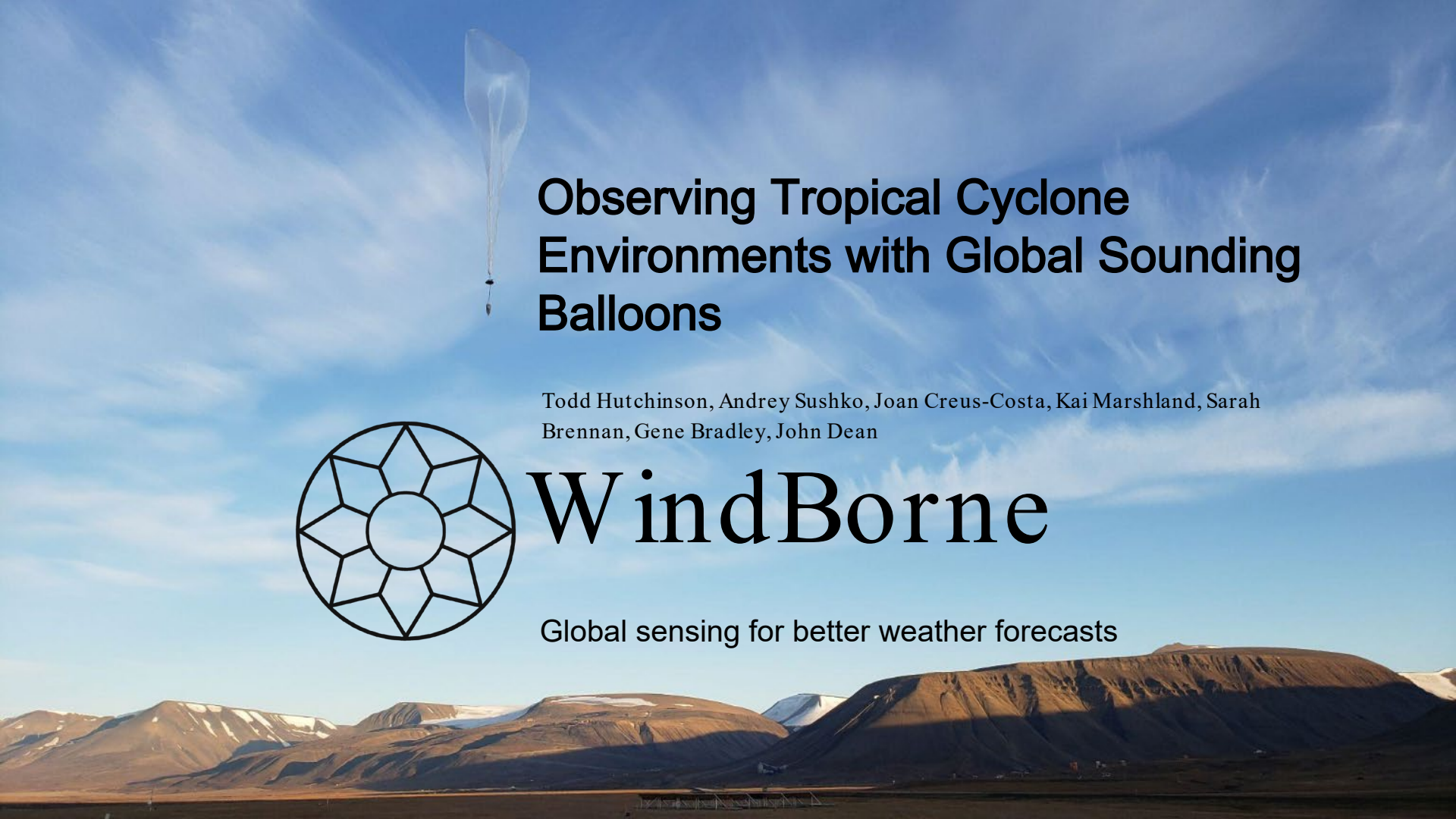
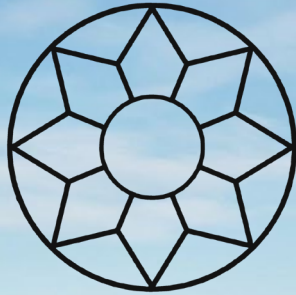




Observing Tropical Cyclone Environments with Global Sounding Balloons

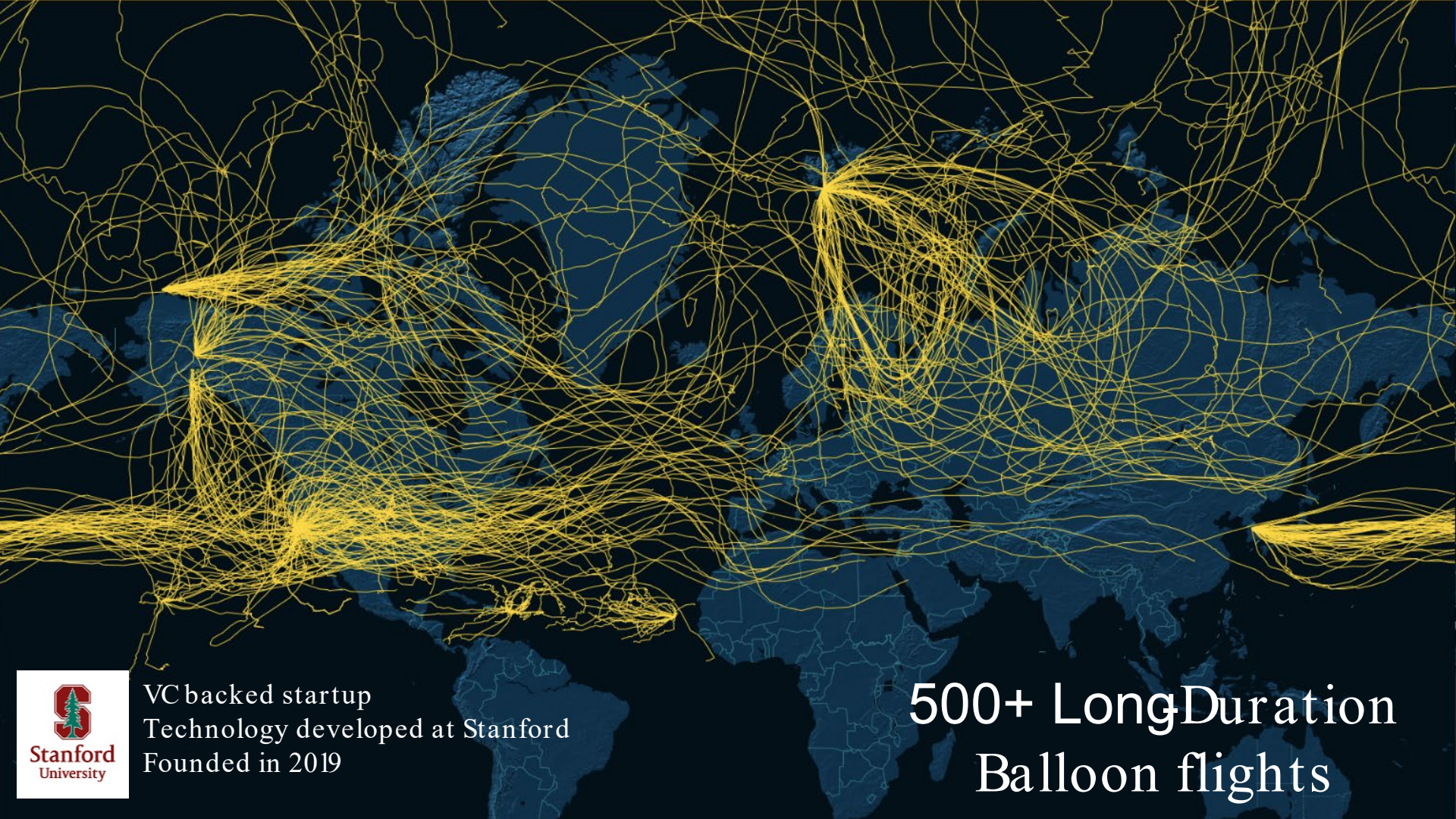
Todd Hutchinson, Andrey Sushko, Joan Creus-Costa, Kai Marshland, Sarah
Brennan, Gene Bradley, John Dean



