

# **Multiple Tropical Cyclone-Baroclinic Trough Interactions over the North Atlantic Ocean during September 2023**

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Albany, NY 12222**

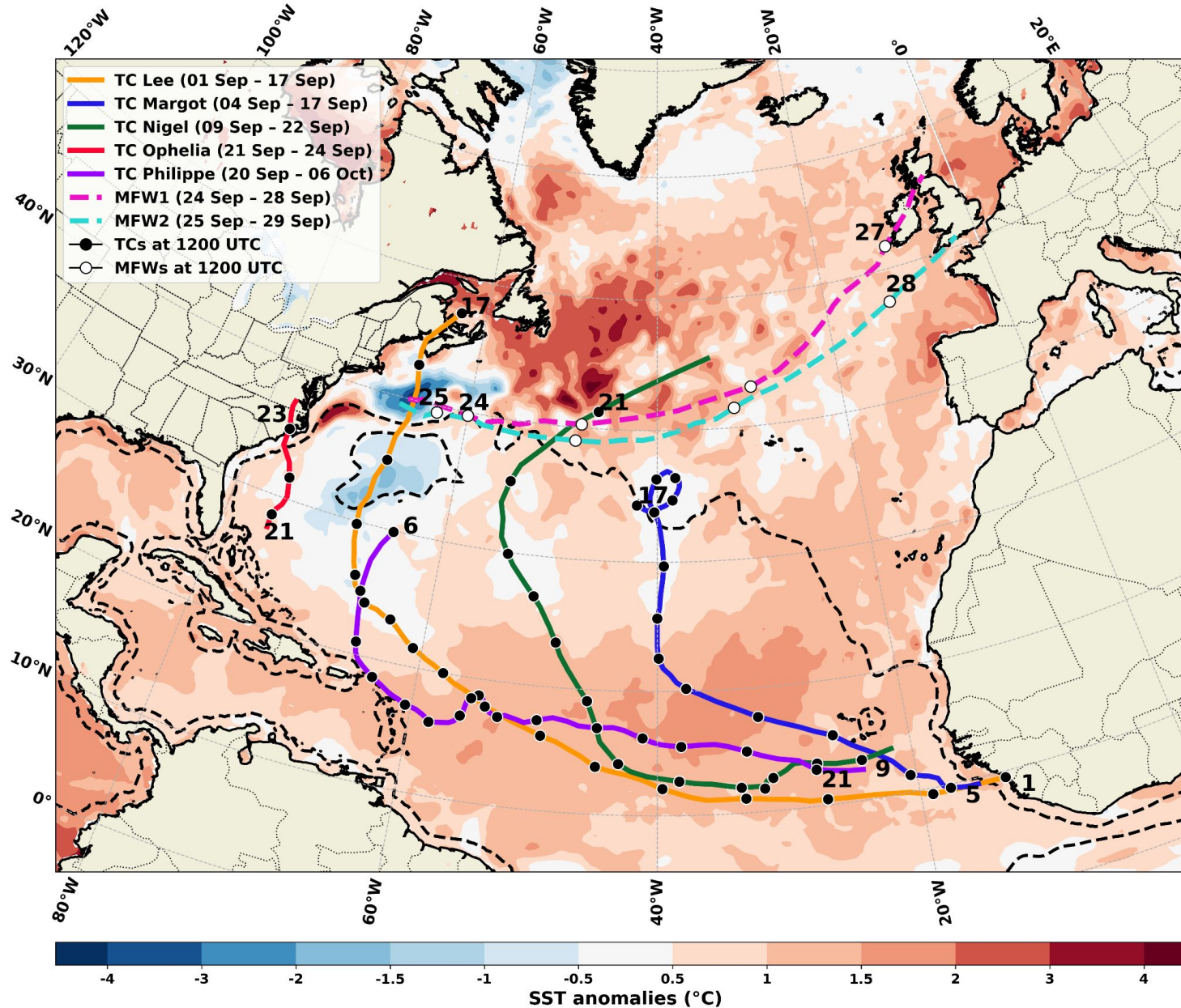
**25<sup>th</sup> Northeast Regional Operational Workshop (NROW)  
ETEC, University at Albany/SUNY  
Friday 15 November 2024  
Support Provided by NSF-AGS-2207179**

# Overview and Purpose

- **September 2023 featured many NATL tropical cyclones (TCs)**
- **Noteworthy TCs included: Lee, Margot, Nigel, Ophelia, and Philippe**
- **TCs Lee and Nigel fostered a strong eastern NATL gyre after ET**
- **TC Ophelia spawned two mesoscale frontal waves (MFWs)**
- **MFW1 became bomb cyclone Agnes and impacted the UK**
- **Focus on TC Ophelia and its baroclinic MFW “offspring”**

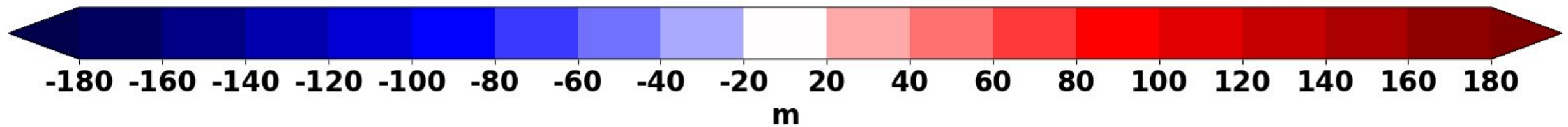
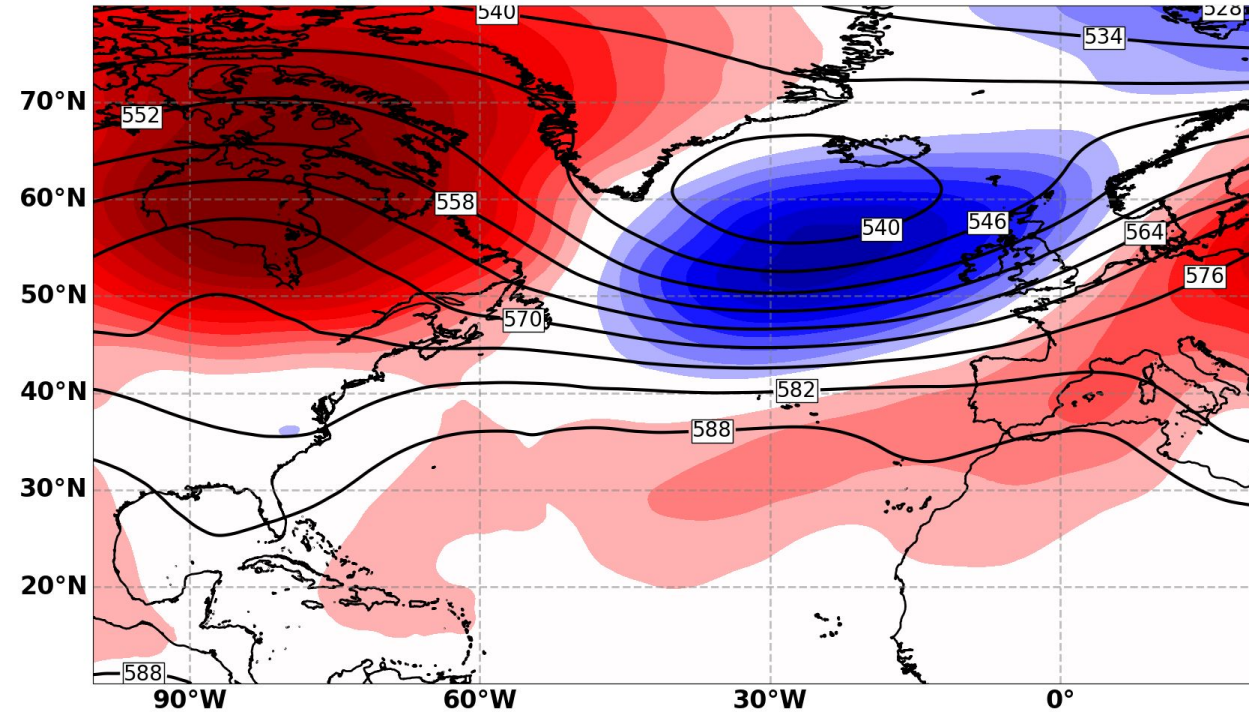
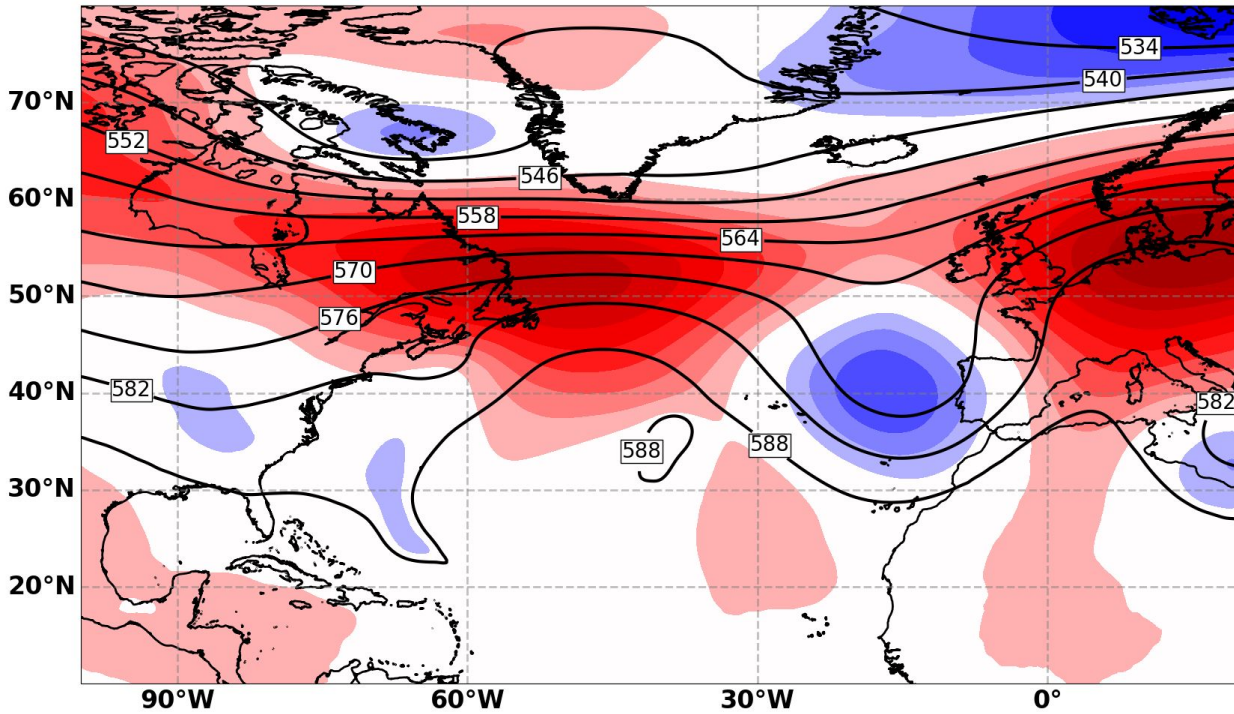
# Background

# September 2023 TC Tracks and NATL SST Anomalies



Dashed black line is the  
26.5 °C SST isotherm

# Mean and Anomaly 500-hPa heights: 5–16 September 2023 (left) and 17–30 September 2023 (right)



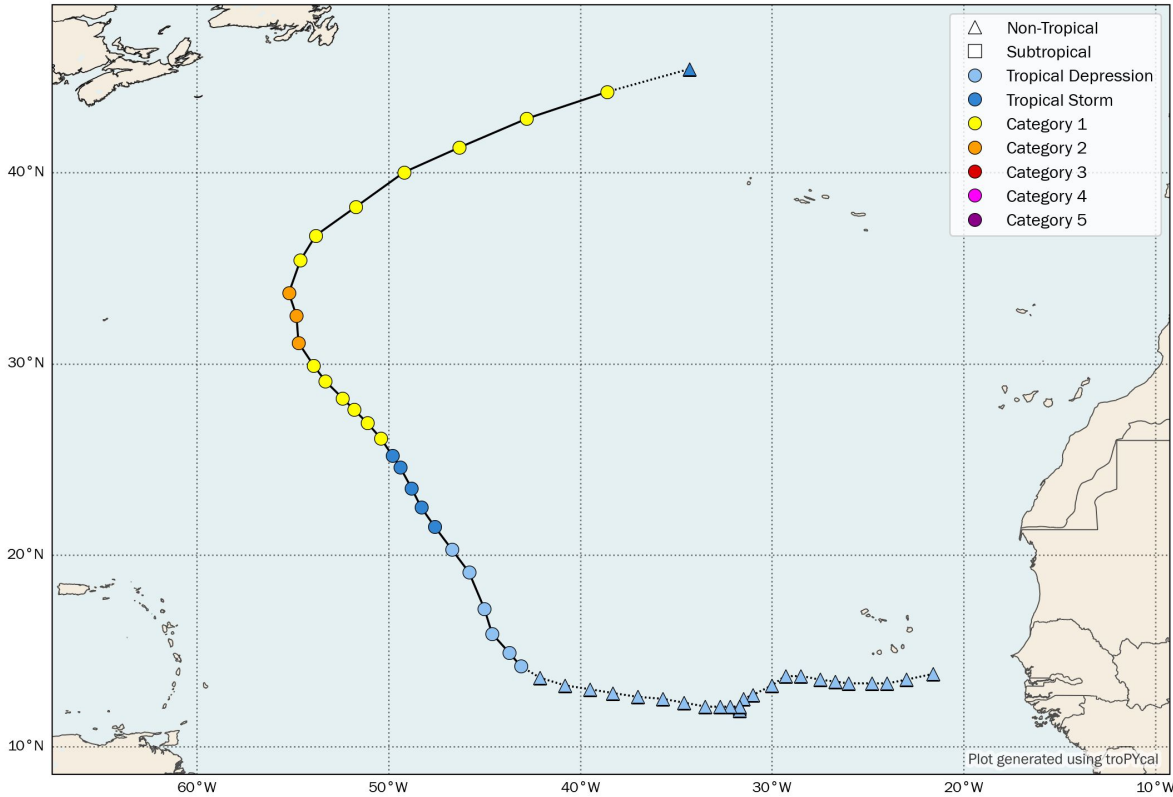
# TC Nigel

- Recurved over the west-central NATL TC
- Peak wind speed 85 kt; minimum central pressure 971 hPa
- Recurved on 20 September 2023
- Underwent ET over the NE NATL on 22–23 September 2023
- Absorbed into a strong NE NATL gyre on 24–25 September 2023

# TC Nigel: 15–22 September 2023

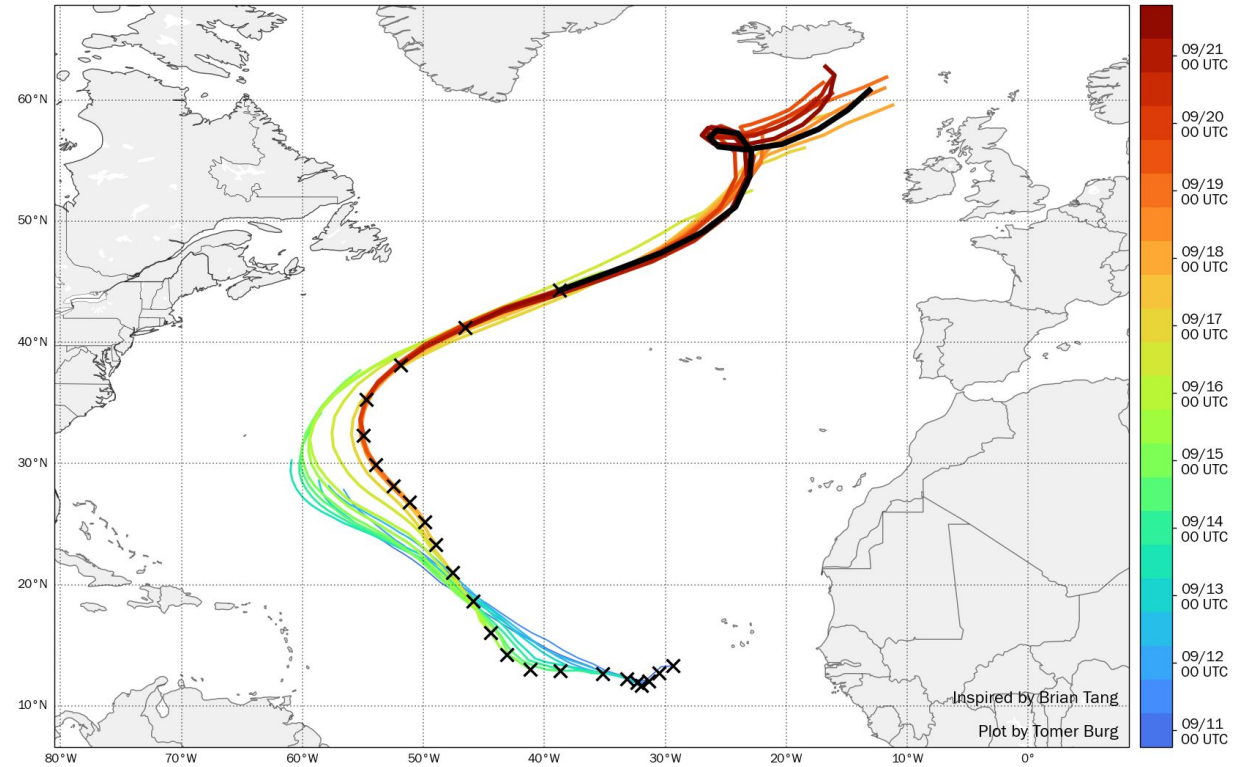
Hurricane NIGEL

15 Sep 2023 – 22 Sep 2023  
85 kt • 971 hPa • 10.5 ACE



Nigel Multi-Model Ensemble (EPS + GEFS + UKMET + CMC)  
Ensemble Mean Trends

Valid 0000 UTC 30 September 2023  
Latest Initialized: 0000 UTC 22 September 2023



# TC Ophelia

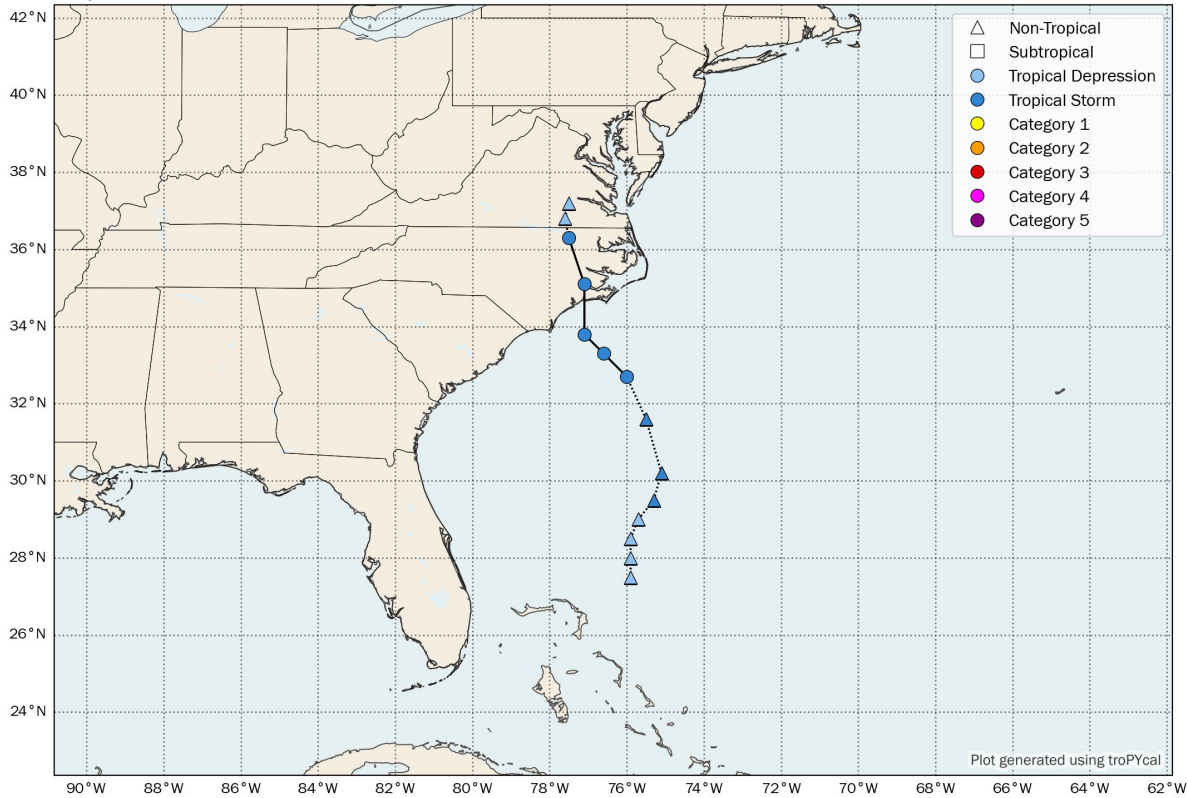
- **Marginal western NATL TC, but a fascinating storm overall**
- **Formed from a weak extratropical cyclone on 21 September 2023**
- **Peak wind speed 60 kt; minimum central pressure 981 hPa**
- **Made landfall in eastern North Carolina**
- **Was an “under-sized” lobster throwback storm, but....**
- **Produced heavy rainfall from the Carolinas to southern New England**
- **“Seeded” two ECs, one of which became a bomb cyclone**
- **Bomb cyclone was ingested into an eastern NATL gyre**



# Tropical Storm Ophelia: 22–23 September 2023

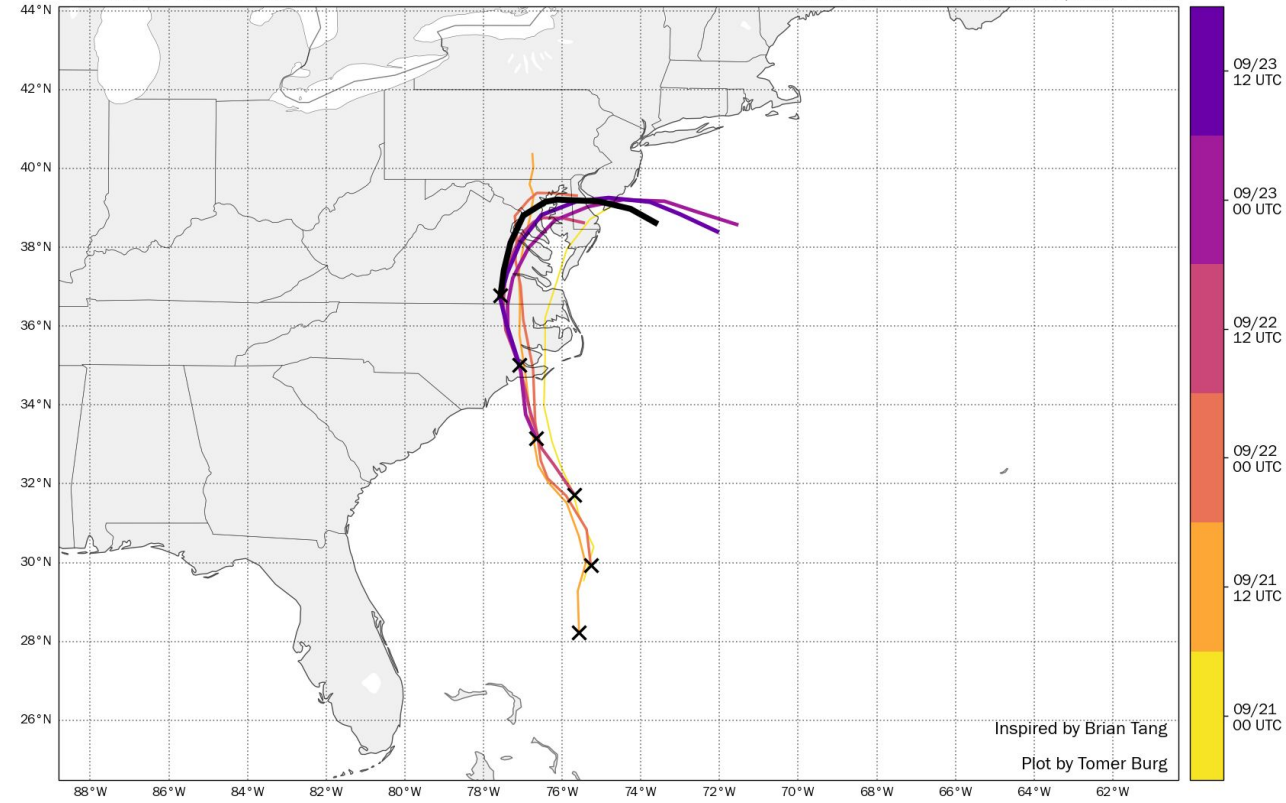
Tropical Storm OPHELIA

22 Sep 2023 – 23 Sep 2023  
60 kt • 981 hPa • 1.4 ACE



Ophelia Multi-Model Ensemble (EPS + GEFS + UKMET + CMC)  
Ensemble Mean Trends

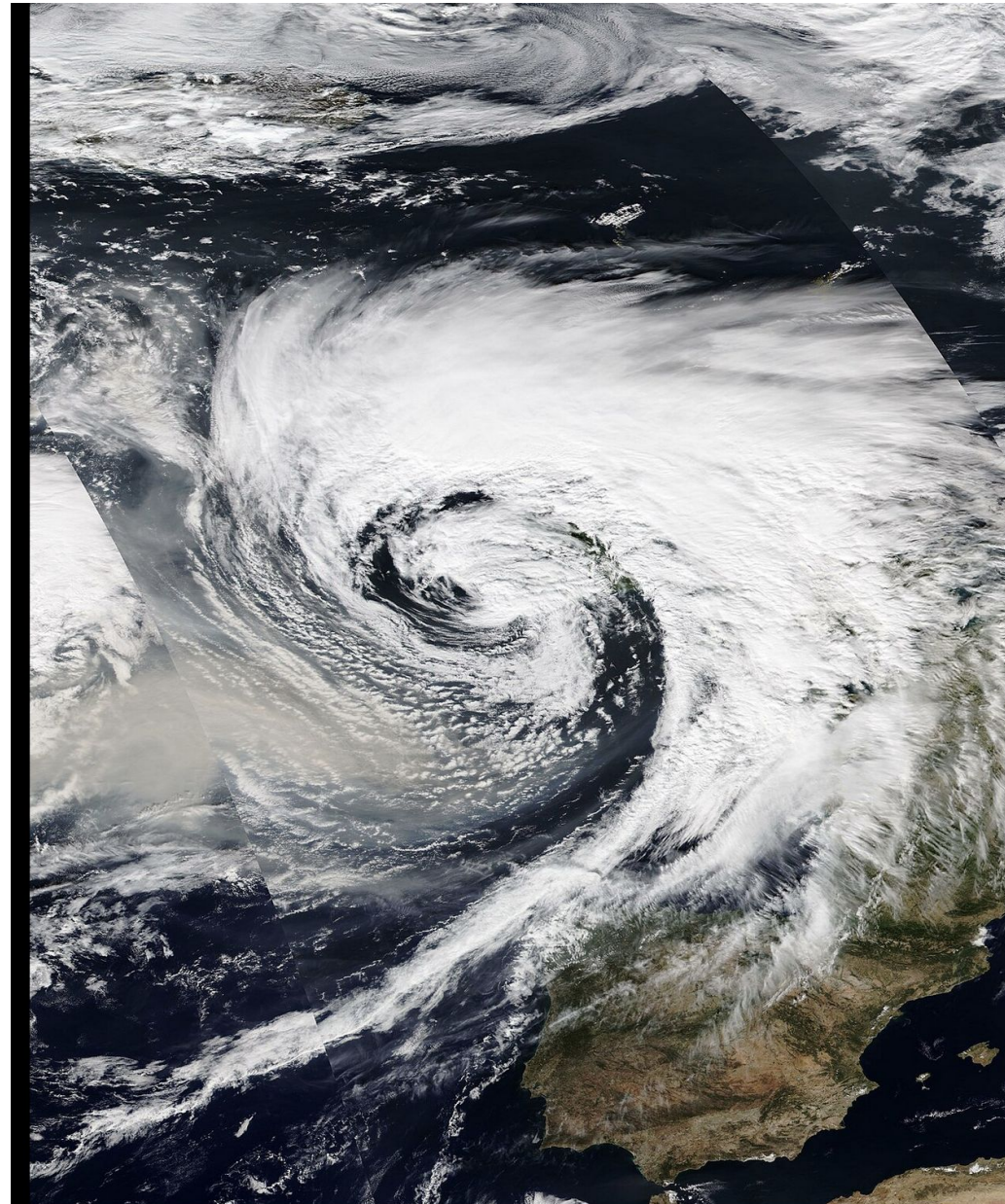
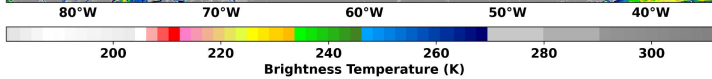
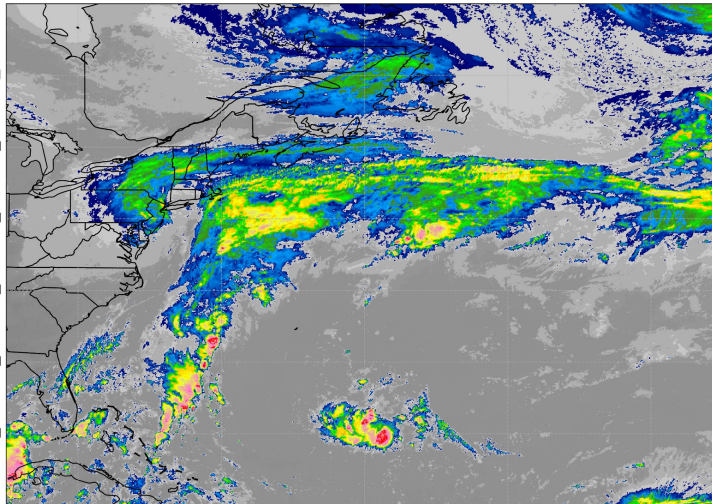
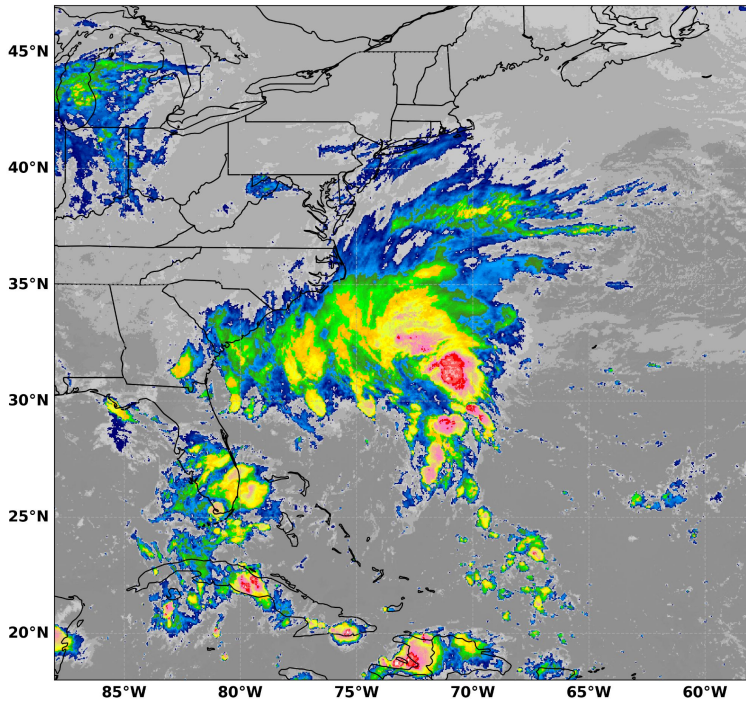
Valid 0000 UTC 02 October 2023  
Latest Initialized: 0000 UTC 24 September 2023



# Eastern North Atlantic Gyre

- Sustained by the extratropical cyclone remnants of TC Nigel
- Reinforced by mesoscale frontal waves (MFWs) from TC Ophelia
- One mesoscale frontal wave became UK bomb cyclone Agnes

# TC Ophelia to UK Storm Agnes



Left: IR brightness temperature from GOES-16 at 00Z 22 Sep (top) and 18Z 24 Sep (bottom)

Right: Visible satellite image at 0315Z 27 Sep (NASA Worldview)

