind measurements, but there is high correlation between the two sources. Wind measurements from the two sources may be complementary and using a combination of lidar winds and AMV winds can provide advantages where one is used to calibrate the other.

- Uncertainty of the moisture-tracking 3Dwinds was found to have significantly lower error than that of 3Dwinds from Aeolus (by more than 2 m/s in RMSE when compared to rawindsondes). Estimates of 5m/s RMS were found for IR-soundings-based 3Dwinds performance compared to 7.5m/s for Aeolus. That being said, 3Dwinds from Aeolus benefit from high vertical resolution while sounders-based 3Dwinds depend on the quality and vertical resolutions of the sounders. This vertical resolution comparison has not been undertaken.

- There is potential in combining wind-lidar observations with AMV-type measurement. This could lead (no factual evidence but SME-based opinions) to the direct measurement of wind (from lidar), even if very narrow in space, could play the role of anchoring the AMV and sounding-based 3Dwinds. Similar to how RO data anchors the sounders in terms of temperature observation (in NWP).

- The table below summarizes the pros and cons of different wind profile measurements:

Wind Measurement Source/Approach	**Pros**	**Cons**
Lidar (current high-TRL technology: e.g. Aeolus)	Direct measurement of wind. High vertical resolution, no assignment error, no reliance on a tracking algorithm.	Requires long averaging length, only available on a narrow track, line of sight (single wind component), not available under clouds. Currently large errors due

		to sensor issues.
IR based Vapor-tracking 3Dwinds (from either LEO or GEO)	Better spatial coverage than Aeolus wind lidar. Higher vertical resolution than microwave. Demonstrated good performance when compared to rawinsondes. If deployed on GEO or LEO swarm: high temporal resolution.	Indirect measurement. Lower vertical resolution than lidar. Not available under clouds.
Microwave based Vapor-tracking 3Dwinds	Better spatial coverage than Aeolus wind lidar. Available in and under clouds. If deployed on GEO or LEO swarm: high temporal resolution.	Indirect measurement. Lower vertical resolution than lidar and IR.

Conclusions and Recommendations:

The strategy toward 3Dwind profiles was discussed at the core-SAT meeting. Given the findings above, known to the core-SAT members and collected at the general SAT meeting, it is expected that direct measurements of wind profiles will eventually be of significant value to NOAA systems. This is documented by previous OSSE studies and by the preliminary recent results obtained in NOAA and other NWP centers using the wind lidar (Aeolus) flown by the European colleagues. However, based on (1) the demonstrated possibility to generate 3D winds profiles from a constellation on sounders with enough accuracy (in fact higher accuracy -RMSE wrt rawinsondes- than that of the Aeolus-based winds), (2) the potential for the upcoming constellations of sounders (SounderSat) to generate an even denser coverage leading to higher quality 3Dwinds product and (3) the multitude of issues identified in the quality assessment process of the Aeolus 3Dwinds (varying biases, high RMS errors when compared to independent measurements), and (4) the apparent high cost of a wind lidar space mission, with the resulting ramifications on the rest of the sensors constellation that NOAA will be able to afford, the core-SAT recommends the following, with regard to the NOAA strategy regarding the 3D wind atmospheric profiles:

- NOAA should pursue further the generation of 3D wind profiles from all existing sounders and further fine tune its quality and/or assessing its impact on global and regional systems (work ongoing within NASA systems).
- NOAA should fold the 3D wind atmospheric profiles requirement into the next round of SounderSat studies that will be looking at a higher density of IR and MW sounders with perhaps higher vertical and spatial resolutions. Sounding of winds should be part of the sounding capabilities of SounderSat.
- NOAA should pursue further the maturation of the wind lidar technology, perhaps as part of the Joint venture program with NASA and appropriate technology vendors. Leaning on NASA's technology choices to possibly consider tropospheric wind, and not only wind limited to the boundary layer.
- NOAA should pursue industry studies, similar to SounderSat studies, to assess the state of the U.S. based technology(ies) in their ability to directly measure wind profiles from space. This will allow us to explore other potential solutions (different or similar) from the European model (Aeolus). And will signal to the industry that NOAA is potentially a serious future customer of such a system if the conditions are right (in terms of cost, technology maturity, performances, quality, etc).
- NOAA should postpone pursuing an operational mission or a demonstration mission of wind lidar at this time, until the above have been considered
- Re-assess the 3Dwinds strategy on a regular basis, perhaps through the annual wind workshop, with partners from NASA, the industry and the academic sector.

Other considerations:

The recommendations made here by the core-SAT should be considered as the best assessment that could be made with available information as of the writing of this memo. It is based on the compilation of independent SMEs opinions from several areas: technology maturation projects, NWP expertise, remote sensing expertise, sensors experts, technology experts, and based on previous experience in the assimilation of new sensors.

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