WindBorne

Global sensing for better weather forecasts





VC backed startup
Technology developed at Stanford
Founded in 2019

500+ Long Duration
Balloon flights

Global Sounding Balloon (GSB)

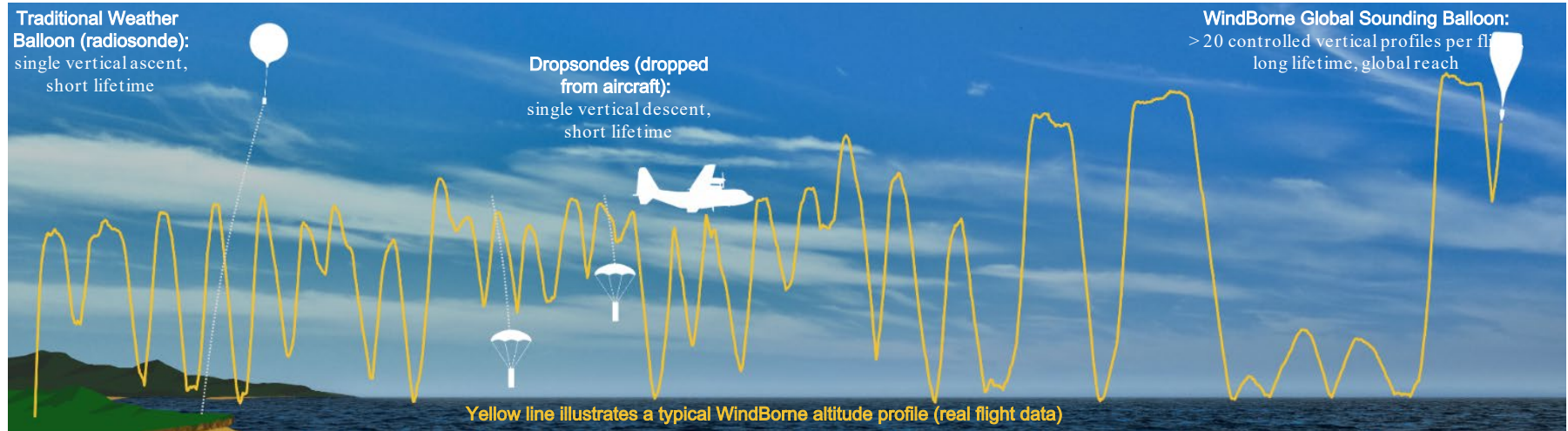
Sensing:
Temperature
Humidity
Wind
Pressure
Solar/thermal radiation

Controllable, long duration radiosonde

- In situ observations from **surface to stratosphere**
- **Long duration** (4-18 days)
- **Long range**(able to cross continents and oceans)
- Realtime, **full -range altitude control**
- Ability to task **balloons to areas of interest** using wind
- Observations available within **15 minutes**
- **Automated** flight control
- **Small & lightweight**
- **Technology Readiness Level 8**

Highly cost-effective platform can collect **10x** more data per dollar over land, **100x** more data per dollar over ocean compared to traditional in situ methods

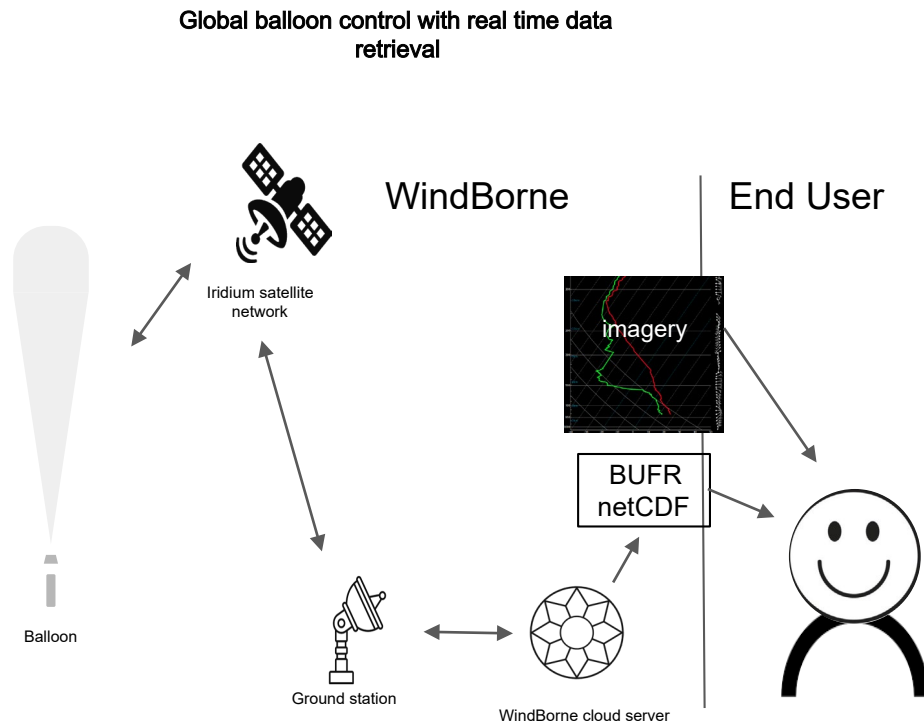
GSB: Dynamic Altitude Control



- Key distinction from other long duration balloon technology is ability to **vertically profile from ground level to lower stratosphere** (altitude ceiling progresses from 11 km to 19 km throughout a balloon's life)
- Ability to sample the planetary boundary layer, collect data below clouds, measure clear-air winds, and many other observables with which satellites struggle

Data-As-A-Service

WindBorne manages balloon constellations, launches, field operations, data retrieval and provides data to the end users via simple web sites and APIs



Streamlined Launch Operations

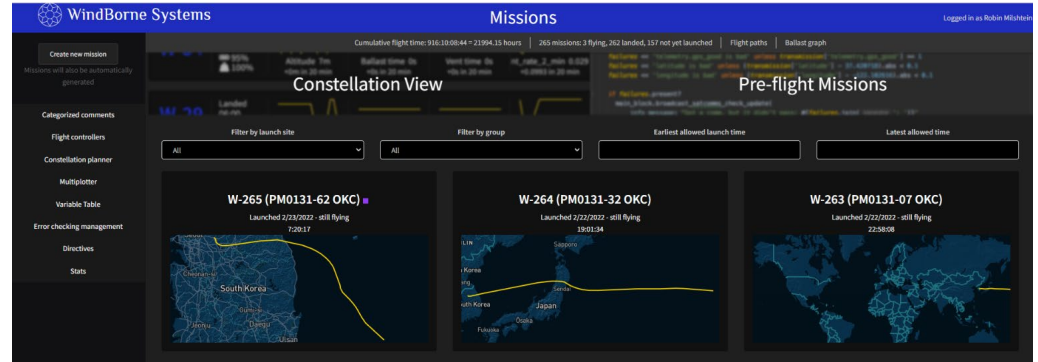
Launch with **1 operator** in **30 minutes** or less

- Collapsible, **portable** launch rig
- Unit storage: 0.5 cubic ft per packed unit
- Launch possible in up to **15 knot winds** (verification at higher winds ongoing)
- 30 mins for one trained operator to
 - Set up launch rig
 - Unpack and secure flight hardware
 - Pre-launch checkout (onsite or by **remote** operator via telemetry)
 - Fill balloon envelope with **helium** or **hydrogen**
 - Release
 - Fold launch rig for **transport** or reset for new launch
- Compliant with FAA & ICAO regulations



Real-time visibility via Mission Control Suite

Custom tools for navigation and flight planning that tell an operator
(1) when to launch balloons, and
(2) where they will fly



Mission Control Suite (internally referred to as WindMC): refer to screenshots on the following slides