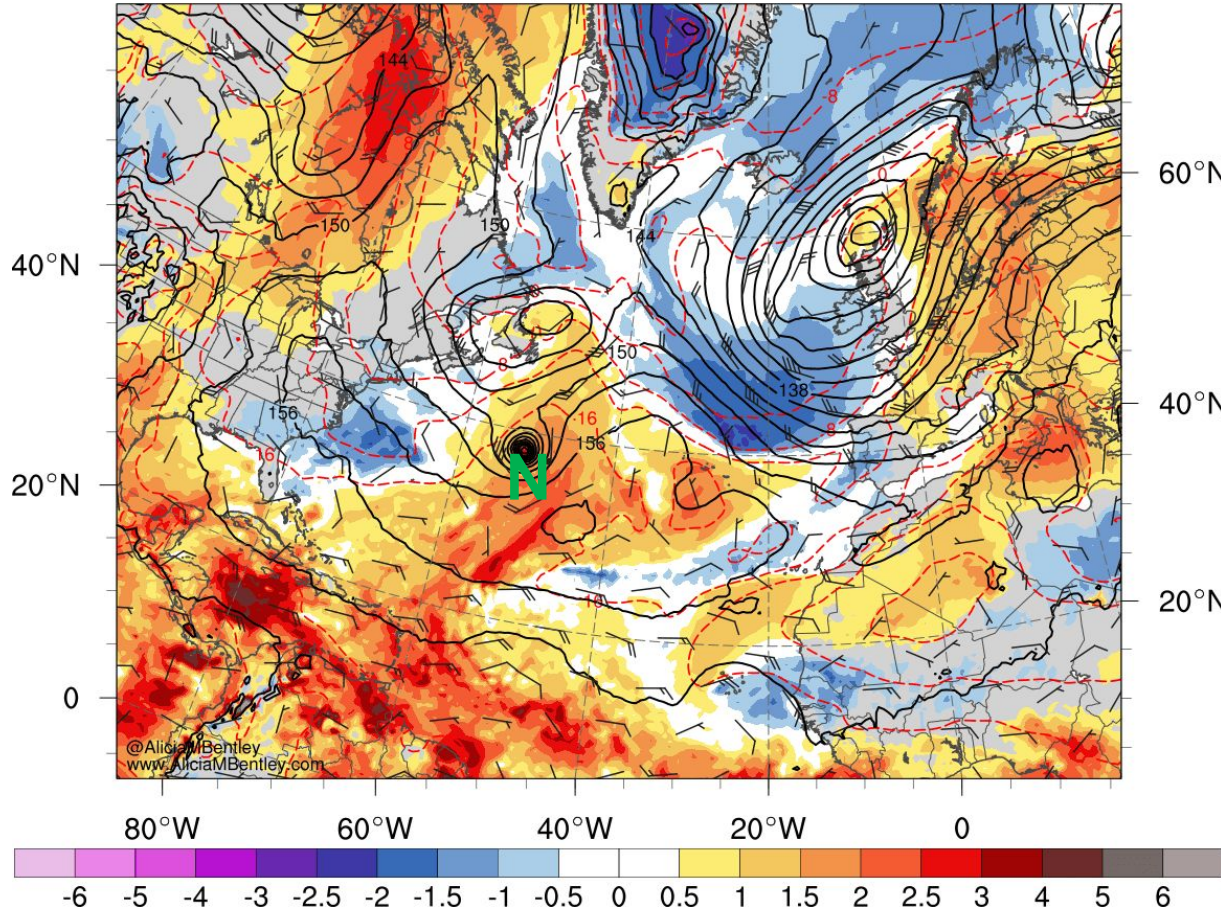
**Storm Agnes Statistics:**

- \*Peak wind: 73 kt**
- \*Highest September Wind Gust on Record in Wales**
- \*Minimum SLP: 958 hPa at 0600 UTC 27 Sep**

**Loop of Standardized 850-hPa Heights, Winds, and  
Temperature Anomalies (left), Mean SLP, 1000–500-hPa  
Thickness, and 250-hPa Winds (right) every 24 h at  
0000 UTC for 21–28 September 2023**

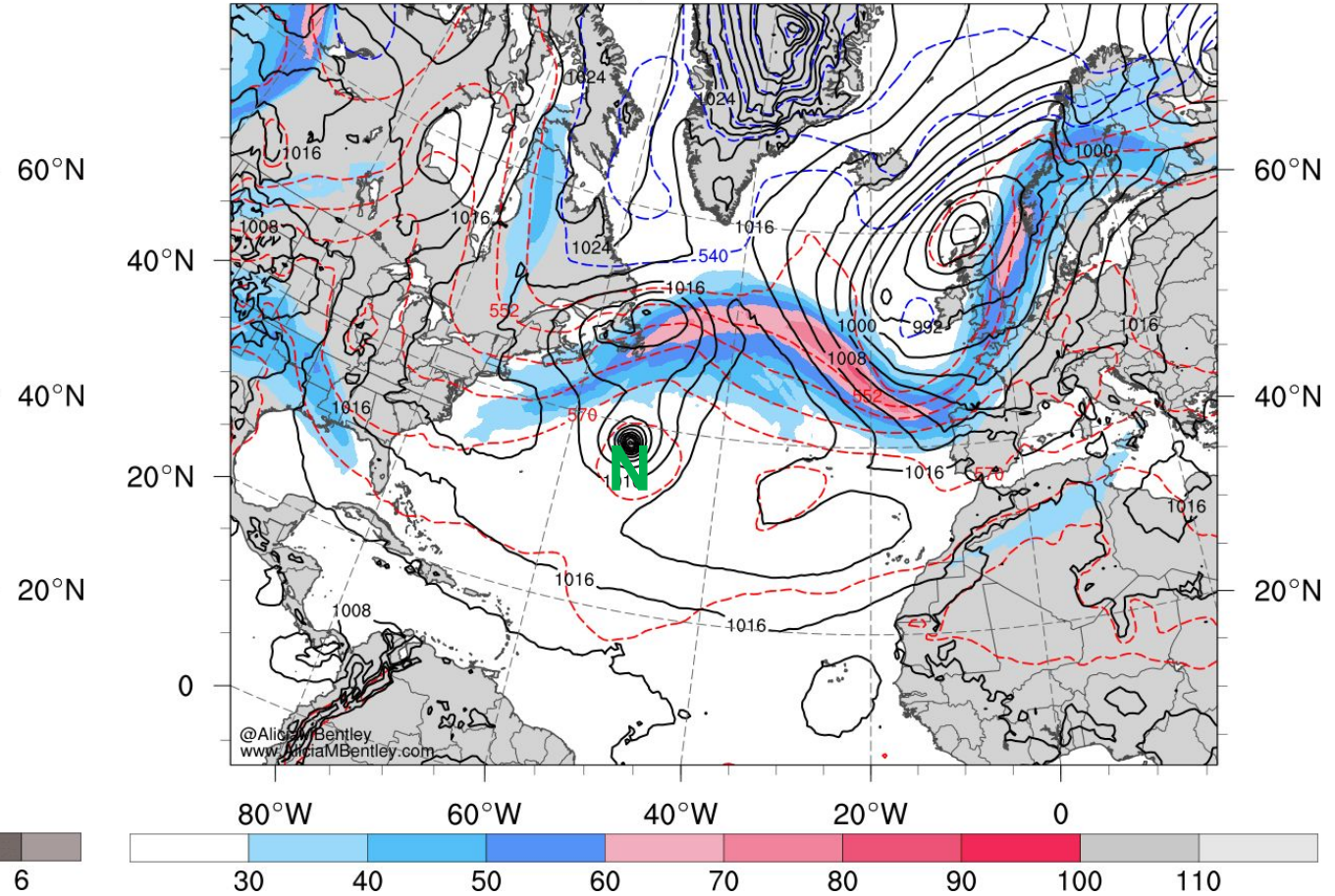
# Valid: 0000 UTC 21 September 2023

850-hPa geo. height (black, dam), temp (red, C), wind (barbs, kt), standardized temp anomaly (shaded, sigma)  
Initialized: 0000 UTC 21 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 21 Sep 2023



**850-hPa Heights (black contours, dam)**  
**Standardized Temperature Anomalies (shaded, sigma)**  
**850-hPa Winds (barbs, kt)**

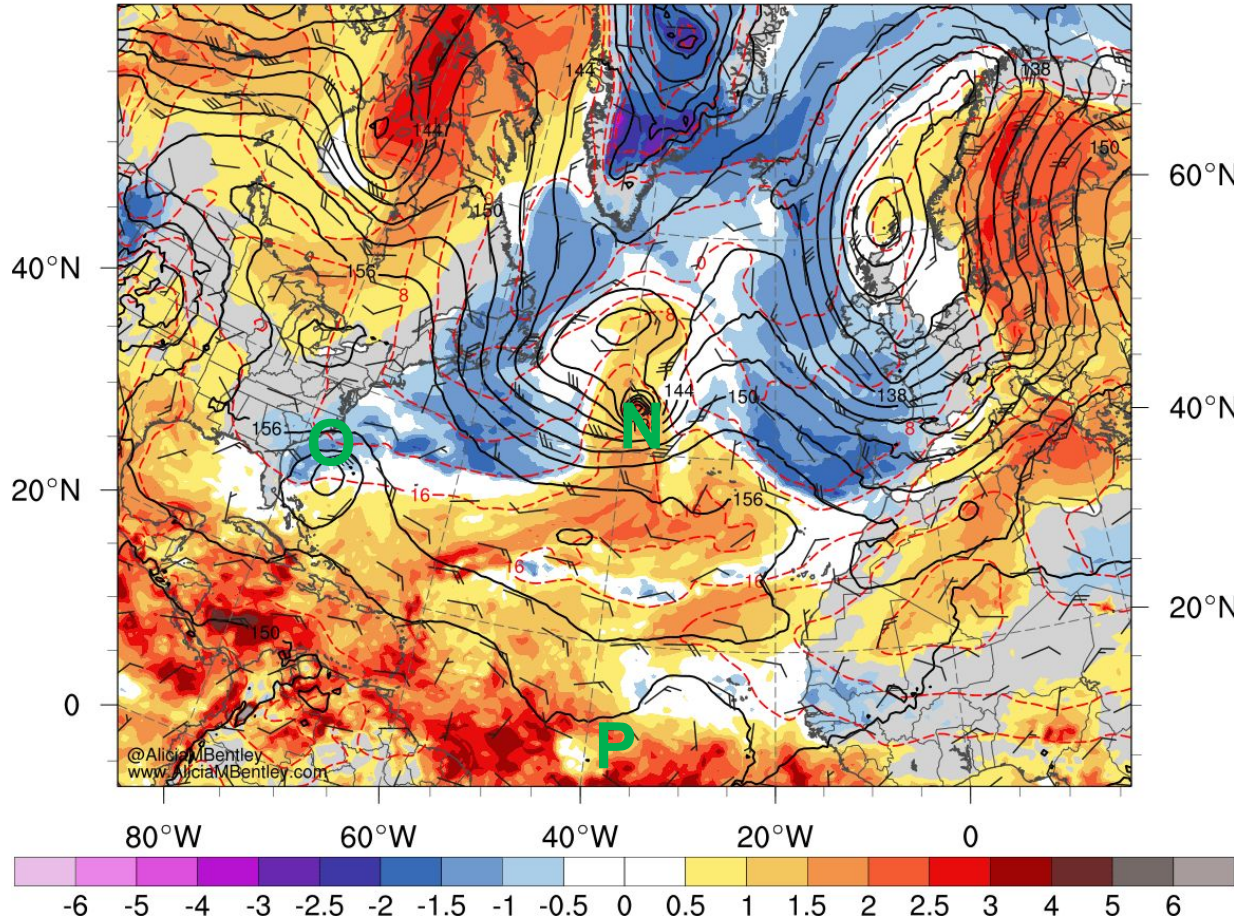
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
Initialized: 0000 UTC 21 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 21 Sep 2023



**SLP (hPa, black contours)**  
**1000-500-hPa Thickness (dam, dashed contours)**  
**250-hPa Winds (shaded, kt)**

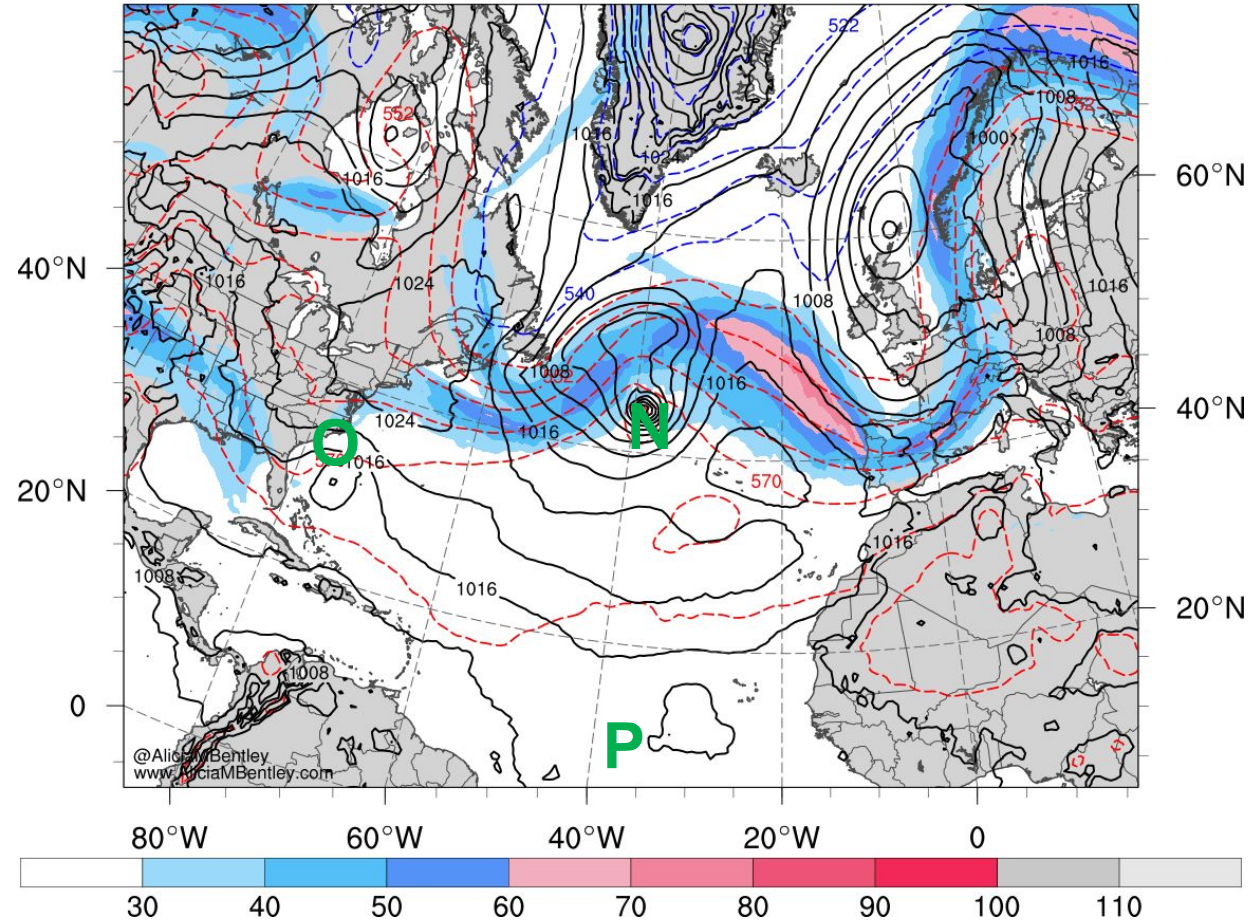
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850-hPa geo. height (black, dam), temp (red, C), wind (barbs, kt), standardized temp anomaly (shaded, sigma)  
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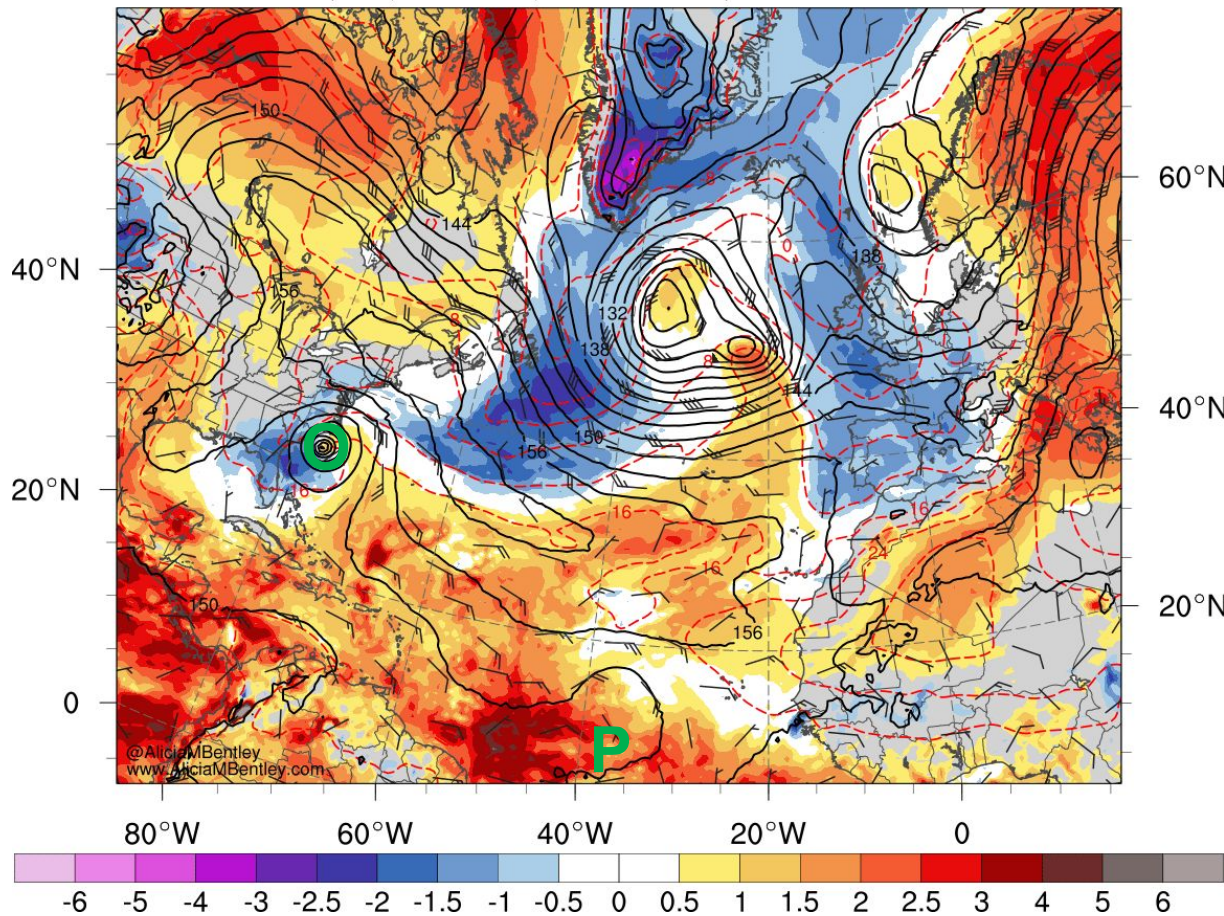
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
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**250-hPa Winds (shaded, kt)**

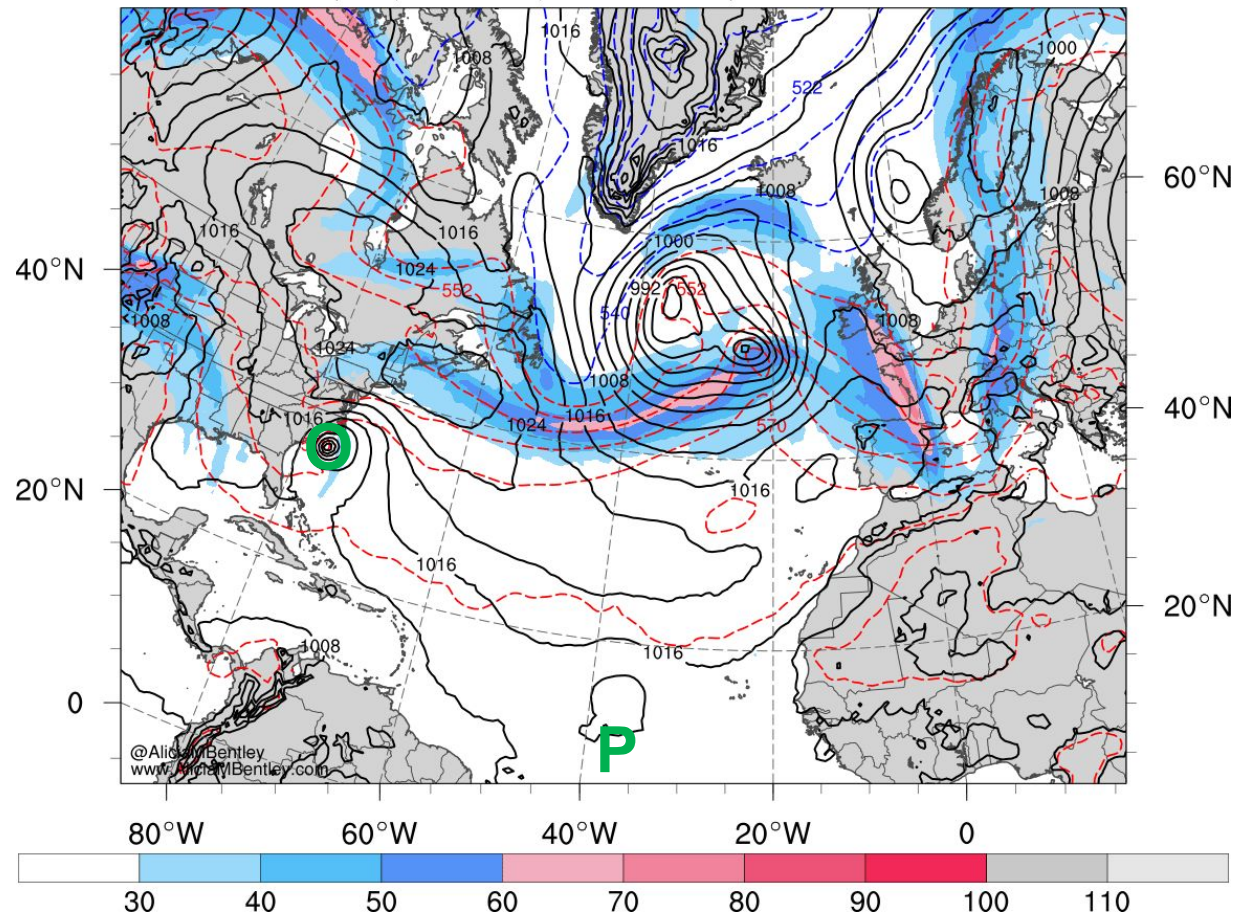
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850-hPa geo. height (black, dam), temp (red, C), wind (barbs, kt), standardized temp anomaly (shaded, sigma)  
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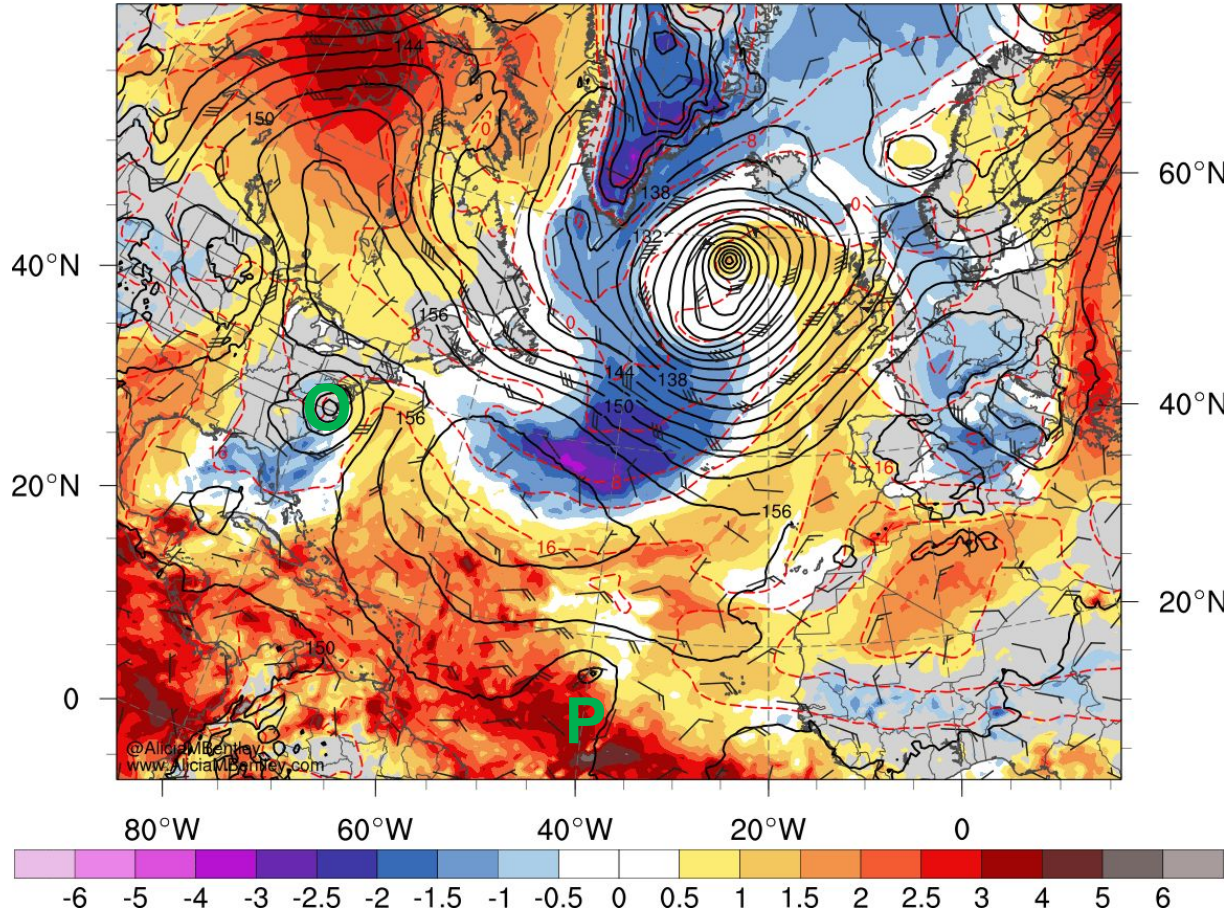
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
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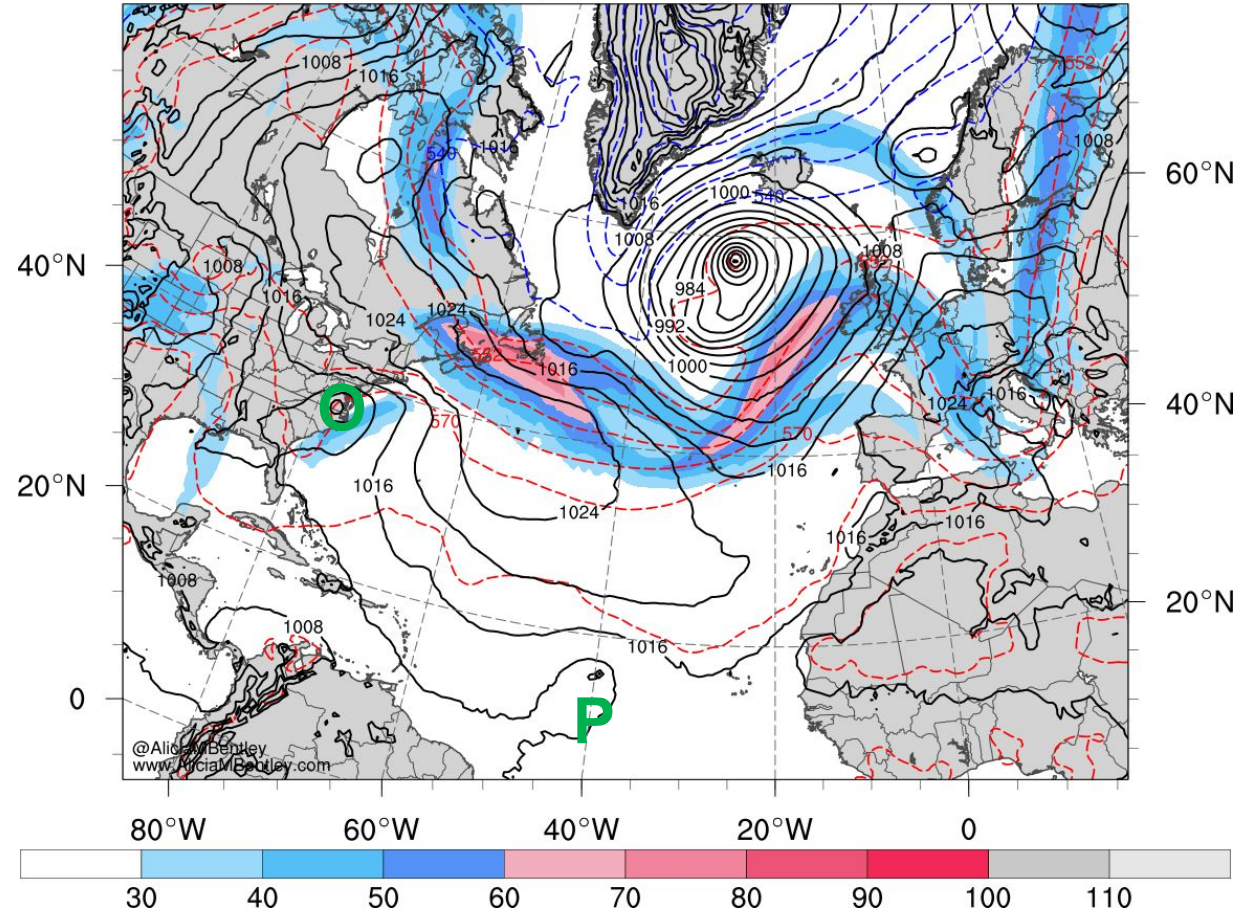
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850-hPa geo. height (black, dam), temp (red, C), wind (barbs, kt), standardized temp anomaly (shaded, sigma)  
Initialized: 0000 UTC 24 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 24 Sep 2023



**850-hPa Heights (black contours, dam)**  
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MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
Initialized: 0000 UTC 24 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 24 Sep 2023

