Continental air flowing over the Gulf Stream supports strong turbulent fluxes, encouraging cloud break-up through entrainment.

Cold-air outbreaks serve as dramatic visual examples of transitions from more closed- to more open-celled morphologies.

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Much still unknown about cold-air-outbreak mixed-phase microphysics - and their relevance relative to the strong surface forcing

*Off of the wintertime eastern US seaboard:*

Wintertime cold-air outbreak clouds are typically mixed-phase, according to space-based lidar+radar (Field and Heymsfield 2015; Mulmenstadt et al., 2015)

cloud droplet numbers concentrations ($N_d$) indicate continental aerosol (e.g., Gryspeerdt et al., 2021)

Similar to subtropical stratocumulus:

• high $N_d$ may extend cloud coverage
• high liquid water paths may encourage precipitation, $\rightarrow N_d$ depletion

Specific to mixed-phase:

• glaciation hastens cloud transitions (Tornow et al., 2021)
• alters cloud spatial organization (Eirund et al, 2019)
The goal:

- select cold-air-outbreak cases from the ACTIVATE* campaign spanning a range of liquid water paths, cloud droplet number concentrations

- examine the in-situ ice microphysics for dependencies

selected 5 cases in which boundary layer flow aligned with flight tracks: a framework

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Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment

See also posters by Florian Tornow et al and Michael Brunke et al.
~ coincident upper-flier King Air:
  lidar (cloud top height), dropsondes, polarimeter (cloud optical depth+effective radius)

Cloud probe (FCDP+2DS) (liquid: 2-20 µm radius, drizzle (20-54 µm radius : rain: 54-732 µm radius ), \( N_d \), LWC, rain rate.
Ice shape, IWC (2DS)

Strengths:
  - many many flights repeating the same strategy
  - good microphysical measurements
  - dedicated analysis effort

Caveats: no radar, no ice-nucleating-particle measurements, poor liquid water path information
5 March 2021

8 March 2021

Flight track

Blue- SST; orange - MODIS LWP
What we have learned #1:

**Wintertime cold-air outbreak clouds over the western Atlantic are not ice-deprived**

4 out of the 5 cases already contained ice as soon as clouds developed

This despite cloud top temperatures > -10°C, and small dropsizes

Original premise that clouds start all-liquid then transition to mixed-phase thrown out the window
\[
\overline{N_d} = 501 \text{ cm}^{-3}
\]
\[
T = -8, -9 ^\circ C
\]

Rimed ice
In-situ radius~ 5 micron
\[
\overline{N_d} = 160 \text{cm}^{-3} \quad T_{ct} \sim -10^\circ C
\]

At the first in-situ sampling, rimed ice is already present.
Ice detected on very first pass through thin cloud; cloud quickly deepened to LWP of 200 g m\(^{-2}\)

\[ \overline{N_d} = 200 \text{cm}^{-3} \quad T_{ct} \sim -8 \, ^\circ\text{C} \]
5 March 2021 (afternoon)

Ice detected on first ACB pass through thinnish cloud

\[ N_d = 250 \text{ cm}^{-3} \quad T_{ct} \sim -10^\circ \text{C} \]
8 March 2021 (afternoon)

- MODIS visible radiance
- 2D-Stereo images along RF51 outbound Flight leg
- RF51 outbound Flight leg
  -5°C -4.4°C -3°C -3.3°C -0.3°C 0.5°C

- MODIS visible radiance
- 2D-Stereo images along RF51 inbound Flight leg shown in RF51 inbound Flight leg

\[ N_d = 200 - 300 \text{ cm}^{-3} (ACBonly) \]

\[ T_{ct} \sim -5°C \]

- the one flight with no evidence of ice

(still has a nice morphological transition into largish cloud rolls)
Conditionally-sampled leg-mean IWC (IWC>0 only) shows ice production starting at $T_{ct}$ of -5°C.
What we have learned #2:

Ice habit either dominated by vapor diffusional growth (2 flights) or riming (2 flights)

vapor diffusional growth produces higher IWCs
3 February 2021 (morning)

Temperature range correct for growth into columns
...and snowflakes in the most ice-super-saturated temperature range approaching -15°C
Ice water contents are higher when vapor diffusional growth dominates

Cloud top temp

\[ \text{IWC} \]

\[ \text{Nd} \]

\[ \text{D}_{\text{eff}} \]
Ice water contents are higher when vapor diffusional growth dominates.
Anecdotal observations:

Transitions, cloud morphology shows little correspondence to ice habit or IWC

Remotely-sensed LWPs (RSP, MODIS) are too high (not shown) compared to profile values, surface rainfall rates not super-high

The cloud deepening can be pronounced (e.g. Naud et al 2020)

Could mesoscale circulations be playing a stronger role in the transitions than the microphysics?

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