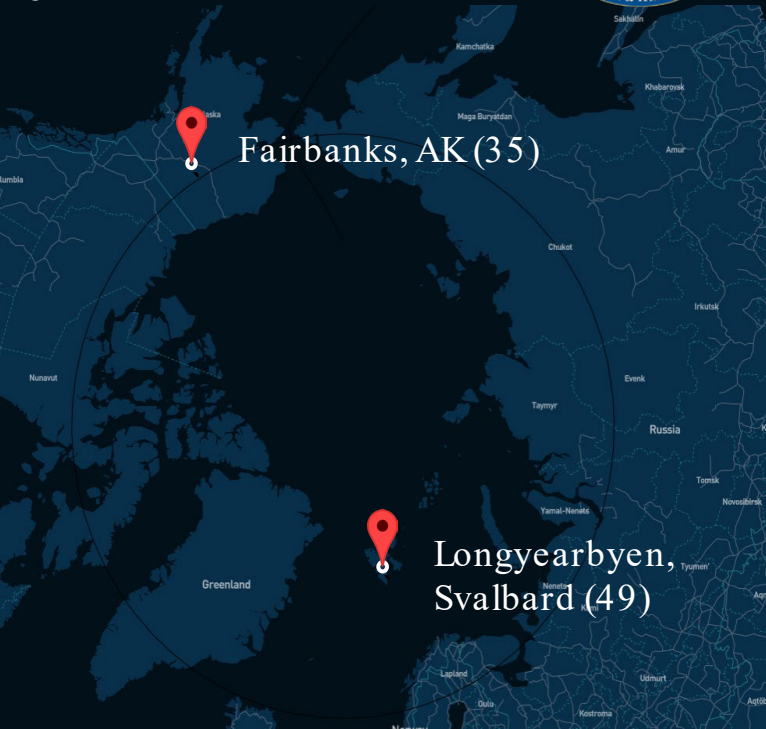
WindBorne's mission control suite:

- Allows a flight director to **communicate with each active balloon** (uplink commands, telemetry, health check)
 - One person can direct and control a constellation of over 30 balloons at one time
 - Automated notifications and error identification
- Allows a meteorologist to **view onboard sensors** in near real time
- Overlays balloon flight paths on top of a **live weather map**
- **Projects flight paths** based on current weather conditions
- Enables **active navigation to a target destination** (“targeting”)
- And more!