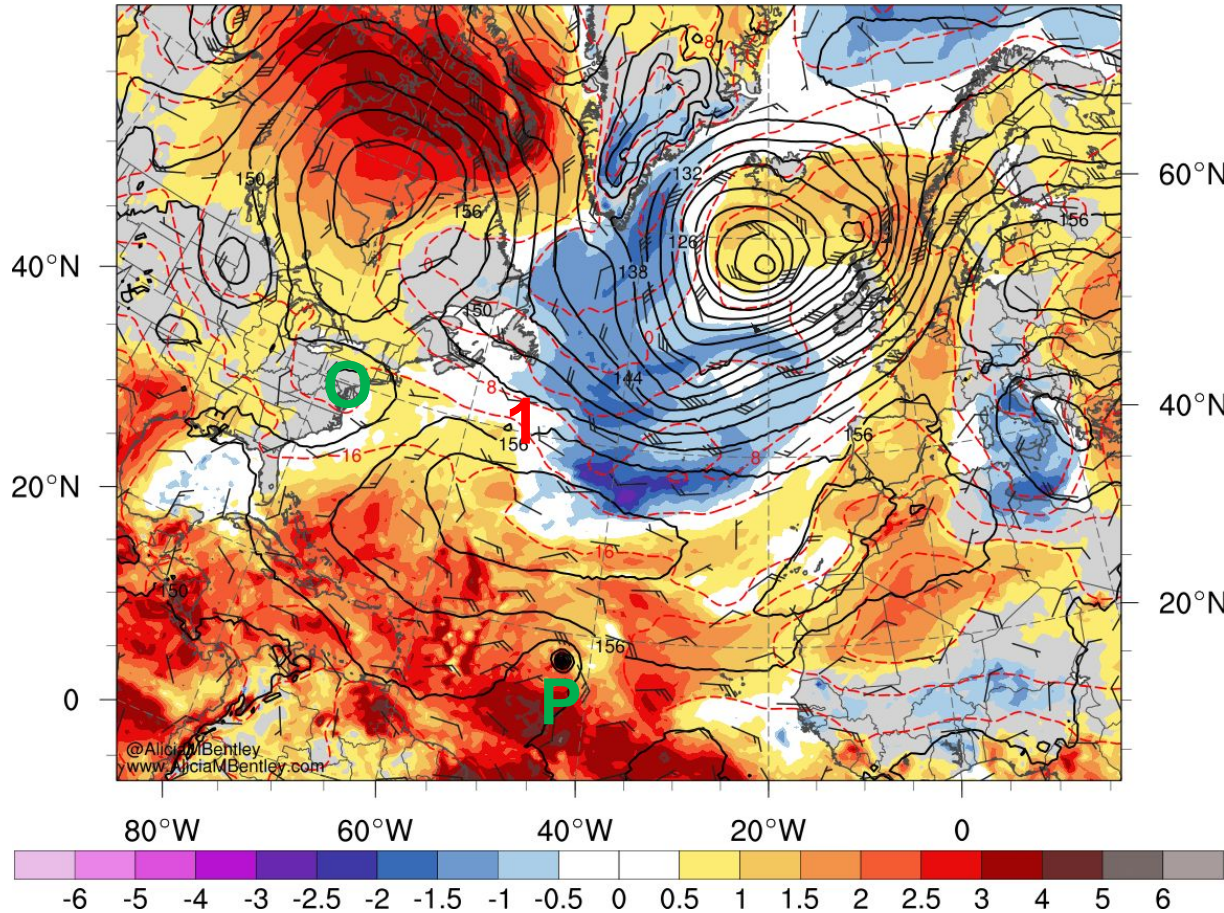


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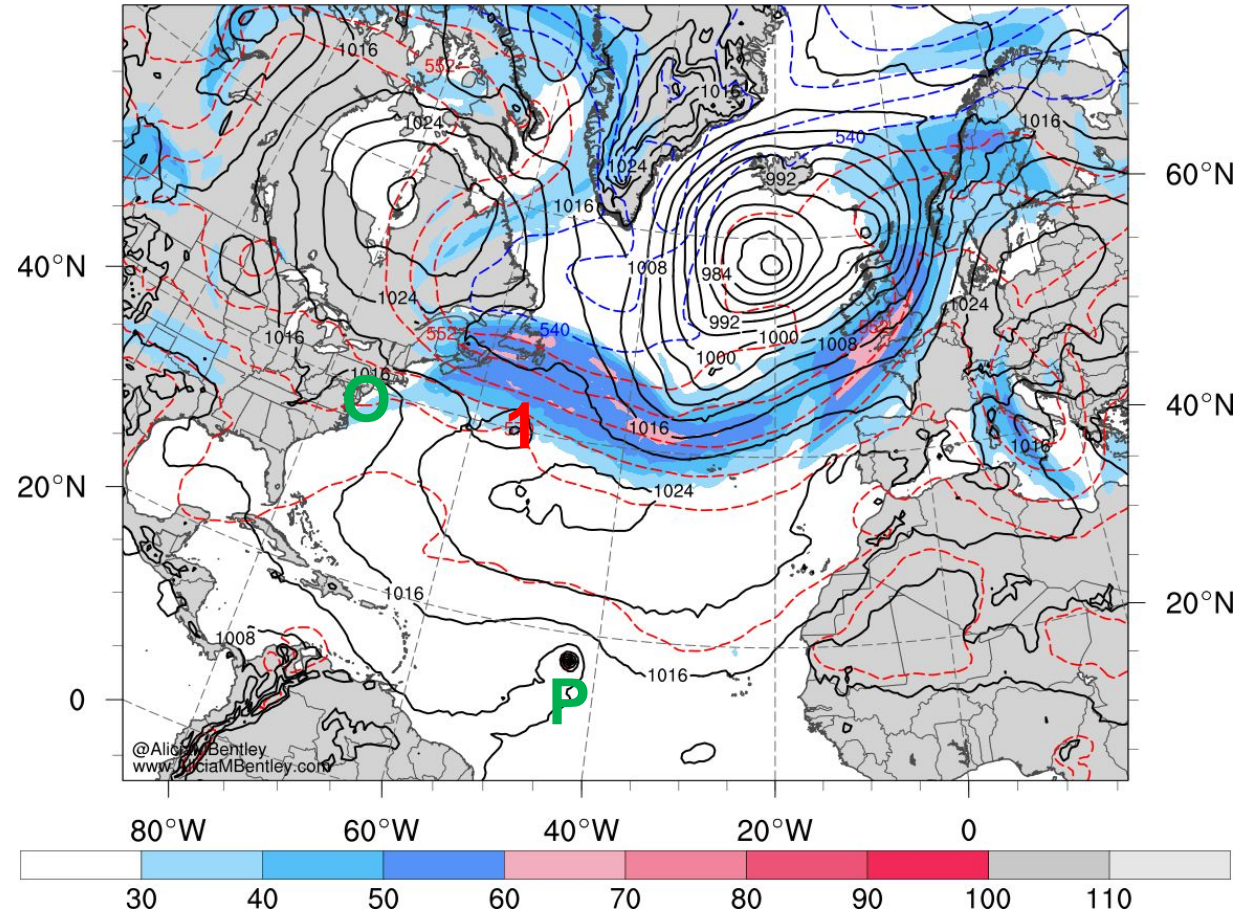
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850-hPa geo. height (black, dam), temp (red, C), wind (barbs, kt), standardized temp anomaly (shaded, sigma)  
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**850-hPa Heights (black contours, dam)**  
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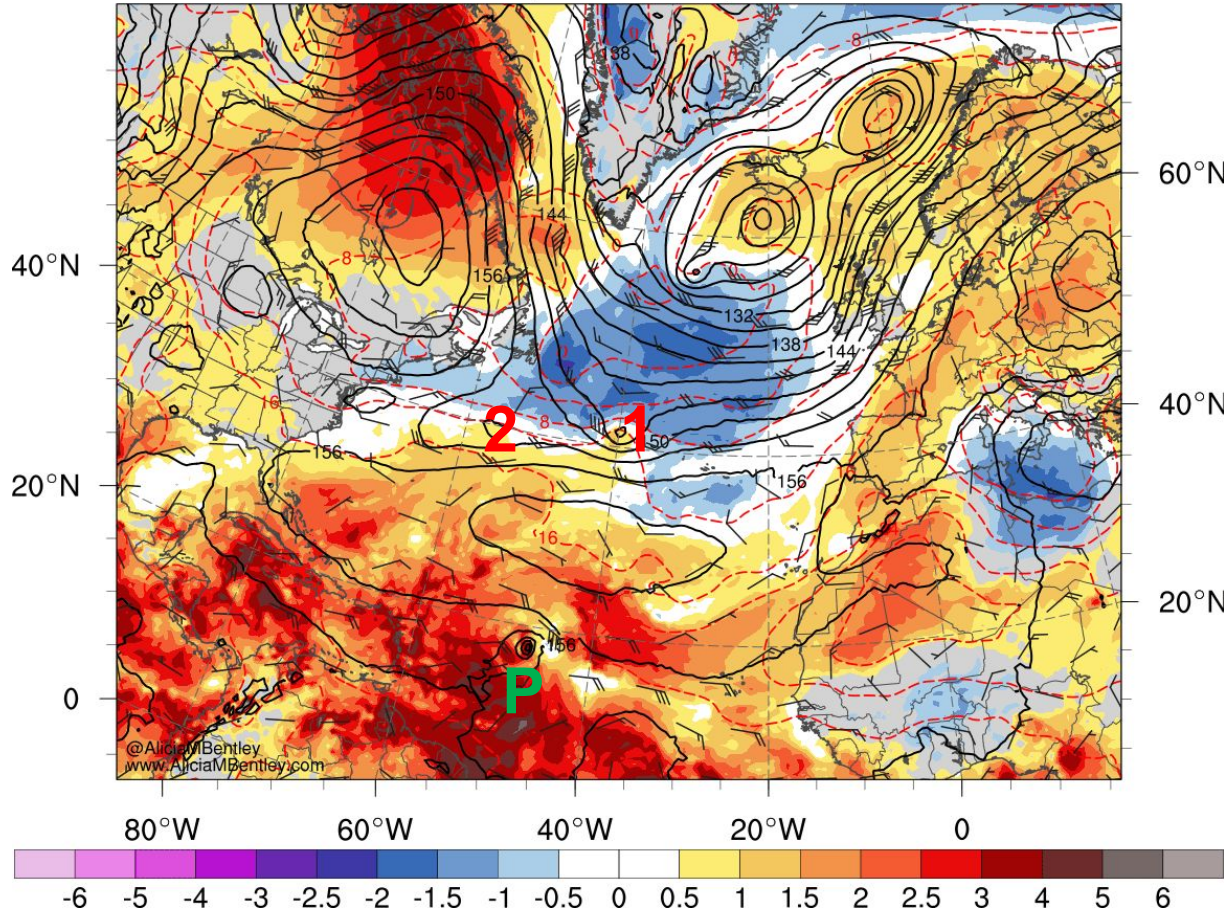
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
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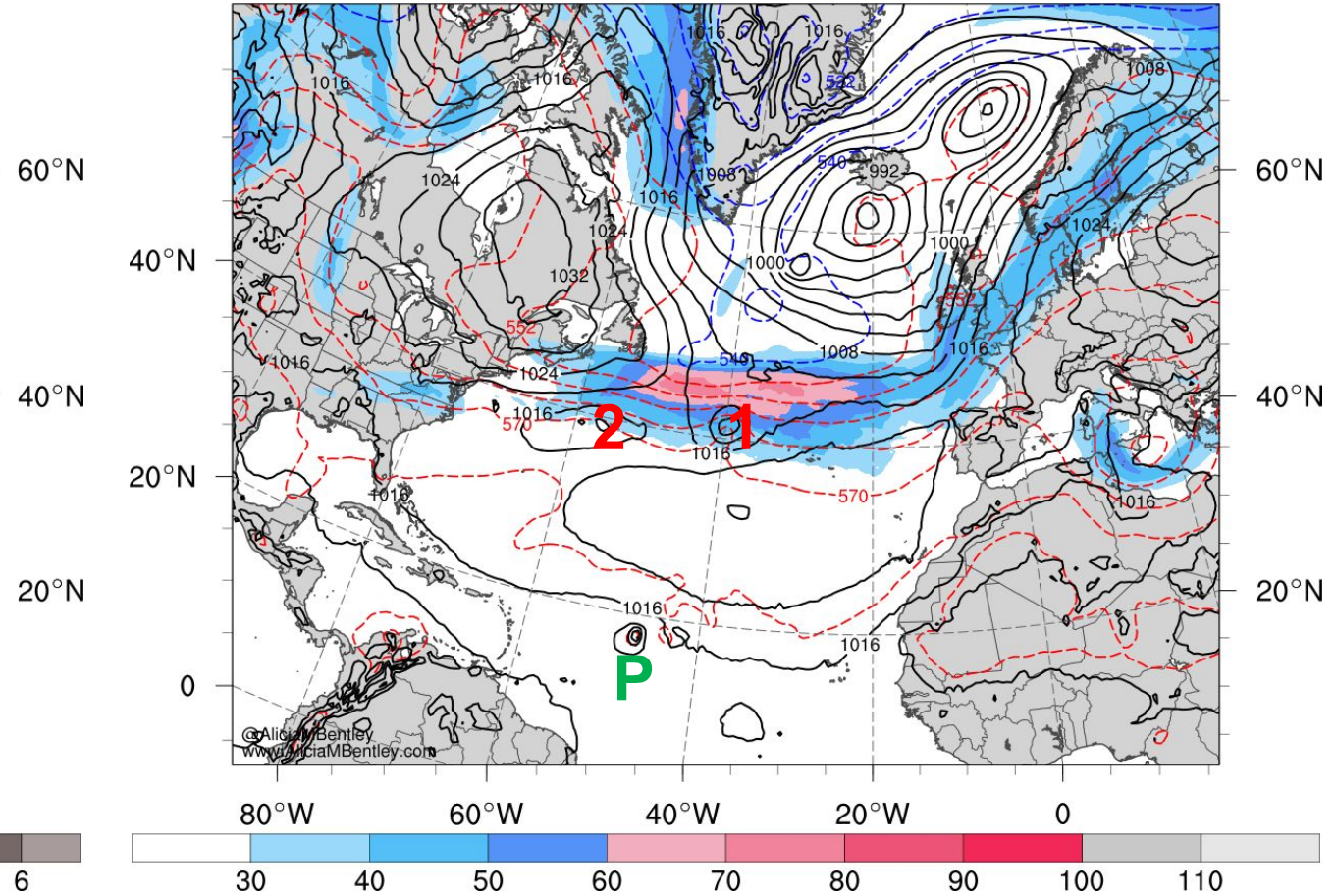
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850-hPa geo. height (black, dam), temp (red, C), wind (barbs, kt), standardized temp anomaly (shaded, sigma)  
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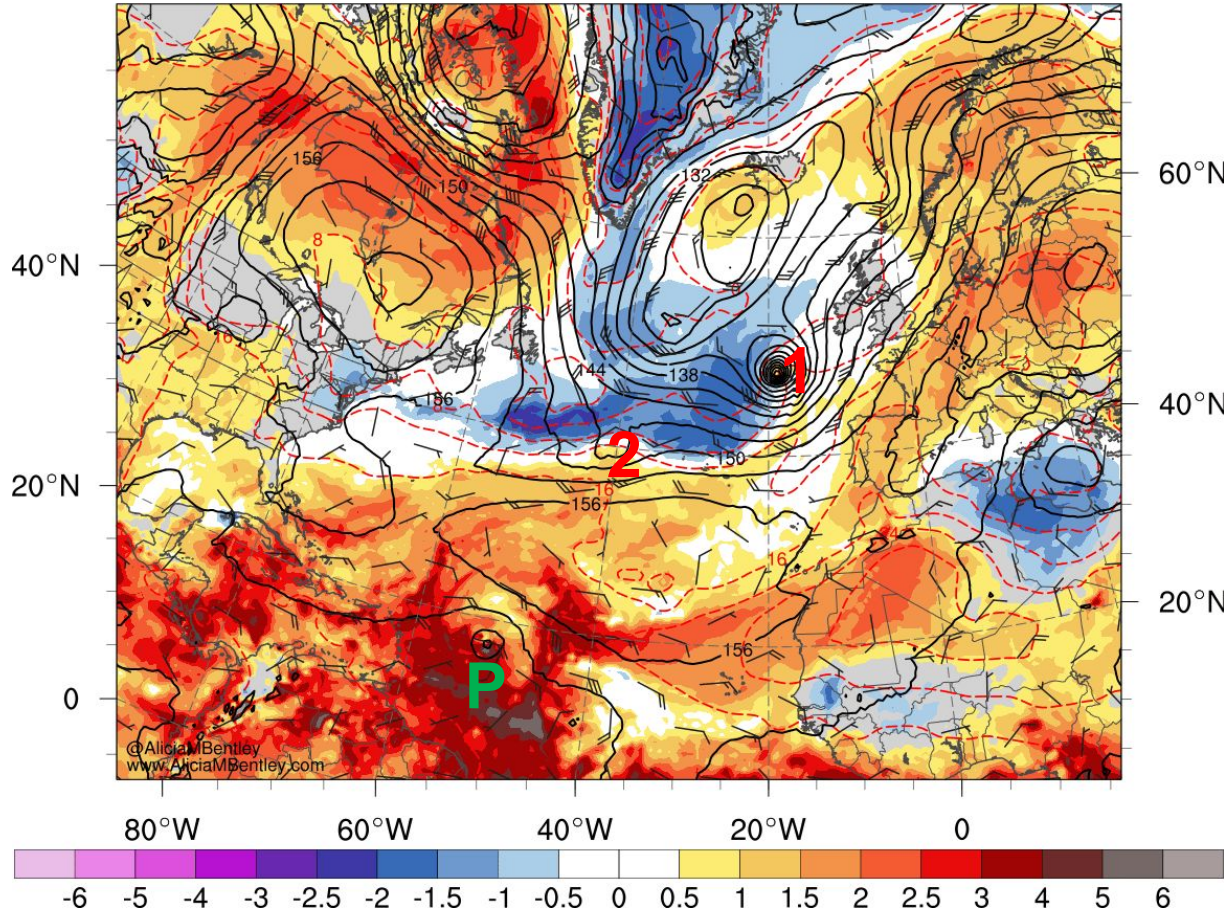
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
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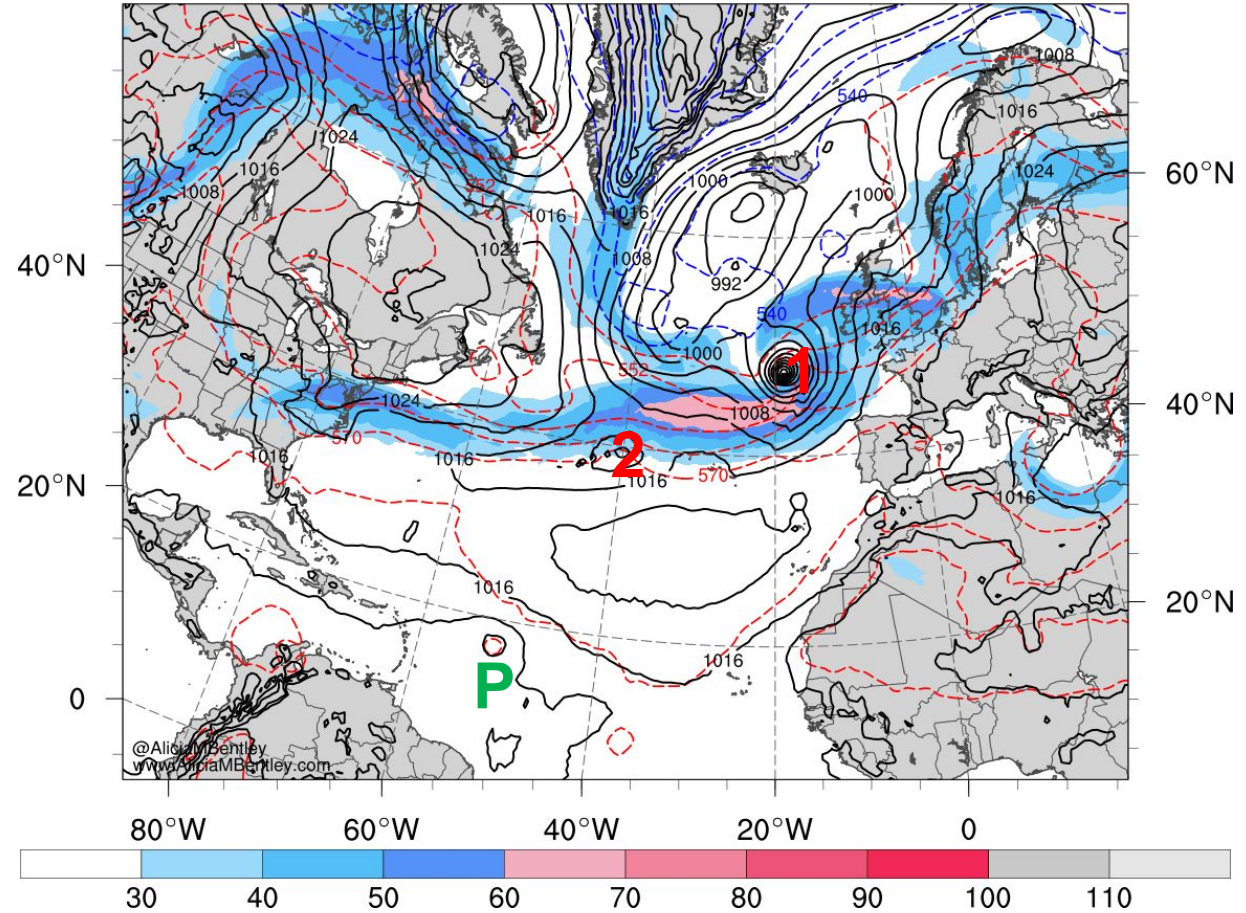
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850-hPa geo. height (black, dam), temp (red, C), wind (barbs, kt), standardized temp anomaly (shaded, sigma)  
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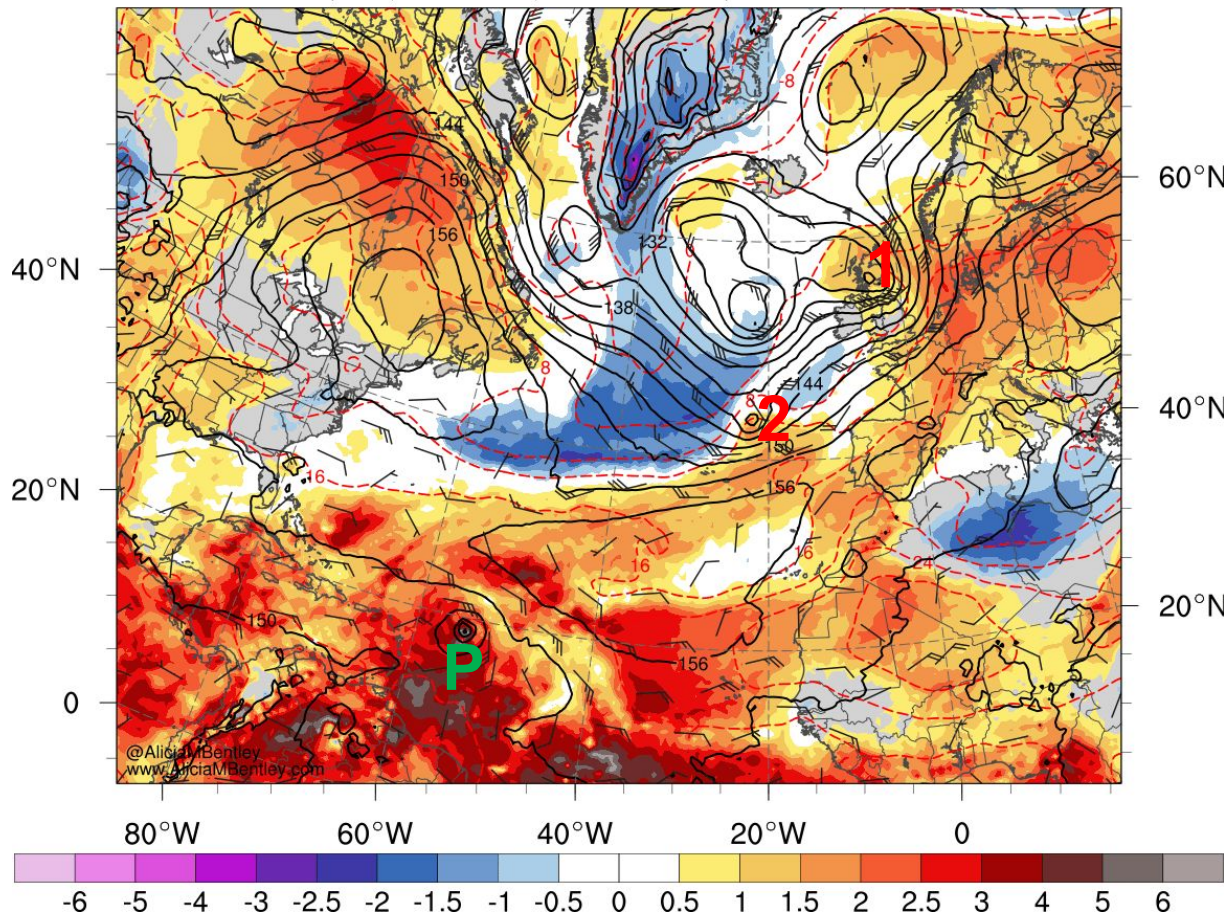
MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
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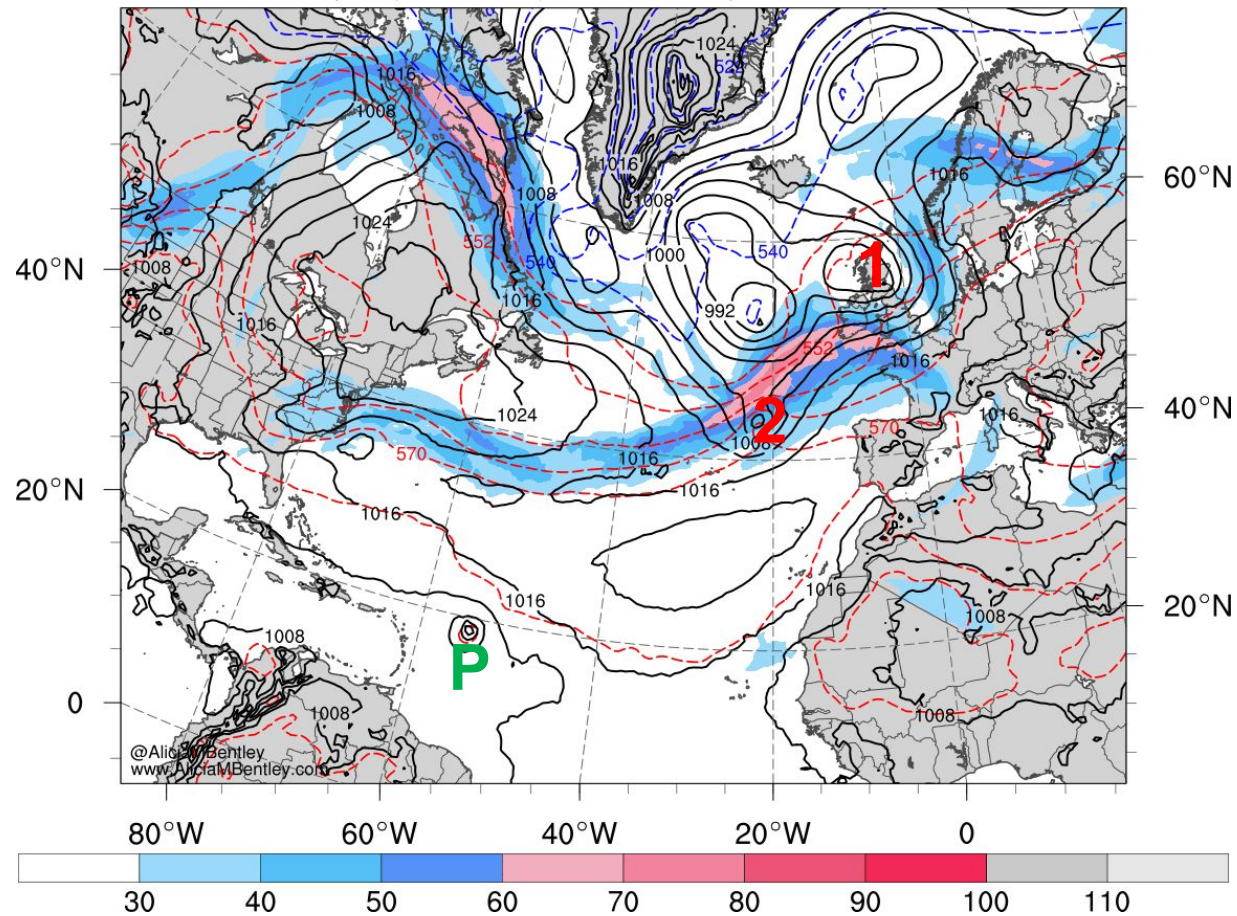
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Initialized: 0000 UTC 28 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 28 Sep 2023



**850-hPa Heights (black contours, dam)**  
**Standardized Temperature Anomalies (shaded, sigma)**  
**850-hPa Winds (barbs, kt)**

MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
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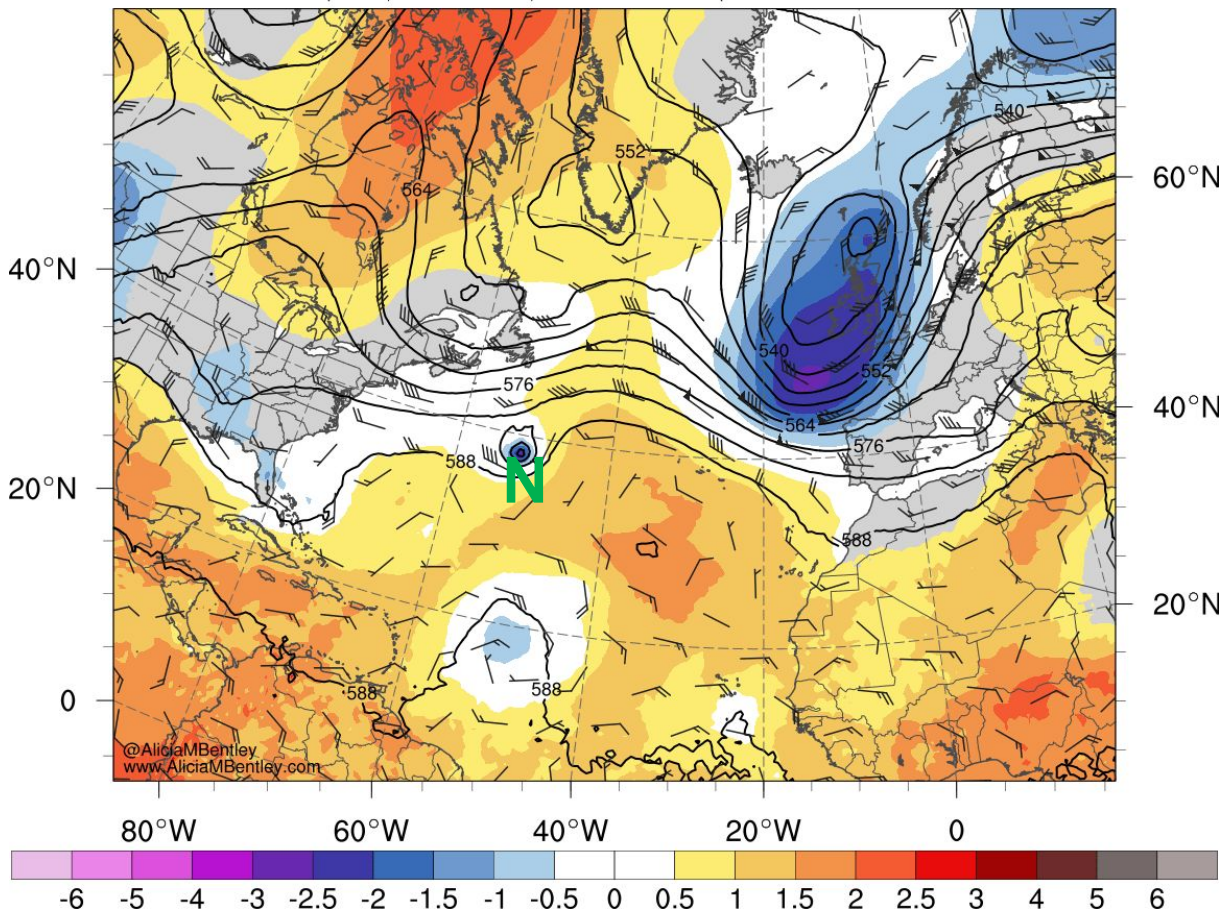


