Investigation of liquid cloud formation mechanisms during the Arctic ozone-depletion events of the 2010/2011, 2015/2016 and 2019/2020 NH winter seasons

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Abstract

The unusually cold springtime Arctic stratospheres of 2011, 2016 and 2020 generated substantial Polar Stratospheric Clouds (PSCs) activity and a significant ozone hole. These events were accompanied by an unusual presence of precipitating liquid clouds in the high Arctic. Satellite lidar measurements helped to identify a possible mechanistic link between tropospheric cloud formation and the PSCs. The synoptic meteorological context provided by the ERA 5 reanalysis was instrumental in the identification of potential liquid-precipitation formation scenarios related to atmospheric rivers.

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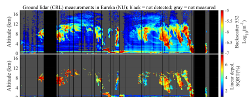
Context

Ground lidar profiles acquired at the Eureka Weather Station (NU, Canada, at 80°N, 86°W) during the intense ozone hole event of March 2020 (**Fig. 1**) revealed episodes of precipitating liquid or mixed phase clouds. These events were identified by their low linear depolarisation ratio (see the blue zones in the lower panel of **Fig. 1**).



Hypothesis

Atmospheric rivers

If a sustainable water vapor source is available near the ground, the interface between the Polar and Ferrel (Mid-latitude) atmospheric circulation cells typically results in the development of atmospheric rivers. The generic structure of atmospheric rivers is shown in the schematic diagrams of **Fig. 2**: in an Arctic (climatological or average) context, the Polar cell would be represented by the cool and dry airmass to the lower left of the Frontal zone of **Fig. 2b** while the Ferrel cell would be on the right of its associated Frontal zone, represented by the upper very dry and the lower warm and humid airmass. Vertical advection along the interface between the two cells may inject water vapor into the stratosphere: this leads to the formation of

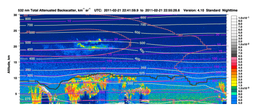
East Arctic 2010/2011 & 2015/2016

2011/02/21, 23:00 UTC

CALIOP night overpass

The three figures immediately below show CALIOP vertical profile products of total attenuated backscatter, linear depolarisation ratio (DR) and cloud phase classification. PSCs are observed to be limited to the -80°C stratospheric temperature contours (see, for example, Trischer *et al*, 2021).

The tropospheric structure in the CALIOP profiles is typical of atmospheric rivers: notably a tropopause fold at the interface (corresponding to the tropopause minimum between the Polar- and Ferrel-cell fronts of **Fig. 2**), a cloud free slant-path from the surface to the stratosphere and condensation along the cold front side (ice and water cloud according to the CALIOP classification scheme). In our experience, these atmospheric structures (including the behavior of analyzed temperature contours) usually frame PSC formation in midwinter. The DR profile appears, we would argue, to be more sensitive than the backscatter profile to optically weak PSCs: this suggests that the PSC extends to the cold/warm front interface between the Polar and Ferrel cells.

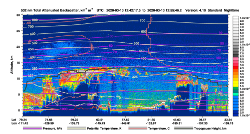


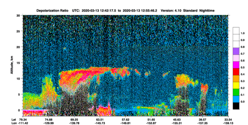
West Arctic 2019/2020

2020/03/13, 13:00 UTC

Calipso night overpass

This late-winter PSC event features the same upper air atmospheric-river structure in spite of it being much weaker in amplitude. The DR is, unlike the previous cases, weak (if noisy). This suggests the presence of small (submicrion) and/or liquid PSC particles (however, this inference in the presence of noisy DR profiles is not supported by the CALIOP classification in the last profile below).





2020/03 upper air profiles at Eureka

Radiosonde measurements

The first block of four vertical profiles immediately below shows radiosonde-derived dynamics above Eureka. The vertical wind speed profie notably shows typical polar vortex subsidence (negative values) above the tropopause.

The second block of profiles shows the temperature and humidity dynamics: water vapor pressure, temperature, RH/water and RH over an ice surface (RH/ice). The temperature and RH/water profiles show strong, near-surface episodes of warm and humid air between ~ 15 and 23 March.

Analysis & Conclusions

The intense PSC seasons of 2010/2011 and 2015/2016 were typically located on the Russian Arctic side (East Arctic). We argued that this is related to atmospheric rivers moving along the Gulf stream path. The 2019/2020 season on the other hand, was subject to heat and water vapour intrusion into the Canadian Arctic (western Arctic) from the Pacific Ocean through the Bering Strait.

The dynamical structure associated with Arctic atmospheric rivers, as evidenced by CALIPSO and ERA5 analyses, appears to influence the ozone hole, PSCs and tropospheric liquid cloud formation. Condensation along the slant-path cold front of the Polar cell, as well as the clockwise motion of moist and warm

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