2022 Summer Medium-Scale Trials

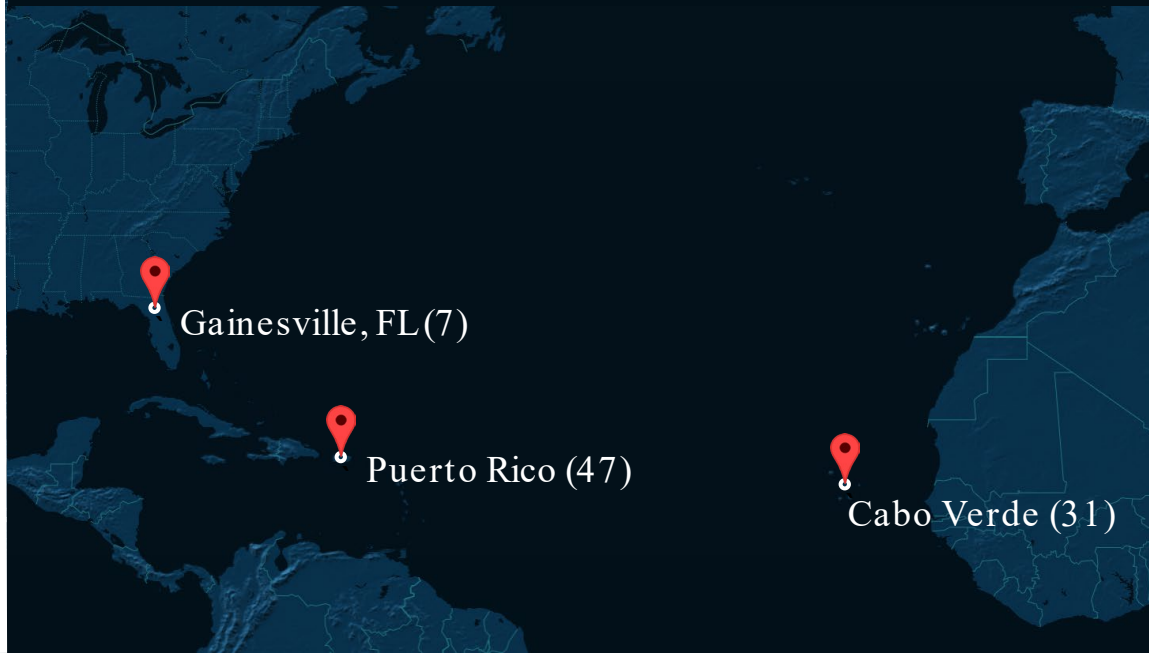
MST-4

August 4 - September 15
84 balloons



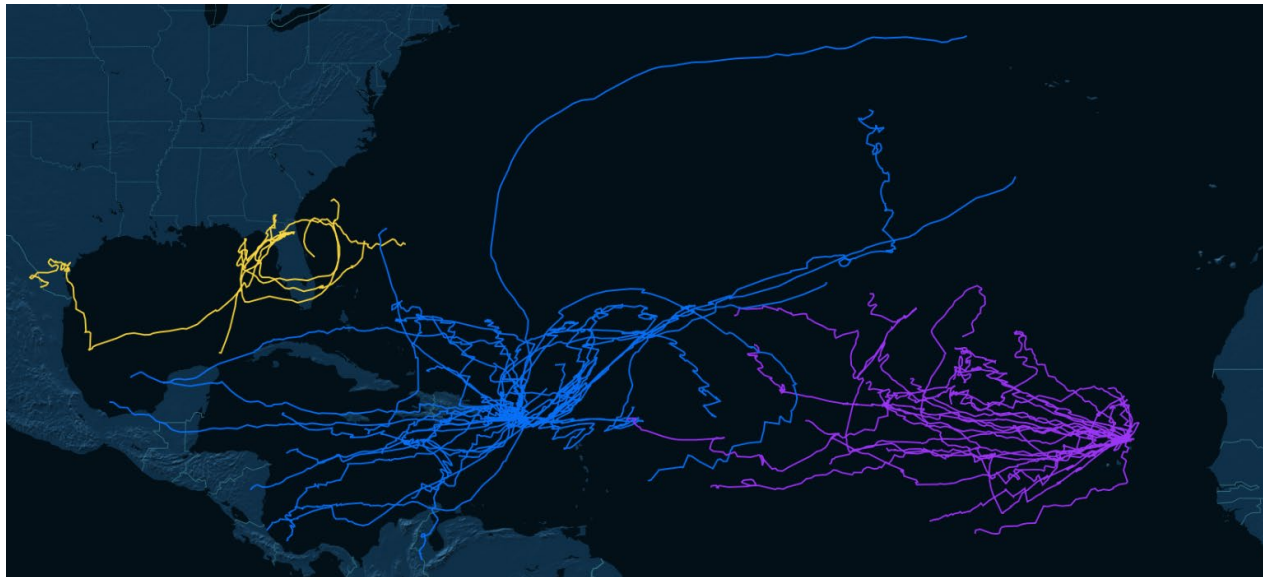
MST-5

August 1 - October 10
85 balloons

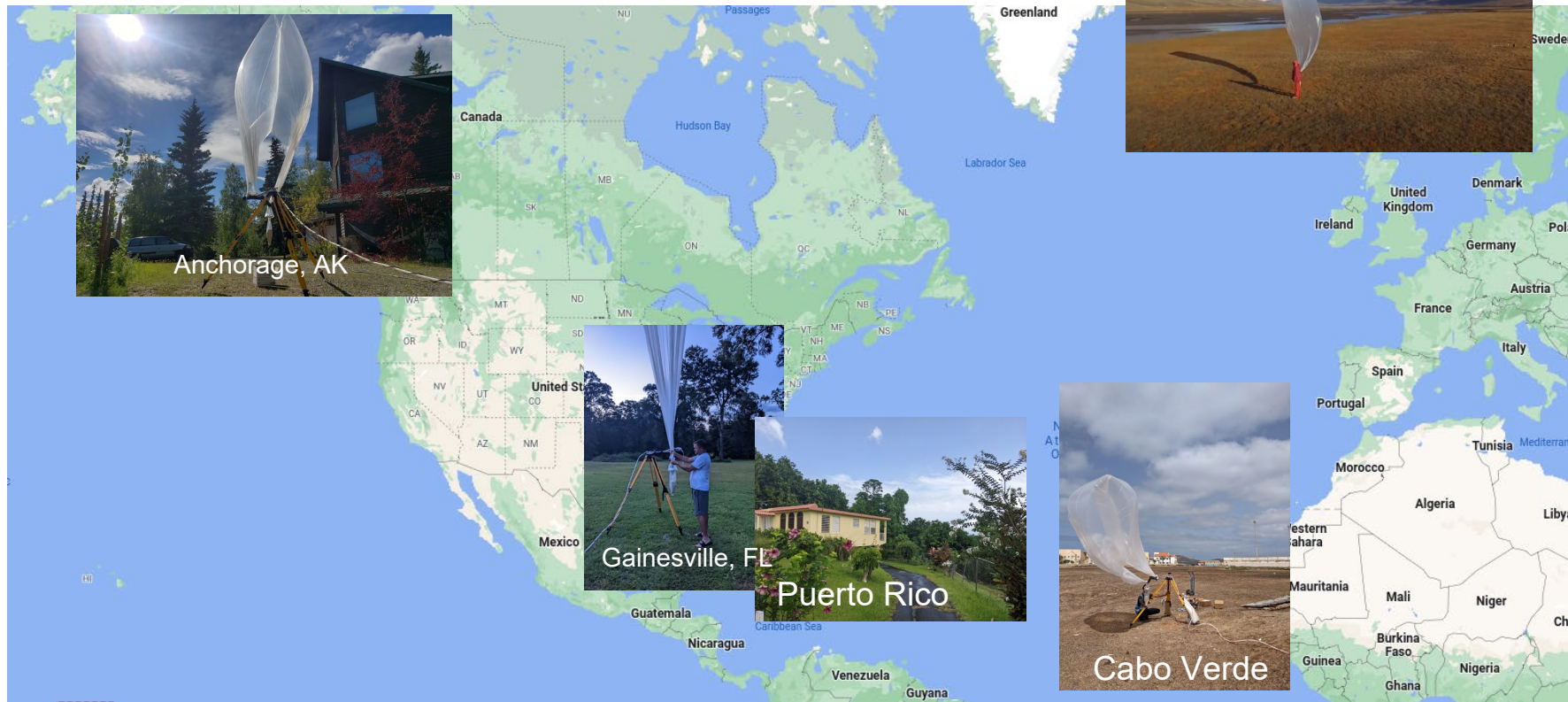


2022 Tropical Season

During the summer of 2022, WindBorne launched 85 balloons in the tropical atlantic to collect observations in tropical cyclone environments.



Summer of 2022- Launch Sites

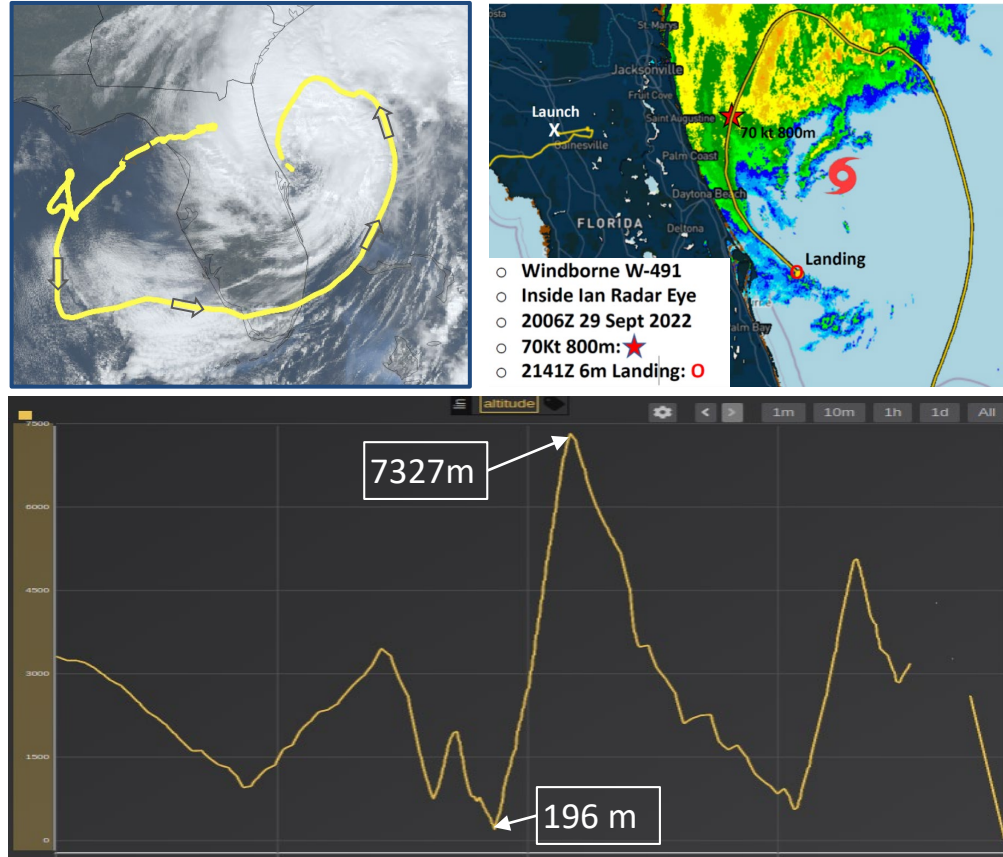


Hurricane Ian - September 2022

WindBorne Balloon launched from **Gainesville, FL** at 19 UTC 27 September. It circled **Hurricane Ian** and reached the western **eye wall** 50 hours later when Ian was east of Florida

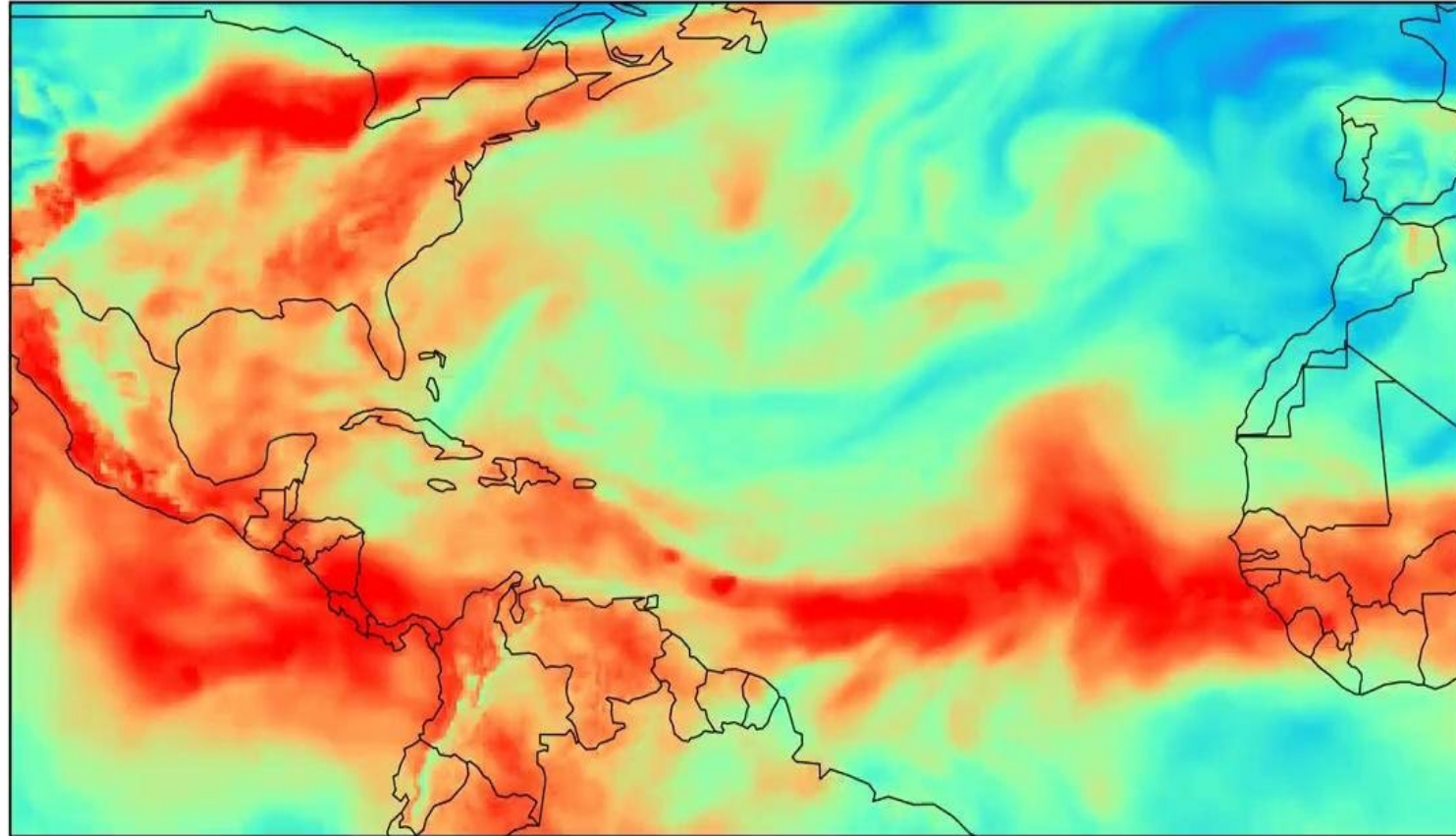
This is the **first** demonstration of **navigating** a WindBorne balloon into a tropical cyclone. The balloon **survived precipitation** and **turbulence** before finally landing.