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**Loop of Standardized 500-hPa Heights, Winds, and  
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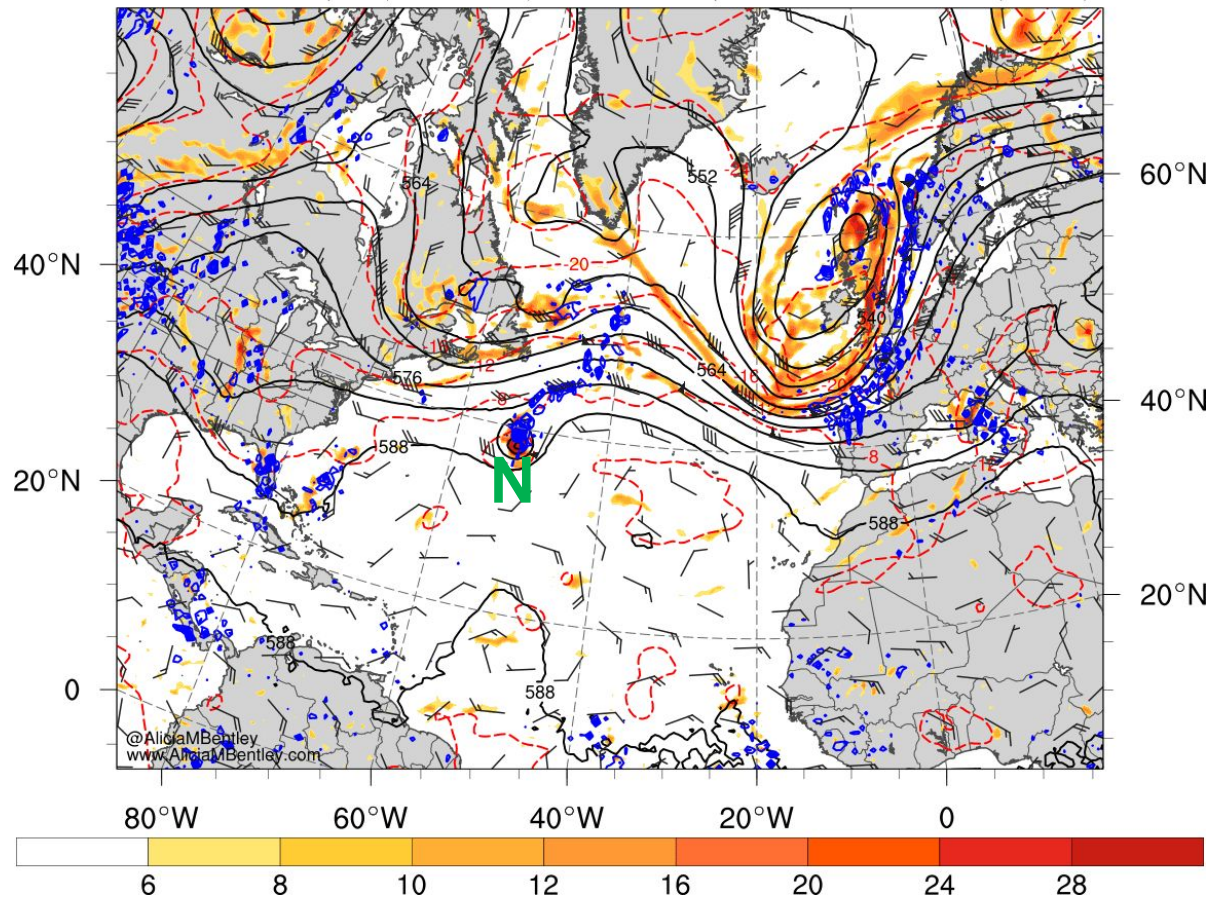
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500-hPa geo. height (black, dam), wind (barbs, kt), standardized geo. height anomaly (shaded, sigma)  
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**500-hPa Heights (black contours, dam)**  
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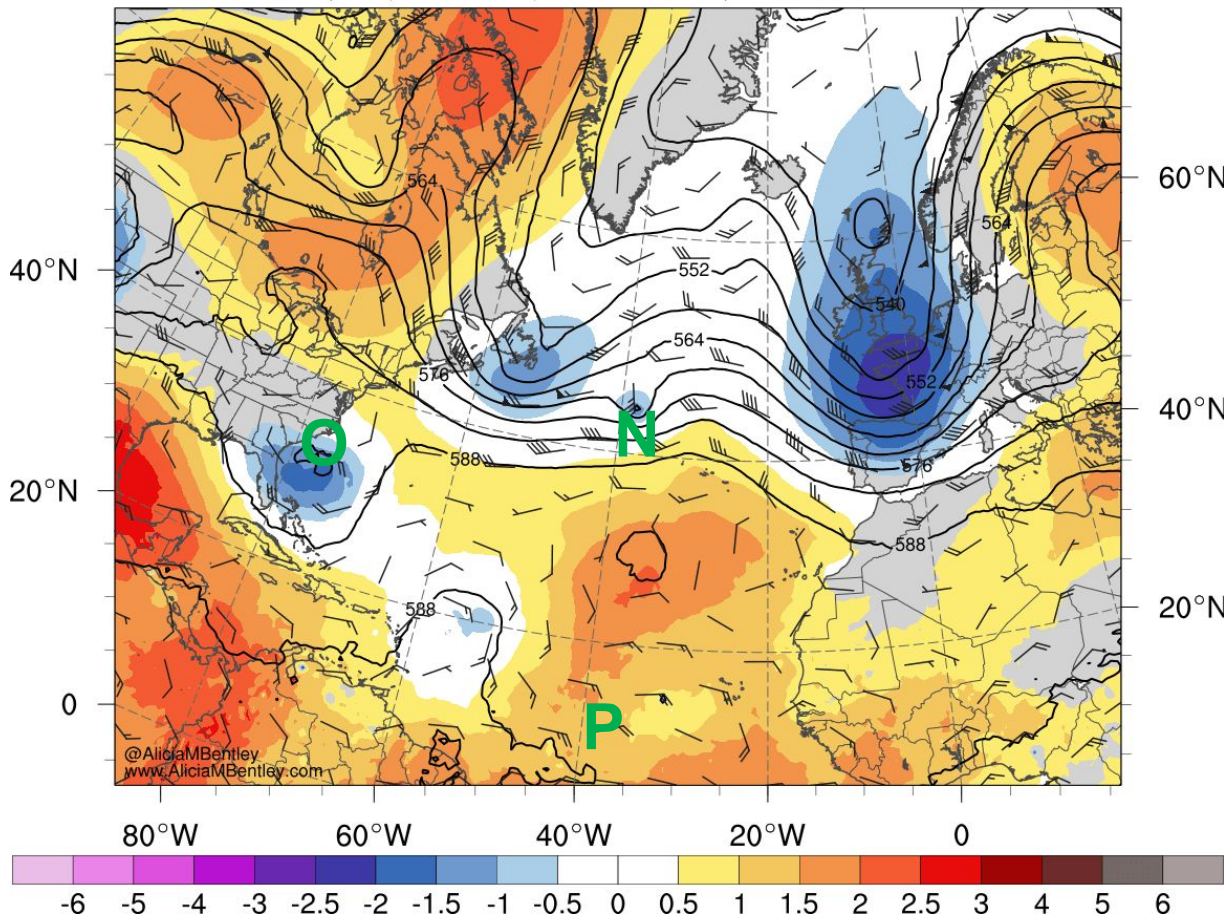
500-hPa geo. height (black, dam), temp. (red, C), ascent (blue,  $5 \times 10^{-3}$  hPa/s), cyc. rel. vort. ( $\times 10^{-5} \text{ s}^{-1}$ ), wind (barbs, kt)  
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**500-hPa Heights (black contours, dam)**  
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**Cyclonic Relative Vorticity (shaded,  $\times 10^{-5} \text{ s}^{-1}$ )**  
**500-hPa Ascent (blue,  $5 \times 10^{-3} \text{ hPa s}^{-1}$ )**

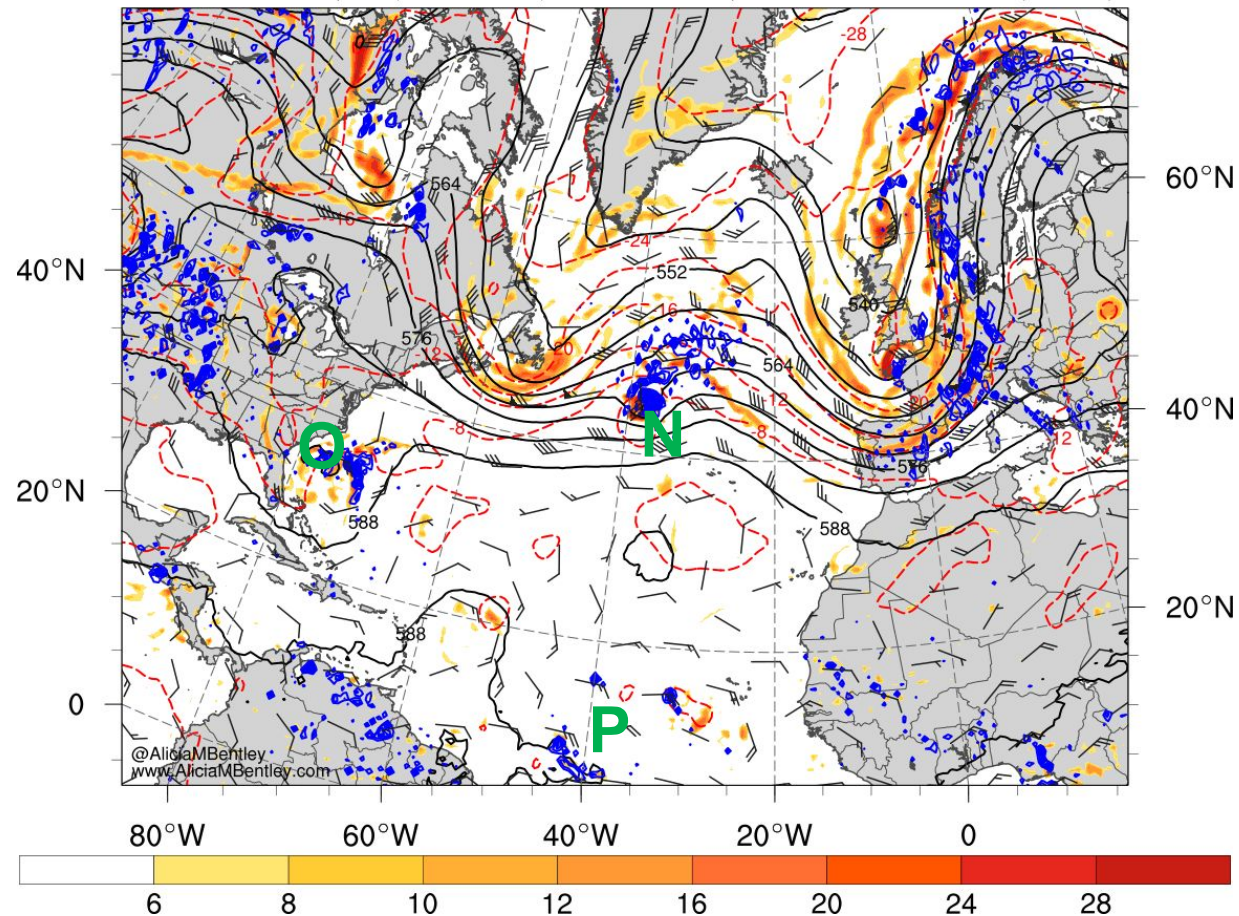
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500-hPa geo. height (black, dam), wind (barbs, kt), standardized geo. height anomaly (shaded, sigma)  
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**500-hPa Heights (black contours, dam)**  
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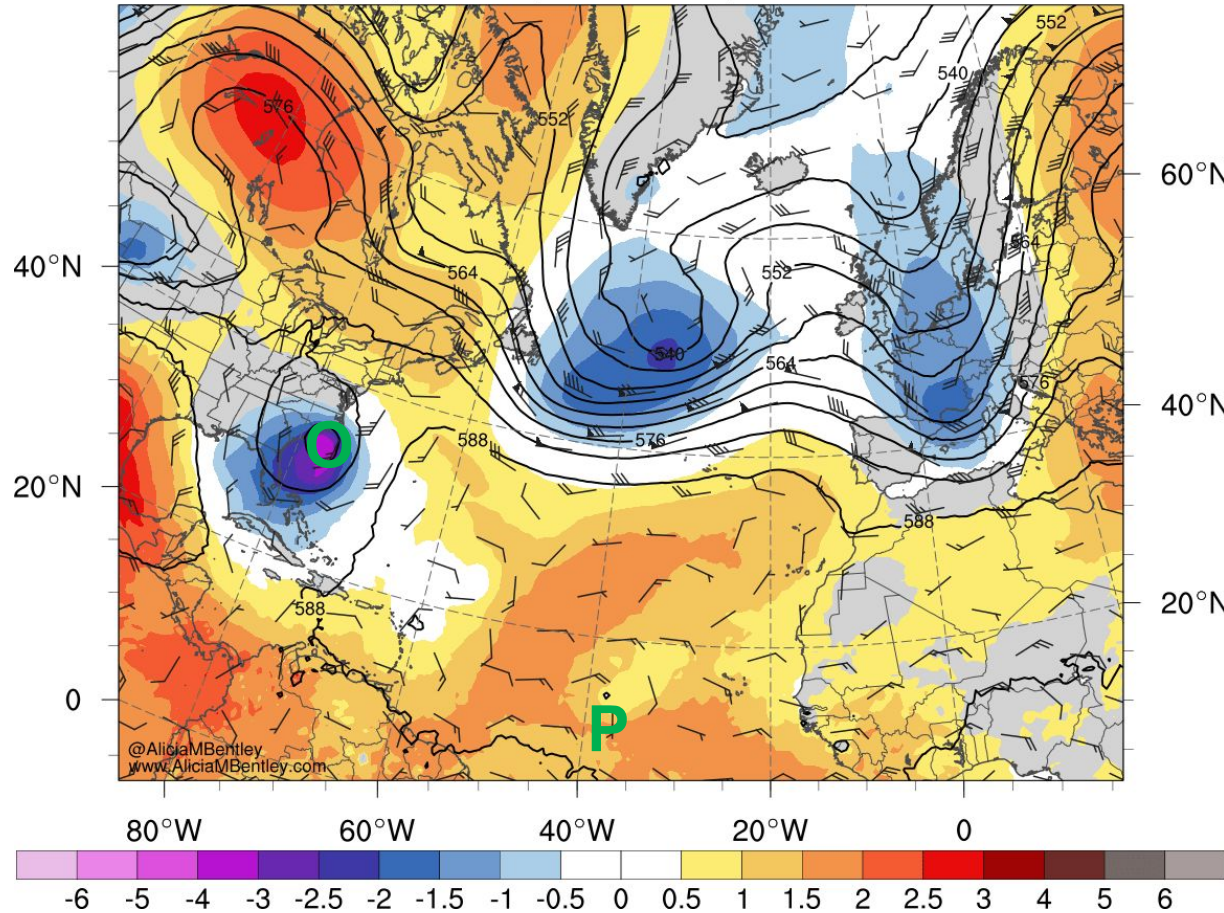
500-hPa geo. height (black, dam), temp. (red, C), ascent (blue,  $5 \times 10^{-3}$  hPa/s), cyc. rel. vort. ( $\times 10^{-5} \text{ s}^{-1}$ ), wind (barbs, kt)  
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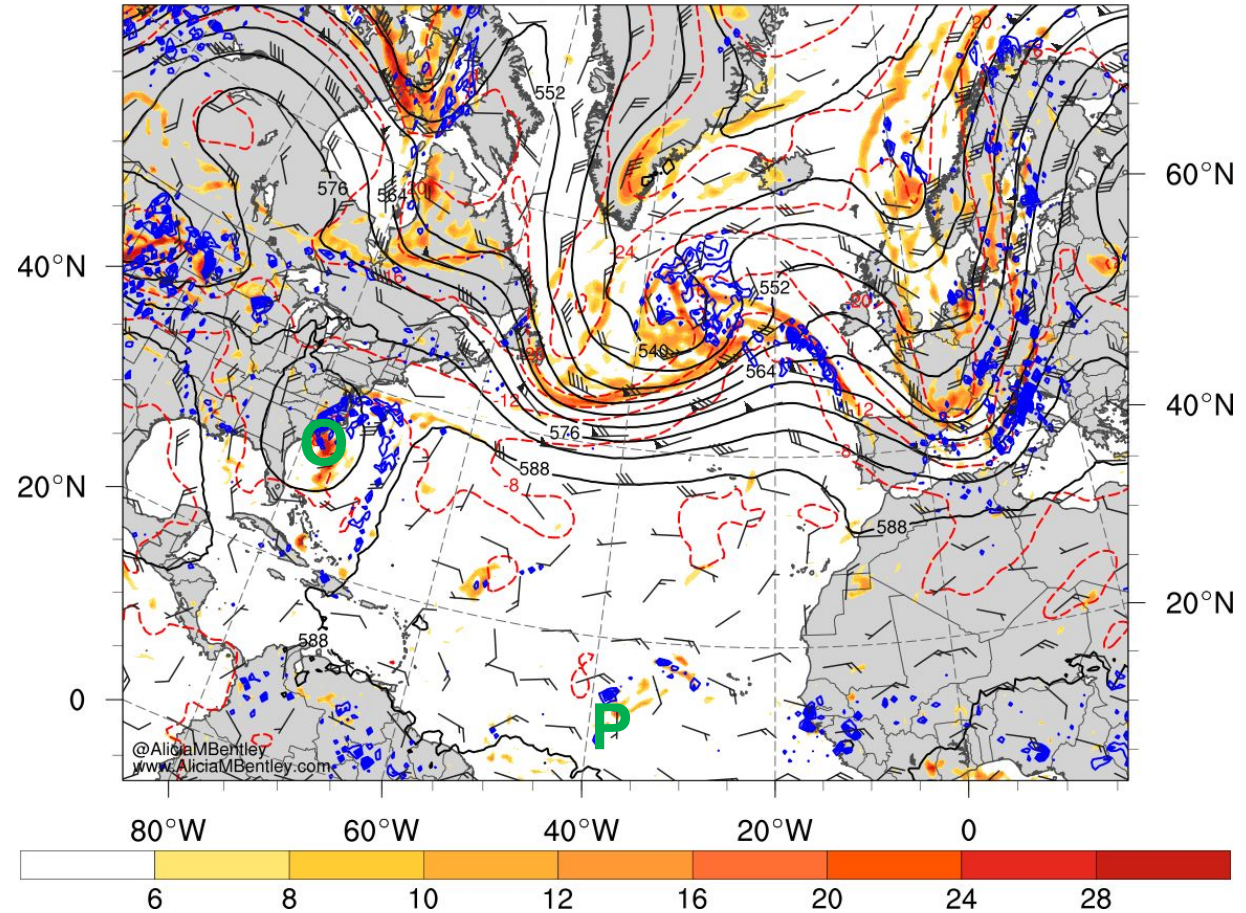
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500-hPa geo. height (black, dam), wind (barbs, kt), standardized geo. height anomaly (shaded, sigma)  
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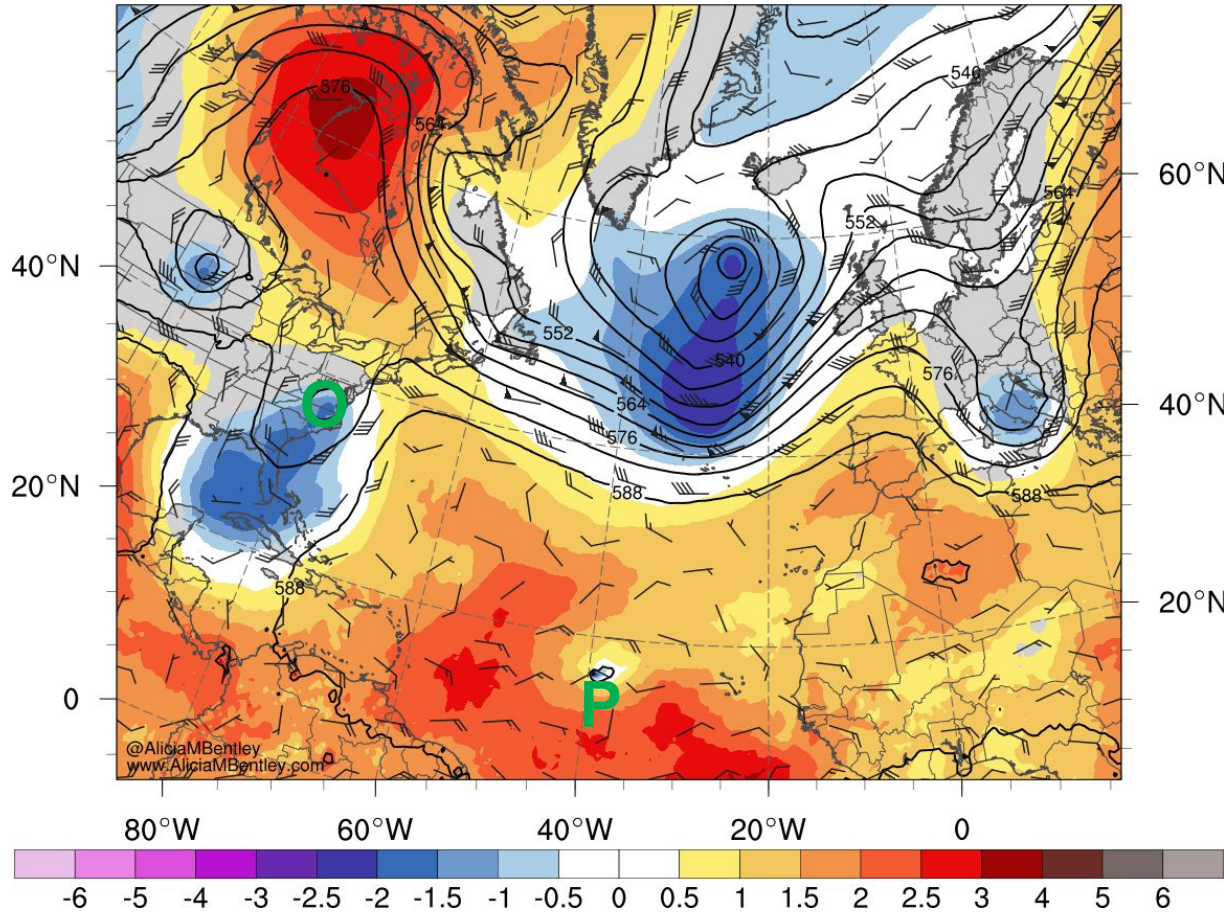


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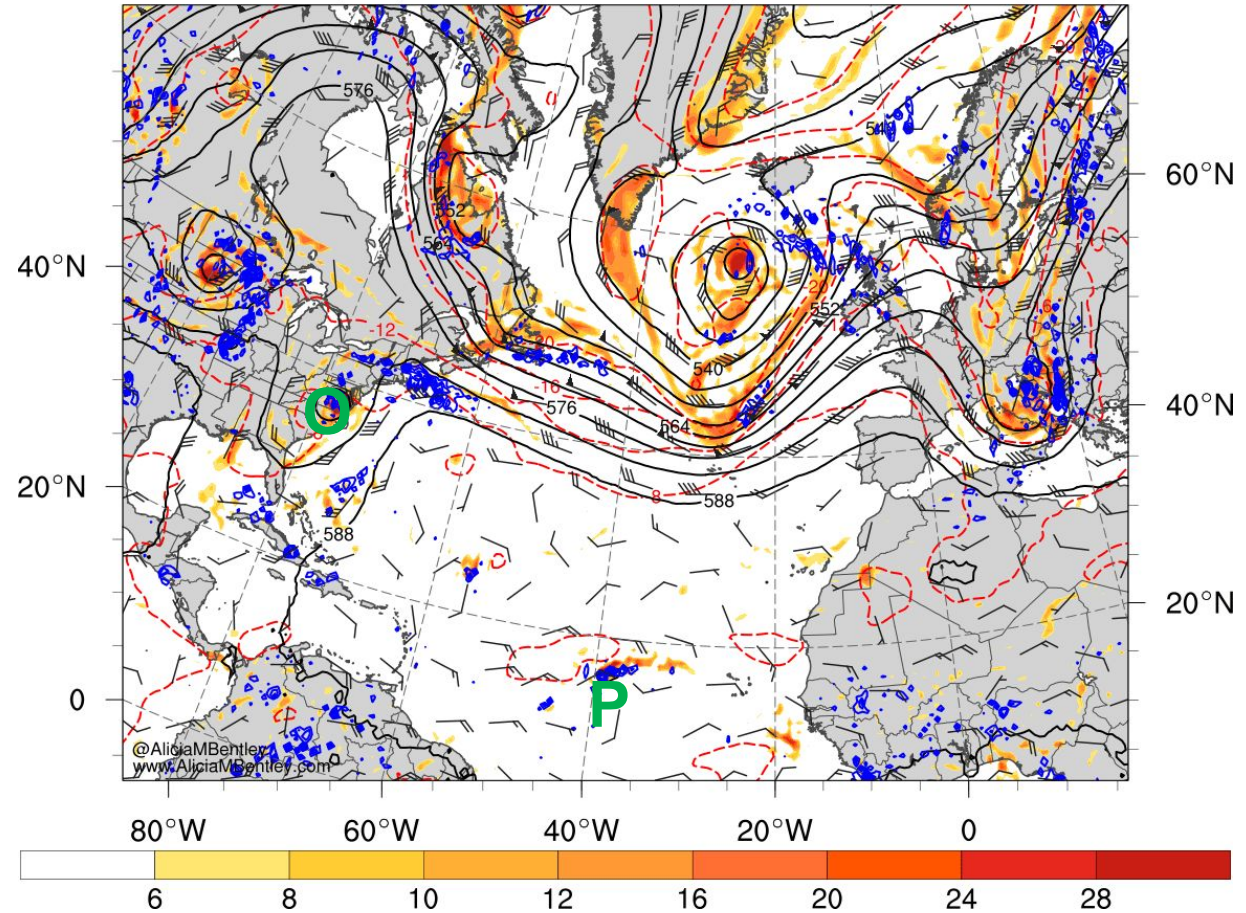
# Valid: 0000 UTC 24 September 2023

