Combining convection-permitting reanalysis with satellite overshooting top detections for investigating hailstorm environments

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Why hail research?

- Severe hailstorms are recurrent events in Europe especially in northern Italy
- Single hailstorm events can produce damages worth >$1B
- Anthropogenic warming is expected to increase hail severity and frequency (Raupach et al. 2021)

Hailstorm near Asti, Italy 27/07/2016

Hailstorm near Fidenza, Italy 26/07/2021

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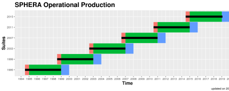
Limitations in hail representation:

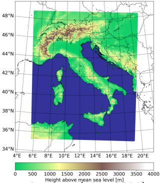
- Lack of homogeneous, continuous and complete observing system
- Inaccuracies of NWP simulations (physical parameterizations)


Hailstorm near Fidenza, Italy 26/07/2021

SPHERA: High rEsolution regional ReAnalysis over Italy

- SPHERA is a new regional reanalysis produced at the **convection-permitting** resolution of 2.2 km, covering Italy and the surrounding seas





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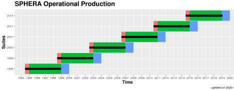
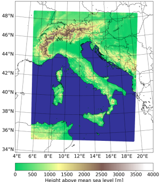


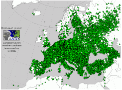


- Downscaled from ERA5, driven by the model COSMO, and assimilating regional observations with a continuous nudging scheme, SPHERA covers 25 years (1995-2020) at hourly frequency
- **Aim of the study**: describe hailstorm frequency of occurrence and ambient signature by combining high-resolution reanalysis proxies with the available hail observations

Hailstorm observations & numerical predictors

Hail observations:
direct and indirect

Hailstorm observations & numerical predictors



Hail observations:
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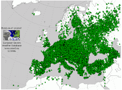
European Severe Weather Database (**ESWD**) based on news, reports, spotters

Hailstorm observations & numerical predictors



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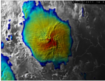
Overshooting Tops (OT):

- Convective cloud intrusions atop updrafts in lower stratosphere
- Indicative of strong updrafts

- Probabilistic detection of cold pixels in IR satellite imagery (NASA) of Meteosat (MSG) SEVIRI cloud top temperature scans (Khlopenkov et al.,2021)



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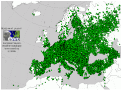

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Coupled with numerical proxies related to ***hail-favouring environments***

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SPHERA dynamic/ thermodynamic conv. indices

- K index
- Surface lifted index (SLI)
- MUCAPE
- Deep layer shear (DLS)
- Freezing level height H0

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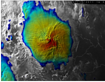

Definition of the OT-filter

- **Approach**: filter out OTs for which hail formation is unlikely, based on the surrounding ambient conditions described by reanalysis proxies
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- **Spatial domain**: SPHERA domain (6-19°E, 35-49°N)

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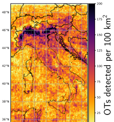

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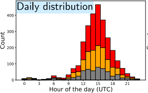
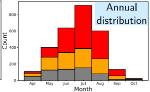
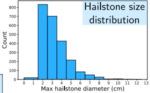
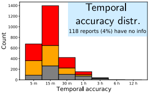
ESWD hail reports dataset



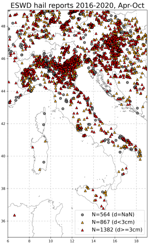


- Total of **2813 reports** ≥QC0+ (i.e. quality controlled), with 80% having info on hail size



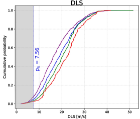


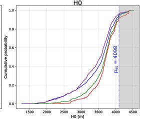
- >98% have temporal accuracy ≤1h
- 18% are QC0+, 81% QC1 and <1% QC2

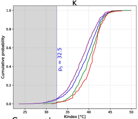


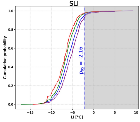
Definition of the OT-filter:

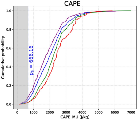
CDF of SPHERA parameters in presence of ESWD hail reports











Separation among:

- all hail
- small hail (d<3cm)
- large hail (d≥3cm)
- very-large hail (d≥5cm)

VARIABLE	Threshold (5/95%)
DLS	$> p_5 = 7.56$ m/s
H0	$< p_{95} = 4098$ m
K	$> p_5 = 32.5$ °C
SLI	$< p_{95} = -2.16$ °C
CAPE	$> p_5 = 666.16$ J/kg

Results: impacts of the OT-filtering

DOMAIN	YEARS	OT UNFILTERED set	OT FILTERED set
Whole	2016-2020	991.042	723.142 (73.0%)
Land only	2016-2020	597.747 (60% of total)	433.862 (72.6%)

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Single SPHERA parameters impacts:

OTset (2016-2020)	Number of OTs	Fraction of removed OTs
Unfiltered (original)	991.042	/
Full Filter (5 params)	723.142	27.0%
SLI Filter	879.640	11.2%
CAPE Filter	892.991	9.9%
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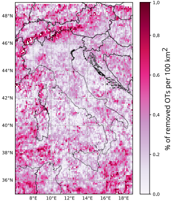

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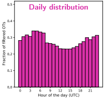

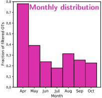

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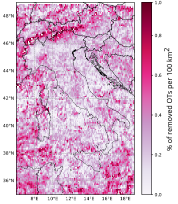
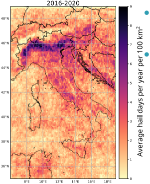


Results: hail proxy characterization



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- **Spatial distribution**:
  - Maximum hail likelihood in southern pre-Alps
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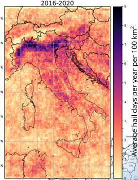