The balloon measured winds exceeding **70 kts at 800m**.

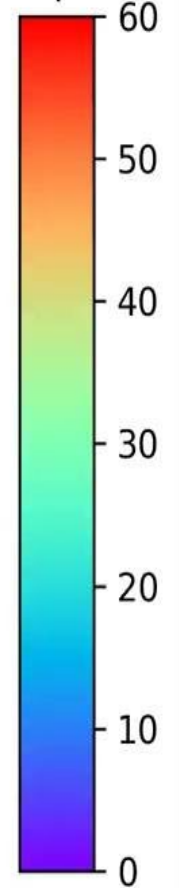


WindBorne MST-5 Tropical Atlantic Balloon Tracks

2022-08-08 02:00



Integrated
vapor



kg/m²

Forecast Impact - NHEM

Results from GFS ($\frac{1}{2}$ resolution) retrospective runs for the Summer 2022 period. Up to 3% **reduction** in errors days 4-7.



Assimilated obs from Arctic and tropics and verified over Atlantic region



Error Reduction over Northern Hemisphere - summer 2022

		northern									
	rms	24 h	48 h	72 h	96 h	120 h	144 h	168 h	192 h		
Height	All Levels	0.02 (0.2%)	0.07 (0.7%)	0.03 (0.3%)	-0.19 (-0.8%)	-0.61 (-2.0%)	-1.00 (-2.2%)	-1.23 (-1.9%)	-0.38 (0.2%)		
	50 - 250 mbar	0.05 (0.5%)	0.12 (0.9%)	0.11 (0.7%)	-0.03 (0.0%)	-0.43 (-1.2%)	-1.05 (-2.2%)	-1.26 (-1.7%)	-0.27 (0.2%)		
	300 - 500 mbar	0.03 (0.4%)	0.10 (0.8%)	0.03 (0.2%)	-0.32 (-1.2%)	-0.97 (-2.7%)	-1.43 (-2.6%)	-1.60 (-2.0%)	-0.51 (0.3%)		
	550 - 750 mbar	0.00 (0.1%)	0.03 (0.4%)	-0.01 (-0.1%)	-0.26 (-1.3%)	-0.63 (-2.3%)	-0.90 (-2.2%)	-1.13 (-1.9%)	-0.48 (0.4%)		
	800 - 1000 mbar	-0.01 (-0.2%)	0.00 (0.1%)	-0.04 (-0.2%)	-0.14 (-0.5%)	-0.35 (-1.1%)	-0.42 (-0.8%)	-0.77 (-1.2%)	-0.30 (0.5%)		
Temperature	All Levels	-0.00 (-0.1%)	0.00 (0.1%)	0.00 (0.2%)	-0.00 (-0.2%)	-0.01 (-0.6%)	-0.02 (-1.0%)	-0.03 (-1.2%)	-0.02 (-0.4%)		
	50 - 250 mbar	0.00 (0.2%)	0.00 (0.2%)	0.00 (0.4%)	-0.00 (-0.3%)	-0.02 (-0.9%)	-0.03 (-1.5%)	-0.04 (-1.5%)	-0.02 (-0.7%)		
	300 - 500 mbar	0.00 (0.0%)	0.00 (0.4%)	0.00 (0.3%)	-0.00 (-0.2%)	-0.02 (-0.9%)	-0.03 (-1.2%)	-0.03 (-1.3%)	-0.02 (-0.4%)		
	550 - 750 mbar	-0.00 (-0.0%)	0.00 (0.3%)	0.00 (0.1%)	-0.00 (-0.3%)	-0.01 (-0.9%)	-0.02 (-1.1%)	-0.04 (-1.4%)	-0.01 (-0.2%)		
	800 - 1000 mbar	-0.00 (-0.3%)	-0.00 (-0.1%)	0.00 (0.1%)	-0.00 (-0.2%)	0.00 (0.0%)	-0.02 (-0.6%)	-0.02 (-0.6%)	-0.01 (-0.2%)		
U wind	All Levels	0.00 (0.1%)	0.00 (0.1%)	0.00 (0.1%)	-0.02 (-0.4%)	-0.06 (-1.0%)	-0.11 (-1.6%)	-0.14 (-1.8%)	-0.08 (-0.8%)		
	50 - 250 mbar	0.01 (0.2%)	0.01 (0.2%)	0.02 (0.4%)	-0.00 (0.0%)	-0.04 (-0.5%)	-0.10 (-1.2%)	-0.13 (-1.3%)	-0.04 (-0.3%)		
	300 - 500 mbar	0.00 (0.2%)	0.01 (0.2%)	-0.01 (-0.1%)	-0.03 (-0.6%)	-0.09 (-1.4%)	-0.18 (-2.3%)	-0.20 (-2.2%)	-0.10 (-0.8%)		
	550 - 750 mbar	-0.00 (-0.2%)	-0.00 (-0.0%)	0.00 (0.0%)	-0.03 (-0.7%)	-0.05 (-1.2%)	-0.07 (-1.3%)	-0.12 (-1.9%)	-0.11 (-1.4%)		
	800 - 1000 mbar	-0.00 (-0.0%)	-0.01 (-0.4%)	0.00 (0.0%)	-0.03 (-0.8%)	-0.04 (-1.0%)	-0.04 (-0.7%)	-0.08 (-1.4%)	-0.07 (-1.1%)		
V wind	All Levels	0.00 (0.0%)	0.01 (0.3%)	0.01 (0.2%)	-0.00 (-0.1%)	-0.07 (-1.1%)	-0.10 (-1.4%)	-0.11 (-1.4%)	-0.06 (-0.5%)		
	50 - 250 mbar	0.00 (0.1%)	0.01 (0.3%)	0.02 (0.6%)	0.00 (0.1%)	-0.05 (-0.7%)	-0.06 (-0.7%)	-0.08 (-0.8%)	-0.04 (-0.1%)		
	300 - 500 mbar	0.00 (0.1%)	0.02 (0.5%)	0.00 (0.1%)	0.00 (0.1%)	-0.11 (-1.6%)	-0.15 (-1.8%)	-0.14 (-1.4%)	-0.08 (-0.4%)		
	550 - 750 mbar	-0.00 (-0.1%)	0.01 (0.3%)	0.01 (0.2%)	-0.01 (-0.3%)	-0.05 (-1.0%)	-0.11 (-1.9%)	-0.14 (-2.2%)	-0.08 (-1.0%)		
	800 - 1000 mbar	-0.00 (-0.2%)	0.00 (0.1%)	-0.01 (-0.2%)	-0.02 (-0.4%)	-0.04 (-0.9%)	-0.08 (-1.5%)	-0.09 (-1.5%)	-0.05 (-0.5%)		
Relative humidity	All Levels	0.01 (0.0%)	0.01 (0.0%)	0.00 (0.0%)	-0.00 (-0.0%)	-0.05 (-0.2%)	-0.13 (-0.5%)	-0.11 (-0.4%)	-0.13 (-0.4%)		
	50 - 250 mbar	0.04 (0.2%)	-0.01 (-0.0%)	0.02 (0.1%)	0.02 (0.1%)	-0.04 (-0.2%)	-0.14 (-0.6%)	-0.16 (-0.6%)	-0.14 (-0.5%)		
	300 - 500 mbar	-0.01 (-0.0%)	0.01 (0.1%)	-0.01 (-0.0%)	-0.03 (-0.1%)	-0.13 (-0.4%)	-0.15 (-0.4%)	-0.05 (-0.1%)	-0.15 (-0.4%)		
	550 - 750 mbar	-0.00 (-0.0%)	0.03 (0.2%)	-0.00 (-0.0%)	0.02 (0.1%)	-0.00 (-0.0%)	-0.11 (-0.4%)	-0.20 (-0.7%)	-0.12 (-0.4%)		
	800 - 1000 mbar	-0.01 (-0.1%)	-0.01 (-0.1%)	-0.00 (-0.0%)	-0.02 (-0.1%)	-0.07 (-0.1%)	-0.10 (-0.3%)	-0.04 (-0.1%)	-0.09 (-0.3%)		