500-hPa geo. height (black, dam), wind (barbs, kt), standardized geo. height anomaly (shaded, sigma)  
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500-hPa Heights (black contours, dam)  
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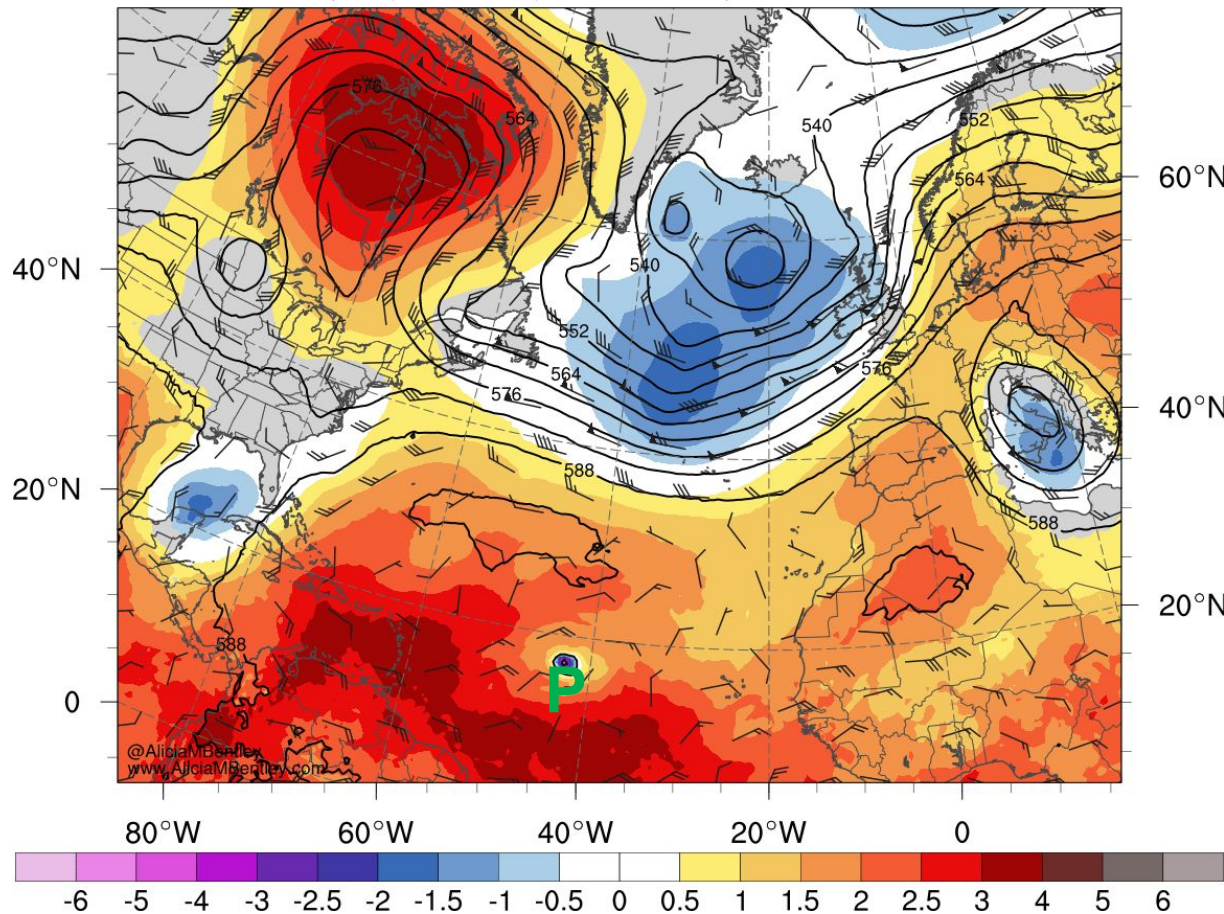
500-hPa geo. height (black, dam), temp. (red, C), ascent (blue,  $5 \times 10^{-3}$  hPa/s), cyc. rel. vort. ( $\times 10^{-5} \text{ s}^{-1}$ ), wind (barbs, kt)  
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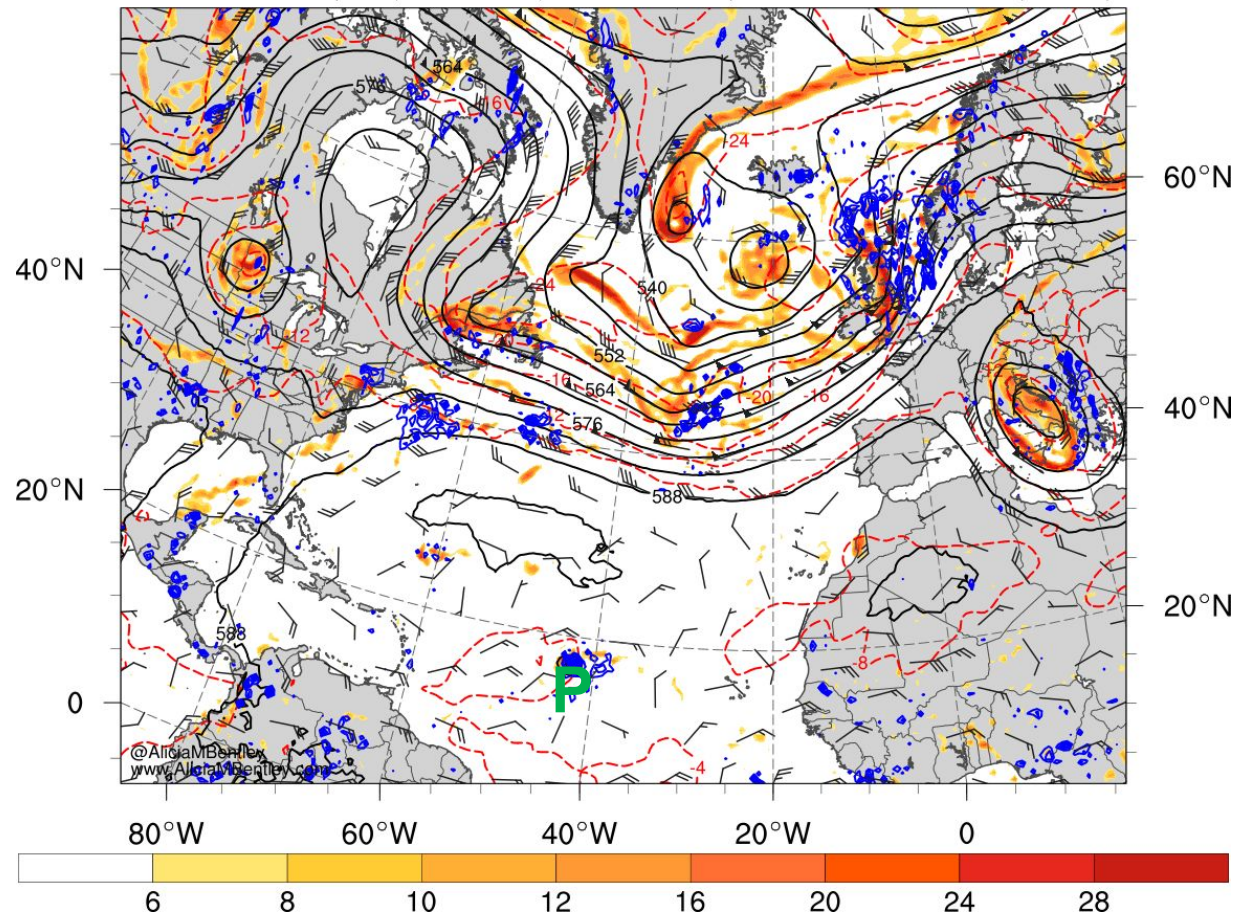
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500-hPa geo. height (black, dam), wind (barbs, kt), standardized geo. height anomaly (shaded, sigma)  
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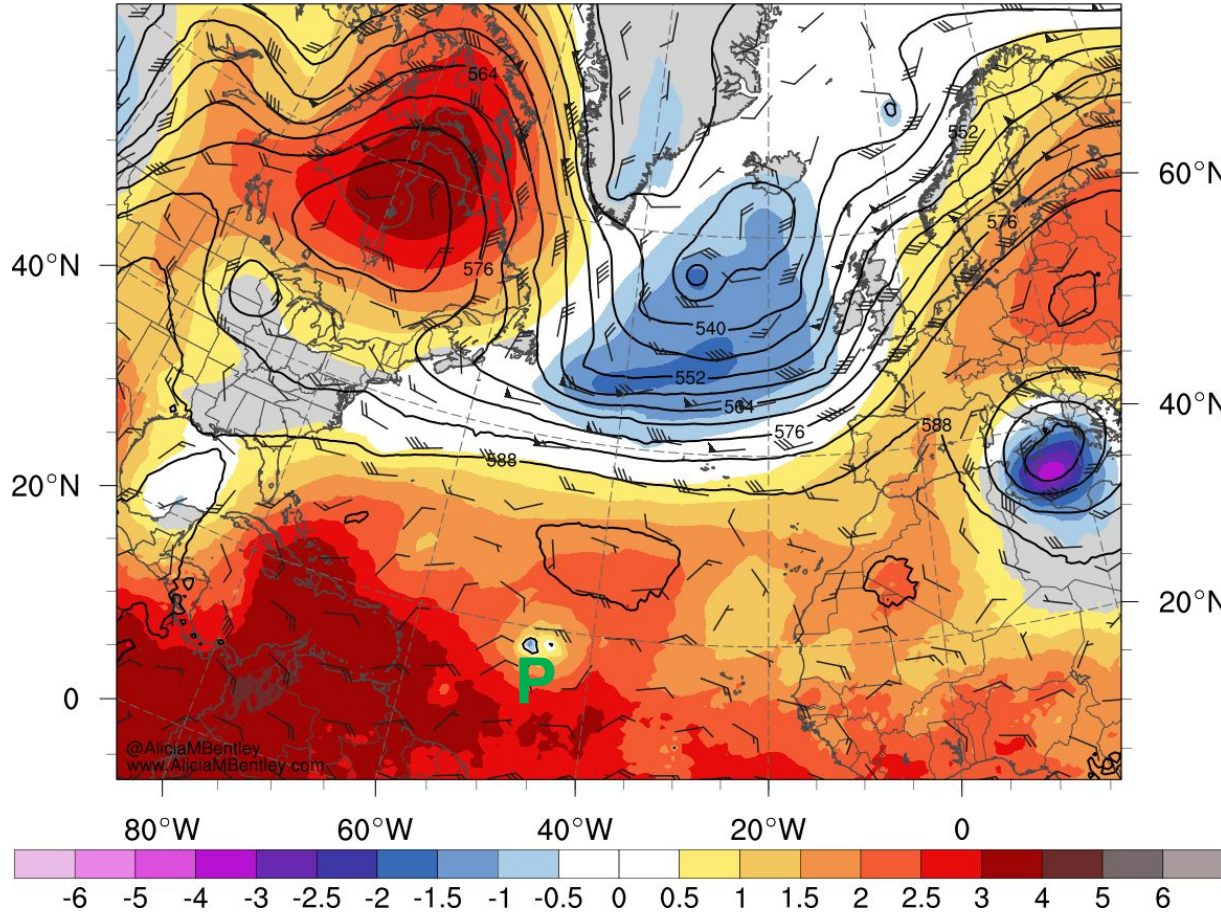
500-hPa geo. height (black, dam), temp. (red, C), ascent (blue,  $5 \times 10^{-3}$  hPa/s), cyc. rel. vort. ( $\times 10^{-5} \text{ s}^{-1}$ ), wind (barbs, kt)  
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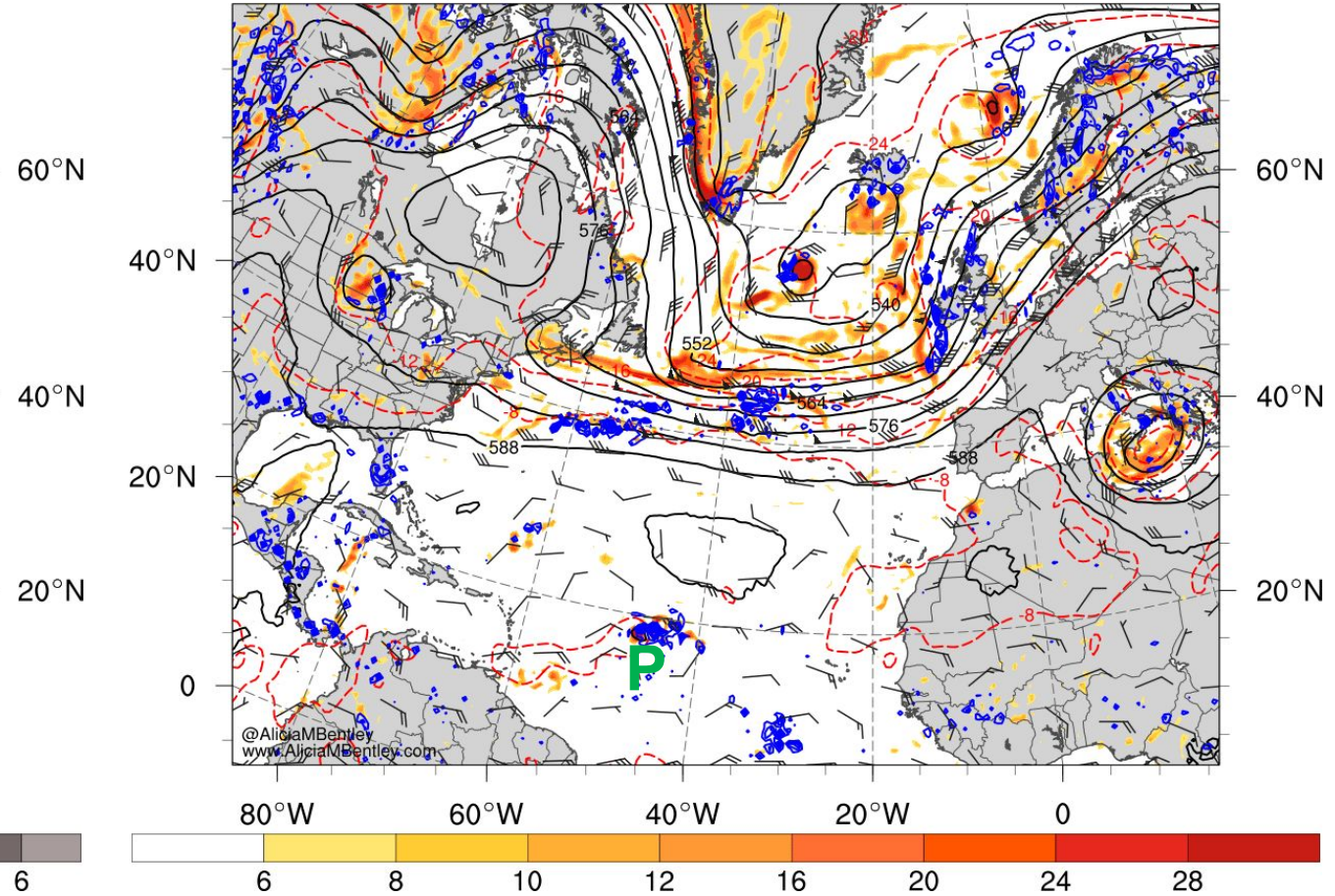
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500-hPa geo. height (black, dam), wind (barbs, kt), standardized geo. height anomaly (shaded, sigma)  
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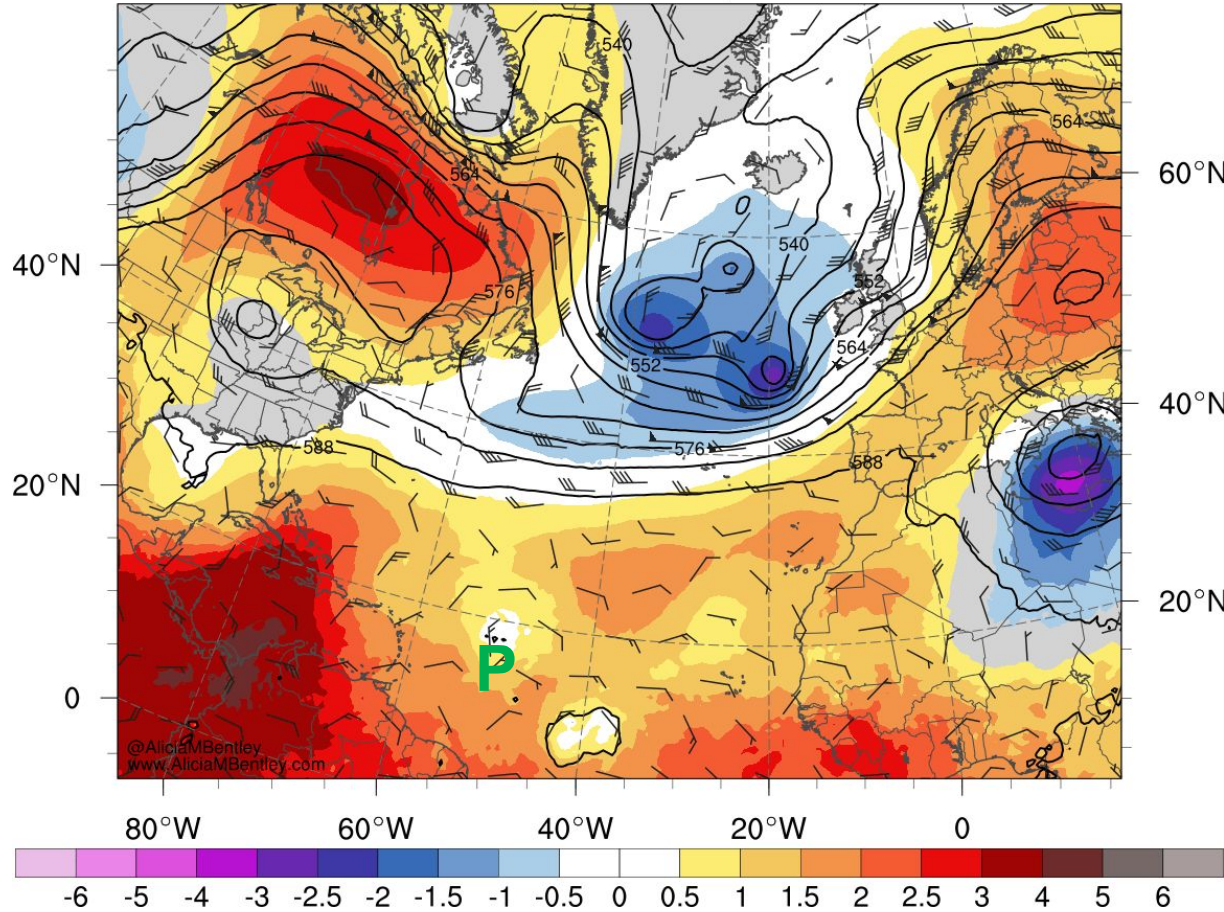
500-hPa geo. height (black, dam), temp. (red, C), ascent (blue,  $5 \times 10^{-3}$  hPa/s), cyc. rel. vort. ( $\times 10^{-5}$  s $^{-1}$ ), wind (barbs, kt)  
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500-hPa Heights (black contours, dam)  
500-hPa Temperatures (red contours, C)  
Cyclonic Relative Vorticity (shaded,  $\times 10^{-5}$  s $^{-1}$ )  
500-hPa Ascent (blue,  $5 \times 10^{-3}$  hPa s $^{-1}$ )

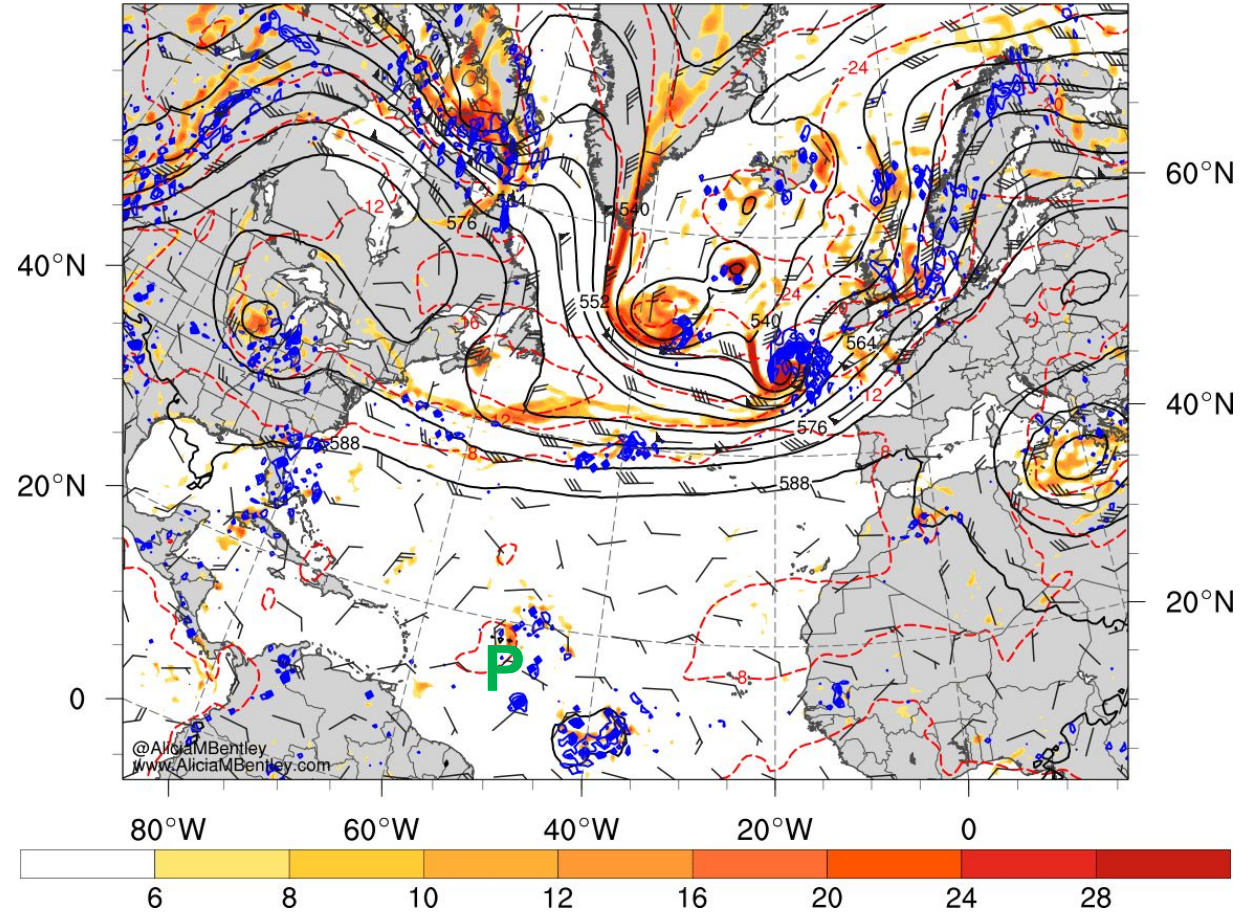
# Valid: 0000 UTC 27 September 2023

500-hPa geo. height (black, dam), wind (barbs, kt), standardized geo. height anomaly (shaded, sigma)  
Initialized: 0000 UTC 27 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 27 Sep 2023



500-hPa Heights (black contours, dam)  
Standardized Height Anomalies (shaded, sigma)  
500-hPa Winds (barbs, kt)

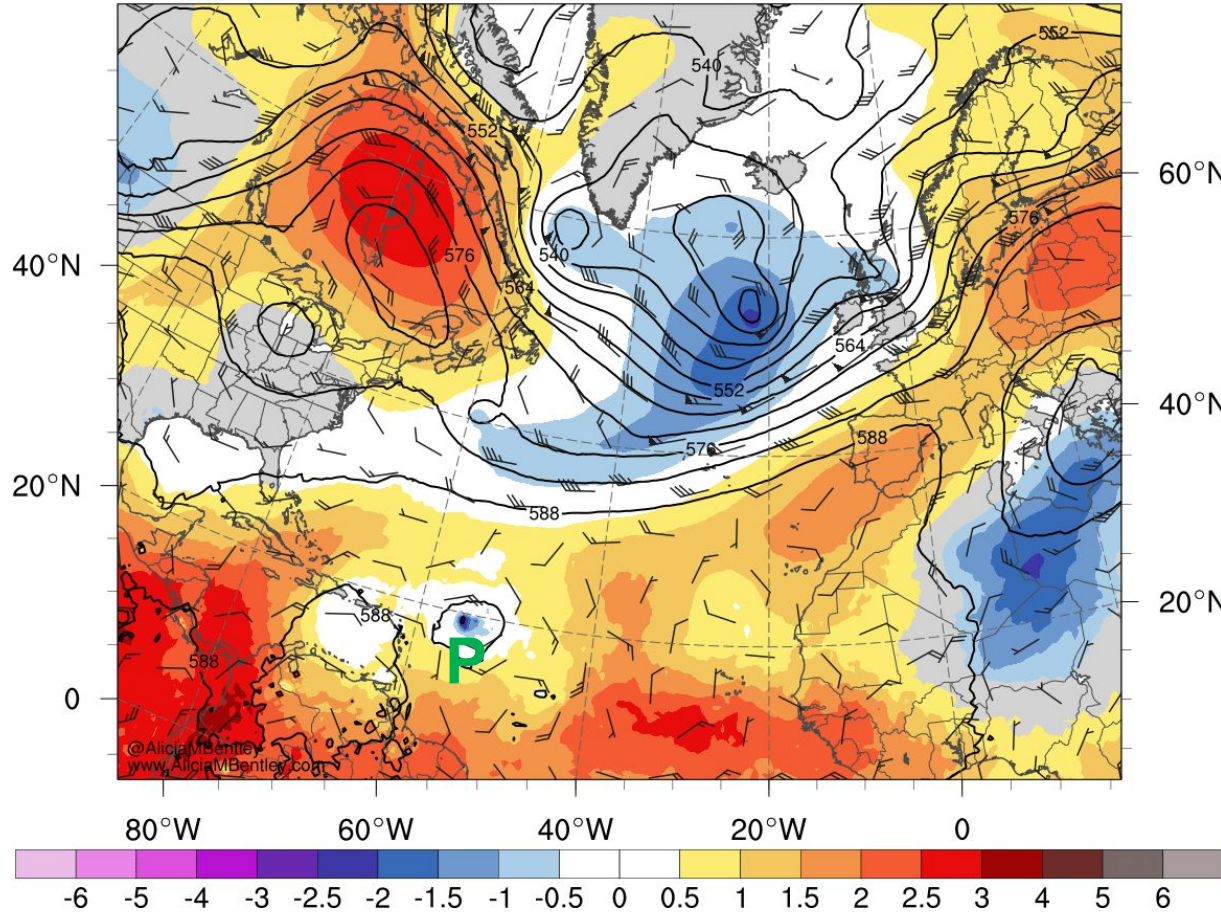
500-hPa geo. height (black, dam), temp. (red, C), ascent (blue,  $5 \times 10^{-3}$  hPa/s), cyc. rel. vort. ( $\times 10^{-5}$  s $^{-1}$ ), wind (barbs, kt)  
Initialized: 0000 UTC 27 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 27 Sep 2023



500-hPa Heights (black contours, dam)  
500-hPa Temperatures (red contours, C)  
Cyclonic Relative Vorticity (shaded,  $\times 10^{-5}$  s $^{-1}$ )  
500-hPa Ascent (blue,  $5 \times 10^{-3}$  hPa s $^{-1}$ )

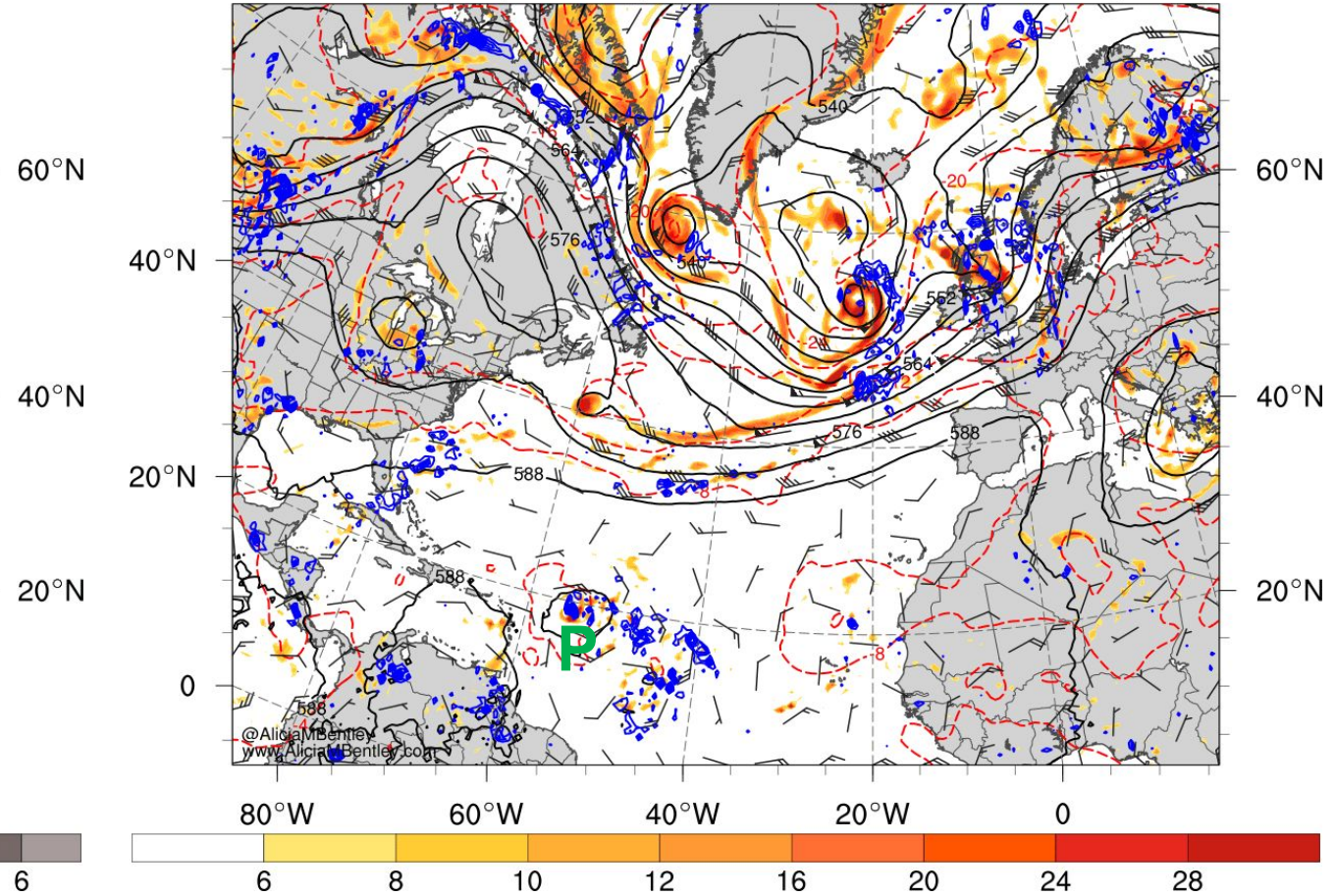
# Valid 0000: UTC 28 September 2023

500-hPa geo. height (black, dam), wind (barbs, kt), standardized geo. height anomaly (shaded, sigma)  
Initialized: 0000 UTC 28 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 28 Sep 2023



**500-hPa Heights (black contours, dam)**  
**Standardized Height Anomalies (shaded, sigma)**  
**500-hPa Winds (barbs, kt)**

500-hPa geo. height (black, dam), temp. (red, C), ascent (blue,  $5 \times 10^{-3}$  hPa/s), cyc. rel. vort. ( $\times 10^{-5} \text{ s}^{-1}$ ), wind (barbs, kt)  
Initialized: 0000 UTC 28 Sep 2023 | Forecast hour: 0 | Valid: 0000 UTC 28 Sep 2023



**500-hPa Heights (black contours, dam)**  
**500-hPa Temperatures (red contours, C)**  
**Cyclonic Relative Vorticity (shaded,  $\times 10^{-5} \text{ s}^{-1}$ )**  
**500-hPa Ascent (blue,  $5 \times 10^{-3} \text{ hPa s}^{-1}$ )**

# Key Takeaways

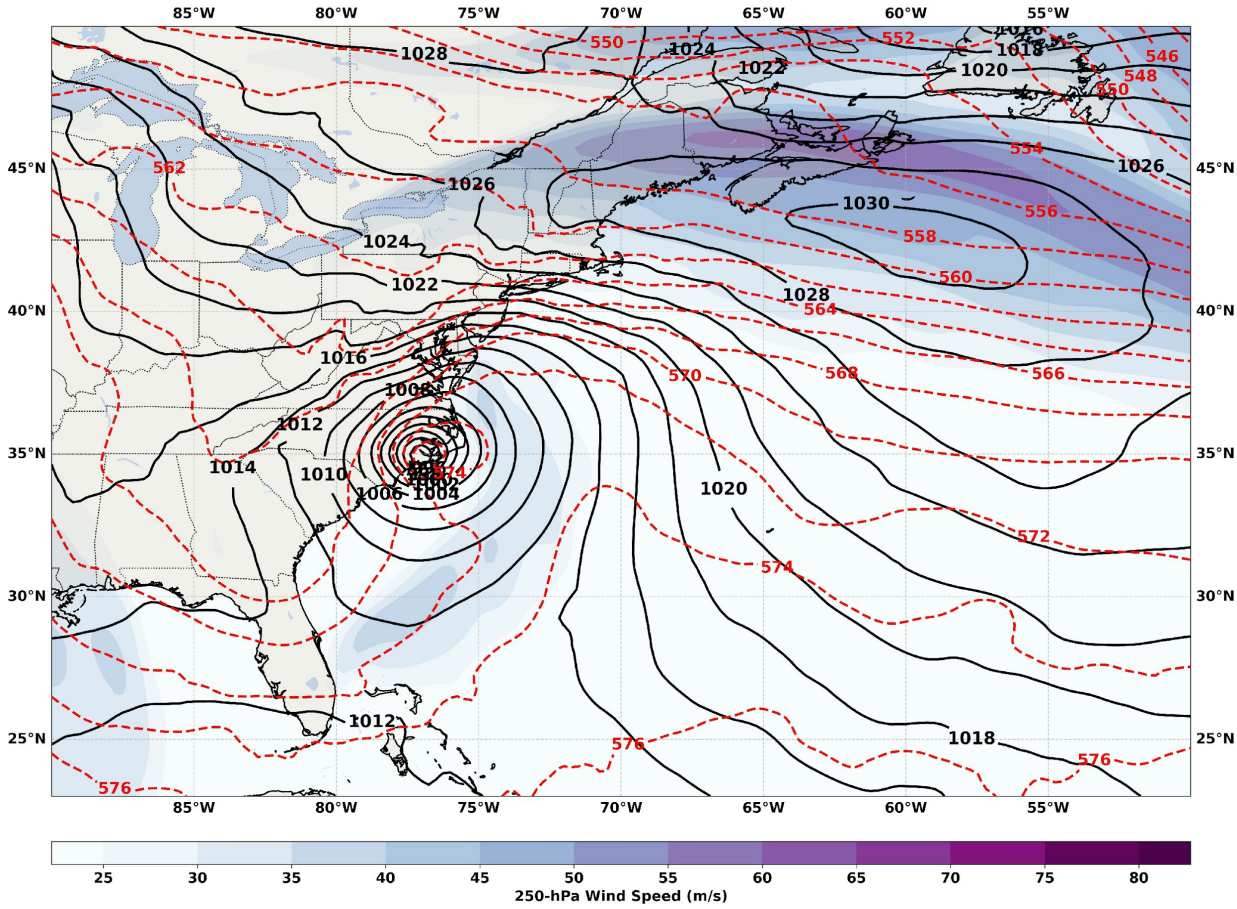
- **TC Lee impacted Atlantic Canada with high winds and heavy rain**
- **TC Lee underwent ET over the WATL and brought heavy rains to the UK**
- **TC Nigel underwent a strong ET and brought heavy rains/wind to the UK**
- **TC Ophelia produced very heavy rains from the Carolinas to New England**
- **TC Ophelia “seeded” two WATL extratropical cyclones that impacted the UK**
- **TC Ophelia-seeded bomb cyclone (EC Agnes) wreaked havoc across the UK**
- **TC Lee, Nigel, and Ophelia remnants collectively sustained a NE NATL gyre**

# **Development of Mesoscale Frontal Wave Number One (MFW1):**

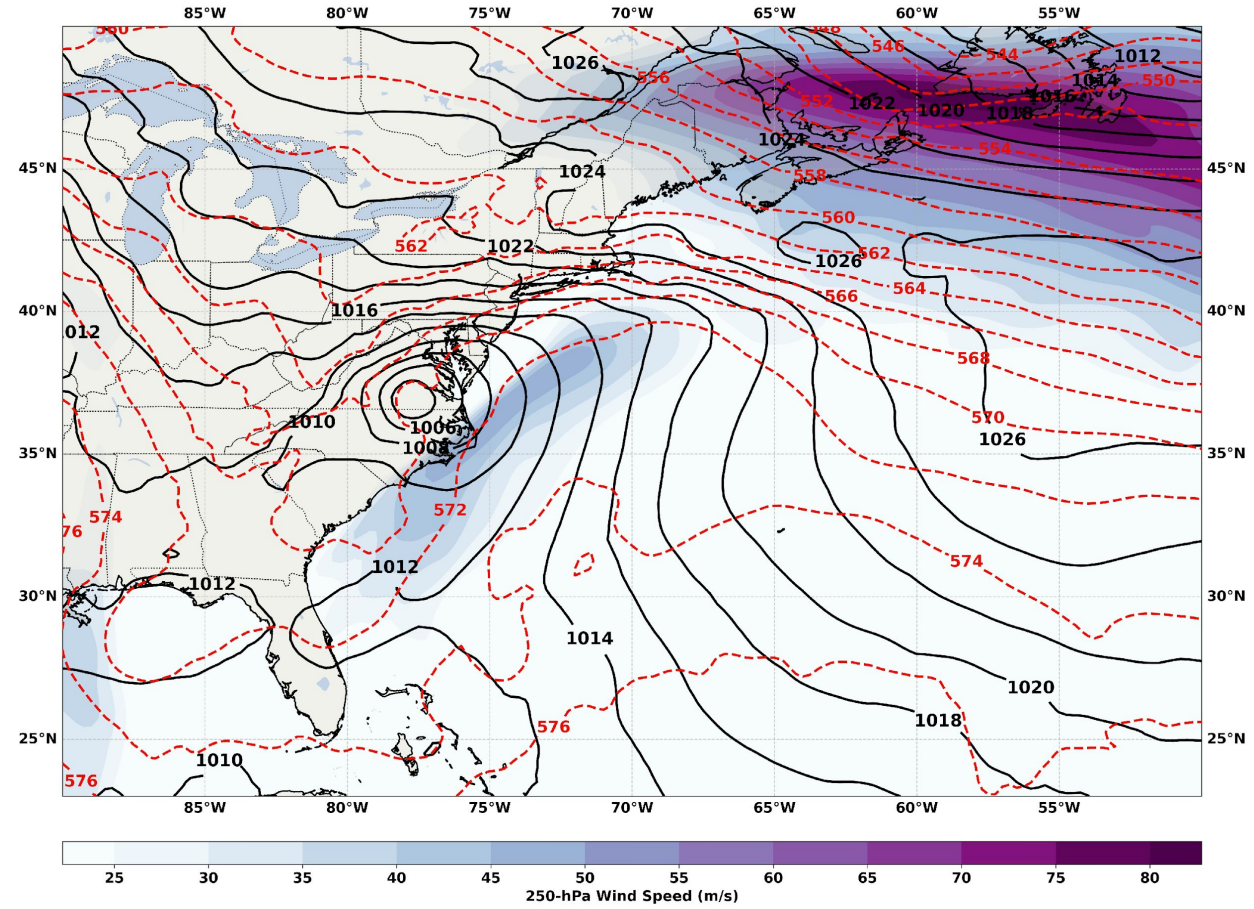
# MSLP (Contours, hPa) and 1000–500-hPa Thickness (dam) and 250-hPa Winds (m s<sup>-1</sup>)

## valid 12 UTC 23 Sep 2023 (left) and 0000 UTC 24 Sep 2023 (right)

MSLP (contours, hPa), 1000–500-hPa Thickness (red/blue, dam) & 250-hPa winds (shaded, m/s)  
Valid at 2023-09-23 12:00:00