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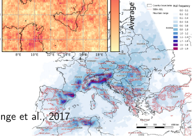
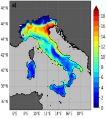
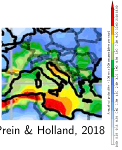


Punge et al., 2017



Torralba et al., 2023



Prein & Holland, 2018

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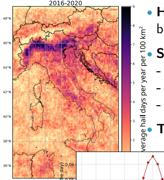
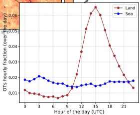
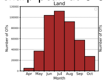
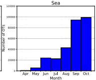
- **Temporal distribution + land/sea separation**:
  - Over Land hail more likely in Jun-Jul at 15 UTC, over Sea shift to Sep-Oct with a less sharp peak at 3 UTC









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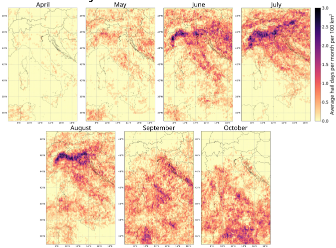
Intra-annual variability:



Results: statistical matching with ESWD reports

- Quantify agreement of the hail proxy with actually occurred hailstorms
- Compare Land OTs against ≥QC1 ESWD reports (sample: 2293, 82%)
- Spatio-temporal window for matching: **25km**, ± **1.5h** around each OT

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HIT ESWD reports	1.488 **64.9%**
OTs sample	433.862
OTs HITTING ESWD rep	14.196 3.27%

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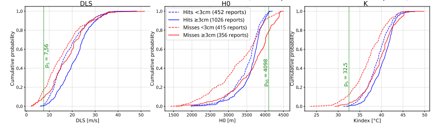
OTs match with hail reports increased by more than **25%**

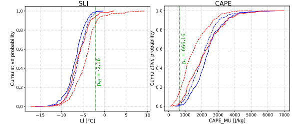
- Comparison with Punge et al. 2017 (EU domain, *non-probabilistic OT detection method*, 2004-2014, ERA-Interim reanalysis)

ESWD reports sample	2.475
HITTED ESWD reports	983 **39.7%**
OTs sample	542.137
OTs HITTING ESWD rep	4.554 0.84%

Results: separating environmental conditions

- CDF of SPHERA parameters separating Hits/Misses and small/large hail





- 2.249 reports with info on hail size
- 69% of hits associated with large hail (≥3cm)
- Most evident separation for the predictors: small-hail missed reports

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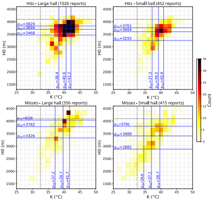

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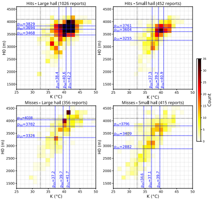
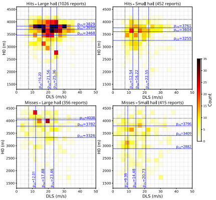
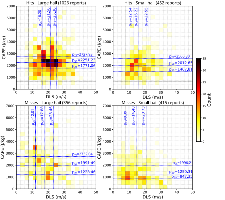


- **Freezing level height (H0) vs. storm organization (DLS):**



Results: separating environmental conditions

- Parameters phase spaces separating Hits/Misses and small/large hail
- **Instability (CAPE) vs. storm organization (DLS):**



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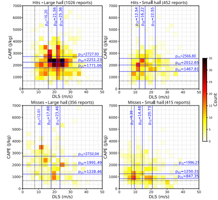

- Numerical predictors indicate ambient signatures in which:

  - *Large hail* is generally related with high instability, wind shear and elevated freezing level heights

  - *Small hail* can form in less unstable and organized environments with colder atmospheric profiles (blocking hail growth)

  - *Hits* show more compact distribut. while *misses* more spread

Results: separating environmental conditions

Min IR Brightness Temperature (IRBT): main parameter in satellite OT detection. *The colder the higher the OT*. ΔT between IRBT and tropopause temperaure (anvil) quantifies the strength of the updraft.
(ΔT<-6K ~ updraft penetration through the anvil of at least 1km)

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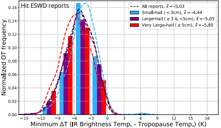

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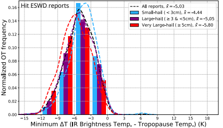

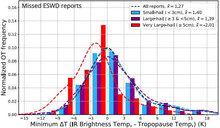

- **Hits:** no net separation among classes but all ΔT<0 K. Similar distributions centered ~-5 K. Mean ΔT difference between small and very-large hail >1 K
- **Misses:** less sharp distributions, 54% cases show ΔT>0 K. Very-large hail on average forms with ΔT>3 K colder than small hail

Conclusions & take home messages

- Filtering **satellite OT detections** with **convection-permitting reanalysis** predictors **enables the distinction** between hailing/non-hailing occurrences
- The obtained **hail proxy** for 2016-2020, Apr-Oct, over South-Central EU is statistically **in agreement with ESWD** hail observations and shows good spatio-temporal matching with diverse recent hail climatologies
- The **ambient characterization** of hail occurrences revealed different conditions depending on **hail severity**, and more appropriateness of the method in case of severe storms producing large hailstones

Limitations:

- Temporal extent (5 years)
- Uncertainties in detecting small-hail producing storms owing to difficulty of IR-based detection algorithm in case of less prominent OTs (warm cloud tops) and its spatio-temporal resolution (3km, 15 minutes)

Thank you for your attention!

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