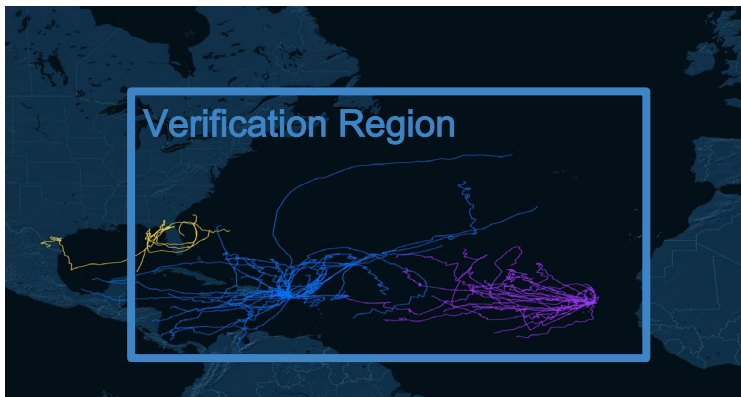
Average root mean square error (RMSE) differences between GFS experimental and control runs initialized daily between 00 UTC 1 August and 10 October 2022 for the mid-Atlantic for lead times as columns every 24 hours through 72 hour lead times. Parameters and vertical levels evaluated for rows in the table are indicated on the left. RMSE (m) is shown with percentage error reductions in parentheses. Color shading indicates the direction of error reduction, with blue (red) indicating positive (negative) forecast impact as a result of WindBorne observations. Statistical significance as determined using a student-t test is indicated with solid bars indicating significance at the 95% level and bold text values indicating significance at the 99% level.

Forecast Impact - Atlantic

Results from GFS (½ resolution)
retrospective runs for the Summer 2022
period. Some reduction in errors