MSLP (contours, hPa), 1000–500-hPa Thickness (red/blue, dam) & 250-hPa winds (shaded, m/s)  
Valid at 2023-09-24 00:00:00

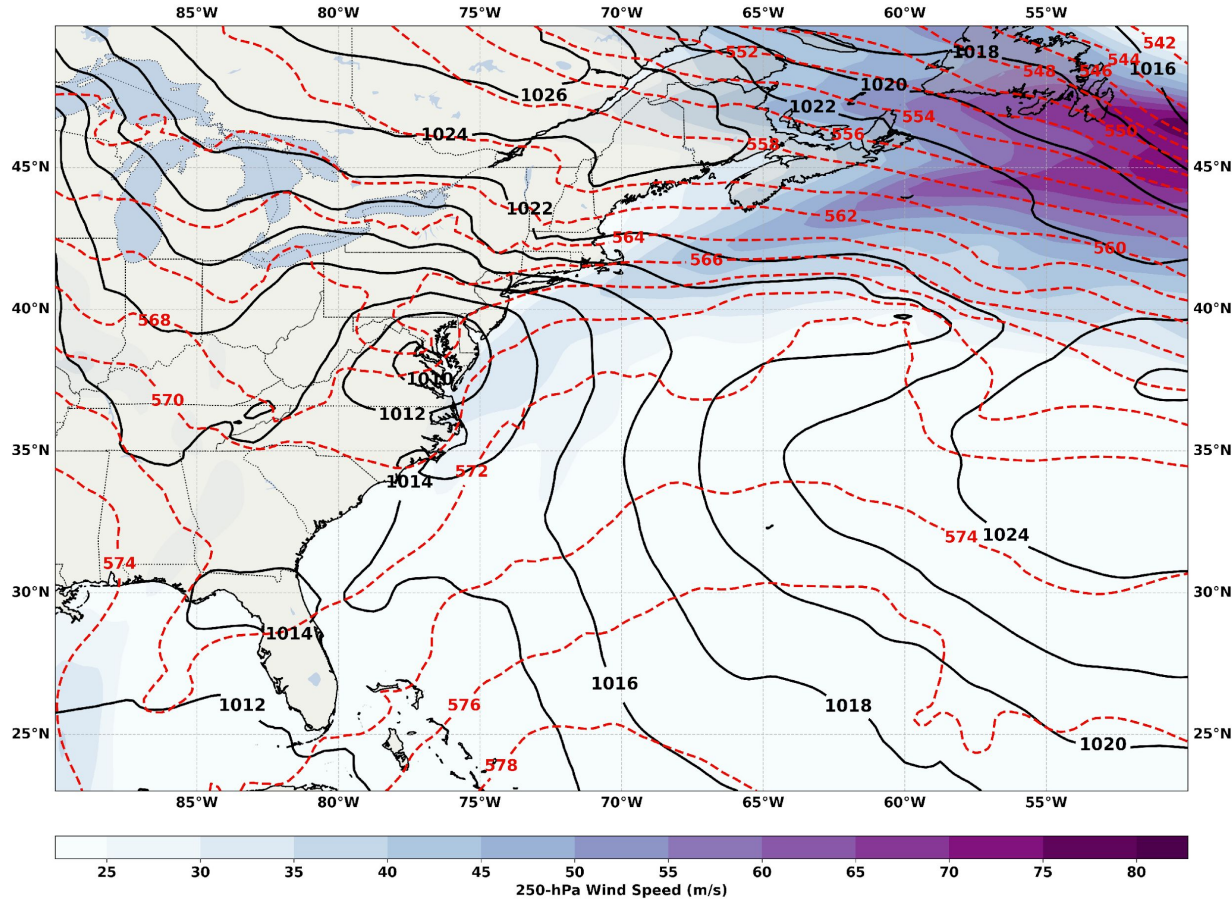




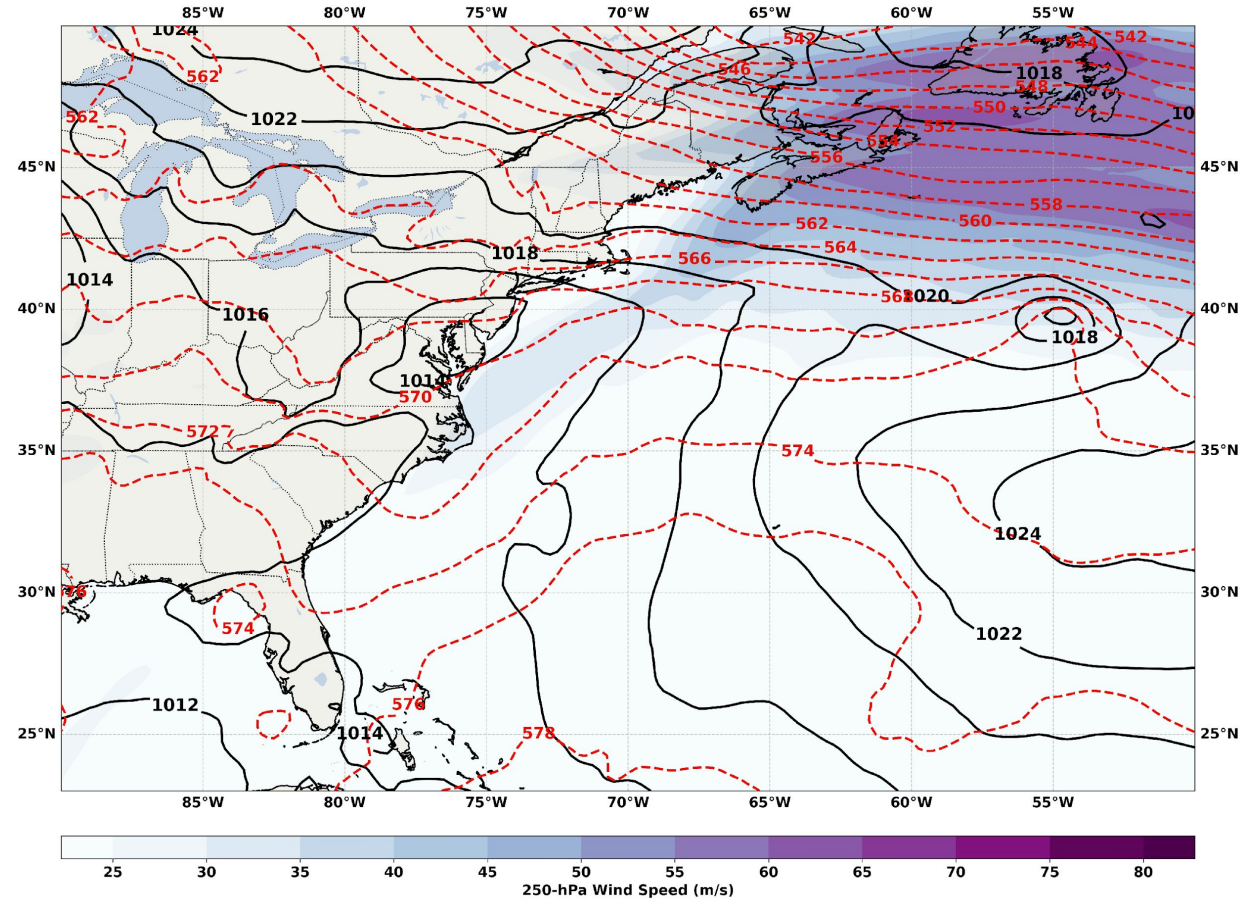
# MSLP (Contours, hPa) and 1000–500-hPa Thickness (dam) and 250-hPa Winds ( $m s^{-1}$ )

## valid 12 UTC 23 Sep 2023 (left) and 0000 UTC 24 Sep 2023 (right)

MSLP (contours, hPa), 1000–500-hPa Thickness (red/blue, dam) & 250-hPa winds (shaded, m/s)  
Valid at 2023-09-24 12:00:00



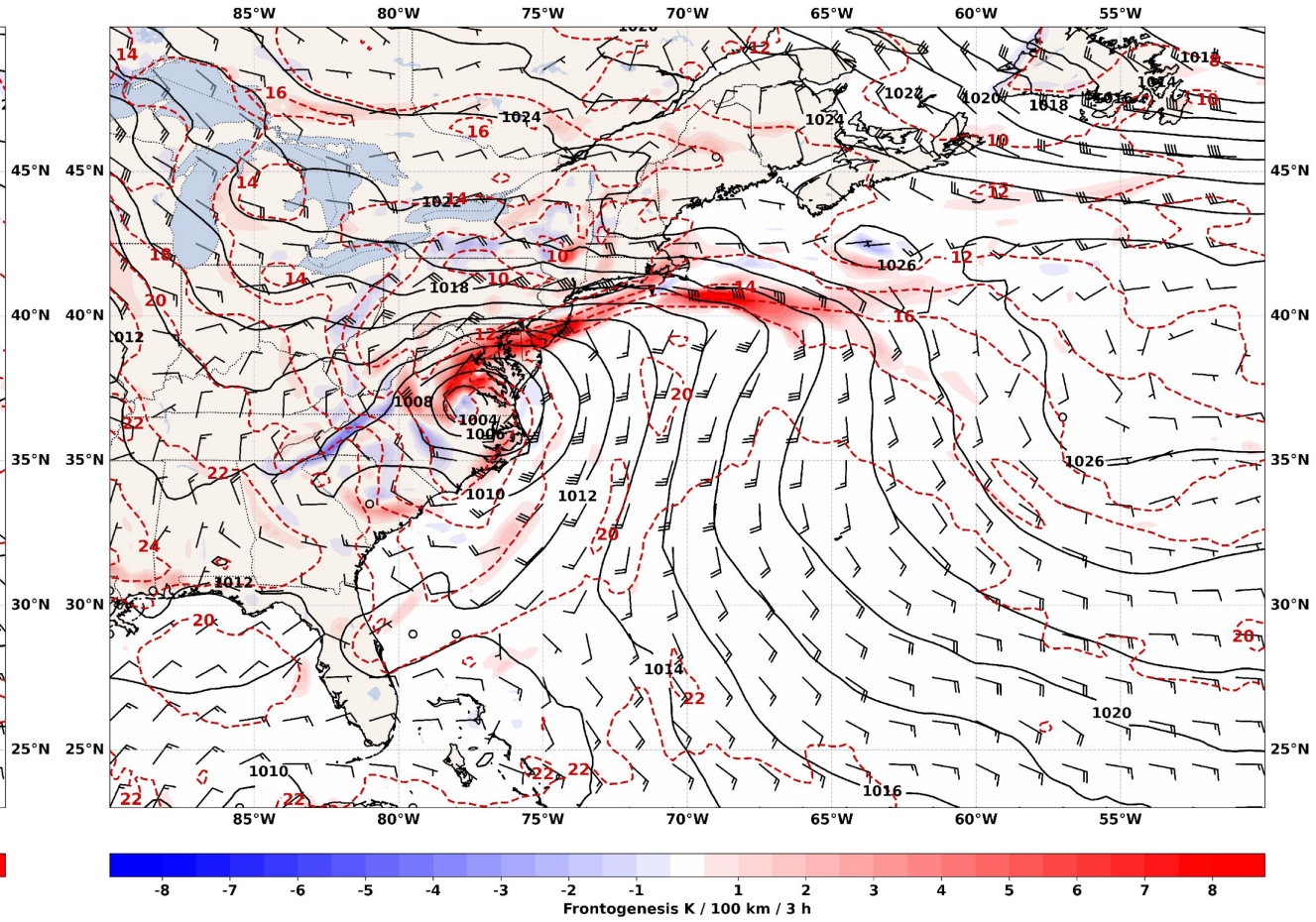
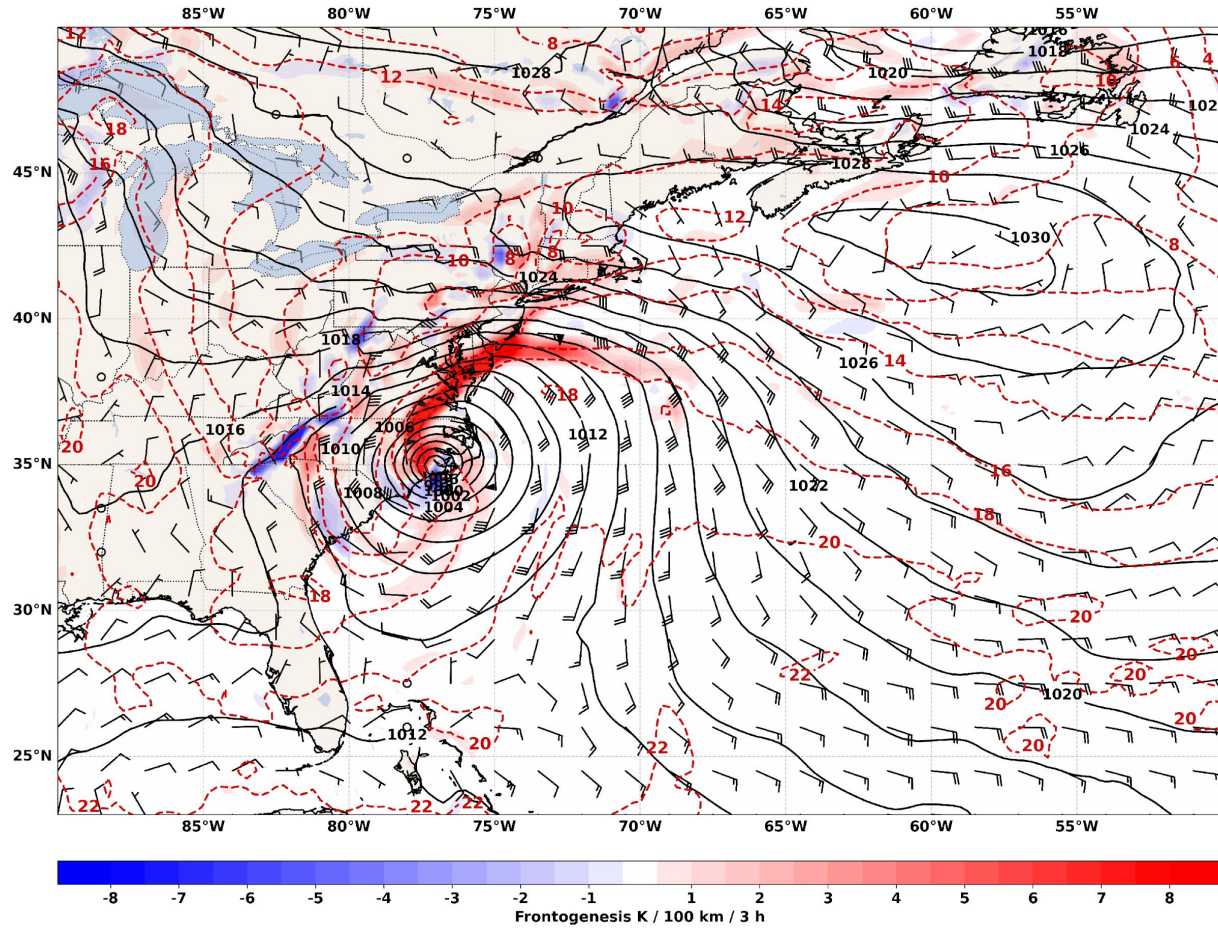
MSLP (contours, hPa), 1000–500-hPa Thickness (red/blue, dam) & 250-hPa winds (shaded, m/s)  
Valid at 2023-09-25 00:00:00



# MSLP (Contours, hPa) and 925-hPa Temperatures (dashed contours, °C), Winds (kt, barbs) and Frontogenesis (K/100 km/3h, shaded) valid 12 UTC 23 Sep 2023 (left) and 0000 UTC 24 Sep 2023 (right)

MSLP (solid, hPa), 925-hPa Temp (dashed, C), Winds (barbs) & Frontogenesis (shaded, K/100km/3h)  
Valid at 2023-09-23 12:00:00

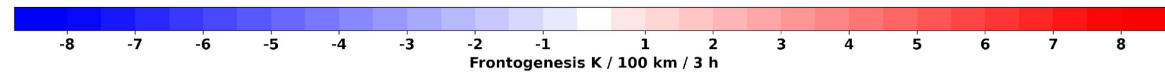
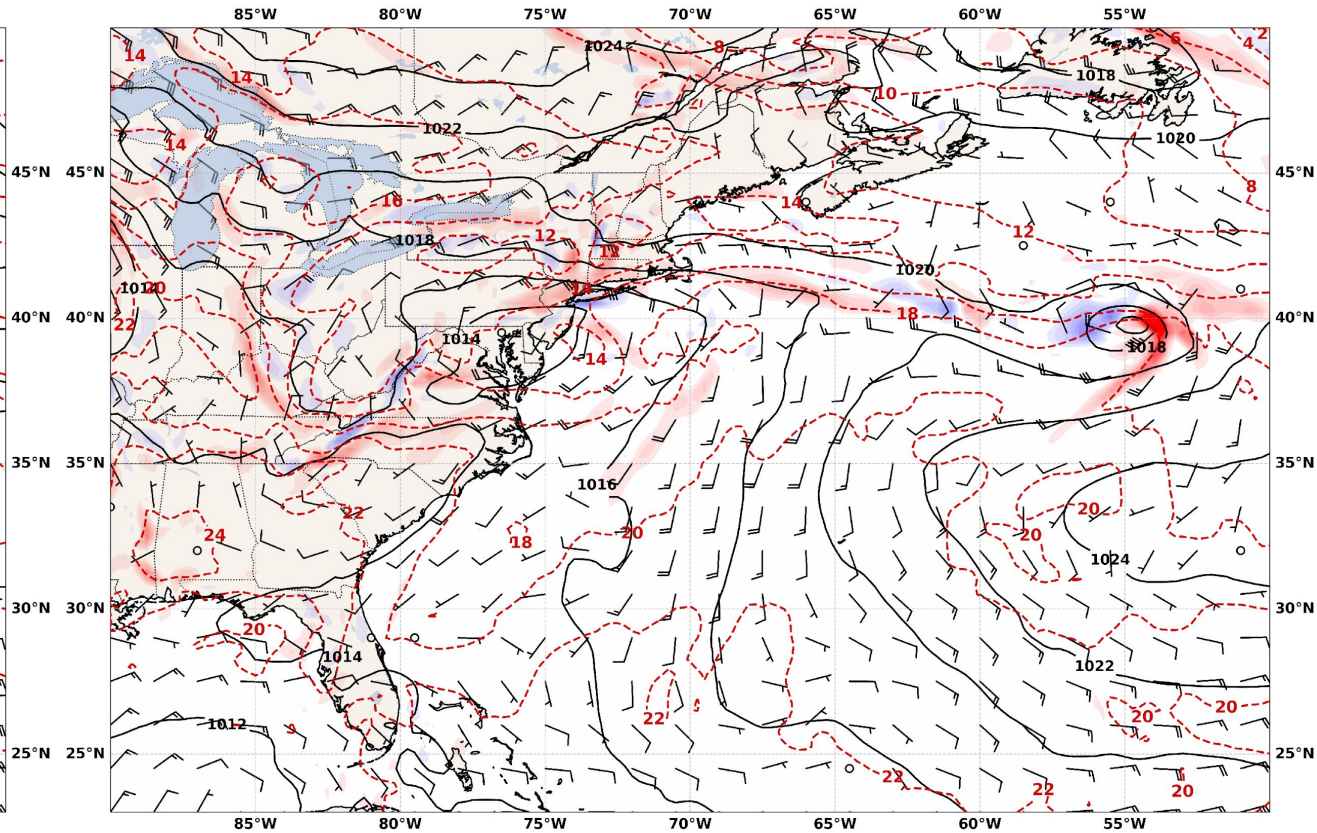
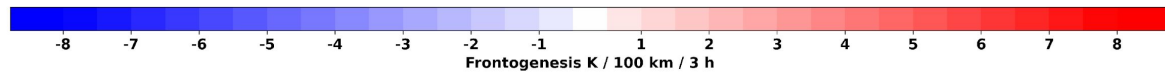
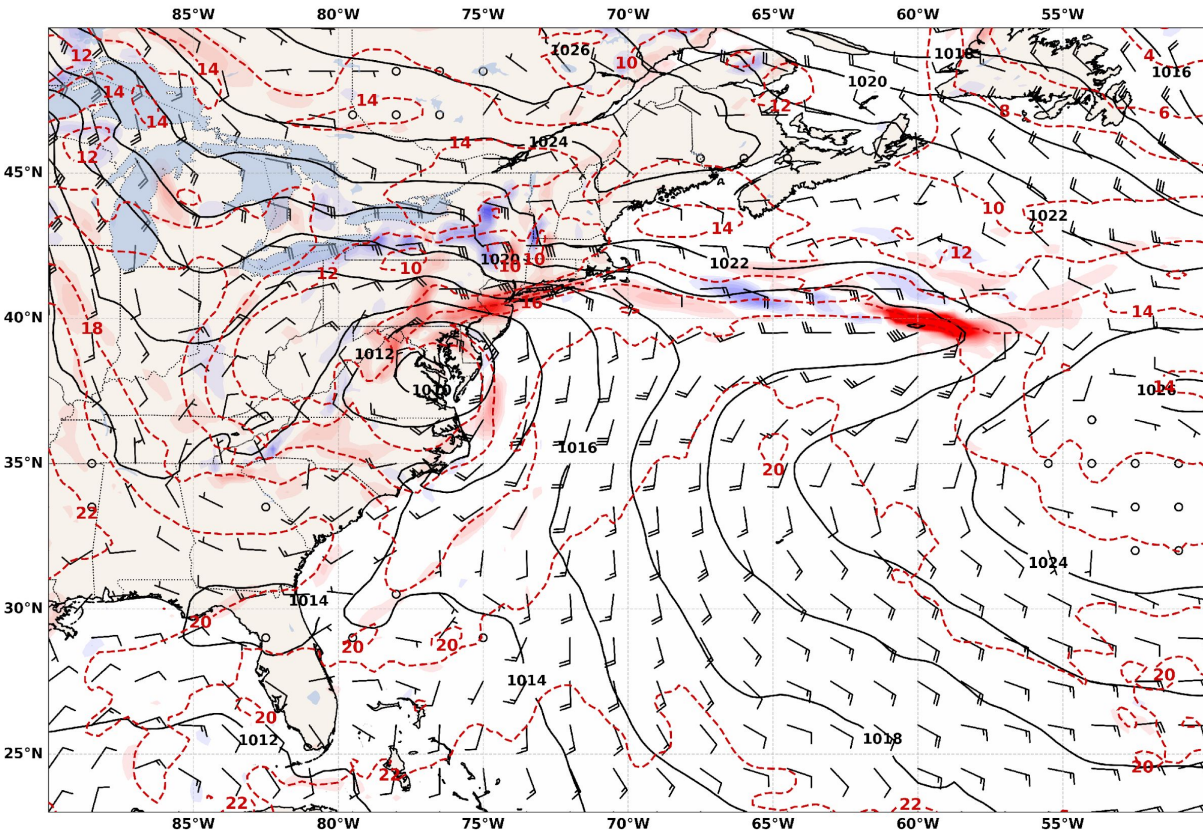
MSLP (solid, hPa), 925-hPa Temp (dashed, C), Winds (barbs) & Frontogenesis (shaded, K/100km/3h)  
Valid at 2023-09-24 00:00:00



# MSLP (Contours, hPa) and 925-hPa Temperatures (dashed contours, °C), Winds (kt, barbs) and Frontogenesis (K/100 km/3h, shaded) valid 12 UTC 24 Sep 2023 (left) and 0000 UTC 25 Sep 2023 (right)

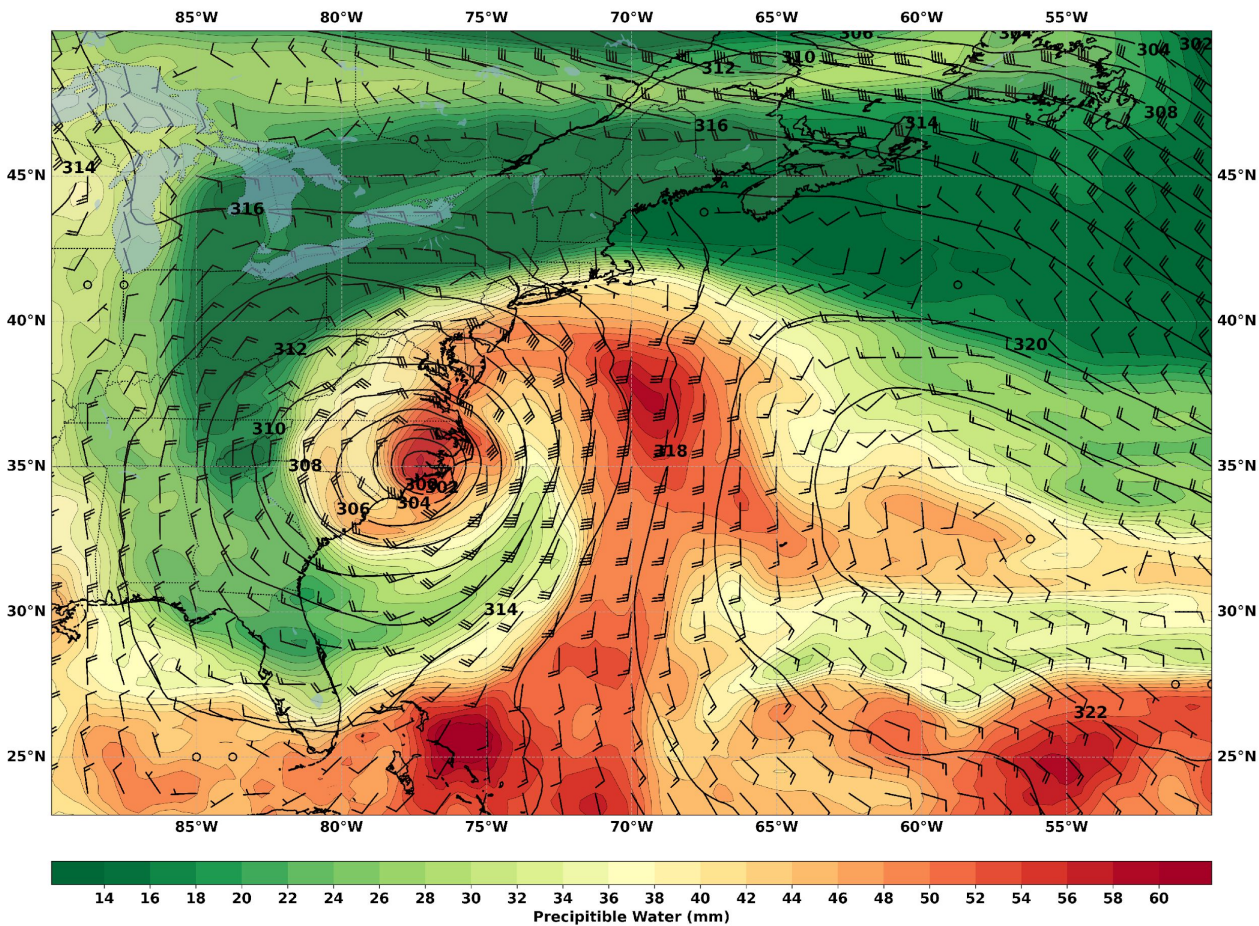
MSLP (solid, hPa), 925-hPa Temp (dashed, C), Winds (barbs) & Frontogenesis (shaded, K/100km/3h)  
Valid at 2023-09-24 12:00:00

MSLP (solid, hPa), 925-hPa Temp (dashed, C), Winds (barbs) & Frontogenesis (shaded, K/100km/3h)  
Valid at 2023-09-25 00:00:00

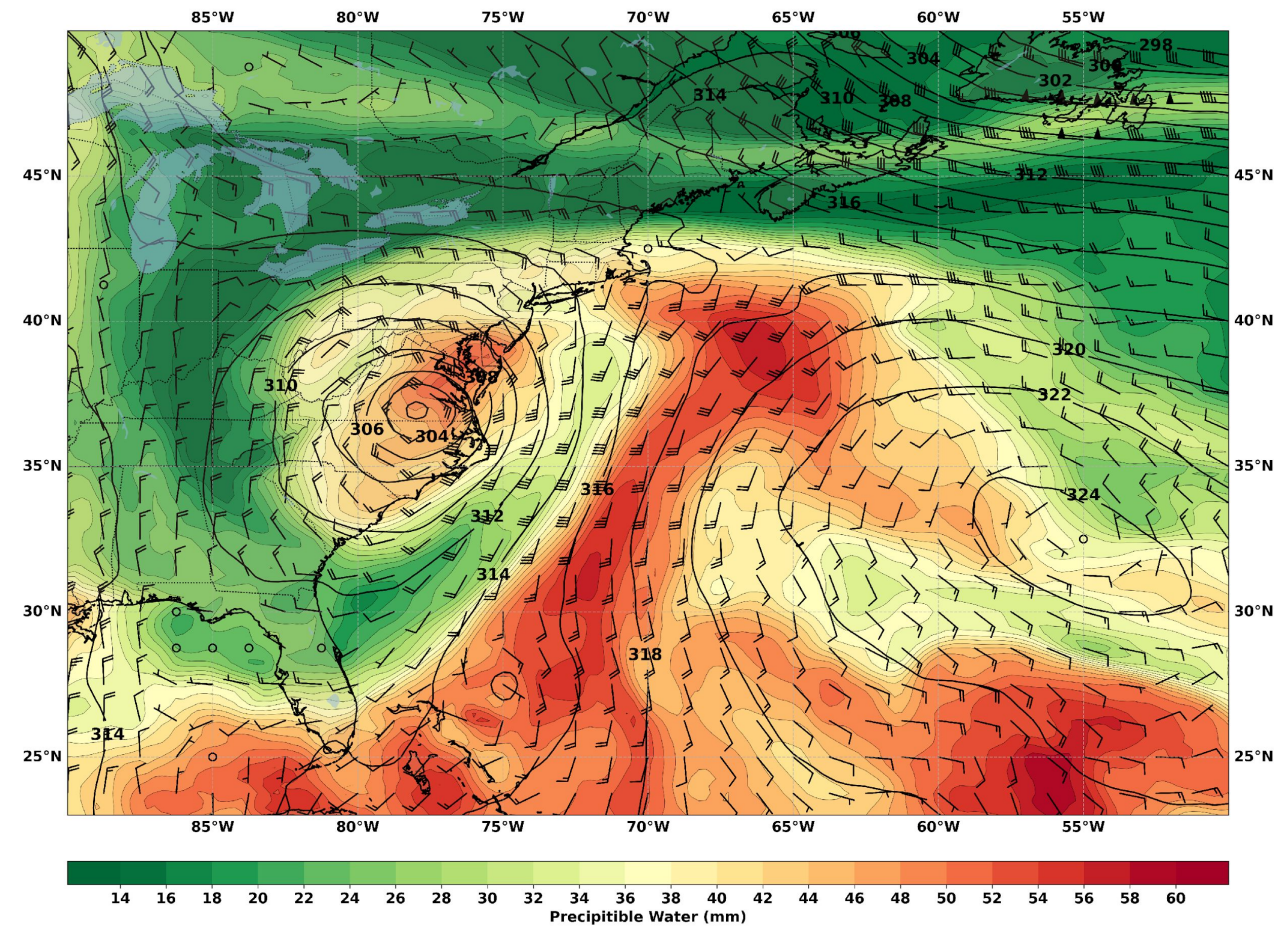


# 700-hPa Heights (contours, dam), Winds (barbs, kt), and Precipitable Water (Shaded, color bar) for 1200 UTC 23 September 2023 (left) and 0000 UTC 24 September 2023 (right)

700-hPa heights (contours, dam), Winds & Precipitable Water  
Valid at 2023-09-23 12:00:00