Assimilated obs from Arctic and tropics
and verified over Atlantic region



Error Reduction over Northern Hemisphere - summer 2022

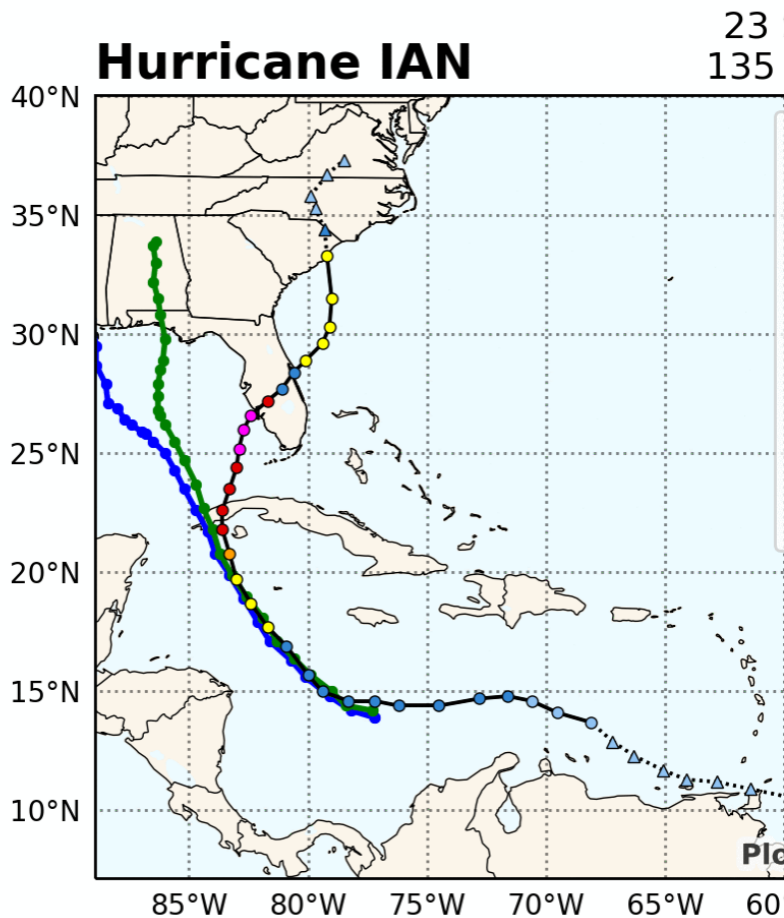
		midatl									
rms		24 h	48 h	72 h	96 h	120 h	144 h	168 h	192 h		
Height	All levels	-0.02 (-0.2%)	0.02 (0.5%)	-0.08 (-0.4%)	-0.18 (-0.8%)	-0.18 (-0.8%)	-0.06 (-0.3%)	-0.17 (-0.1%)	-0.45 (-1.6%)		
	50 - 250 mbar	-0.04 (-0.4%)	0.00 (0.2%)	-0.11 (-0.4%)	-0.25 (-0.8%)	-0.29 (-1.0%)	-0.28 (-1.0%)	-0.22 (-0.4%)	0.03 (0.9%)		
	300 - 500 mbar	0.03 (1.1%)	0.03 (1.2%)	-0.11 (-0.4%)	-0.07 (0.3%)	-0.06 (0.8%)	-0.18 (-0.6%)	-0.17 (0.4%)	-0.72 (-2.3%)		
	550 - 750 mbar	-0.04 (-0.6%)	0.01 (0.6%)	-0.10 (-1.3%)	-0.19 (-1.2%)	0.14 (2.9%)	0.19 (2.8%)	-0.23 (-0.1%)	-0.94 (-4.2%)		
	800 - 1000 mbar	-0.04 (-0.4%)	0.01 (0.2%)	-0.11 (-1.6%)	-0.20 (-1.6%)	0.10 (2.5%)	0.26 (3.7%)	-0.13 (1.2%)	-0.42 (-0.7%)		
Temperature	All levels	-0.00 (-0.1%)	-0.00 (-0.5%)	-0.00 (-0.2%)	-0.00 (-0.3%)	-0.01 (-1.0%)	-0.01 (-0.3%)	-0.01 (-0.6%)	-0.01 (-0.9%)		
	50 - 250 mbar	0.00 (0.1%)	-0.00 (-0.3%)	-0.00 (-0.2%)	-0.01 (-0.3%)	-0.02 (-1.4%)	-0.02 (-1.1%)	-0.01 (-0.6%)	-0.01 (-0.1%)		
	300 - 500 mbar	-0.00 (-0.1%)	-0.00 (0.0%)	-0.00 (-0.2%)	-0.01 (-0.3%)	-0.02 (-1.2%)	-0.02 (-1.2%)	-0.01 (-0.4%)	-0.01 (-0.3%)		
	550 - 750 mbar	-0.00 (-0.6%)	-0.01 (-0.9%)	-0.01 (-0.7%)	0.00 (0.5%)	-0.00 (-0.1%)	-0.01 (-0.3%)	-0.00 (0.0%)	-0.02 (-1.9%)		
	800 - 1000 mbar	-0.00 (-0.0%)	-0.01 (-0.7%)	0.00 (0.4%)	-0.00 (-0.1%)	0.00 (0.1%)	-0.01 (-0.2%)	0.00 (0.2%)	-0.02 (-1.1%)		
U wind	All levels	-0.00 (-0.2%)	-0.01 (-0.1%)	-0.02 (-0.5%)	-0.05 (-1.0%)	-0.02 (-0.2%)	-0.03 (-0.3%)	-0.05 (-0.5%)	-0.09 (-1.1%)		
	50 - 250 mbar	-0.00 (-0.1%)	-0.02 (-0.3%)	-0.04 (-0.7%)	-0.07 (-1.1%)	-0.04 (-0.4%)	-0.07 (-0.7%)	-0.07 (-0.5%)	-0.13 (-1.0%)		
	300 - 500 mbar	0.01 (0.4%)	0.02 (0.9%)	0.00 (0.2%)	-0.05 (-0.9%)	-0.02 (-0.3%)	-0.01 (0.2%)	-0.10 (-1.4%)	-0.10 (-0.7%)		
	550 - 750 mbar	-0.02 (-0.9%)	-0.02 (-0.7%)	-0.03 (-0.7%)	-0.04 (-0.5%)	0.02 (1.1%)	0.01 (0.8%)	-0.02 (-0.3%)	-0.08 (-1.1%)		
	800 - 1000 mbar	-0.00 (-0.0%)	-0.01 (-0.3%)	-0.02 (-0.6%)	-0.03 (-0.5%)	-0.00 (0.6%)	-0.02 (0.3%)	0.03 (1.3%)	-0.05 (-0.6%)		
V wind	All levels	-0.01 (-0.3%)	-0.00 (-0.1%)	-0.02 (-0.5%)	-0.02 (-0.2%)	-0.07 (-1.1%)	-0.05 (-0.9%)	0.02 (0.8%)	0.03 (1.2%)		
	50 - 250 mbar	-0.00 (-0.0%)	-0.00 (0.0%)	-0.02 (-0.1%)	-0.01 (0.1%)	-0.14 (-1.8%)	-0.13 (-1.6%)	0.04 (1.0%)	0.11 (2.1%)		
	300 - 500 mbar	0.00 (0.2%)	0.00 (0.2%)	-0.03 (-0.7%)	-0.02 (-0.1%)	-0.08 (-1.3%)	-0.03 (-0.2%)	0.00 (0.7%)	0.01 (1.2%)		
	550 - 750 mbar	-0.03 (-1.3%)	-0.02 (-0.7%)	-0.02 (-0.4%)	-0.02 (-0.3%)	0.02 (1.0%)	0.02 (0.8%)	0.01 (0.7%)	-0.07 (-0.7%)		
	800 - 1000 mbar	-0.02 (-0.8%)	-0.01 (-0.2%)	-0.02 (-0.3%)	-0.02 (0.3%)	-0.01 (0.7%)	-0.00 (0.5%)	-0.00 (0.7%)	-0.01 (0.3%)		
Relative humidity	All levels	0.00 (0.0%)	-0.01 (-0.0%)	-0.02 (-0.1%)	-0.05 (-0.2%)	-0.18 (-0.7%)	-0.21 (-0.8%)	-0.10 (-0.3%)	-0.11 (-0.3%)		
	50 - 250 mbar	0.12 (0.6%)	0.00 (0.1%)	-0.07 (-0.3%)	0.03 (0.1%)	-0.13 (-0.5%)	-0.34 (-1.2%)	-0.24 (-0.8%)	-0.09 (-0.2%)		
	300 - 500 mbar	-0.06 (-0.3%)	0.09 (0.4%)	0.04 (0.1%)	-0.10 (-0.3%)	-0.33 (-1.0%)	-0.24 (-0.7%)	-0.14 (-0.3%)	-0.26 (-0.7%)		
	550 - 750 mbar	-0.05 (-0.4%)	-0.11 (-0.6%)	-0.04 (-0.2%)	-0.06 (-0.2%)	-0.16 (-0.5%)	-0.16 (-0.5%)	0.00 (0.1%)	-0.03 (0.1%)		
	800 - 1000 mbar	-0.01 (-0.1%)	-0.10 (-0.8%)	-0.03 (-0.2%)	-0.08 (-0.6%)	-0.03 (-0.1%)	-0.05 (-0.2%)	0.05 (0.5%)	0.01 (0.2%)		

Average root mean square error (RMSE) differences between GFS experimental and control runs initialized daily between 00 UTC 1 August and 10 October 2022 for the mid-Atlantic for lead times as columns every 24 hours through 72 hour lead times. Parameters and vertical levels evaluated for rows in the table are indicated on the left. RMSE (m) is shown with percentage error reductions in parentheses. Color shading indicates the direction of error reduction, with blue (red) indicating positive (negative) forecast impact as a result of WindBorne observations. Statistical significance as determined using a student-t test is indicated with solid bars indicating significance at the 95% level and bold text values indicating significance at the 99% level.

Forecast Impact - Ian Track

Control runs (blue) vs Experimental (green)

Track impacts are evident throughout, though which is “better” is not clear.



2023 Summer Possible Operations

This is the maximum possible operations during summer 2023.

If Balloons from Schenectady or S. Korea reach Atlantic they would follow same rules as those released in Atlantic

August 1 - October 10
Up to 75 balloons

Gainesville, FL (30%)

Puerto Rico (70%)

Cabo Verde (0%)

Continuous



DEFENSE
INNOVATION UNIT

Svalbard (20/month)

S. Korea (20/month)

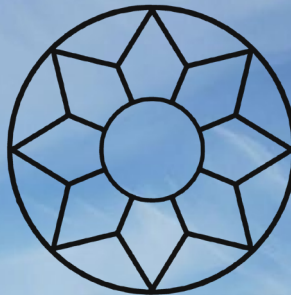
Schenectady (40/month)

Data Availability

WindBorne data is available upon request:

todd@windbornesystems.com

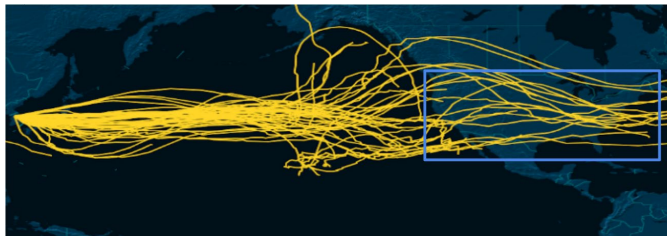
bufr, netcdf, textual, skew-T images available



Thank you

Forecast Impact

Results from the Jan/Feb 2022 Atmospheric Rivers Campaign yielded up to **1.5% error reduction** over CONUS in **GFS retrospective forecasts**



Error Reduction over CONUS - winter 2022							
RMS		conus					
		12 h	24 h	36 h	48 h	60 h	72 h
Height	All levels	0.09 (1.5%)	0.04 (0.7%)	-0.09 (-0.5%)	-0.19 (-1.0%)	-0.03 (-0.0%)	0.35 (2.1%)
	300 mbar	0.03 (0.9%)	-0.13 (-1.1%)	-0.23 (-0.7%)	-0.42 (-1.9%)	-0.39 (-1.7%)	0.20 (1.7%)
	500 mbar	0.13 (2.7%)	0.10 (2.1%)	-0.05 (0.0%)	-0.22 (-0.6%)	-0.01 (0.0%)	0.47 (3.6%)
	700 mbar	0.12 (2.4%)	0.14 (2.2%)	0.04 (0.6%)	-0.00 (0.1%)	0.32 (2.6%)	0.73 (5.3%)
	850 mbar	0.06 (1.4%)	0.04 (0.7%)	-0.06 (-0.8%)	-0.11 (-0.4%)	0.33 (2.6%)	0.72 (4.9%)
	1000 mbar	0.01 (0.2%)	-0.02 (-0.1%)	-0.22 (-1.7%)	-0.31 (-1.6%)	0.10 (0.8%)	0.46 (2.5%)
Temperature	All levels	-0.00 (-0.1%)	-0.01 (-0.4%)	-0.01 (-1.0%)	-0.02 (-1.5%)	-0.02 (-1.4%)	-0.01 (-0.4%)
	300 mbar	-0.01 (-1.1%)	-0.02 (-3.2%)	-0.02 (-1.9%)	-0.01 (-1.2%)	-0.00 (-0.1%)	-0.01 (-0.3%)
	500 mbar	-0.00 (-0.7%)	-0.01 (-1.2%)	-0.02 (-1.7%)	-0.02 (-1.7%)	-0.01 (-0.3%)	0.02 (2.1%)
	700 mbar	0.00 (0.4%)	0.00 (0.2%)	-0.01 (-1.0%)	-0.04 (-2.8%)	-0.02 (-1.1%)	-0.00 (0.1%)
	850 mbar	0.00 (0.2%)	-0.00 (-0.2%)	-0.02 (-0.9%)	-0.03 (-1.6%)	-0.03 (-1.4%)	-0.01 (-0.3%)
	1000 mbar	-0.01 (-0.2%)	-0.01 (-0.2%)	-0.02 (-0.6%)	-0.03 (-1.0%)	-0.04 (-1.4%)	-0.02 (-0.6%)
U wind	All levels	-0.02 (-1.0%)	-0.03 (-1.4%)	-0.04 (-1.3%)	-0.05 (-1.4%)	-0.03 (-1.0%)	0.04 (0.6%)
	300 mbar	-0.05 (-1.9%)	-0.06 (-1.8%)	0.05 (1.4%)	-0.02 (-0.3%)	-0.05 (-1.3%)	0.09 (1.2%)
	500 mbar	-0.03 (-1.4%)	-0.06 (-2.1%)	-0.07 (-2.0%)	-0.08 (-2.0%)	-0.02 (-0.1%)	0.06 (1.3%)
	700 mbar	-0.02 (-1.0%)	-0.02 (-0.9%)	-0.03 (-0.9%)	-0.06 (-2.0%)	-0.04 (-1.0%)	-0.01 (-0.5%)
	850 mbar	-0.01 (-0.5%)	0.01 (0.5%)	-0.02 (-0.6%)	-0.05 (-2.0%)	-0.03 (-0.9%)	0.02 (0.9%)
	1000 mbar	-0.01 (-0.5%)	-0.01 (-0.5%)	-0.01 (-0.9%)	-0.02 (-1.5%)	-0.01 (-0.8%)	0.02 (1.1%)
V wind	All levels	-0.01 (-0.5%)	-0.04 (-1.7%)	-0.07 (-2.2%)	-0.07 (-1.8%)	-0.04 (-1.0%)	-0.00 (0.1%)
	300 mbar	-0.05 (-1.7%)	-0.08 (-2.3%)	-0.12 (-2.7%)	-0.12 (-2.4%)	-0.07 (-1.1%)	0.03 (1.2%)
	500 mbar	-0.03 (-1.3%)	-0.05 (-1.8%)	-0.08 (-2.2%)	-0.10 (-2.5%)	-0.05 (-0.8%)	-0.03 (-0.4%)
	700 mbar	-0.00 (-0.1%)	-0.00 (-0.1%)	-0.05 (-1.5%)	-0.07 (-1.8%)	-0.02 (-0.3%)	-0.03 (-0.7%)
	850 mbar	-0.02 (-1.1%)	-0.03 (-1.2%)	-0.02 (-0.8%)	-0.04 (-1.2%)	-0.02 (-0.5%)	0.04 (1.0%)
	1000 mbar	-0.01 (-0.4%)	-0.00 (-0.1%)	-0.01 (-1.0%)	-0.01 (-0.7%)	-0.02 (-0.7%)	-0.01 (-0.4%)
Relative humidity	All levels	-0.08 (-0.6%)	-0.13 (-1.0%)	-0.16 (-1.0%)	-0.19 (-1.0%)	-0.18 (-0.9%)	-0.05 (-0.2%)
	300 mbar	-0.10 (-0.4%)	-0.20 (-1.1%)	0.05 (0.4%)	-0.19 (-0.8%)	-0.12 (-0.3%)	0.11 (0.6%)
	500 mbar	-0.20 (-1.6%)	-0.28 (-1.8%)	-0.25 (-1.2%)	-0.26 (-1.0%)	-0.13 (-0.4%)	-0.16 (-0.6%)
	700 mbar	0.02 (0.1%)	-0.02 (-0.2%)	-0.06 (-0.2%)	-0.35 (-1.8%)	-0.41 (-1.7%)	-0.16 (-0.4%)
	850 mbar	0.05 (0.4%)	0.00 (0.0%)	0.02 (0.2%)	-0.09 (-0.5%)	-0.05 (-0.1%)	0.13 (0.8%)
	1000 mbar	0.02 (0.2%)	-0.02 (-0.1%)	-0.04 (-0.3%)	-0.08 (-0.6%)	-0.02 (-0.2%)	0.01 (0.1%)
Sea level pressure	Surface	-0.02 (0.1%)	-0.45 (-0.2%)	-2.85 (-1.6%)	-3.93 (-1.6%)	0.74 (0.6%)	5.03 (2.2%)
100 metre U wind	Surface	-0.01 (-0.5%)	-0.01 (-0.5%)	-0.03 (-1.2%)	-0.05 (-2.3%)	-0.02 (-0.8%)	0.03 (1.2%)
100 metre V wind	Surface	-0.01 (-0.5%)	-0.00 (-0.2%)	-0.02 (-1.2%)	-0.03 (-1.3%)	-0.03 (-0.8%)	-0.00 (-0.0%)
10 metre U wind	Surface	-0.00 (-0.3%)	-0.00 (-0.3%)	-0.02 (-1.2%)	-0.03 (-2.1%)	-0.01 (-0.7%)	0.02 (1.4%)
10 metre V wind	Surface	-0.00 (-0.2%)	-0.00 (-0.3%)	-0.01 (-1.1%)	-0.01 (-0.9%)	-0.02 (-0.8%)	-0.00 (-0.1%)
2 metre dewpoint	Surface	-0.00 (-0.1%)	-0.00 (-0.0%)	-0.00 (-0.1%)	-0.01 (-0.3%)	-0.00 (-0.0%)	0.01 (0.4%)
2 metre temperature	Surface	-0.01 (-0.3%)	-0.01 (-0.2%)	-0.01 (-0.4%)	-0.01 (-0.3%)	-0.02 (-0.6%)	0.00 (0.1%)

Average root mean square error (RMSE) differences between GFS experimental and control runs during January/February 2022 for CONUS for lead times as columns every 12 hours through 72 hour lead times. Parameters and vertical levels evaluated for rows in the table are indicated on the left. RMSE (m) is shown with percentage error reductions in parentheses. Color shading indicates the direction of error reduction, with blue (red) indicating positive (negative) forecast impact as a result of WindBorne observations. Statistical significance as determined using a student-t test is indicated with solid bars indicating significance at the 95% level and bold text values indicating significance at the 99% level.

Validation of WindBorne Sensors

WindBorne and University of Utah launched a balloon from Cabo Verde with WindBorne and instruments

- Attached to a standard latex balloon
- Consistent observations seen:
 - Nearly identical Temperature and Winds
 - Small differences in dewpoint especially for with low values
- WindBorne Data:
 - Becomes available after sensor deploy about 40 mb above surface
 - Comms lost temporarily above 190mb due to rapid ascent rates; this is not an issue with WindBorne balloons

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