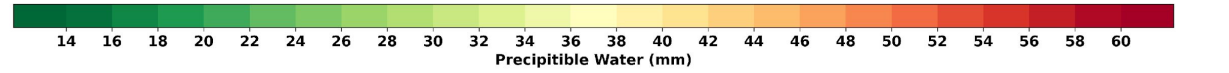
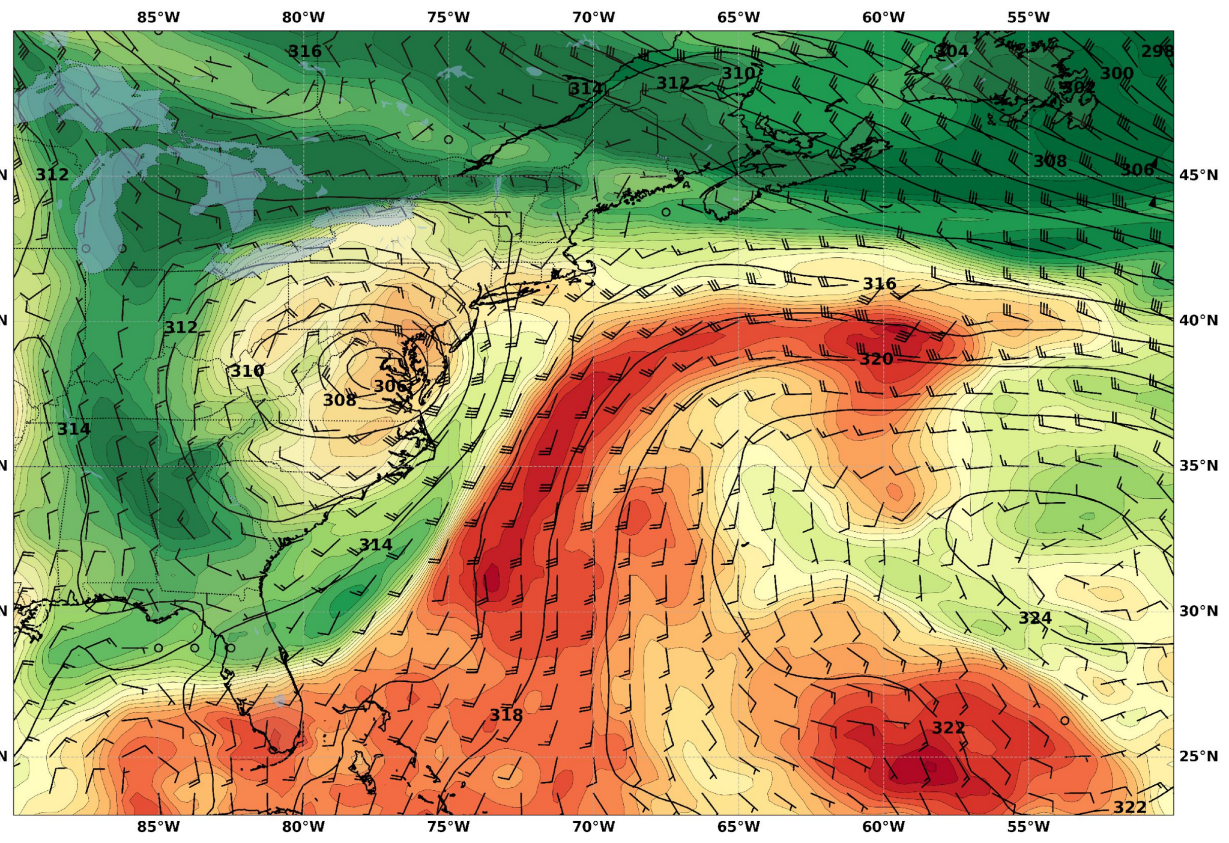


700-hPa heights (contours, dam), Winds & Precipitable Water  
Valid at 2023-09-24 00:00:00

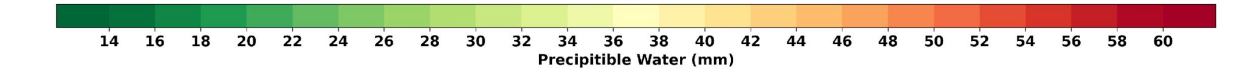
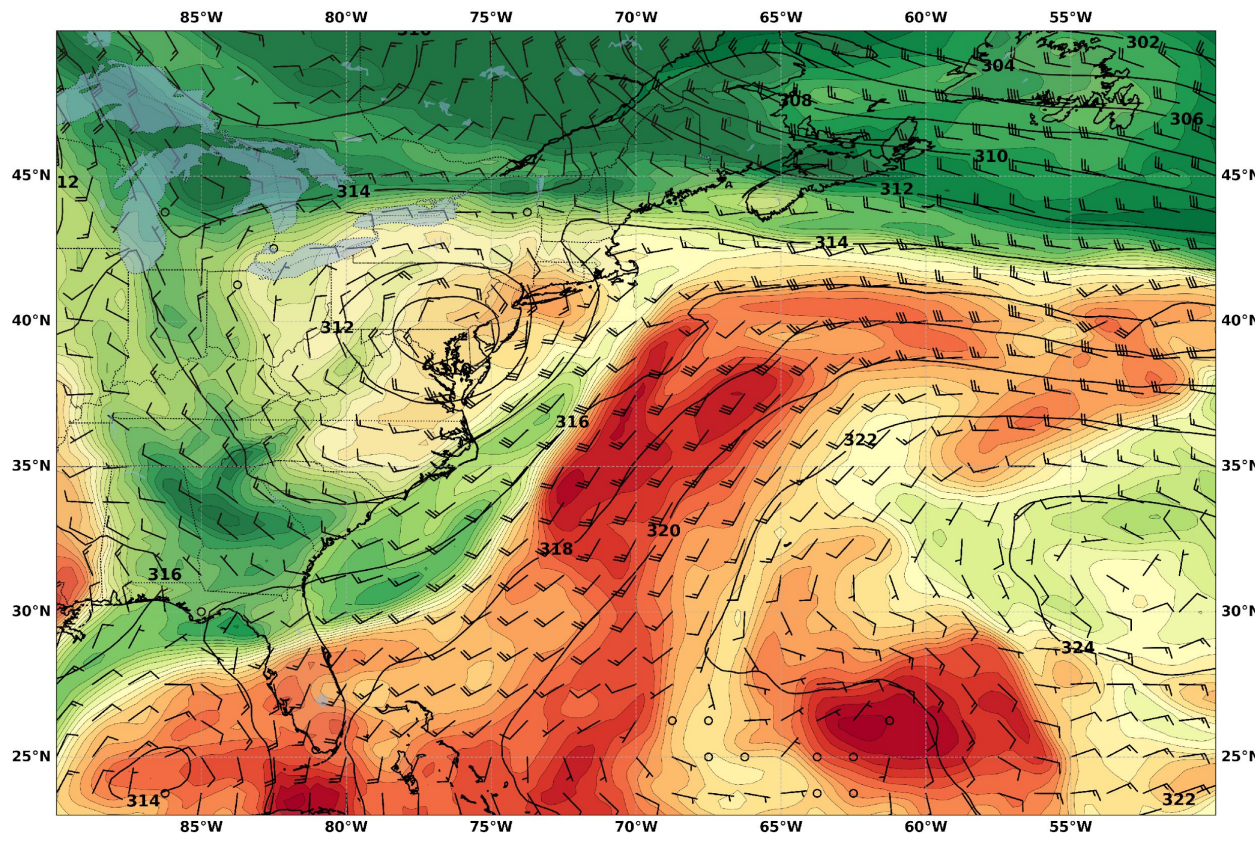


# 700-hPa Heights (contours, dam), Winds (barbs, kt), and Precipitable Water (Shaded, color bar) for 1200 UTC 24 September 2023 (left) and 0000 UTC 25 September 2023 (right)

700-hPa heights (contours, dam), Winds & Precipitable Water  
Valid at 2023-09-24 12:00:00



700-hPa heights (contours, dam), Winds & Precipitable Water  
Valid at 2023-09-25 00:00:00

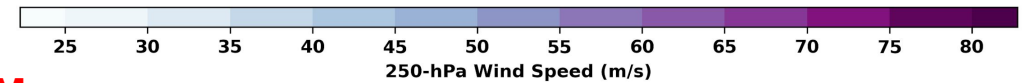
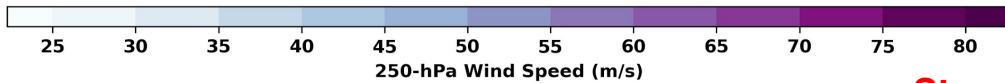
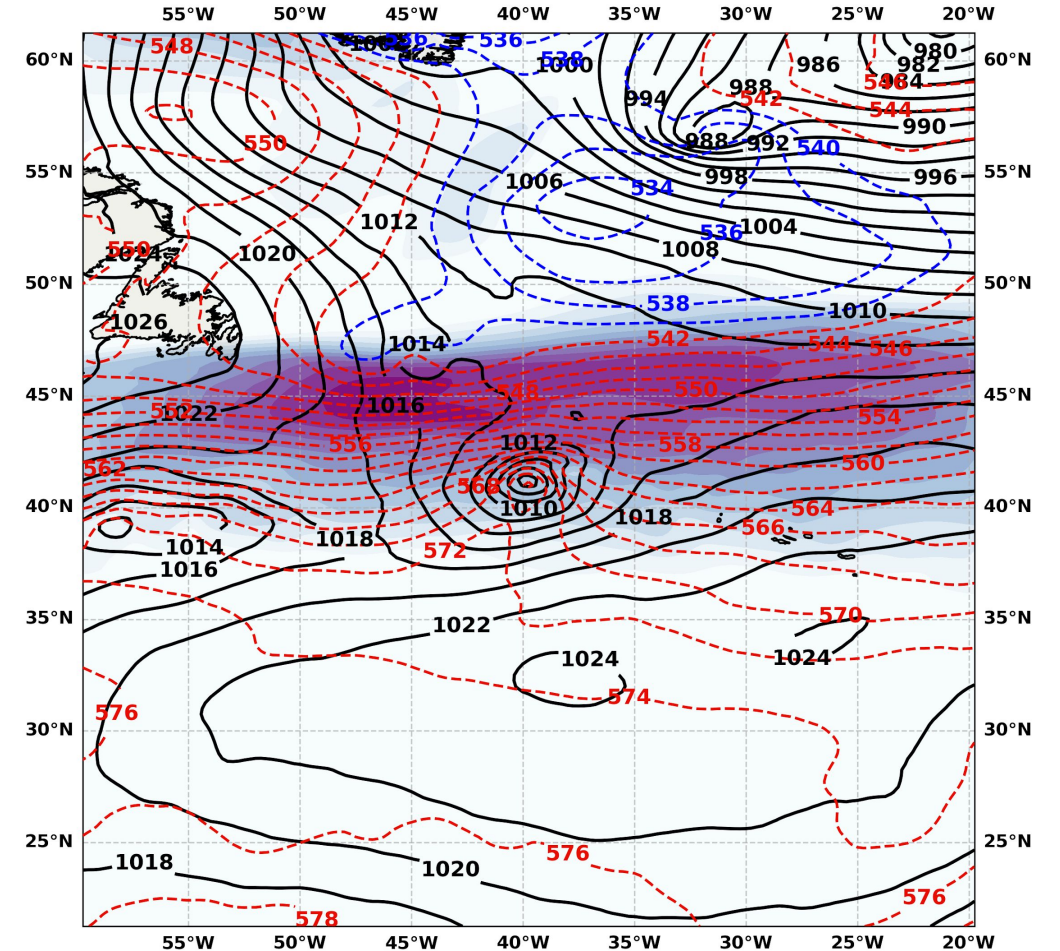
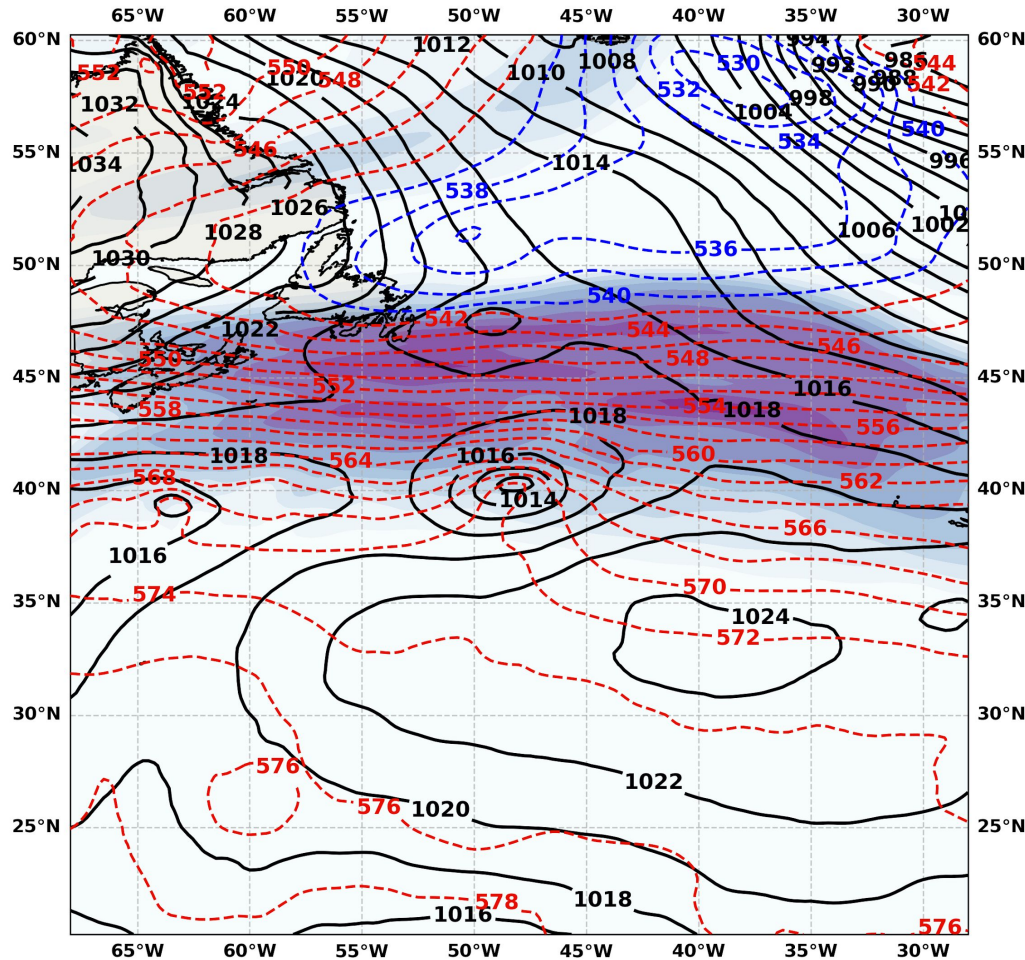


# MSLP (Contours, hPa) and 1000-500-hPa Thickness (dam) and 250-hPa Winds (m s<sup>-1</sup>)

## valid 1200 UTC 25 Sep 2023 (left) and 0000 UTC 26 Sep 2023 (right)

MSLP (contours, hPa), 1000-500-hPa Thickness (red/blue, dam) & 250-hPa winds (shaded, m/s)  
Valid at 2023-09-25 12:00:00

MSLP (contours, hPa), 1000-500-hPa Thickness (red/blue, dam) & 250-hPa winds (shaded, m/s)  
Valid at 2023-09-26 00:00:00

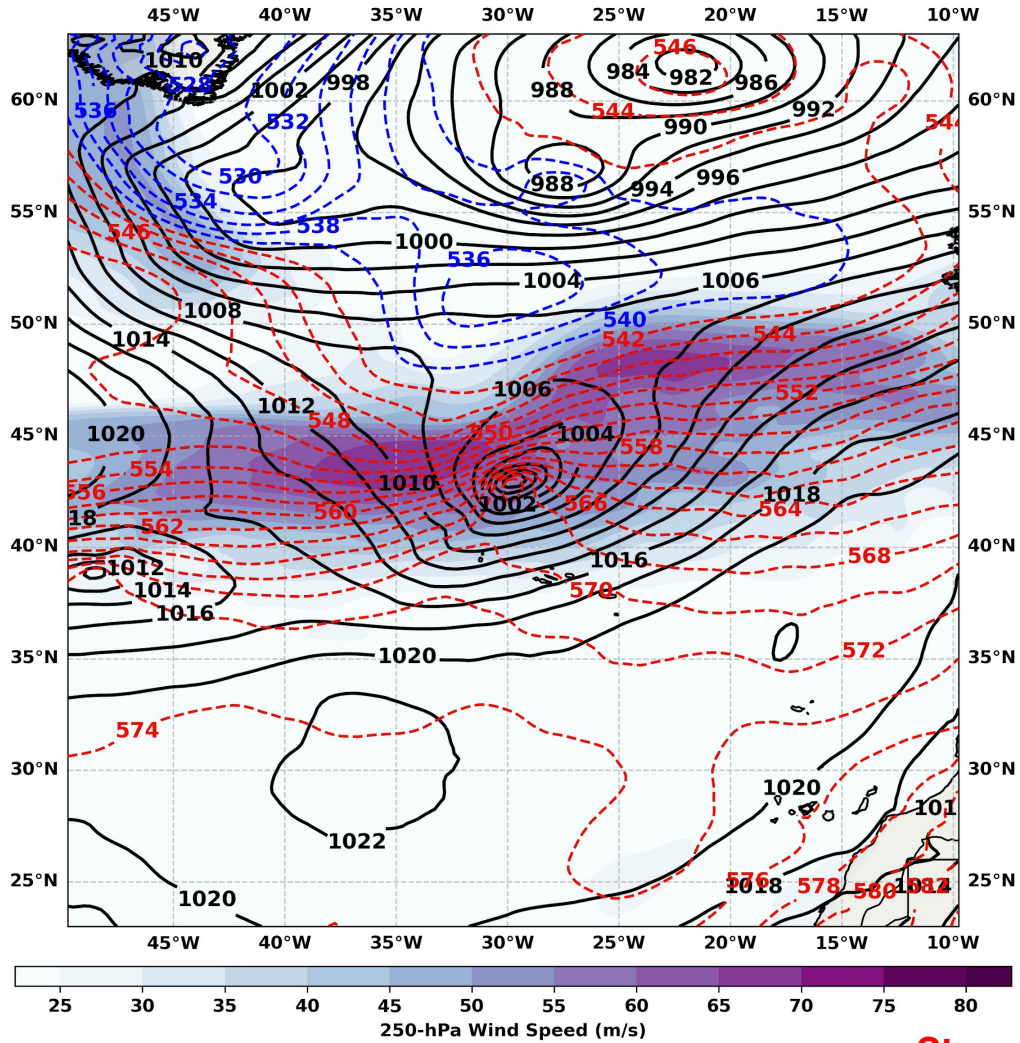


Storm-Centered Maps

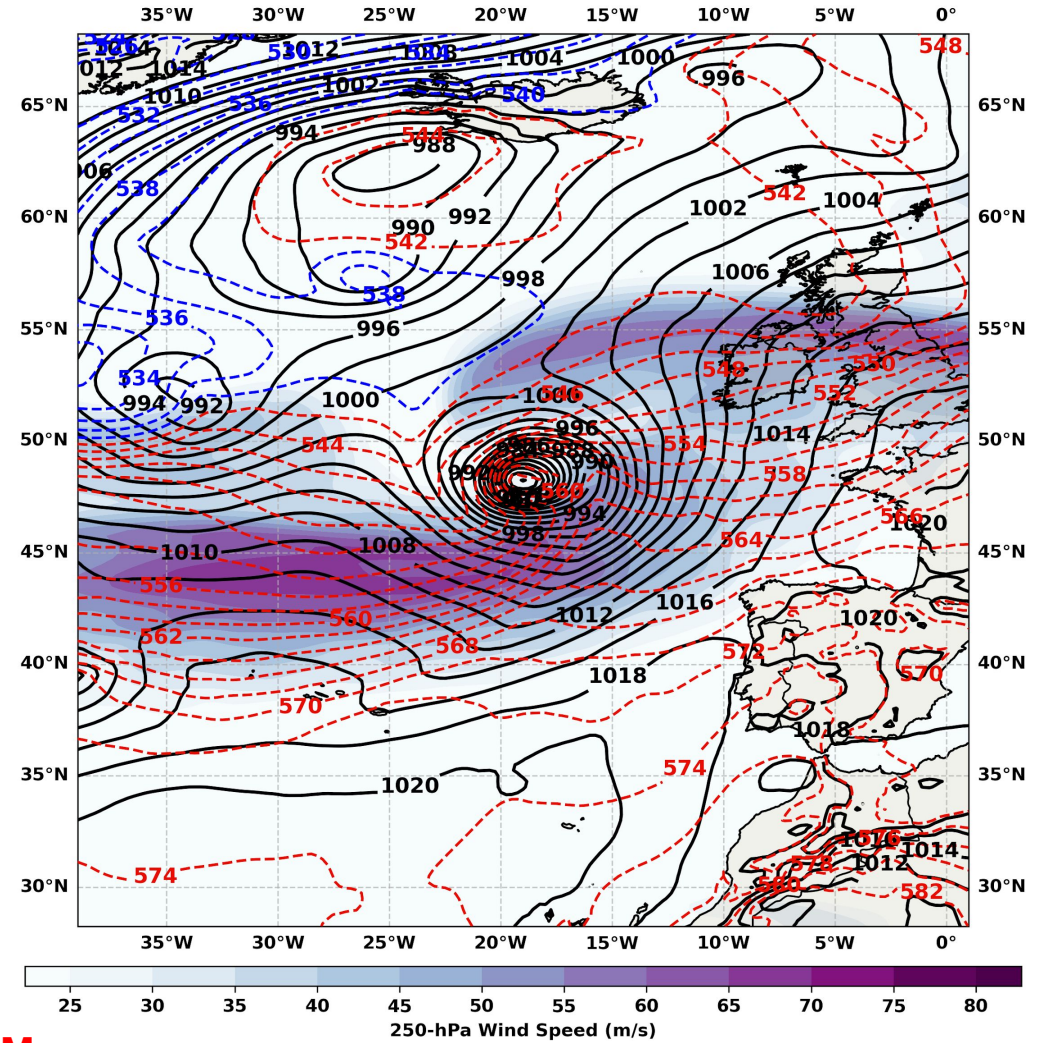
# MSLP (Contours, hPa) and 1000–500-hPa Thickness (dam) and 250-hPa Winds ( $m s^{-1}$ )

## valid 1200 UTC 26 Sep 2023 (left) and 0000 UTC 27 Sep 2023 (right)

MSLP (contours, hPa), 1000–500-hPa Thickness (red/blue, dam) & 250-hPa winds (shaded, m/s)  
Valid at 2023-09-26 12:00:00



MSLP (contours, hPa), 1000–500-hPa Thickness (red/blue, dam) & 250-hPa winds (shaded, m/s)  
Valid at 2023-09-27 00:00:00



Storm-Centered Maps

# Conclusions

- **Five North Atlantic (NATL) TCs were active during September 2023: Lee, Margot, Nigel, Ophelia, and Philippe.**
- **TC Nigel moved eastward, underwent extratropical transition, and spawned a bomb cyclone that was absorbed into a northeastern NATL gyre**
- **TS Ophelia was the most meteorologically interesting of the five NATL TCs during September 2023**
- **TC Ophelia “birthed” two mesoscale frontal waves (MFWs) while offshore of the MidAtlantic coast**
- **The northern-most MFW moved eastward across the NATL, became a strong bomb cyclone, and wrought havoc in the UK as Storm Agnes**

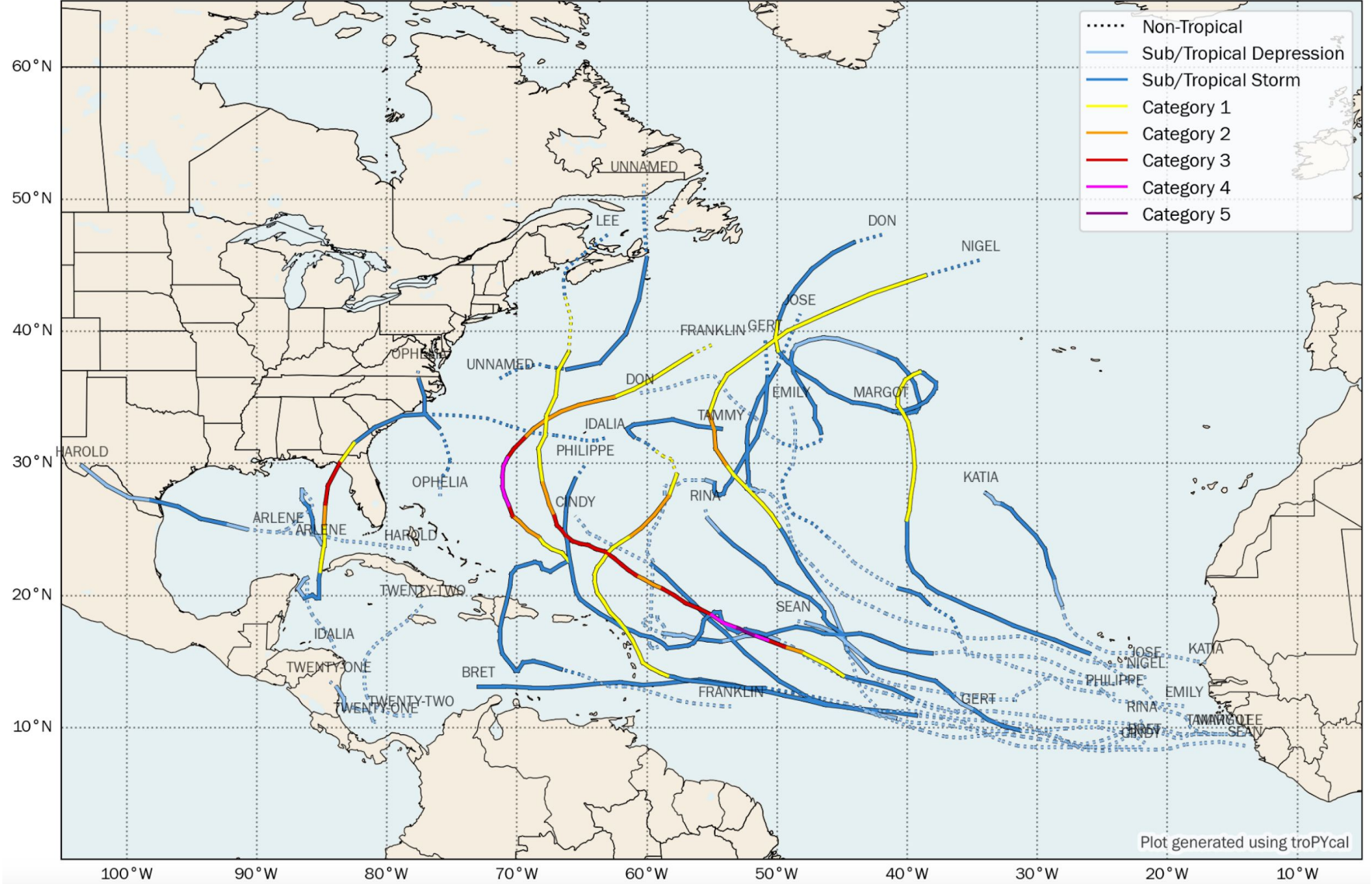


# Extra Slides

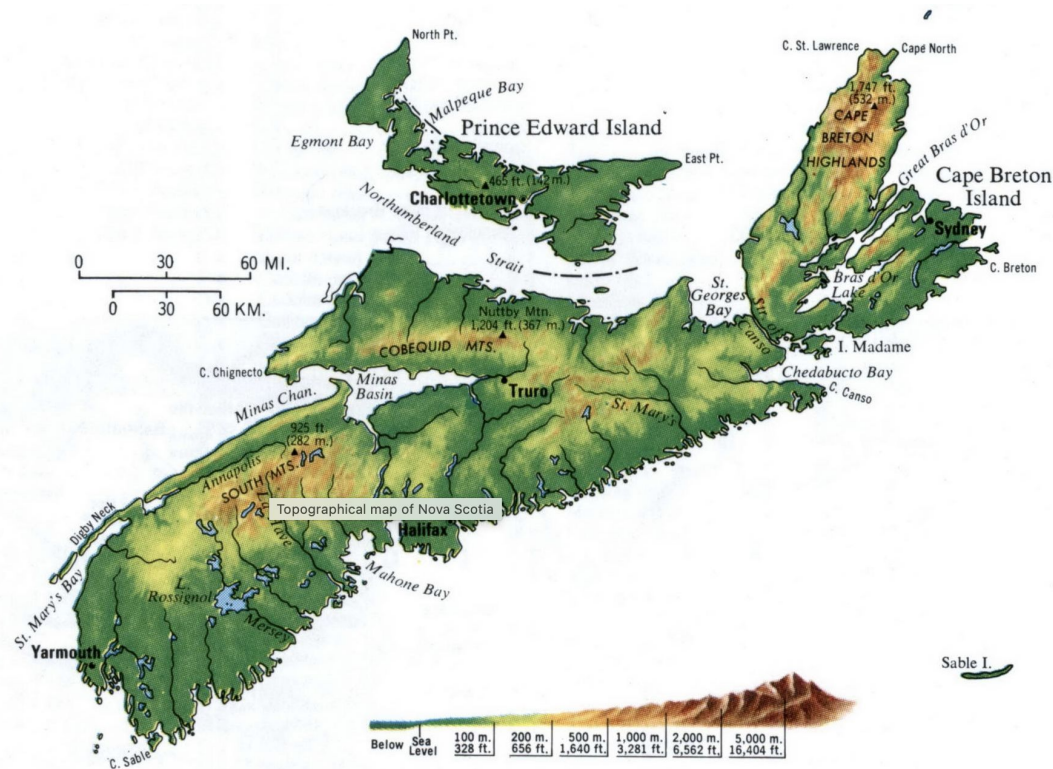
# 2023 NATL TC Season Tracks (Tomer Burg)

2023 Atlantic Hurricane Season

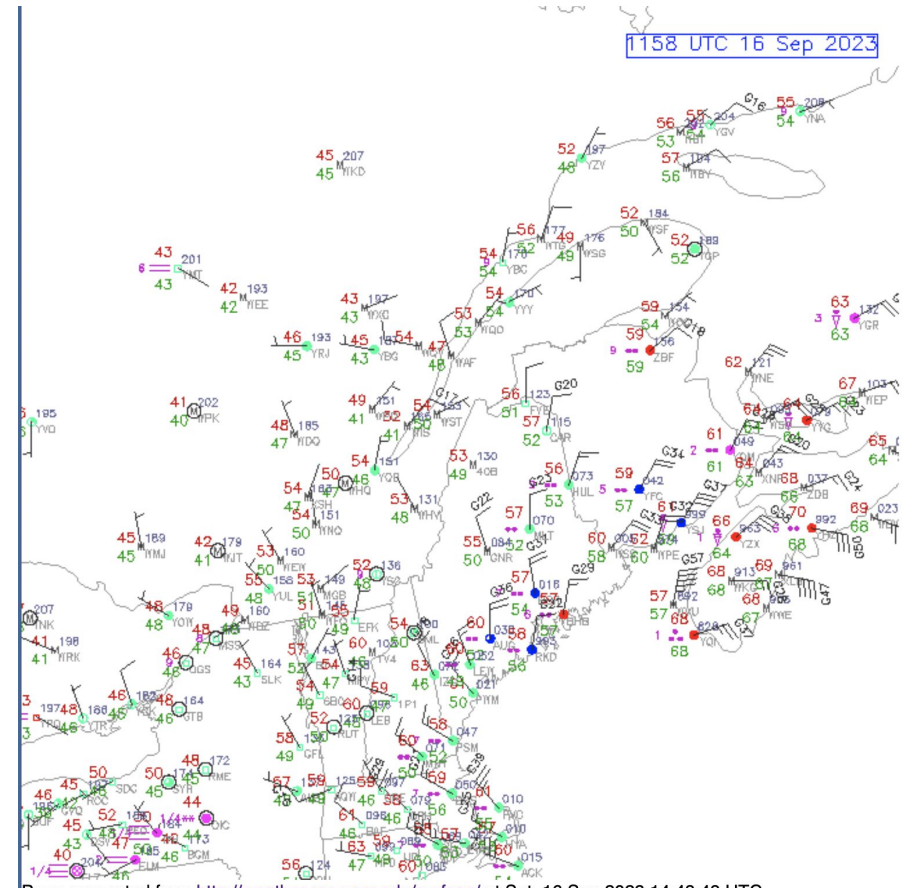
20 named • 7 hurricanes • 3 major  
145.4 Cumulative ACE



# TC Lee: Nova Scotia Terrain (left) and Surface Map (right) for 1200 UTC 16 September 2023

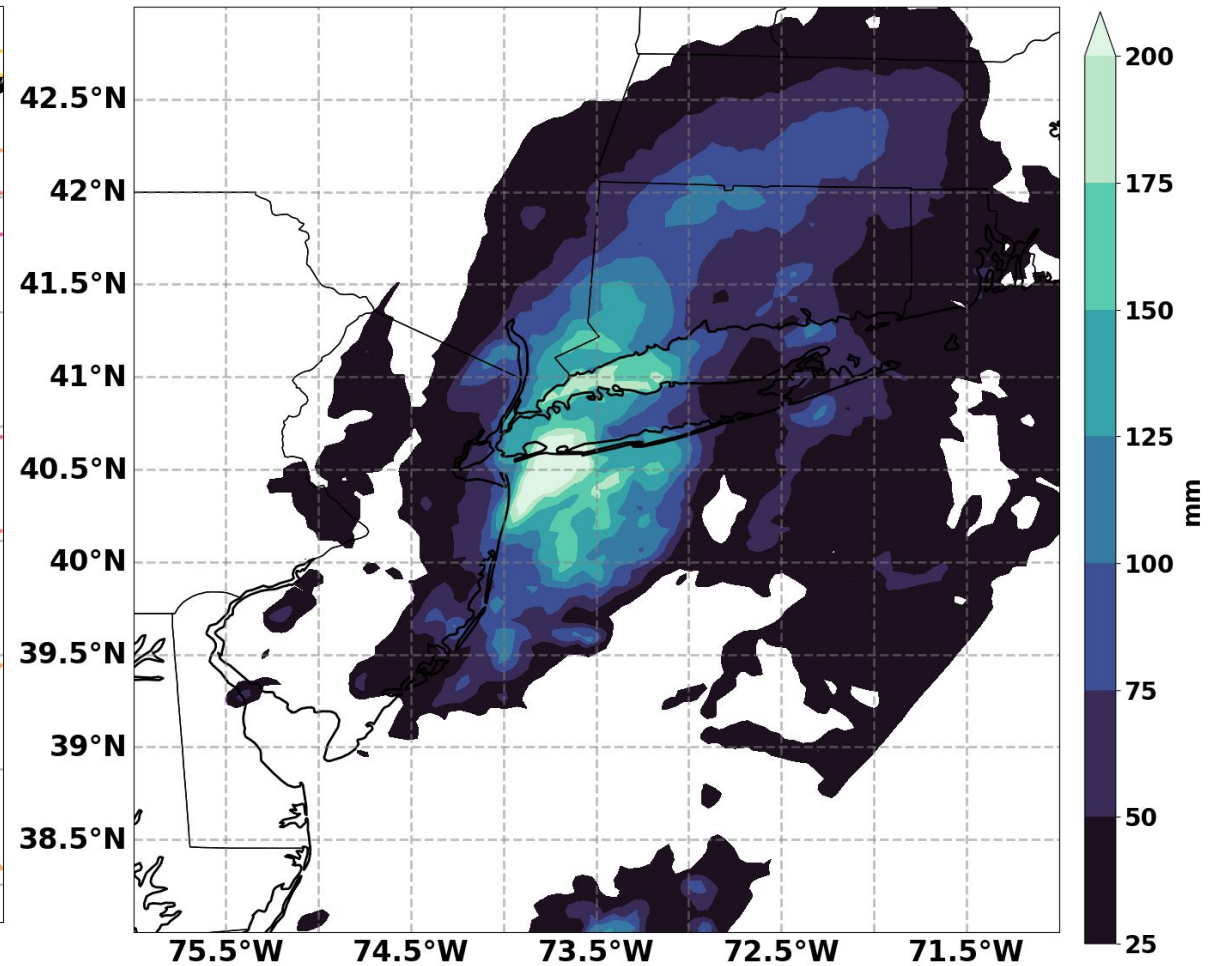
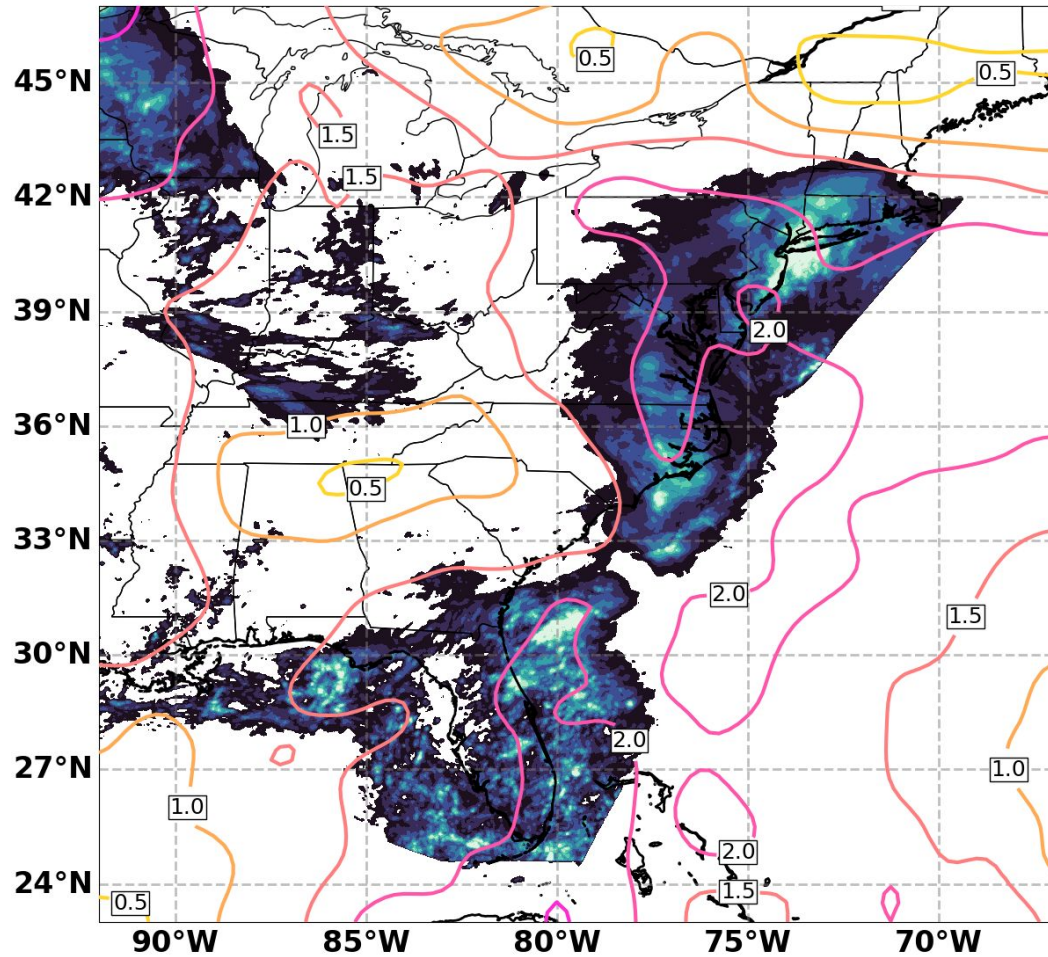


Nova Scotia topographical map  
Topographical map province Nova Scotia. Free printable topographic map Nova Scotia, Canada.

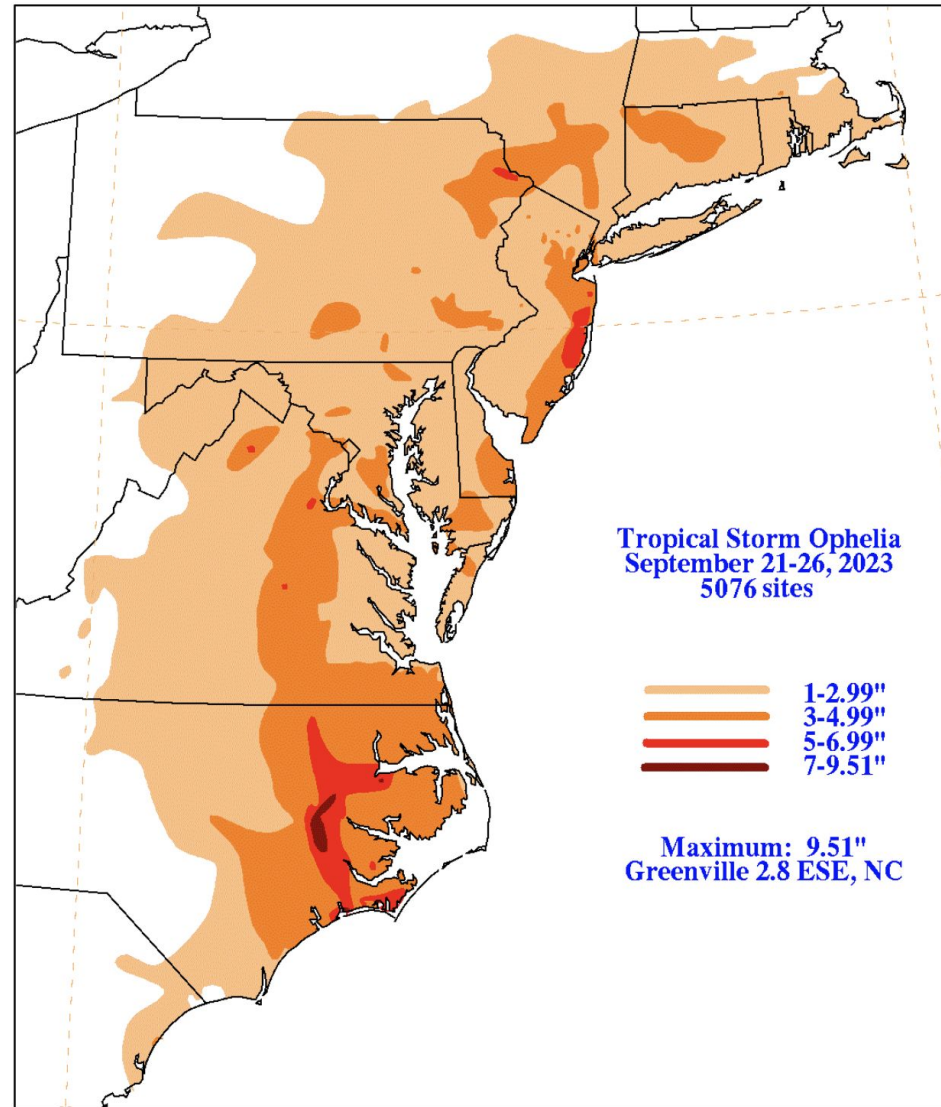


Page generated from <http://weather.rap.ucar.edu/surface/> at Sat, 16 Sep 2023 14:48:48 UTC.

# TC Ophelia (2023): Rainfall, 22–29 Sep and max PWAT (left) and rainfall, 28–29 Sep (right)



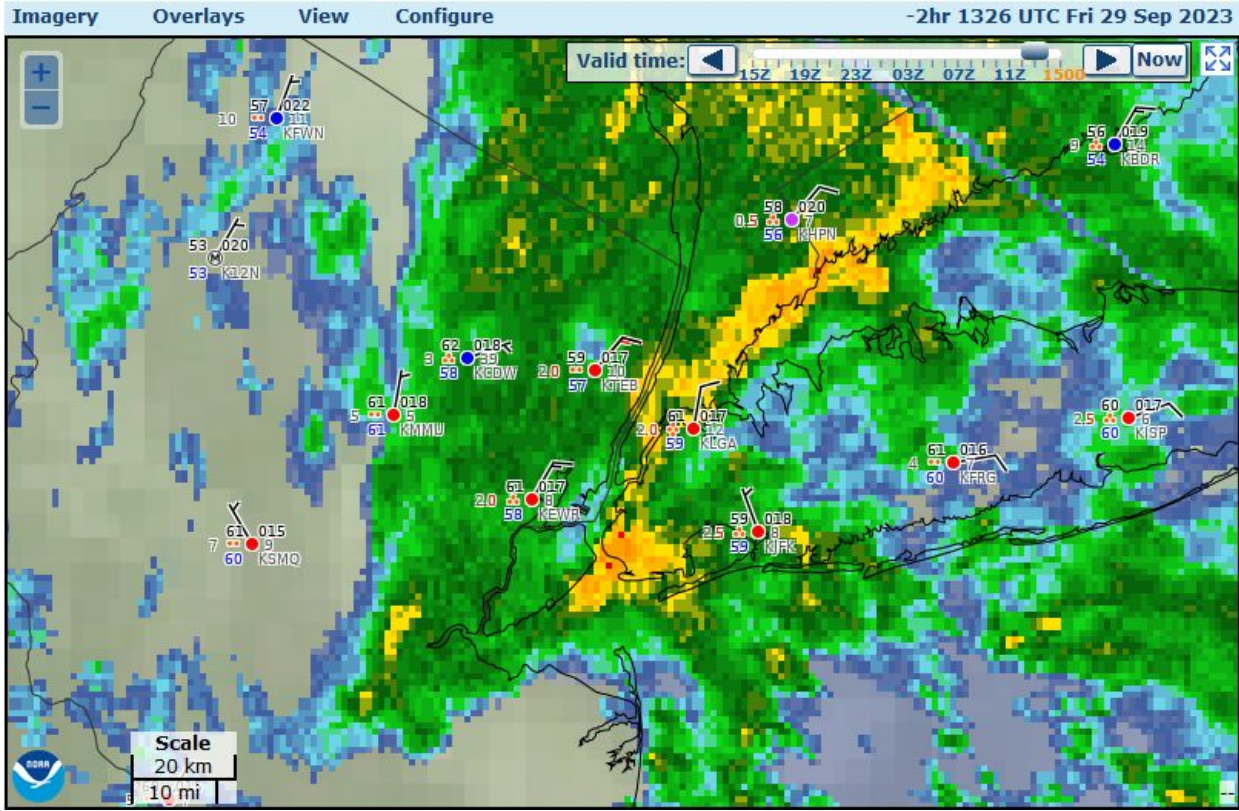
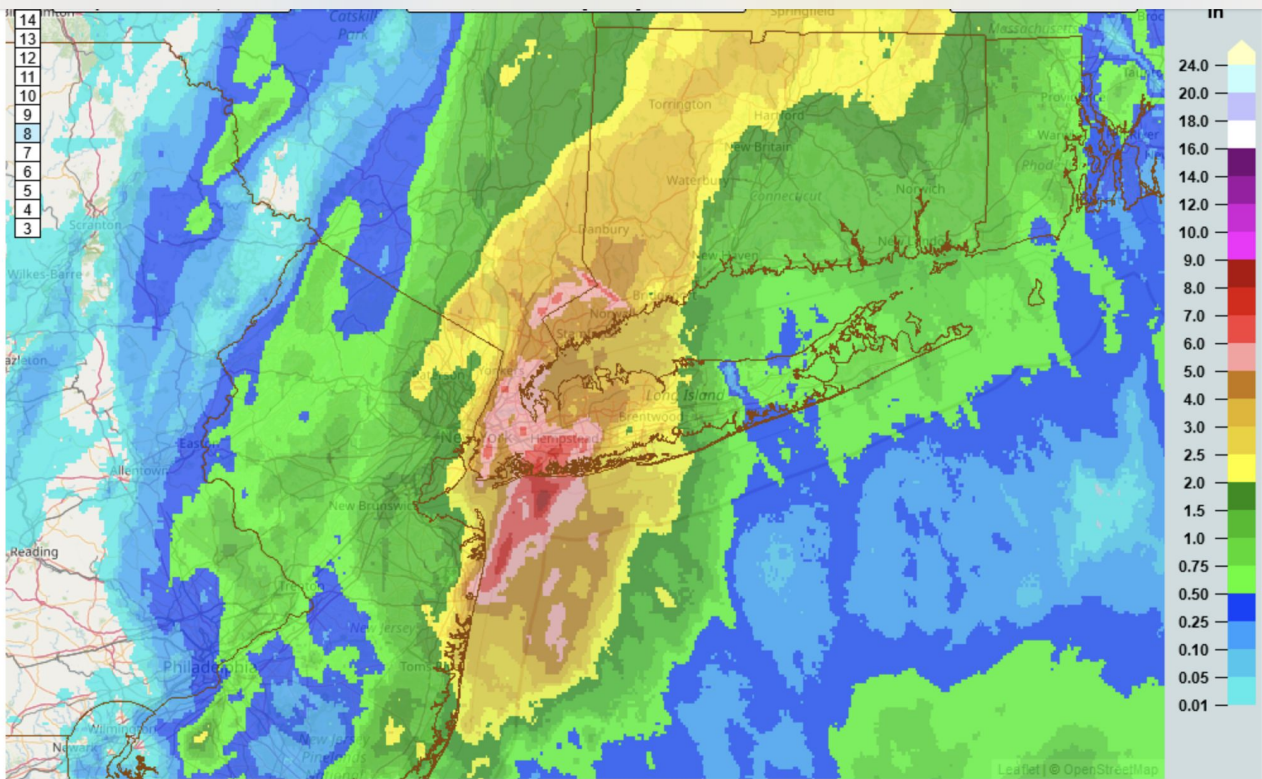
# TC Ophelia (2023): Rainfall (WPC)



Observed rainfall (inches) from Tropical Storm Ophelia over the eastern United States. Image courtesy of David Roth NOAA's Weather Prediction Center.

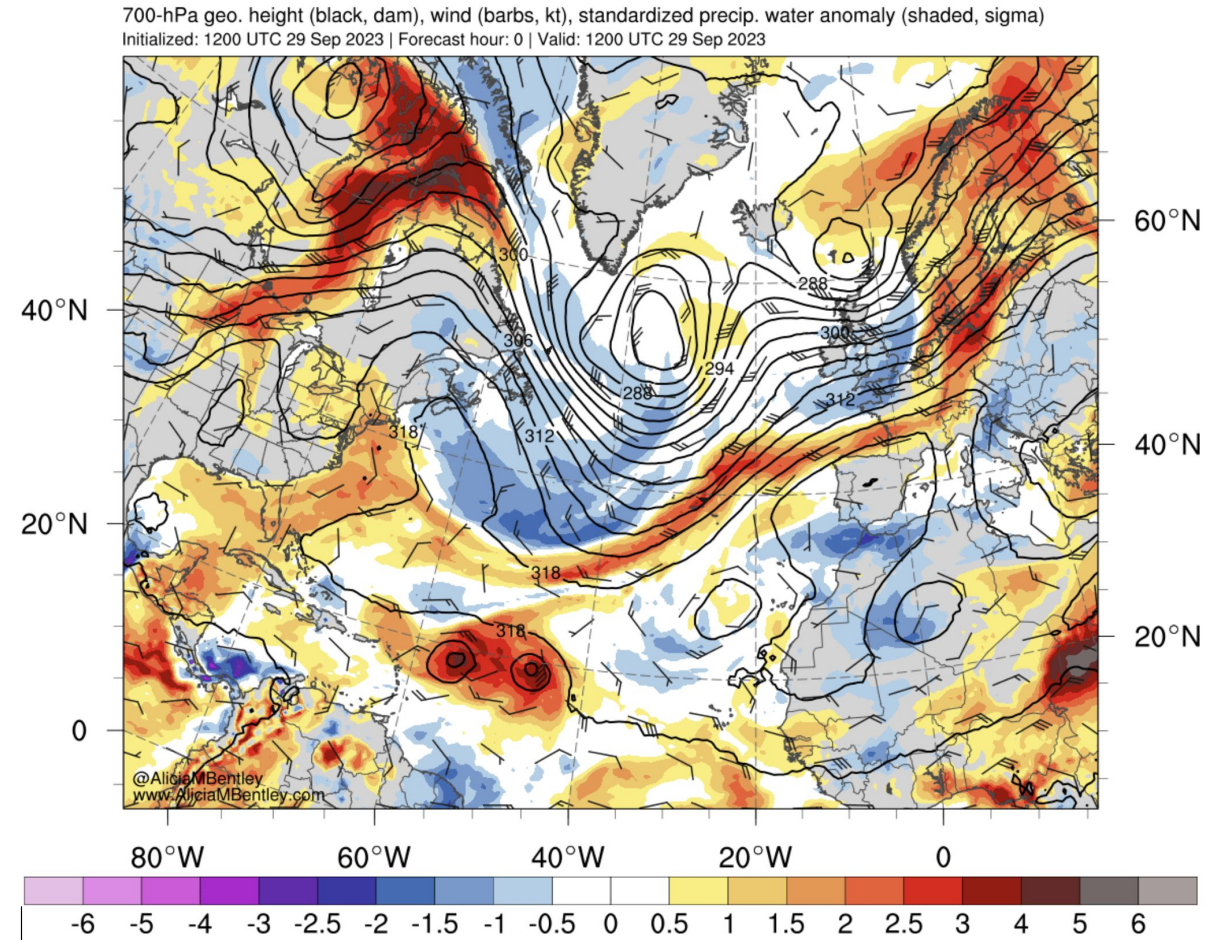
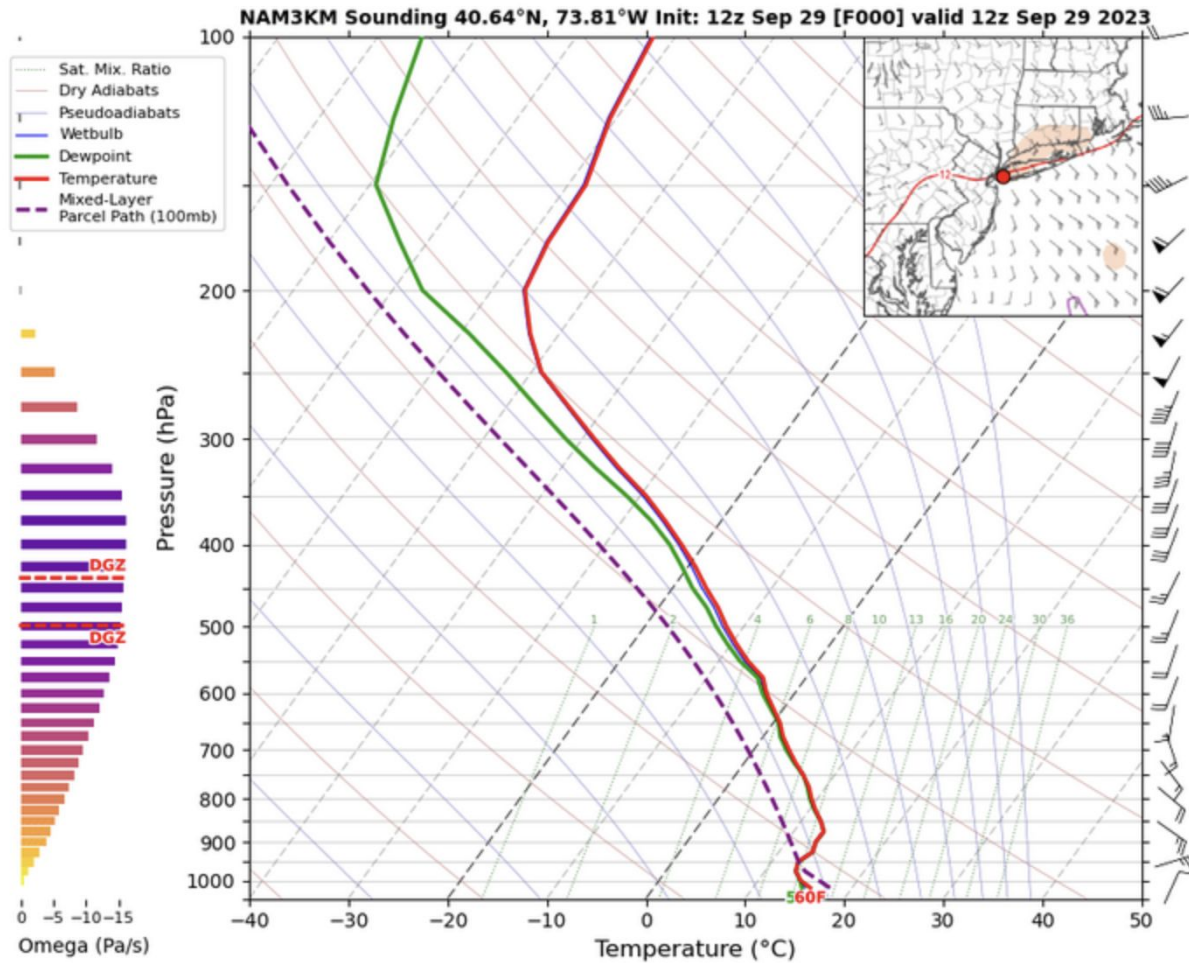
# Heavy Rainfall in New York City on 28–29 September 2023

Observed Rainfall (Left) and 2-h Rainfall ending 1326 UTC 29 September 2023



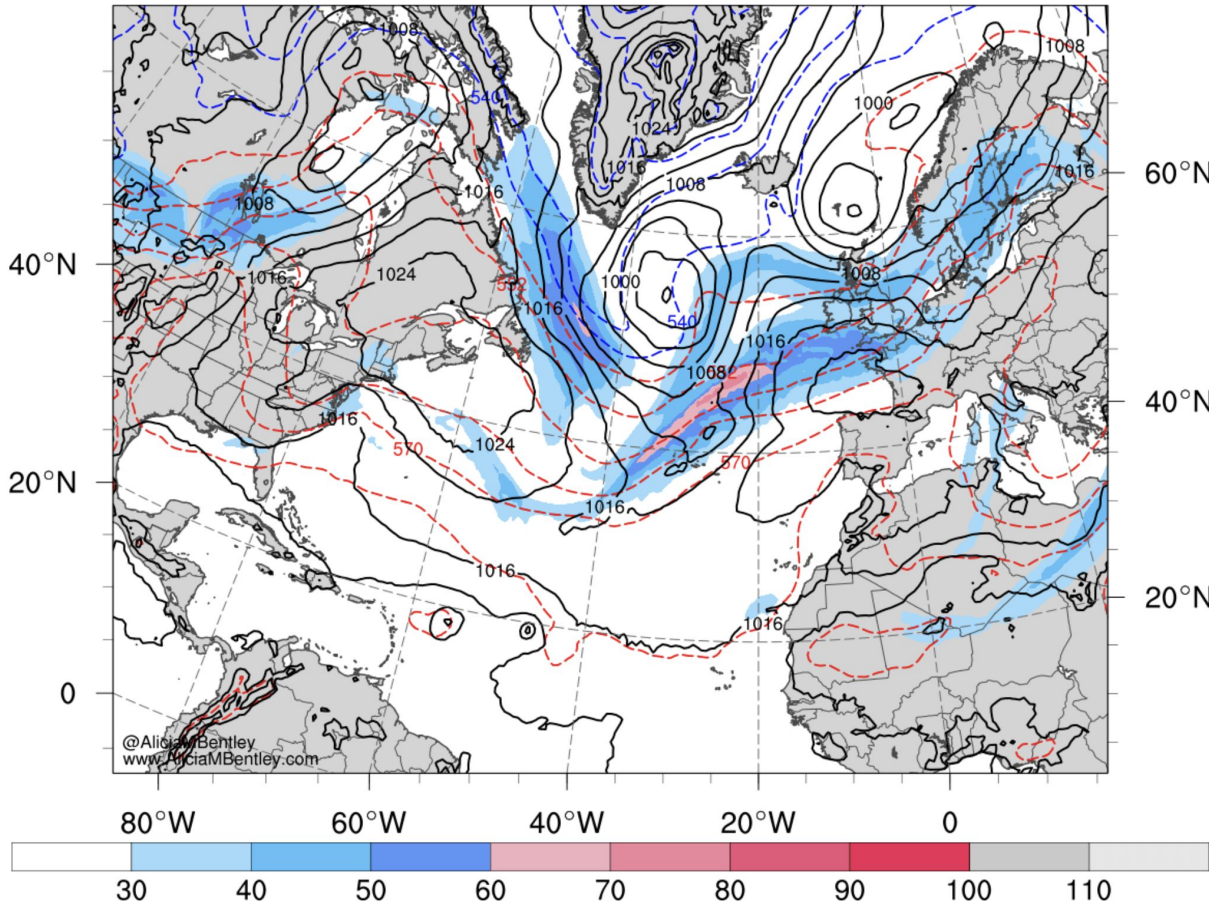
Source: Yeechian Low

# NAM Sounding for New York City Valid 1200 UTC 29 Sep 2023 (Left); 700-hPa Heights (contours), Winds (barbs), and Standardized PW Anomalies (shaded, mm) (Right)



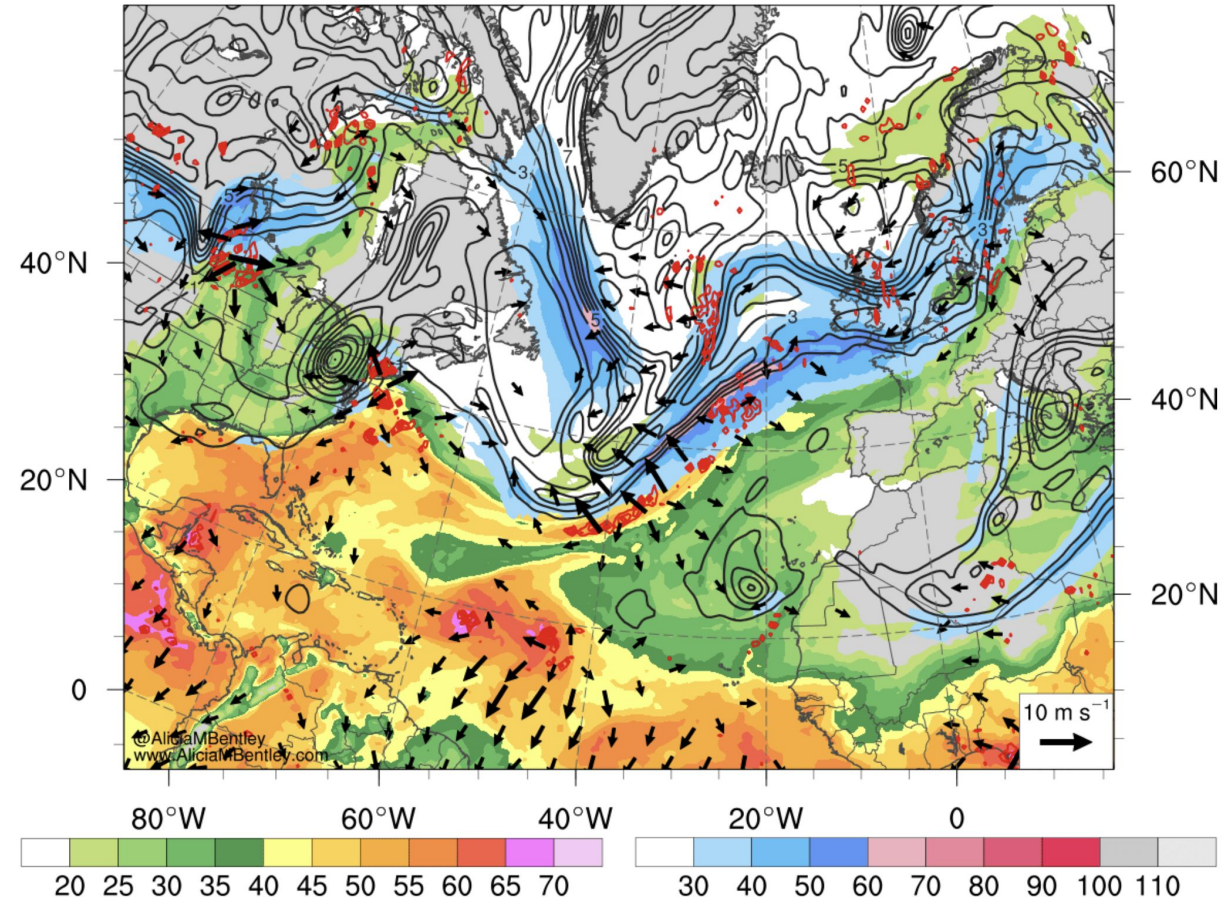
# Valid 1200 UTC 29 September 2023

MSLP (black, hPa), 1000-500-hPa thickness (red/blue, dam), 250-hPa wind speed (shaded, m/s)  
 Initialized: 1200 UTC 29 Sep 2023 | Forecast hour: 0 | Valid: 1200 UTC 29 Sep 2023



**SLP (contours, hPa)**  
**1000-500-hPa thickness (dashed contours, dam)**  
**250-hPa winds (shaded, kt)**

300-200-hPa PV (gray, PVU) & irro. wind (vectors, m/s), 600-400-hPa ascent (red,  $5 \times 10^{-3}$  hPa/s), 250-hPa jet (shaded, m/s), PW (shaded, mm)  
 Initialized: 1200 UTC 29 Sep 2023 | Forecast hour: 0 | Valid: 1200 UTC 29 Sep 2023



**300-200-hPa PV (dark gray contours, PVU)**  
**Irrotational Wind Vectors (black arrows, reference vector)**  
**250-hPa Winds (shaded, cool colors,  $m s^{-1}$ )**  
**PW (shaded, warm colors, mm)**